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Research Article

Water Footprint of main crops in Austria

Wasser-Fußabdruck wichtiger Nutzpflanzen in Österreich

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Summary

Water is a key resource for human activities and a critical trigger for the welfare of the whole society. The agricultural sector makes up the main share in global freshwater consumption and is therefore responsible for a large part of the water scarcity in many drought prone regions. As an indicator that relates human consumption to global water resources, the "Water Footprint" (WF) concept can be used, where in case of crop production the total consumed water of crop fields for the crop growing seasons is related to the harvested dry matter crop yield (such as grains). In our study, we simulated the green and primary blue WF of selected main crops for Austrian conditions. Different irrigation scheduling scenarios, demonstrated for a main agricultural production area and various crops in Austria with significant irrigation acreage, were studied. The impact of climate and soil conditions on the green crop WFs of reference crops over the whole territory of Austria were simulated in a second step. Sunflower, winter wheat and grain maize showed the highest WF in the semi-arid study regions, especially on soils with low water capacity. In more humid regions, low temperatures were the main limiting factor on the crop yield potential and frequently led to higher WFs due to lower yields.

Keywords: crop growth model, AquaCrop, irrigation, green water footprint, blue water footprint

Zusammenfassung

Wasser ist eine wichtige Ressource für menschliche Aktivitäten und ein kritischer Faktor für das Wohlergehen der gesamten Gesellschaft. Die Landwirtschaft ist global der größte Süßwasserverbraucher und in vielen niederschlagsarmen Regionen daher der Hauptverursacher für Wasserknappheit. Als Indikator, der den menschlichen Verbrauch auf globale Wasserressourcen bezieht, kann das Konzept "Wasser-Fußabdruck" (WF) verwendet werden, wobei sich im Fall der Nutzpflanzenproduktion das gesamte während der Wachstumsperioden verbrauchte Wasser von Pflanzenbeständen auf die Trockenmasseerträge des geernteten Anteils (wie Kornertrag) bezieht. In unserer Studie simulierten wir den grünen und blauen WF ausgewählter Nutzpflanzen in Österreich. Hierbei wurden zum einen verschiedene Bewässerungsszenarien, die für die bewässerten landwirtschaftlichen Flächen sowie Nutzpflanzen in Österreich interessant sind, untersucht. Zum anderen wurde der grüne WF für zwei Referenzpflanzen über das gesamte österreichische Gebiet simuliert, welche die unterschiedlichen Klima- und Bodenverhältnissen wiederspiegelt. Sonnenblumen, Winterweizen und Körnermais zeigten den höchsten WF im semi-ariden Untersuchungsraum, der wiederum stark von der Bodenwasserspeicherkapazität beeinflusst wurde. In feuchteren Regionen waren niedrige Temperaturen der Hauptbegrenzungsfaktor für das Ernteertragspotential und führten somit häufig zu höheren WFs aufgrund niedrigerer Erträge.

Schlagworte: Pflanzenwachstumsmodel, AquaCrop, Bewässerung, grüner Wasser-Fußabdruck, blauer Wasser-Fußabdruck

1. Introduction

Water is a key resource for human activities and a critical trigger for the welfare of the whole society. Priority should be given to its sustainable and effective use. The agricultural sector makes up the main share in global freshwater consumption (Hoekstra and Mekonnen, 2012), and is therefore responsible for a large part of the water scarcity in many drought prone regions (Zhuo et al., 2016). Additionally, the increasing world population, welfare and the subsequent increasing need of water for food and bioenergy production, industry and other human activities, will require a more efficient agriculture; especially with regard to crop water productivity, where irrigation is the dominant consumer of freshwater resources. Numerous attempts have been undertaken to improve the effective use of water in agricultural crop production but many results are only locally valid and cannot easily be extrapolated to other regions. In addition, the factors influencing water use efficiency in crop production are manifold and vary with crops, crop management, environment and scales. Meeting the growing water demands and at the same time reducing the water footprint of agricultural production is therefore one of the greatest societal challenges of our time (Foley et al., 2011; Hoekstra and Wiedmann, 2014).
As an indicator that relates human consumption to global water resources, the concept of "Water Footprint" (WF) was defined by Hoekstra (2003), and later elaborated on by Hoekstra and Chapagain (2008). For example, the WF can be calculated for crops, goods, services, a specific activity, a business, an organization, and an individual or for a community. The WF of a product is the total volume of fresh water used to produce the product, summed over the various steps in the production chain (Hoekstra et al., 2009). The international trade in commodities forms flows, the "virtual water" (Allan, 1998; Hoekstra and Hung 2005; Chapagain and Hoekstram, 2008), by importing and exporting goods that require water for production. The virtual water indicator provides valuable information for a global assessment of how water resources are used, and if the regional water scarcity could be caused, for example, by consumption in distant countries or regions.
The WF of a crop offers a calculable indicator to measure the volume of water consumption per unit of crop, as well as the volume of water pollution (Hoekstra and Chapagain, 2008; Hoekstra et al., 2011). The harvested yield (i.e., grains) forms the basis for WF estimations of crop products and resulting commodities. The green WF measures the volume of rainwater consumed during the growing period of the crop; the blue WF includes the volume of surface and groundwater consumed. The grey WF measures the volume of freshwater, which is required to assimilate the nutrients and pesticides leaching, running off from crop fields and reaching the groundwater or surface water, based on natural background concentrations and existing ambient water quality standards (Hoekstra et al., 2011; Mekonnen and Hoekstra, 2014).
Most farmers maximize their economic return through raising their productivity per unit of input such as capital, labor, land and fertilizer. Once water is scarce, raising the production per unit of water (i.e., increasing water productivity in terms of t/m^3 or reducing the WF in m^3/t) is a key challenge to save water and achieve sustainable water use. Non-beneficial consumptive water use at field level and the non-recoverable losses at system level are important parts of these considerations (Falkenmark and Rockström, 2006; Steduto et al., 2007; Perry et al., 2009; Hoekstra, 2013). Even when water is not limited, it makes sense to have a reasonable level of water productivity, that is, a good amount of "crop per drop" with consequences for the ecosystem as well (e.g., surface runoff and related soil erosions). Unfortunately, farmers generally show lack of incentives for saving water, when they pay little for the use of water as compared to other input factors, even under the conditions of high water scarcity (Zhuo et al., 2016). At field level, the effort is to decrease the field evapotranspiration (ET) over the growing period per unit of yield (Y). Decreasing this ET/Y ratio is the same as increasing the inverse (Y/ET), which is named as water productivity (WP) (Molden et al., 2010; Amarasinghe and Smakhtin, 2014; Chukalla et al., 2015).
For water resource management, it is beneficial to understand the water resource use in crop production by source (rainwater, irrigation water from surface and groundwater, water from capillary rise). Here the concepts of green versus blue water by Falkenmark and Rockström (2006) and green versus blue WF by Hoekstra et al. (2011) are a useful advance.
The approach of WF can provide information on crop water demand and related possibilities to save water, especially under water-limited production conditions, such as in the semi-arid region of north-eastern Austria. Additionally, changes in the mean and the variability of climatic parameters will have an essential influence on the water resource use in crop production in Austria.

