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Economic evaluation of green water in cereal crop production: A production function approach

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ABSTRACT

A great majority of agricultural water is provided by precipitation that is stored in soil moisture, defined as green water. This water evaporates or transpires through plants, and plays a determinative role in crop growth particularly for rainfed agriculture. This study aims to assess the economic value of green water production factor that has often been ignored in the literature, as the focus was mainly given on blue water resources. We employed the production function valuation method and specify a Cobb-Douglas production function, using cereal production in the Czech Republic as a case-study. Green water use was quantified through CROPWAT model, using year-to-year precipitation and evapotranspiration data at a national level for the period 1993-2014. The green water use values were incorporated into the production function, and the marginal value of green water was elicited by computing its marginal contribution with annual average crop market prices. Estimations were based on empirical time-series data at the national level. The marginal value of green water ranged from 17 to 25 USD/1000 m^3. To our best of knowledge this is the first study that reveals the value of green water and its contribution in the production value of cereals compared to other production factors. Our findings complement previous studies regarding the crop productivity of green water. We conclude with policy implications of the study findings, highlighting the use of green water value estimations in the compilation of water accounts, as emerged in the System of Environmental-Economic Accounting for Water.

1. Introduction

Green water ($Green_w$) stands for the proportion of precipitation water which infiltrates into the unsaturated zone of soil and is temporarily stored in soil and in vegetation canopy [12-14,45,46]. The $Green_w$ concept was introduced in the mid-1990s by Falkenmark[70] who highlighted its importance as a valuable water resource. Since then, the researcher community (e.g. Savenije, 2000 [49]; Rockström, 2001 [44]; Rijsberman, 2006 [43]; Liu et al., 2009 [32]; Hanasaki et al., 2010 [21]; Aldaya et al., 2010 [1]; Hoekstra and Mekonnen, 2012a,b [23,24]; Schyns et al., 2015 [50]), as well as global initiatives (such as the ISRIC–FAO Green Water Initiative) tried to raise attention regarding this water resource.

At global scale, almost 60% of the precipitation ends up as $Green_w$ resource [38] being almost exclusively consumed by crops as well as by other terrestrial ecosystems [31]. In the study by Mekonnen and Hoekstra [34] it is reported that $Green_w$ accounts for more

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than 80% of the total consumptive water use for crop production (equivalent to 5771 km^3/year) at the global scale, with cereal crops such as wheat, rice and maize taking the largest share of total $Green_w$ use. Similar findings were also reported by previous global assessments studies [11,31,51].

Despite the strong evidence regarding the importance of $Green_w$ and the recognition of its significant contribution to food production by the scientific community and international institutions, studies on $Green_w$ are still scarce. Policy and research attention has been mainly given to blue water resources i.e. the water that partly runs off to the ocean via rivers and groundwater and is the resource that is used for irrigation as well as drinking purposes [25,26,50]; for an extensive review see Hackbart et al. [20]. Blue water, compared to $Green_w$, is more manageable and can be re-distributed to other uses through engineering applications [11,68]. However, water scarcity issues require attention to both types of water resources [26,65].

The limited number of previous studies that refer to $Green_w$ assessment followed either a water footprint quantification approach or impact assessment frameworks (e.g. Seibert and Döll, 2010 [51]; Pfister et al., 2011 [40]; Mekonnen and Hoekstra, 2011 [34]; Nuñez et al., 2013 [36]; Chenoweth et al., 2014 [4]; Quinteiro et al., 2015 [42]; Garrido et al., 2010 [17]; Hoekstra et., 2012a [23]; Schyns and Hoekstra, 2014 [57]). In these assessments, the consumptive use and productivity of water is typically computed on average terms for a certain number of years (e.g., a decade).

In this study we investigate the contribution of $Green_w$ in cereal crops production, under rainfed agriculture in Czech Republic. Both the country and the crop group were selected due to their high dependence on $Green_w$ use.[1] $Green_w$ in rainfed agriculture refers to the actual evaporation or evapotranspiration [27,50,62] and more precisely to the transpiration and soil evaporation [11]. Given the vital role of $Green_w$ in biomass production and the limited number of studies on $Green_w$ valuation, we aim to address this knowledge gap by exploring both conceptually and empirically the valuation of $Green_W$ at national scale. Our objective is to estimate the crop $Green_w$ productivity in marginal terms, i.e. the change in the output of crop production when one additional unit of water is used. For this we employ the production function method. Various methods including the residual value, mathematical programming and hedonic pricing, have been employed in past empirical studies to estimate the contribution and the economic value of freshwater[2] in several sectors (e.g. Graveline, 2016 [19]). To the best of our knowledge, this is the first study that attempts to assess the monetary value of $Green_w$ in shadow price terms.