In our study, we simulated the green and blue WF of selected main crops for Austrian conditions. To demonstrate the impact of climate and soil conditions on the green WF of reference crops over the whole territory of Austria, we simulated rainfed conditions without groundwater impact for grain maize and spring barley due to their different lengths of growing season. Blue WF was analyzed for various crops on a main agricultural production area, the Marchfeld plain in NE Austria, where irrigation is mainly necessary. We do not consider potential losses of water distribution systems, as in Austria, the main source of irrigation water is from groundwater wells at or near the fields. However, the applied irrigation technology and scheduling can have a significant impact on water demand, where we consider different irrigation scheduling scenarios.

2. Material and methods

2.1 Soil water balance and crop growth modelling

In the current study, the WF of growing crops in Austria were calculated on a daily basis from the outputs of FAO's crop water productivity model AquaCrop (Hsiao et al., 2009; Raes et al., 2009; Steduto et al., 2009). The model is developed to simulate the yield response of crops as a function of water consumption (Raes et al., 2009; Steduto et al., 2009). The elements of the AquaCrop soil-plant-atmosphere continuum focus on (i) the soil water balance, (ii) the plant's development, growth, and yield processes, and (iii) the atmospheric temperature regime, evaporative demand, rainfall and CO_2 concentration (Raes et al., 2009; Steduto et al., 2009; Mebane et al., 2013). Compared to other crop growth models, AquaCrop uses a significantly smaller number of input parameters to predict daily biomass and water requirement (Heng et al., 2009). In this model, the calibration procedure represents a simple prerequisite (Hsiao et al., 2009) and according to Garcia-Vila and Fereres (2012), AquaCrop represents a good balance between simplicity, accuracy and robustness. The model has already been tested in WF accounting at field (Chukalla et al., 2015), river basin (Zhuo et al., 2016a), and national level (Zhuo et al., 2016b) at high spatial resolution. AquaCrop calculates a dynamic daily soil water balance by simulating the incoming and outgoing water fluxes with well-described subroutines. It can simulate different degrees of water supply to the plant, varying from rainfed and supplementary irrigation to deficit and full irrigation (Raes et al., 2012). For the soil profile explored by the root system, AquaCrop performs a water balance, which comprises the processes of runoff (through the curve number), infiltration, redistribution or internal drainage, deep percolation, capillary rise, uptake, evaporation, and transpiration. As a daily step, the soil water balance can be determined as the stored soil water retained in the root zone subject to incoming and outgoing water fluxes at the boundaries (Steduto et al., 2008).

Capillary rise occurs from shallow groundwater and is based on the depth of water table and the soil hydraulic characteristics. The model uses the Darcy equation and relates the soil matric potential to the hydraulic conductivity (Raes et al., 2012). Two parameters are estimated for different soil textural classes that have similar water retention curves. Water limitations on plant growth are simulated through three types of water stress response: canopy expansion rate, stomatal closure and senescence acceleration (Steduto et al., 2009b; Chukalla et al., 2015).

The biomass (B) in AquaCrop is estimated from a water productivity parameter (WP) and transpiration (T): $B = WP \times \sum T$. The harvestable portion of the biomass (yield Y) is calculated by multiplying biomass by a crop-specific harvest index (HI, %): $Y = B \times HI$. The WP is in kg (biomass) per m^2 (land area) per mm (water transpired), normalized for atmospheric evaporative demand and atmospheric CO_2 concentration (Steduto et al., 2009a; Chukalla et al., 2015). HI depends on timing and extent of water and temperature stress implemented as an adjustment factor (f_{HI}) to the reference harvest index (HI_0) (Raes et al., 2011). The model does not calculate the partitioning of biomass into various organs (e.g., leaves, roots, etc.). This choice avoids dealing with the complexity and uncertainties related to partitioning processes, which remains among the least understood and most difficult processes to model. The relationship between shoot and root is affirmed by a functional balance between canopy and root development (Steduto et al., 2008).

The water balance in AquaCrop depends on the effective rooting depth (ERD) and the water extraction pattern. The ERD is characterized as the soil depth where most of the root water uptake is taking place, also when some crops may have a few roots beyond that depth. Within ERD, 90-95% of the water is considered to be taken up. By default, the water extraction patterns follow a standard 40%, 30%, 20% and 10% for each quarter of the ERD. However, a specific extraction pattern for different crops and soils may be inferred from soil physical or chemical limitations (Steduto et al., 2008).

AquaCrop separates the actual evapotranspiration (ET) into unproductive (soil evaporation E) and productive (crop transpiration T) water fluxes. Consequently, AquaCrop can address the effect of management practices on these two types of consumptive water use distinctively (Chukalla et al., 2015).

The model calculates soil evaporation (E) by multiplying the evaporative demand of the atmosphere (ET_O) by factors, which consider the effect of water shortage and the fraction of the soil surface not covered by canopy. Crop canopy increases from the initial canopy cover, which is the product of plant density and the size of the canopy cover per seedling. After adjustment for micro-advective effects, the canopy cover can be estimated and used in the evaporation calculation. The soil moisture conditions control evaporation from the soil surface not covered by canopy in two stages. When the soil surface is wet from rainfall or irrigation, the evaporation rate is fully determined by the energy available for soil evaporation until the readily evaporable water. Thereafter, the evaporation is not only determined by the available energy, but also depends on the hydraulic properties of the soil. This two-stage approach for calculating evaporation is described in Ritchie (1972), who affirms the ability of the method to predict evaporation for a wide variety of soil types and climatic conditions (Chukalla et al., 2015).