The selection of the production function method was decided in line with the recommendations provided by the System of Environmental-Economic Accounting (SEEA) [61] regarding the eligibility of economic valuation methods [9,37,61]. Recent studies in ecosystem accounting suggest that $Green_w$ should be incorporated into accounting in line with SEEA framework and call for a better consistency in the System of Environmental-Economic Accounting framework for Water[3] (SEEA-Water) [30,48,60]. To this end our empirical outcomes aim to demonstrate an application of production function method that can facilitate the compilation of water accounts in the future.

2. Case study area

The Czech Republic is located in central Europe. Its area covers 78,866 km^2 and is inhabited by 10.5 million people. The climate is temperate continental with blending of oceanic and continental effects. The average annual temperature for the studied period 1993-2014 ranged between 6.3 °C and 9.4 °C, while the 1961-1990 long-term air temperature normal being 7.5 °C. The average annual precipitation ranged between 516 mm and 867 mm over the studied period, with long-term precipitation normal 1961-1990 being 674 mm [7]. The fluctuation of temperature and precipitation patters influences the irregular occurrence of drought and flood events in the Czech Republic [54]. Long periods of low precipitation have a significant impact on agriculture; within the study period, draughts have been recorded in the years 2000, 2003, 2007, 2009, 2012 and 2014 [54]. An excessive rainfall has also a negative impact on agricultural production, i.e. after reaching a rainfall water amount threshold the production decreases. To account for these variations in $Green_w$ estimations and its contribution to production function, we use aggregated yearly precipitation values at the national level. In 2014 the agricultural land accounted for more than 54% of the total area of the country while 99.5% of the agricultural land was non-irrigated [64]. The main agricultural crops produced in the Czech Republic are cereals, of which wheat and barley are the most harvested. The study considers all cereal crops grown in the country between 1993 and 2014 (Table 1); this period covers 10 years before and after the country's accession to the European Union. During this period, cereal crop production had been decreasing in both harvested area and output, while the gross production value showed a slightly increasing trend.

3. Methods and data

3.1. Green water use calculations

Several models have been developed to quantify the consumptive crop water use, such as IMPACT [55] and GCWM-global crop

[1] Cereals crops require significant $Green_w$ [51] and $Green_w$ footprint of cereal crops was found almost three times higher in Eastern Europe than in Northern and Western regions [35].

[2] Market price or unit resource rent price methods cannot reflect the value of water resources, let alone $Green_w$ resource, as water is usually not priced at its marginal value [34,36]. In cases where water price estimates were available, research focus was on blue water and on water basins [5,41].

[3] SEEA-Water is the statistical framework that integrates data on both environmental and economic aspects of water supply and use.

Table 1
Average cereal crops production in Czech Republic during years 1993–2014.

Cereal type	Area (1000 ha)	Output (1000 tonnes)	Yield (tonnes/ ha)	Gross production value of cereals (constant 2004-2006 prices in million I $[b])	Share of gross production value of cereals to all other crops (constant 2004-2006 prices in 1000 I $[b])
Wheat	831.86	4,068.38	4.89	631.59	32%
Barley	501.25	2,025.06	4.04	241.27	12%
Maize	74.78	529.16	7.07	70.87	4%
Oats	57.14	178.63	3.12	20.54	1%
Triticale	39.37	161.81	4.11	21.64	1%
Millet	1.77	2.87	1.61	0.53	0%
Buckwheat	1.19	2.30	1.93	0.49	0%
Canary seed	0.15	0.68	4.53	0.18	0%
Grain, mixed	5.34	10.12	1.89	1.57	0%
Cereals, nes[a]	4.94	10.52	2.12	2.81	0%
Rye	47.67	188.09	3.94	21.32	1%

Source [15].
[a] Other cereal crops that are not identified separately due to their minor relevance at the international level [16].
[b] **I$** stands for the international dollar currency.

water model [51]. In this study, the year-to-year Green_w use by cereal crops in Czech Republic was quantified using the FAO's CROPWAT model and the crop water requirement option [3,52]. As suggested by Hoekstra et al. [25] this model is commonly used in crop water use assessments (e.g., Stancalie et al., 2010 [53]; Surendran et al., 2015 [56]).

Crop water requirement at the field level (m^3/ha) is defined as the total water needed for evapotranspiration from planting to harvest for a given crop under a specific climate regime. It is assumed that cereal crops grow under optimal conditions, meaning that sufficient soil water is maintained by rainfall (or irrigation) so that it does not limit plant growth and crop yield. Under this assumption, crop evapotranspiration (ET_c [c], mm/day) is equal to crop water requirements and is calculated as follows:

$$ET_c[c] = K_c[c] \times ET_0 \tag{1}$$

where, ET_0 (mm/day) is the reference evapotranspiration and K_c (dimensionless) is the crop coefficient of cereal crop c, that incorporates the crop characteristics and the effects of soil evaporation. The green crop evapotranspiration of each cereal crop (ET_{green} [c], mm/day) is calculated as follows:

$$ET_{green}[c] = \min(ET_c[c], P_{eff}) \tag{2}$$

where P_{eff} (mm/day) is the effective rainfall, defined as the part of the total amount of precipitation that is retained by the soil so that it is potentially available for meeting the water need of a crop. There are various methods to compute effective rainfall based on total rainfall. In this study, effective precipitation is calculated based on the widely-used method of the Soil Conservation Service of the United States Department of Agriculture, as suggested by Smith [52]. The irrigation (blue) water requirements can be calculated as the difference between the crop water requirement and effective precipitation. However, as the study focuses on Green_w use, the blue water component was not computed. Also, compared to Green_w, blue water requirement is typically negligible in cereal crops grown in Czech Republic [18].