AquaCrop was initially calibrated and validated against process oriented crop models for the Marchfeld plain in NE Austria (i.e., Thaler et al., 2012; Eitzinger et al., 2013) but further calibration would be needed for specific crop, irrigation management options and cultivar effects. Phenology and statistical yields were used to calibrate the model for the different regions in Austria. No specific field management was added to simplify the model simulations and to make a first WF overview for Austria. Therefore, the crop yield levels may significantly differ from single field yields, especially from controlled field experiments which show, in general, higher yields due to the optimized crop management. A fixed sowing date was set for spring barley on 22th March, for sugar beet on 1st April, for potatoes and sunflower on 15th April, for grain maize on 1st May and for winter wheat on 1st October for the study region Marchfeld plain (NE Austria) and for the country Austria. The applied approach is focused on relative regional differences and changes of the reference crops rather than providing robust estimates on water balance quantities.

2.2 The green and blue water footprint of growing crops

The (green and blue) WF of growing a crop equals the total actual ET over the cropping period divided by the crop yield (Y). ET is often regarded as the total amount of freshwater used. Water used for evapotranspiration is either from rainfall or irrigation (blue and green WF). The WF of a crop is equal to the virtual water content of the crop, and it can be calculated as follows:

$$WF = 10 \times \frac{ET}{Y} \tag{1}$$

where ET is actual evapotranspiration during the cropping season in mm (1 mm = 10 m^3/ha), the constant 10 is used to convert mm to m^3/ha, and Y is the crop yield in kg/ha (Hoekstra et al., 2011).

The green and blue WFs can be calculated by green and blue ET over the cropping period, respectively, divided by Y. AquaCrop simulates yield in kg/ha of dry matter.

The AquaCrop output divides soil water content and ingoing and outgoing water fluxes into green and blue components. Furthermore, the blue soil water content and the blue water fluxes are separated into blue water originating from irrigation water ($S_{b\text{-}1}$) and blue water originating from capillary rise ($S_{b\text{-}CR}$). The model can track which fractions of ET originate from rainwater, irrigation water and capillary rise. In the daily green-blue soil water balance, (i) rainfall (R) adds to the green soil water stock and, (ii) irrigation (I) and (iii) capillary rise (CR) add to the blue soil water stock. Daily evaporation (E), transpiration (T) and drainage (Dr) are partitioned into three soil water stocks (green, blue from irrigation, blue from capillary rise) based on the relative soil water stock composition. Runoff (RO) is partitioned into green and blue water stock in proportion to the amount of rainfall and irrigation, respectively (Chukalla et al., 2015).

In the following three equations, the changes in the green (S_g), blue from irrigation ($S_{b\text{-}1}$) and blue from capillary rise ($S_{b\text{-}CR}$) soil water stocks are shown:

$$\frac{dS_g}{dt} = R - (Dr + ET)\left(\frac{S_g}{S}\right) \tag{2}$$

$$\frac{dS_{b\text{-}CR}}{dt} = CR - (Dr + ET) \tag{3}$$

$$\frac{dS_{b-1}}{dt} = I - (Dr + ET)\left(\frac{S_{b-1}}{S}\right) - RO\left(\frac{I}{I+R}\right) \quad (4)$$

where dt is the time step of calculation (1 day), R is rainfall (mm), I is irrigation (mm), RO is surface runoff (mm), ET (E+T) is evapotranspiration (mm), Dr is drainage (percolation) (mm), and CR is capillary rise (mm) (Chukalla et al., 2015). The initial soil water moisture at the start of the growing period is assumed to be green water.

2.3 AquaCrop input data

AquaCrop requires the following data as inputs, which are user specific: climatic data, soil data, crop parameters, management conditions and initial soil moisture conditions (more details in Raes et al., 2009).

The climate data from the weather station Groß-Enzersdorf (48°12'N, 16°33'E, 157 m a.s.l.) in the Marchfeld plain for the period 1992-2012 were used as a basis. In a second step, we created classes covering all the annual temperature and precipitation levels in Austria in all possible combinations with Groß-Enzersdorf as the reference station: +1°,0°,-1°,-2°,-3°,-4°,-5°C from the reference temperature and 80%, 90%, no change, 110%, 125%, 150%, 200% and 250% of the reference precipitation (Figure 1). The reference evapotranspiration (ET_O) was calculated for each temperature class with the software ET_O Calculator, developed by the Land and Water Division of FAO. Its main function is to compute ET_O as per FAO standards (Raes, 2012).

Three soil classes (termed herein as soil 1, soil 2 and soil 3, respectively) were defined for Austria according to the plant available water capacity up to 100 cm soil depth, based on the digital Austrian Soil Map 1:25 000 (BFW 2007): (i) soil 1 with a low water capacity (<139 mm; 9.5% of the Austrian arable land area), (ii) soil 2 with a moderate water capacity (140-219 mm; 54.8% of the Austrian arable land area) and (iii) soil 3 with a high water capacity (>219 mm; 35.7% of the Austrian arable land area) (Figure 2). A few smaller agricultural regions could not be considered in our simulations for whole Austria due to missing soil data in our data base. Different irrigation scenarios were simulated and compared with rainfed (R) conditions: B1: irrigated sprinkler - automatic fixed amount 30 mm, B2: irrigated sprinkler - automatic 50% depletion, B3: irrigated sprinkler - deficit irrigation (max 80% field capacity).

3. Results and discussion

3.1 Regional green and blue WF in the Marchfeld plain

The WF in the Marchfeld plain in NE Austria was simulated with AquaCrop for grain maize, potatoes, spring barley, sugar beet, sunflower and winter wheat for the period 1992-2012. This semi-arid region has the highest acreage of irrigated area in Austria. All green and blue WF simulations did not consider potential groundwater impact on the water balance of the crops. An overview of the mean (1992-2012) and standard deviation (SD) of dry matter yield (t/ha) of all simulated crops in the Marchfeld plain under rainfed conditions are presented in Table 1. It can be seen that under soil 1 (with lowest soil water storage capacity) also the lowest yield level for all crops is achieved due to frequently dry periods occurring in that region.

Figure 3 illustrates the ET–WF relationship for the three soil classes: small ET was associated with large WFs due to low yields resulting from water stress. The smallest WFs were found at intermediate ET values, where yield was not at a maximum, and additional ET went along with decreasing productivity. Rainfed sunflower, grain maize and winter wheat presented the highest WF in this frequently water limited region, especially on soil 1 with the lowest available water capacity.