Crop water use refers to the total volume of water that is consumed by a crop over a growing season. The total Green_w use per cereal crop and year (Green_w, m^3/year) is calculated by summing the daily crop evapotranspiration over the complete growth period from day 1, as follows:

$$\text{Green}_w[c, t] = \left(10 \times \sum_{d=1}^{lp} ET_{green}[c, t]\right) \times A[c, t] \tag{3}$$

where the factor 10 is applied to convert the estimated crop evapotranspiration that is in mm to m^3/ha, lp denotes the length of growing period in days, and A (ha/year) is the total harvested area of each cereal crop c in year t.

3.2. Production function method

The production function method estimates the value of a non-marketed factor by assessing its contribution as an input into the production process of a commercially marketed good. It is a micro-economic method, based on empirical data and it models how each input contributes to the production output. The contribution is revealed through the marginal productivity indicator. This indicator shows the effect on total production, i.e. total quantity of produced output, associated to the use of an additional unit of the selected factor. To compute the monetary value of factors, marginal productivity is multiplied by the output market price.

These estimations are provided by the first order conditions (F.O.C) of the maximization problem, subject to certain restrictions [19,33]. In the case that the production factor is provided by the ecosystem (as with Green_w) and at no cost, it can be internalized in the maximization problem through the introduction of shadow prices, as follows:

$$\max y = p_i \cdot q_i - \sum c_{ij} \cdot (l_i, k_i, z_i) - \lambda_i e_i \quad (4)$$

$$s.\ t.\ \ q_i = f(l_i,\ k_i, z_i, e_i)\ \text{ and } l_i, k_i, z_i, e_i \geq 0$$

where i is a commodity, j is input, p is the output price, q is the output quantity, l is labor, k is capital and z is the other inputs, e denotes the ecosystem input, c the cost per unit, and λ the implicit value or shadow price of ecosystem input.

The implicit price of ecosystem input is estimated by solving for F.O.C.

$$\frac{\vartheta y}{\vartheta e_i} = 0 \rightarrow \frac{\vartheta q_i}{\vartheta e_i} p_i \ - \lambda_i = 0 \rightarrow \lambda_i = \frac{\vartheta q_i}{\vartheta e_i} p_i \quad (5)$$

3.3. Cobb-Douglas function and model specifications

Cobb-Douglas (CD) production function is a commonly employed function to describe the technical relationship between the inputs and outputs of a production process. The function has been widely used for estimating the contribution of inputs in crop (e.g. Yao, 1996[66]) and fish production (e.g. Karagiannis and Katranidis, 2000 [28]; Ali et al., 2016 [2]), as well as the contribution of water as a resource input in several sectors (e.g. Onofri et al., 2017 [39]; Wang and Lall, 2002 [63]).

A classical CD function takes the form $q = ax_{1,\dots}^{b_1} x_n^{b_n}$ where $b_{1..n}$ denote elasticities. The elasticity of a production factor indicates the percentage change in the production output due to a percentage change in the use of the production input, given that all other inputs remain unchanged. By applying the log to the function, the classic CD production function is transposed in a linear form, as follows:

$$lnq = lna + b_1 lnx_1 \dots\dots + b_n lnx_n \quad (6)$$

The classic form of CD function may be susceptible to certain limitations due to the assumptions of additivity and homogeneity. To overcome such limitations, alternative representations of the function are often been employed by researchers. The most widely applied is the transcendental logarithmic or translog production function representation [28,63]. The function takes the following form [6]:

$$lnq = lna + \sum_{i=1}^{n} b_i lnx_i + \sum_{i=1}^{n} b_{ii} \frac{ln^2 x_i}{2} + \sum_{i=1}^{n} \sum_{j=1}^{m} b_{ij} lnx_i lnx_j \quad (7)$$

The elasticity of production with respect to each input is calculated by taking the partial derivative of output with respect to the input under consideration, as follows:

$$\eta_i = \frac{\vartheta(lnq)}{\vartheta(lnx_i)} = b_i + b_{ii} lnx_i + \sum_{j=1}^{m} b_{ij} lnx_j \quad (8)$$

Marginal productivity is calculated as:

$$\sigma_i = \frac{\vartheta(q)}{\vartheta(x_i)} = \frac{\vartheta \ln(q)}{\vartheta \ln(x_i)} \frac{q}{x_i} = \eta_i \frac{\bar{q}}{\overline{x_i}} \quad (9)$$

The implicit value or shadow price of ecosystem input as indicated above will be the product of marginal productivity and price of output.