Table 1. Mean yield (t/ha) and Standard Deviation (SD) of the simulated crops in the Marchfeld plain from 1992-2012 for the three soil types under rainfed agriculture

Tabelle 1. Mittlerer Ertrag (t/ha) und Standardabweichung (SD) der simulierten Nutzpflanzen im Marchfeld von 1992-2012 für die drei Bodenklassen im Regenfeldbau

	grain maize			potatoes			spring barley			sugar beet			sunflower			winter wheat		
	Soil 1	Soil 2	Soil 3	Soil 1	Soil 2	Soil 3	Soil 1	Soil 2	Soil 3	Soil 1	Soil 2	Soil 3	Soil 1	Soil 2	Soil 3	Soil 1	Soil 2	Soil 3
Mean	2.5	5.0	6.0	6.6	8.9	9.2	4.7	5.3	5.4	7.5	10.3	11.0	2.3	2.9	2.9	2.6	4.6	4.8
SD	1.5	1.6	1.7	1.5	0.8	0.7	1.0	0.8	0.7	3.3	1.7	1.3	0.4	0.1	0.1	1.5	0.5	0.5

Table 2. Water foodprint (WF) (green, blue and total) and ET of main crops depending on the three soil types in Marchfeld, (ET= actual evapotranspiration during the crop growing period)
Tabelle 2. Wasser-Fußabdruck (WF) (grün, blau und Summe) und ET der wichtigsten Nutzpflanzen in Abhängigkeit der drei Bodenklassen in der Region Marchfeld, (ET= aktuelle Evapotranspiration während der Vegetationsperiode)

Soil 1	Green WF	Blue WF	Total WF	ET
	m³/kg	m³/kg	m³/kg	mm
Grain maize	0.74	0.24	0.98	429.1
Potatoes	0.21	0.18	0.39	481.1
Spring barley	0.29	0.17	0.46	308.8
Sugar beet	0.20	0.16	0.36	515.0
Sunflower	0.84	0.51	1.35	464.4
Winter wheat	0.49	0.29	0.78	588.6
Soil 2				
Grain maize	0.58	0.17	0.75	469.2
Potatoes	0.22	0.17	0.39	481.7
Spring barley	0.27	0.20	0.47	356.8
Sugar beet	0.21	0.15	0.36	512.3
Sunflower	0.93	0.35	1.28	434.2
Winter wheat	0.52	0.26	0.78	589.2
Soil 3				
Grain maize	0.52	0.18	0.70	490.1
Potatoes	0.22	0.17	0.39	482.3
Spring barley	0.27	0.20	0.47	359.5
Sugar beet	0.21	0.15	0.36	514.0
Sunflower	0.94	0.35	1.29	436.8
Winter wheat	0.53	0.26	0.79	589.9

The mean yearly blue and green WF in Marchfeld for all simulated crops are presented in Table 2. In the AquaCrop simulation, an irrigation scenario (B2) of automatic irrigation after 50% soil water depletion of plant available soil water storage capacity (AWC) was applied. In this scenario, maximum water was needed by sunflower, followed by winter wheat and grain maize. Potato, spring barley and sugar beet showed the lowest WF among the considered crops. In case of sugar beet and potato, the high share of the harvested part of total crop biomass determines the low WF compared to the grain crops; in case of spring barley, low values are explained by the shortest growing period of all the simulated crops, and thus, lower water consumption through evapotranspiration. The amount of blue water was much higher as compared to the other two soil types, especially in soil type 1, due to higher simulated irrigation rates.

Grain maize (Figure 4) presents a marked increase in blue WF during dry summer months (1994, 1996, 2000, 2001, 2003, 2011). The correlation coefficient between precipitation and blue WF during the vegetation period was for soil 2 and 3 significant with 0.74 and 0.78, respectively ($p < 0.001$). For soil 1, the correlation was not significant. It seems that soil 1 with its low soil water storage capacity, even in relatively humid summer month, can reach periods, where water shortages for grain maize can occur and irrigation is useful for avoiding yield losses.

For all soils, the irrigation scenarios B2 (automatic irrigation after 50% depletion of available soil water) show the highest WF among the irrigation scenarios, whereas B1 showed the lowest WF in most cases due to less irrigation and stable yields (Figure 5). This contrasts with the higher crop water use efficiencies of deficit irrigation methods (i.e., Fereres and

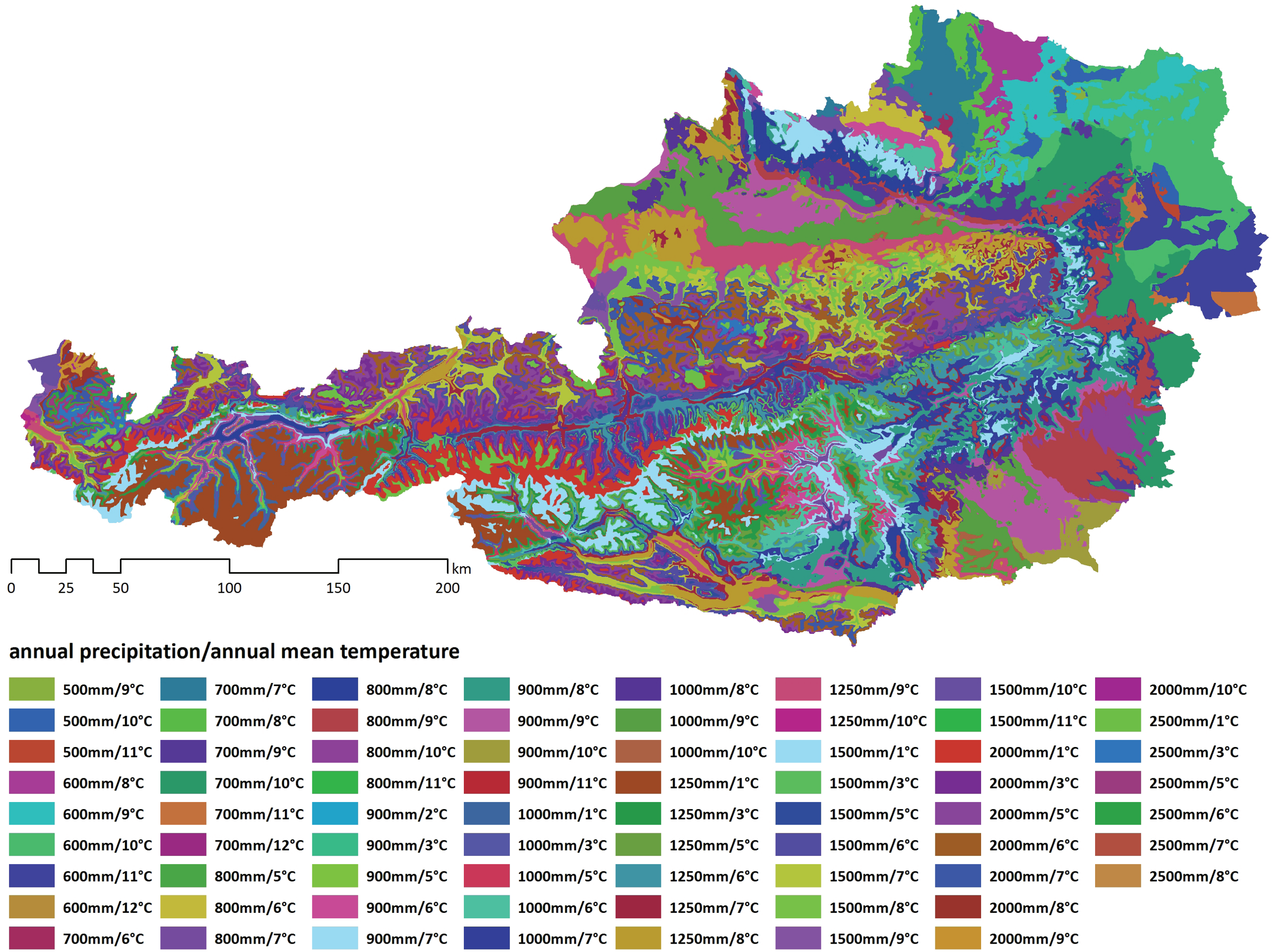

Figure 1. Developed classes of climate for Austria using annual temperatures and precipitation (relative to Groß-Enzersdorf weather station)
Abbildung 1. Entwickelte Klimaklassen für Österreich (in Bezug zu Jahrestemperatur und -niederschlag der Wetterstation Groß-Enzersdorf)

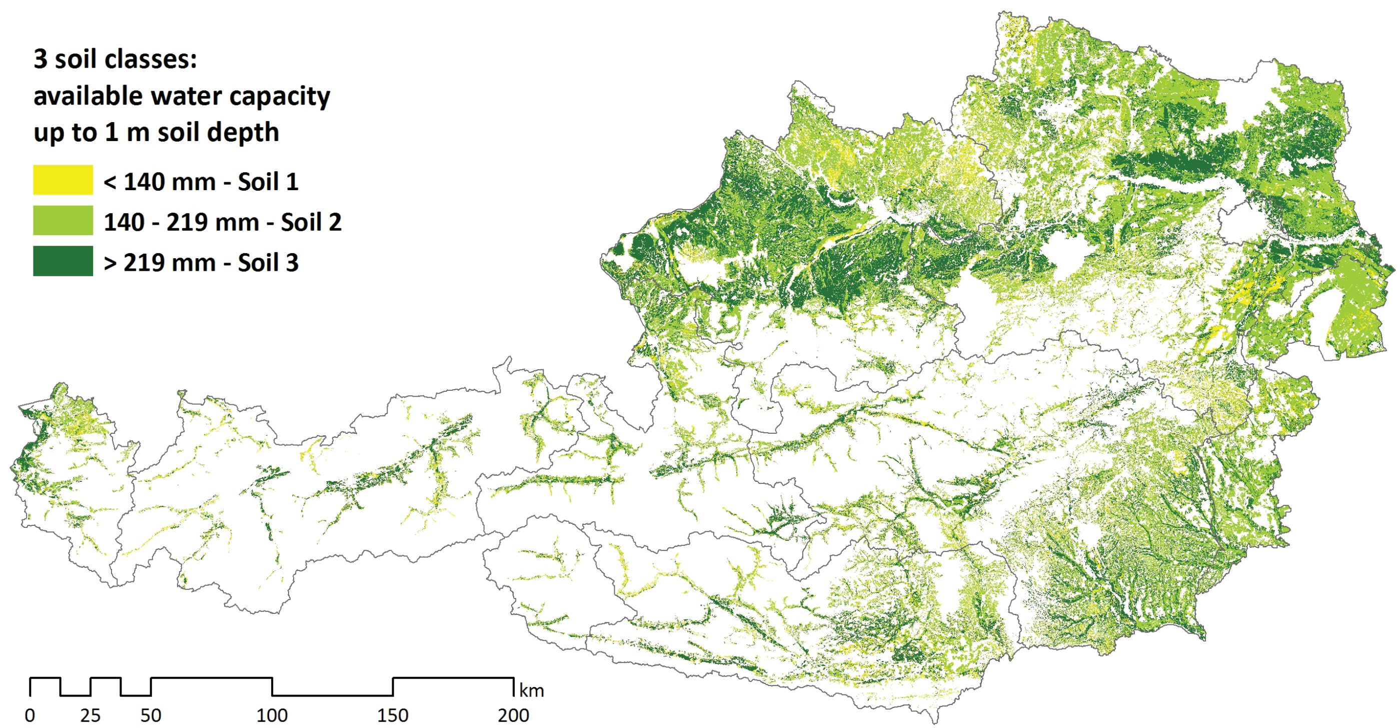

Figure 2. The three applied soil classes for agricultural land use for Austria according to the available water capacity
Abbildung 2. Die drei angewandten Bodenklassen unter landwirtschatflicher Landnutzung für Österreich gemäß der nutzbaren Feldkapazität

Table 3. Austrian green water footprint (WF) for spring barley and grain maize classified by annual mean temperature and precipitation sums for three soil types (means for 1992-2012)
Tabelle 3. Österreichischer grüner Wasser-Fußabdruck (WF) für Sommergerste und Körnermais gruppiert nach jährlicher mittleren Temperatur und Niederschlagssumme für die drei Bodenklassen (Mittelwerte für 1992-2012)