In our analysis, the CD function is specified as:

$$Q = f(L,\ F,\ P,\ M,\ TF,\ Green_w,\ \ A). \quad (10)$$

where the dependent variable Q is the production output and the independent variables stand for labor (L), fertilizers (F), pesticides (P), harvesting equipment (M), transport fuel (TF), Green_w use (Green_w) and harvested crop area (A).

We performed two model specifications. Model 1 is specified in a translog form (Eq. (7)). Model 2 is the same as Model 1, but it includes crop specific interactions with Green_w input, for the five most important cereal crop species. The models were analyzed in a panel data structure, i.e. for 10 different cereal crops and for 22 time periods specified in years.

The assumption that the error components are independently and identically distributed (IDD) is rarely realistic with panel data and ordinary least squares error estimates may not be efficient. The error terms can be treated as fixed or random parameters to be estimated. A fixed effect model introduces a matrix of dummy variables that correspond to the observations of each group of the panel. This is called least square dummy variable (LSDV) model due to the introduction of dummies that capture the specific shocks caused by the panel structure [8]. Our models were first specified as one-way fixed effect models that account for group (here the group refers to crop type) specific shocks. Next, we also explored the two-way fixed effect models that account for time-specific shocks. The analysis was performed using the Nlogit 6 software package (Econometric Software, Inc., Plainview, NY, USA).

3.4. Data and assumptions

3.4.1. Green water data

For the calculation of Green_w use, daily potential evapotranspiration and precipitation values for Czech Republic over the period

Table 2
Average $Green_w$ consumption per cereal crop type for the period 1993-2014.

Crop type	Average $Green_w$ (Mm^3/year)	Std. Deviation	Average $Green_w$ (m^3/ha/year)	Std. Deviation
Wheat	2,081.959	301.921	2,500.911	307.361
Barley	1,239.095	232.108	2,490.630	295.278
Maize	213.513	104.004	2,818.327	311.894
Oats	156.209	25.183	2,758.714	280.734
Triticale	90.402	41.173	2,271.927	277.768
Millet	4.359	0.754	2,451.927	273.857
Buckwheat	2.229	0.634	1,864.707	276.642
Grain, mixed	12.534	4.676	2,406.264	283.132
Cereals, nes	9.305	3.057	1,864.707	276.642
Rye	22.285	8.766	478.769	71.256
Total	384.837	683.233	2,198.505	692.170

1993-2014, were obtained from the high-resolution dataset (CRU CY v. 3.24.01) of [22]; these data refer to the daily average conditions at the national level. Crop planting and harvesting dates were obtained from Sacks et al. [47] and crop coefficients from Allen et al. [3]. A range of planting and harvesting dates was tested (i.e., early, average and late), yet no significant differences were found in $Green_w$ use; thus, for simplicity we assumed that cereals were planted and harvested in the mid (average) range of each period, respectively. The total production and harvested area per cereal crop per year was derived from the FAOSTAT database, as reported at country level.

CROPWAT model revealed the $Green_w$ consumption per crop type. Table 2 presents the mean consumption per crop type during the time period 1993-2014. On average, cereal crops consumed around 385 Million m^3/year of $Green_w$ or 2199 m^3/ha/year.

3.4.2. *Production function factors*

Based on available data the following production inputs have been identified[4]: labour, fertilizers, pesticides, machinery equipment, transport fuels and harvested area. The data were obtained from FAOSTAT database [15]. With the exception of harvested area, all other production inputs data were not provided by each crop but rather were available at an aggregated level. In order to approximate the data of inputs for each cereal crop, we assumed weights which were specified in accordance to the share of each crop to the total production output of all crops (as in Yao, 1996 [66]). Missing values[5] of data were filled using linear interpolations (Table 3).

4. Results

Table 4 presents the estimated parameters of the one-way fixed effects econometric models of translog specification, where decreasing return to scale and substitution effects are accounted for. The R^2 value, showed an adequate fit of models. The fixed effect coefficients (Table 1, appendix) were found statistically significant for model 1, implying that variation in crop production can be explained by crop specific factors that are not captured by the independent variables. Considering the F-statistics test, the null hypothesis that the ordinary least squares model is better than the one-way fixed effects model was rejected in both models 1 and 2. The results of the two-way fixed model of translog model 1 are reported in Table 2 appendix.[6]

Most of the production inputs had positive elasticities as expected (Table 5). Harvested land showed the largest contribution in crop production with elasticity level being close to 0.9. The elasticity of $Green_w$ ranged from 0.04 to 0.06 indicating that a 10% increase in $Green_w$ would result in a 0.4–0.6% increase in crop production, all other things being equal. This is a sizeable effect on food provision also compared to the effect of other production inputs. The interaction terms revealed the relationship between these inputs. $Green_w$ is positively related to land, as expected and hence the marginal effect of $Green_w$ on crop production is determined by the size of harvested land.