temperature (°C)	percentage of arable land area	spring barley	grain maize	precipitation (mm)	percentage of arable land area	spring barley	grain maize
			Soil 1				
<5°C	2.7%	0.71	2.90	>500	0.4%	0.55	6.53
5°-6°C	14.5%	0.60	1.39	500-600	10.9%	0.54	4.35
6°-7°C	26.7%	0.59	1.33	600-700	12.3%	0.55	2.50
7°-8°C	26%	0.57	1.39	700-800	10.6%	0.55	1.60
8°-9°C	15.8%	0.55	1.68	800-1000	35.6%	0.57	1.39
9°-10°C	11%	0.56	4.64	1000-1250	15.3%	0.61	1.32
>10°C	3.3%	0.51	3.80	<1250	14.9%	0.65	1.33
			Soil 2				
<5°C	0.9%	0.68	1.54	>500	1.6%	0.56	1.19
5°-6°C	7%	0.57	1.06	500-600	21.2%	0.55	0.93
6°-7°C	15.3%	0.57	0.94	600-700	16.3%	0.56	0.90
7°-8°C	21.6%	0.56	0.87	700-800	12.3%	0.55	0.85
8°-9°C	27.2%	0.55	0.83	800-1000	27.2%	0.56	0.89
9°-10°C	22%	0.57	1.00	1000-1250	11.5%	0.57	0.94
>10°C	6%	0.53	0.88	<1250	9.9%	0.59	1.01
			Soil 3				
<5°C	1.1%	0.69	1.40	>500	1.9%	0.56	0.85
5°-6°C	4.3%	0.58	1.01	500-600	16.7%	0.56	0.79
6°-7°C	10.9%	0.57	0.89	600-700	11.5%	0.56	0.76
7°-8°C	17.5%	0.57	0.83	700-800	9.0%	0.56	0.76
8°-9°C	39.6%	0.55	0.76	800-1000	36.6%	0.56	0.80
9°-10°C	23.0%	0.58	0.82	1000-1250	16.9%	0.57	0.87
>10°C	3.6%	0.53	0.72	<1250	7.5%	0.59	0.94

Soriano, 2006), and could be explained as a simulation effect of the yield response in AquaCrop, where 50% depletion already results in significant drought stress. Local calibrations of these response levels would be necessary to support this result. In all cases, the rainfed cropping produced the highest WF. At soil 1, extremely high values occurred mainly due to simulated crop failures (10 years out of all simulated years). Irrigation increased the grain maize yield by around 160% for soil 1, 20% for soil 2 and 11% for soil 3. At the same time, the water demand for the crop increased only 39% for soil 1, 11% for soil 2 and 7.5% for soil 3.

3.2 Green crop water footprint characteristics in Austria

Table 3 showed the green WF response in relation to annual temperatures and soil types under rainfed conditions without groundwater impact in the root zone. Spring barley presented the highest WF values at low temperature (>5°C annual mean temperature) and the smallest WF with annual mean temperature over 10°C, reflecting optimum growing conditions for barley. So, the high WF can occur through low yields in cooler climates. The higher the precipitation sum, the higher the WF for spring barley,

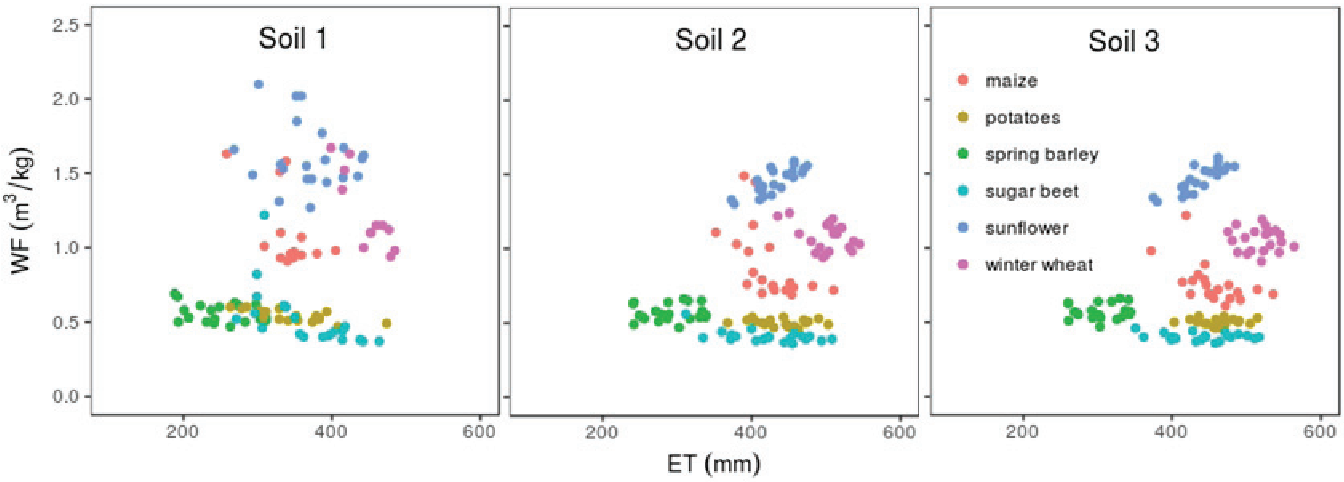

Figure 3. Evapotranspiration (ET) and water footprint (WF) for the crops grain maize, potatoes, spring barley, sugar beet, sunflower and winter wheat in the Marchfeld plain for the three soil types from 1992-2012
Abbildung 3. Evapotranspiration (ET) und Wasser-Fußabdruck (WF) der Nutzpflanzen Körnermais, Kartoffel, Sommergeste, Zuckerrübe, Sonnenblume und Winterweizen im Marchfeld für die drei Bodenklassen von 1992-2012

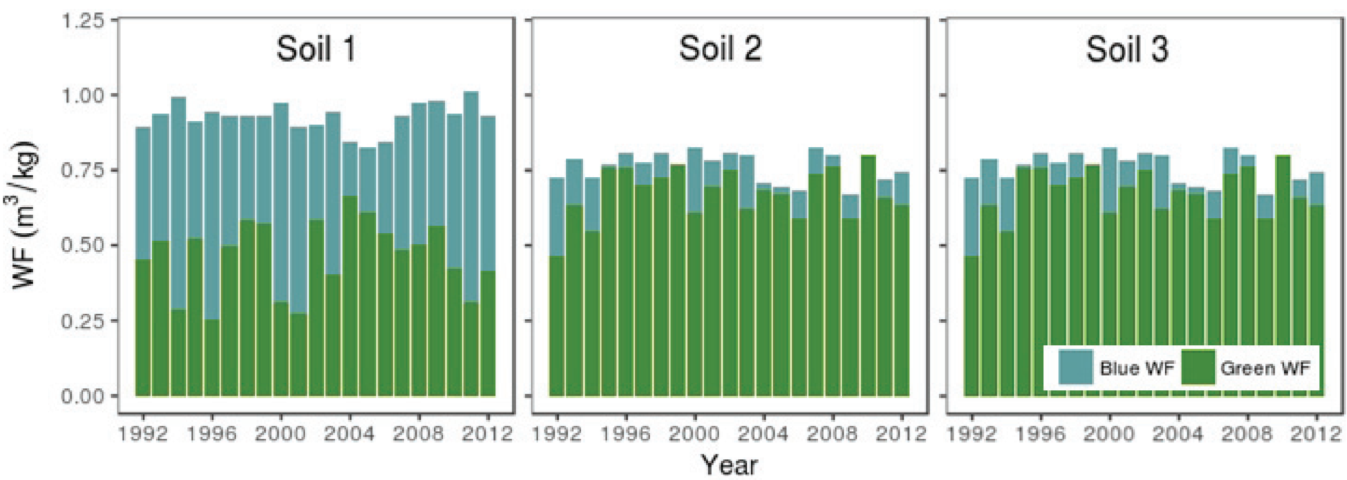

Figure 4. Simulated yearly grain maize water footprint (WF) in the Marchfeld plain for the three soil types from 1992-2012
Abbildung 4. Simulierter jährlicher Wasser-Fußabdruck (WF) für Körnermais im Marchfeld für die drei Bodenklassen von 1992-2012

due to negative impacts on crop growth (i.e., too low temperatures and radiation). This was most clear for soil 1: a WF of 0.54 m³/kg for an annual precipitation sum > 600 mm and a WF of 0.65 m³/kg for an annual precipitation sum between 600 mm and 1250 mm. The lowest WF of spring barley for all three soil types was simulated at an annual mean temperature of 11°C and an annual precipitation sum between 500 and 700 mm, where the lowest ET values were simulated.

The green WF of grain maize showed a different behavior between the soil type 1 (lowest AWC) and the soils 2 and 3. When the mean annual temperature is too low (<5°C) or too high (>9°C), the WF of soil 1 increased. In case the annual temperature was above 9°C, the temperature limiting effect disappeared and an effect in combination with extremely low precipitation occurred. Here, the low plant available water capacity of soil 1 caused this effect. Most lowland conditions with higher annual temperatures

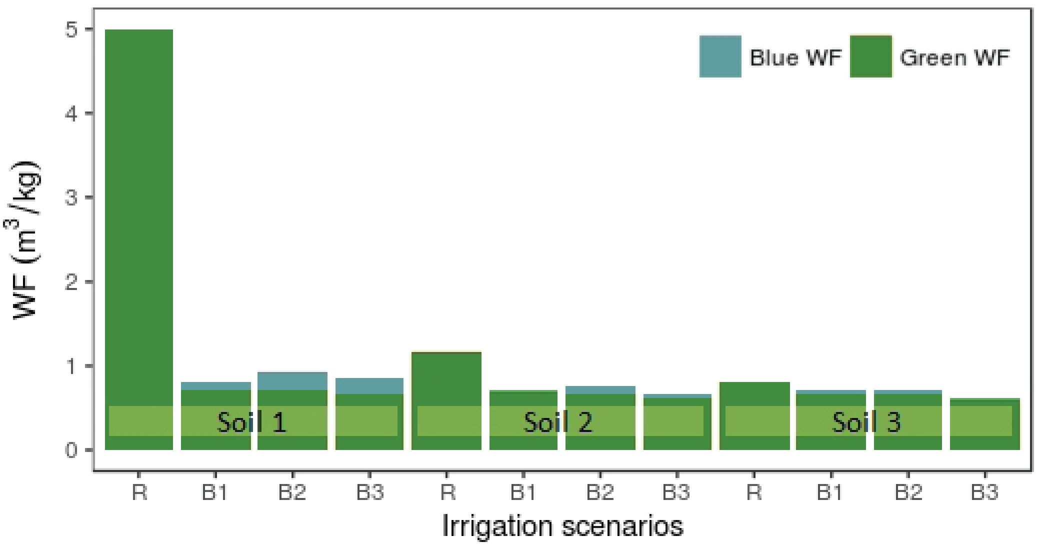

Figure 5. Water foodprint (WF) of grain maize depending on irrigation method and soil conditions in the Marchfeld plain from 1992-2012. R: rainfed, B1: irrigated sprinkler - automatic fixed amount 30 mm, B2: irrigated sprinkler - automatic 50% depletion, B3: irrigated sprinkler - deficit irrigation (max 80% field capacity)

Abbildung 5. Wasser-Fußabdruck (WF) von Körnermais in Abhängigkeit von der Bewässerungsmethode und den Bodenverhältnissen im Marchfeld, nordöstliches Österreich, von 1992-2012. R: nicht bewässert, B1: Beregnung mit Sprenger - automatisch mit 30 mm fixiert, B2: Beregnung mit Sprenger - automatisch bei max. 50 % Abnahme des pflanzenverfügbaren Bodenwassergehalts, B3: Beregnung mit Sprenger - Defizitbewässerung (max. 80 % der Feldkapazität)

were also the regions with the lowest annual precipitation. Soil 1 showed the lowest WF for grain maize at an annual mean temperature of 8-9°C and an annual precipitation sum 1250-1500 mm. The other two soils showed similar results with overall lower green WF due to a higher AWC. The lowest WF values for grain maize occurred for soil type 2 and 3 and with the temperature range of 8° and 9°C. Considering the annual precipitation sum, soil 1 presented a clear trend of – the drier the year, the higher the grain maize WF. Soil 2 and 3 had high WF values, both in very dry and very humid conditions but with only a marginal difference. The lowest WF of grain maize was in climates between 600 and 1000 mm annual precipitation (Table 3). Annual mean temperatures of 8-9°C and a precipitation sum of 700-800 mm presented the lowest WF for soil 2; the lowest WF of soil 3 is characterized as an annual temperature of 11°C and 700 mm annual precipitation.

The highest percentage of arable land area cropped with spring barley for all three soils depicted a WF of around 0.5 m³/kg. The three soils simulated for grain maize also behaved differently: soil type 1 (lowest AWC) had a WF value higher 1.3 m³/kg, soil 2 and 3 showed a WF of 0.7-0.8 m³/kg on most barley growing area.