The estimates of elasticity of $Green_w$ per crop type ranged from −0.1 to 0.79 (Table 5). Maize and wheat presented the highest elasticity estimates. A 10% increase in $Green_w$ use would cause almost an 8% increase in the maize production and a 6% in wheat production. Considering that maize is the third most important crop in the Czech Republic in terms of harvested area, this outcome

[4] According to the Farm Accountancy Data Network (FADN) report (EC, 2014) [10] 60% of the main costs of farms producing common wheat in the Czech Republic originated from the non-specific costs, i.e. transport fuel, machinery/buildings upkeep and by and the specific ones, i.e. seeds, fertilizers, crop protection and water. Labor (paid and unpaid) accounted for almost 20% of the production cost.

[5] For fertilizers and pesticides inputs almost half of the data were missing. For the rest of inputs the shortage was less severe with missing cases to represent around 15–30% of sample size.

[6] The two-way fixed effect models (Table 3, appendix) showed statistically significant time specific coefficients for model 1 while model 2 of the thanslog specification with interactions didn't converge to a solution. The null hypothesis of a one-way fixed effects model being more appropriate than a two-way fixed effects one was rejected at 0.02 significance level in model 1. On this basis, we decided to leave the two-way fixed effect models results out of the core body of the manuscript and proceed with calculations considering only the one-way fixed effects models.

Table 3
Summary statistics of variables in CD function.

Variables	Definition (unit)	Mean	Min	Max
Q	Production (tonnes)	683,553.49	569	5,442,349
Green$_w$	Green water (m^3)[a],[b]	2,196.179	367.00	3,337.30
L	Labor (1000 persons)	9.817	0.024	81.100
F	Fertilizers (kg)[b]	4.004	0.01	34.41
P	Pesticides (kg)[b]	0.089	0.01	0.2
M	Machinery equipment (number of harvesters)	624.502	1.68	5402.10
TF	Transport fuels (terajoule)	810.663	2.101	10,007.650
A	Harvested area (ha)	156,536.00	905	970,435

Source: FAOSTAT.
[a] Computations based on CROPWAT model.
[b] Scaled by hectares of harvested larea.

Table 4
Results of the one-way fixed effects for models 1 and 2.

	Model.1: Translog		Model.2: Translog with crop interactions	
	Coef.	Std.error	Coef.	Std.error
Ln $Green_w$	−5.372**	2.063	−3.794	3.342
Ln F	2.629*	1.364	3.254**	1.370
Ln P	3.184**	1.333	3.132**	1.481
Ln L	−2.257	1.536	−2.280	1.528
Ln TF	0.742	1.234	0.518	1.219
Ln M	−0.432	1.352	0.098	1.369
Ln A	−2.236	1.972	−2.665	2.092
½ Ln $Green_w^2$	0.286*	0.162	−0.008	0.302
½ Ln F^2	−0.086	0.135	−0.090	0.135
½ Ln P^2	−0.076	0.097	−0.075	0.100
½ Ln L^2	−0.710***	0.212	−0.685**	0.212
½ Ln TF^2	−0.112	0.285	−0.048	0.283
½ Ln M^2	−0.061	0.082	−0.054	0.082
½ Ln A^2	0.035	0.141	0.029	0.140
Ln $Green_w$*Ln F	−0.067	0.099	−0.101	0.100
Ln $Green_w$*Ln P	−0.256**	0.082	−0.252**	0.103
Ln $Green_w$*Ln L	0.054	0.124	0.025	0.124
Ln $Green_w$*Ln TF	−0.059	0.086	−0.049	0.085
Ln $Green_w$*Ln M	0.001*	0.079	−0.040	0.081
Ln $Green_w$*Ln A	0.257	0.114	0.311**	0.137
Ln L* Ln F	0.323	0.132	0.334**	0.131
Ln L* Ln P	0.142*	0.091	0.104	0.095
Ln L* Ln M	−0.020	0.145	−0.002	0.145
Ln L* Ln TF	0.190	0.184	0.132	0.184
Ln L* Ln A	0.194	0.140	0.223	0.139
Ln F*Ln P	0.017*	0.074	0.035	0.073
Ln F*Ln M |	−0.016**	0.045	−0.022	0.044
Ln F*Ln TF	−0.156	0.112	−0.140	0.111
Ln F*Ln A	−0.139*	0.095	−0.175*	0.095
Ln P*Ln M	−0.088	0.113	−0.049	0.118
Ln P*Ln TF	0.098*	0.082	0.104	0.081
Ln P*Ln A	−0.151*	0.098	−0.168*	0.100
Ln M*Ln TF	0.054	0.159	0.026	0.158
Ln M*Ln A|	0.002*	0.074	0.004	0.075
Ln TF*Ln A	0.033	0.121	0.033	0.121
Barley*$Green_w$			0.265	0.419
Wheats*$Green_w$			0.979**	0.405
Maize*$Green_w$			0.024	0.454
Oats*$Green_w$			0.736	0.507
Barley*$Green_w$			0.224	0.387
Sample size	231		231	
F-stats (p-value)	9.61 (0.000)		2.63 (0.015)	
$\overline{R^2}$	0.997		0.997	
R^2 based on within group variation	0.931		0.936	

The *, ** and *** denote significant levels at 10%, 5% and 1%, respectively.

Table 5
Elasticities of production factors per model specification.

	Elasticity	
	Model 1: Translog	Model 2: Translog with crop interactions
$Green_w$	0.060	0.041
Fertilizers	−0.020	−0.029
Pesticides	0.047	0.038
Labor	0.087	0.077
Machinery equipment	−0.124	−0.108
Transport Fuels	0.139	0.122
Harvested area	0.870	0.878
Barley		0.084
Wheat		0.555
Maize		0.798
Oats		−0.156
Triticale		0.043

Table 6
$Green_w$ marginal productivity, implicit price and economic return per model.

	Marginal productivity of $Green_w$ (tonnes per additional 1000 m^3)	Implicit price of $Green_w$ (USD/1000 m^3)[a]	Monetary value of cereal crop production generated by $Green_w$ (million USD)[a]
Translog	0.127	24.999	9.620
Translog with crop interactions	0.086	16.885	6.498

Note: Prices from FAOSTAT in USD/kg were available only for wheat, barley, maize, oats and triticale. The selection of units is based on data availability from FAOSTAT database.
[a] Based on average prices during 2004-2014 and $Green_w$ consumption as estimated by CROPWAT model (Table 2).

highlights the important role of $Green_w$ in cereal production at national level.[7]

Table 6 reports the marginal productivity, the implicit price or value and the economic return of $Green_w$ (i.e. the value of the average use of input in crop production). One additional unit (i.e. 1000 m^3) of $Green_w$ increases crop production by 0.9 to 0.13 tonnes. Given the estimates of marginal productivity, we elicited the implicit price of $Green_w$. Implicit price estimates were based on producer prices in USD/kg for the time period 2004-2014, which were available only for wheat, barley, maize, oats and triticale. This should be regarded as an approximation and subject to price volatilities within years. The impicit price of $Green_w$ ranged from 17 to 25 USD/1000 m^3. The economic return or contribution of $Green_w$ to crop production ranged between 6.5 and 9.6 million USD per year.

In Table 7 we report the estimates of average and marginal product of $Green_w$ in the four most important crop types in Czech Republic (Oats has been neglected due to the negative estimated elasticity). Although the average product across maize, wheat, barley and triticale was ranged at almost the same level, in marginal terms the picture was different. One additional unit of $Green_w$ would increase wheat and maize production at almost ten times the size of effect on barley or triticale. Maize and wheat showed the highest $Green_w$ implicit price, with the price ranging between 221 and 368 USD/1000 m^3 which is almost ten times larger than the implicit price of barley and triticale as well as that of cereal crops on average. For wheat, a value of approximately 460 million USD per year is generated by the provision of $Green_w$. This is due to the high consumption of $Green_w$ per year for wheat production and the high implicit price of $Green_w$ that result to high implicit cost of ecosystem input that is not internalized in the production function.

5. Discussion and conclusions

5.1. Overview of findings

This study employed the production function method to estimate the marginal productivity as well as the value of green water ($Green_w$) in cereal crops production. The production function was specified as a Cobb-Douglas (CD) function where the coefficients of production factors represent elasticities, i.e. the % increase of crop production given a % increase in the production factor. $Green_w$

[7] All estimates are provided under the assumptions that coefficients of inputs are the same across the different crop types, where an average (country level) $Green_w$ value varies per year. The former does not take into account that production depends on a crop-specific technology (i.e. over the study period we assume constant production technology), while the latter disregard the dynamic use of $Green_w$ which depends on crop-specific needs that change dynamically over space and time, as well as the precipitation rate. These assumptions were regarded necessary given data availability. We provide the results of a classic CD function per crop type and $Green_w$ estimates for three different planting and harvesting dates in supplementary material. A translog model per crop type could not be feasible since there are only 22 observations per crop.

Table 7
$Green_w$ average and marginal product, implicit price and economic return per crop type.

	Average product of $Green_w$ (tonnes/Mm^3)	Marginal product of $Green_w$ (tonnes/Mm^3)	Implicit price of $Green_w$ (USD/1000 m^3)[a]	Monetary value of crop production generated by $Green_w$ (million USD)[a]
Barley	1,665.727	139.958	29.169	36.143
Wheat	1,973.713	1,095.514	221.012	460.138
Maize	2,349.070	1,875.526	368.398	78.658
Triticale	1,796.314	77.155	16.658	1.506

Note: Prices from FAOSTAT in USD/kg were available only for wheat, barley, maize, oats and triticale. The selection of units is based on data availability from FAOSTAT database.