The green WF of the various crops was calculated for different climates and soil classes in combination with all agricultural land use areas in Austria. In Figure 6, the green WF for spring barley and grain maize are presented. It can be seen that there were clear regional differences for green WF for grain maize, whereas for spring barley, it was more uniform for most regions, with just small regional deviations due to, for example, very low temperatures or soils with low AWC (soil 1). It should be mentioned that the WF values for spring barley ranged mainly between 0.5 and 0.6 m³/kg, whereas for grain maize, the range were from 0.69 to more than 1.8 m³/kg. Also, the growing period for spring barley was earlier than for grain maize and much shorter (from March until June). The green WF of grain maize was highest in warm-semi-arid and colder agricultural production regions. Warm and dry regions on soils with low AWC presented the highest WF, for example, the Parndorf Plain (northern part of Burgenland), Steinfeld (south of Vienna), around Retz (NW Weinviertel) or in the Marchfeld plain. In the colder regions, the low simulated grain maize yields (and high WFs) are the main cause of a too short vegetation period where the simulated maize maturity type could not reach harvest maturity (i.e. at higher elevations).

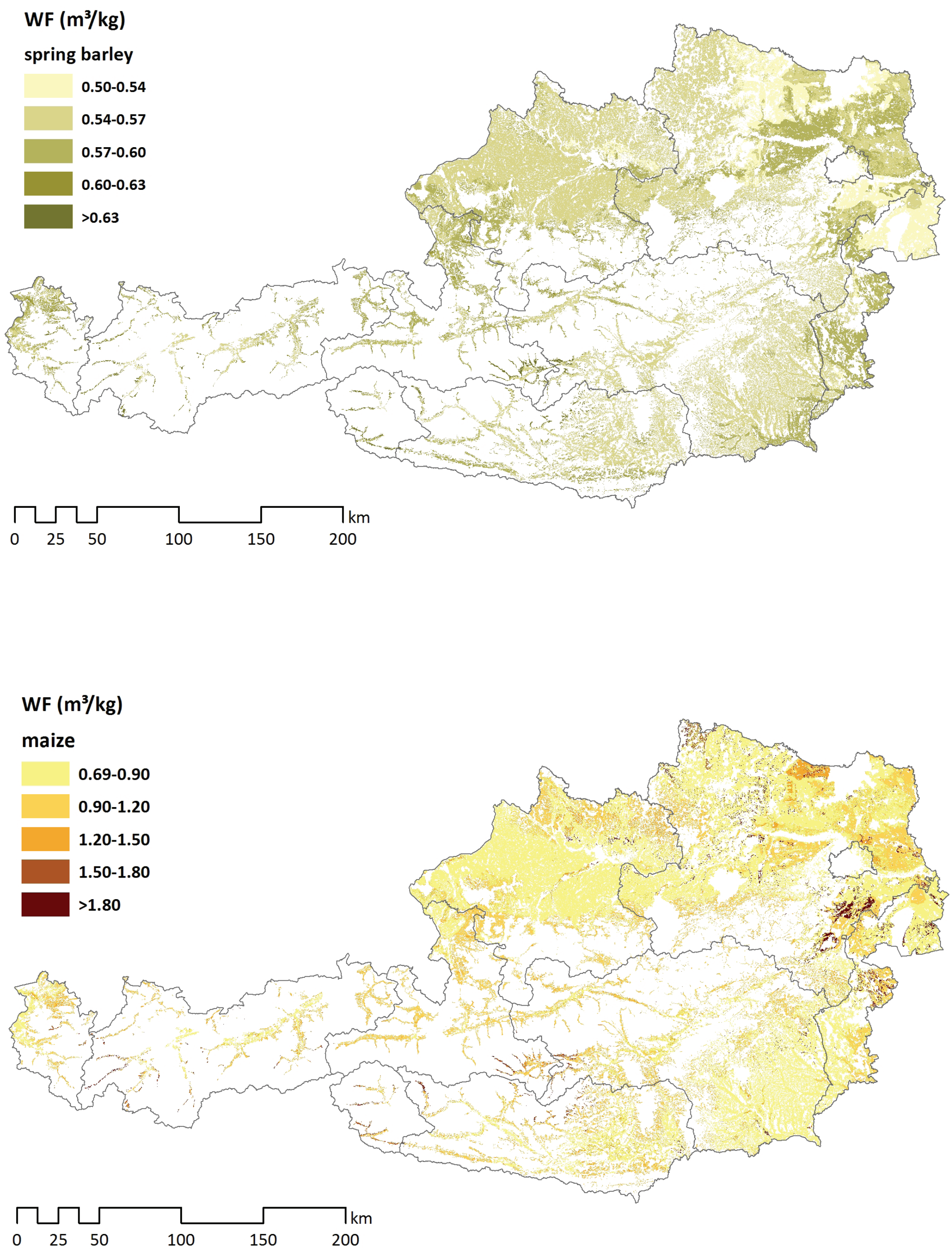

Figure 6. Average yearly (1992-2012) green water footprint (WF) for spring barley and grain maize in Austria (m^3/kg)
Abbildung 6. Durchschnittlicher jährlicher (1992-2012) grüner Wasser-Fußabdruck (WF) für Sommergerste und Körnermais in Österreich (m^3/kg)

A reasonable level of water productivity should be strived, that is, a good amount of "crop per drop". This approach also includes the consideration of evaporative losses in field crops, which is increasing under higher irrigation rates or precipitation. Thus, high transpiration efficiency is frequently related to somehow lower than achievable yields. In the context of plant breeding, however, regarding the reduce crop water demand of the plant itself, maximization of water uptake (transpiration) should be achieved. Since biomass production is strongly linked to transpiration, breeding for maximized soil moisture capture for transpiration is the most important target for yield improvement under drought stress (Blum, 2009).

4. Conclusions

Our study showed, based on climatic and soil conditions of the agricultural regions in Austria, distinct differences of regional simulated crop WFs, which were strongly related to the crop type as demonstrated for grain maize and spring barley. This can be explained by the crop growing duration of the specific crops.

Therefore, the crop selection can contribute to a reduction of crop WFs, for example, by selecting winter crops or spring crops with a relatively short growing season. Another option for reaching a low WF is the use of crops with a high share of harvested biomass on total crop biomass, however, these crops can still have a high water demand in case of a long growing period, also covering summer months (e.g., sugar beet). Our WF study showed that the total crop water consumption needs to be considered together with WF estimates in order to increase the sustainable use of regional water resources for both rainfed and irrigated crop production. Our study is based on a simplified crop model and soil water balance approach in AquaCrop. Thus, the applied study methodology has limitations regarding site representativeness and more accurate crop specific crop water balance estimations, considering i.e. also different crop management options (such as other yield impacting factors as i.e. soil cultivation and fertilization effects). Further, the underlying data base on soil and weather input data can have significant small-scale biases.

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