[a] Based on average prices during 2004-2014 and $Green_w$ consumption as estimated by CROPWAT model (Table 2).

elasticities ranged between 0.04 and 0.06 implying that a 10% increase in $Green_w$ use would result in 0.4–0.6% increase of cereal crop production. This is substantial compared also to the corresponding elasticity estimates of the other production inputs.

The elasticity estimates were used for assessing the value of marginal productivity and the shadow value of $Green_w$. The marginal productivity and the implicit value of $Green_w$ were assessed within the range of 0.09–0.12 tonnes/1000 m^3 and 17-25 USD/1000 m^3, respectively. The model with crop interactions revealed that the marginal productivity and value of $Green_w$ for maize and wheat were at the highest level compared to other crop estimates. With respect to overall $Green_w$ contribution, wheat is the crop with the highest overall benefits which is expected given the high yearly harvested area and the consumption of $Green_w$ for wheat production. Both indications, i.e. marginal and return value reflect the contribution of $Green_w$ in the economy that is often ignored in literature.

These figures complement previous water footprint studies that focus on the consumptive use of water in crop production. As a first step towards $Green_w$ valuation, $Green_w$ use per year is estimated for each cereal crop at the national level and is then incorporated as a component in a crop production function. This enables the estimation of marginal crop productivity of $Green_{w,}$ where additional to water, other production inputs have been accounted for.

5.2. Policy implications

The valuation of $Green_w$ offers important insights for the compilation of water accounts and their integration to the environmental-economic accounting in national accounts. Ecosystem accounting is a relatively recent research domain that attracts increasing interest. For water resources in particular, the SEEA-Water [60] includes all water resources, and more specifically surface, groundwater (blue water) as well as soil water (here defined as $Green_w$). Examples of water accounts that include also $Green_w$ resources are still scarce.

The production function method that was employed here is concurrent with the objectives of the SEEA principles [61]. Physical supply and use tables are the primary tables that countries are expected to compile, while monetary accounts are optional depending on data availability and policy willingness [61]. Our estimates facilitate both parts of the accounts, in the case of cereal crops for the Czech Republic; the same approach can be applied to all crops and can integrate all water resources (i.e., green and blue water), subject to data availability.

The valuation of water resources has policy implications in water resource management, climate change adaptation policies and conservation policy. Water resource management calls for decisions on land use and allocation of both blue and green water resources, considering that both are interrelated and under a scarcity threat [58]. Economic returns and efficiency are part of the criteria in decision making [39]. According to our Czech Republic case study findings, wheat, maize and barley attain the highest economic returns as well as the highest efficiency of $Green_w$ use. This may be important information in policy making and land use scenario assessments, along with social, economic and technological factors that determine demand and reallocation of crop production in Czech Republic.

$Green_w$ depends on climate factors, i.e. temperature, precipitation as well as on land use, population growth, and technological developments. Hydro-geological studies have questioned before how climate change may affect the stability of the green-blue water ratio (e.g. Konar et al., 2016 [29]). Moreover, research conducted in Czech Republic (e.g. [Potova et al., 2015 [69]; Trnka et al., 2016 [59]) showed the increasing trend of drought events and their effects on crop yields as well as on total farm-level production. Our findings are indicative of the economic consequences in the case of drought events and respond to critical questions, such as what the forgone benefits or the economic loss could be if an additional unit of $Green_w$ is no longer available for cereal production. For wheat production in particular, the economic loss in case of frequent drought events will be substantial, considering the high contribution of $Green_w$ in the production earnings per year.

5.3. Study limitations

As with all economic and crop water use modelling studies, our study has certain limitations, mostly related to data availability, which are worth noting. The data which are provided by a global database, i.e. by FAO, are national level data and hence our model doesn't capture spatial variation. Moreover, we confronted with a lack of data for several variables in the model and also limited data availability for all variables in temporal terms. Hence we were not able to model per crop type estimates but we rather employed a panel data approach. Furthermore, due to the lack of spatio-temporal data we restrict the estimation to average $Green_w$ use. In reality,

$Green_w$ varies over space and time, thus our model estimates are prone to this uncertainly. The dynamic determination of $Green_w$ use implies that the reported elasticity estimates should be interpreted as proxies within a range of uncertainty.

5.4. Future perspectives

High resolution datasets are eligible for exploratory purposes but come at the expense of the reliability and validity of findings. Local data would be more preferable in regards to crop coefficients and cropping pattern (e.g., planting and harvesting dates, farming practices, etc.). Such information would probably improve the precision of our estimates, and would also allow for modelling each crop type, something which can be applied in the future or at countries and regions where such data are available and reliable.

In addition, future assessments could include spatial valuation tools that would account for the variance of $Green_w$ availability and demand over space, as well as the variance of crop production at local, regional or even farm level. In such more refined models and downscaled applications, a sensitivity analysis can be applied to account for model uncertainties (e.g., Zhuo et al., 2014 [67]). Furthermore, the temporal dimension, which is critical in the case of precipitation and therefore $Green_w$, could be better captured with more refined datasets, including the variability of $Green_w$ between wet, dry and average years.

From an ecosystem perspective $Green_w$ flow supports biomass provision (food, fibre and fodder) but at the same time is vital for non-economic biomass provision like weeds and vegetation in open drainage ditches [44,50]. This enables a trade-off between food sufficiency and nature conservation. Monetary estimates of $Green_w$ offer valuable insights on this debate. Future research is essentially required to estimate the value of $Green_w$ in the provision of both agricultural and non-agricultural ecosystem services, which would enable more informed decisions and policy-making regarding the use of land and water resources.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wre.2019.100148.

Appendix

Table 1
Set of effects of the one-way estimated fixed effects model

Crop type	Model.1: Translog			Model.2: Translog with crop interactions		
	Coef.	Std.error	t-ratio	Coef.	Std.error	t-ratio
1	44.640	15.582	2.865	35.544	22.208	1.601
2	44.322	15.603	2.841	38.897	22.477	1.731
3	44.882	15.627	2.872	33.731	22.305	1.512
4	44.660	15.640	2.856	41.042	20.923	1.962
5	43.992	15.583	2.823	40.322	23.258	1.734
6	43.394	15.501	2.799	39.865	20.741	1.922
7	43.545	15.521	2.806	40.013	20.768	1.927
8	44.384	15.636	2.839	39.140	22.368	1.749
9	0.000	0.000	0.000	0	0	0
10	0.000	0.000	0.000	0	0	0

Table 2
Results of the two-way estimated fixed effects model

	Model.1: Translog	
	Coef.	Std.error
Ln $Green_w$	−3.870*	2.154
Ln F	3.701**	1.448
Ln P	4.497***	1.457
Ln L	−5.273***	1.694
Ln TF	1.292	1.323

(*continued on next page*)

Table 2 (*continued*)

	Model.1: Translog	
	Coef.	Std.error
Ln M	−2.819*	1.538
Ln A	2.052	2.384
½ Ln $Green_w^2$	0.308	0.201
½ Ln F^2	−0.173	0.158
½ Ln P^2	0.130	0.109
½ Ln L^2	−1.043***	0.234
½ Ln TF^2	−0.099	0.314
½ Ln M^2	−0.013	0.094
½ Ln A^2	−0.264	0.172
Ln $Green_w$*Ln F	−0.122	0.099
Ln $Green_w$*Ln P	−0.195**	0.080
Ln $Green_w$*Ln L	0.124	0.122
Ln $Green_w$*Ln TF	0.160*	0.093
Ln $Green_w$*Ln M	−0.043	0.083
Ln $Green_w$*Ln A	0.025	0.123
Ln L* Ln F	0.375***	0.140
Ln L* Ln P	0.127	0.101
Ln L* Ln M	−0.035	0.163
Ln L* Ln TF	0.320	0.195
Ln L* Ln A	0.415***	0.160
Ln F*Ln P	0.111	0.078
Ln F*Ln M |	−0.014	0.047
Ln F*Ln TF	−0.088	0.116
Ln F*Ln A	−0.198*	0.104
Ln P*Ln M	−0.140	0.117
Ln P*Ln TF	−0.052	0.085
Ln P*Ln A	−0.141	0.101
Ln M*Ln TF	−0.051	0.173
Ln M*Ln A|	0.127	0.085
Ln TF*Ln A	−0.062	0.142
Constant	26.609	17.171
Sample size	231	
F-stats (p-value)	1.86 (0.023)	
$\overline{R^2}$	0.998	

The *, ** and *** denote significant levels at 10%, 5% and 1%, respectively.

Table 3
Full sets of effects of the two-way estimated fixed effects model

Crop type	Coef.	Std.error	t-ratio
1	0.687	0.258	2.662
2	0.499	0.189	2.640
3	0.533	0.150	3.558
4	0.245	0.219	1.120
5	0.019	0.155	0.120
6	−1.024	0.336	−3.049
7	−0.765	0.316	−2.422
8	0.128	0.159	0.805
9	0.000	0.043	0.000
10	0.000	0.000	0.000
Periode of time			
1	0.032	0.084	0.382
2	−0.052	0.085	−0.611
3	−0.232	0.100	−2.332
4	−0.229	0.076	−3.007
5	−0.132	0.092	−1.430
6	−0.131	0.087	−1.496
7	−0.101	0.061	−1.663
8	−0.166	0.061	−2.725
9	−0.123	0.058	−2.133
10	−0.037	0.060	−0.610

(*continued on next page*)

Table 3 (*continued*)

Crop type	Coef.	Std.error	t-ratio
11	−0.075	0.061	−1.237
12	0.145	0.054	2.692
13	0.030	0.051	0.591
14	−0.129	0.055	−2.362
15	−0.020	0.052	−0.376
16	0.145	0.069	2.099
17	0.126	0.077	1.629
18	0.008	0.077	0.107
19	0.223	0.083	2.697
20	0.149	0.078	1.927
21	0.228	0.083	2.745
22	0.354	0.088	4.025

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