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Water use indicators at farm scale: methodology and case study

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Abstract

Indicators for water use at farm scale can assist farmers in understanding the water flows on their farms and in optimizing water use by adapting agronomic measures and farm management. The objective of this work is to develop a methodology to estimate water flows at the farm scale, to derive indicators for farm water use, and to apply them in a first case study. After the spatial and temporal boundaries of the farm system and the water flows are defined, three indicators to assess water use at the farm scale are developed: farm water productivity, degree of water utilization, and specific inflow of technical water. Farm water productivity describes the ratio of farm output to water input, where the water input is the total of those water inflows into the farm system that can be assigned to the generation of farm output. Farm output is expressed on a mass basis, food energy basis, and monetary basis. The degree of water utilization characterizes the relationship between productive water to the total water inflow into the farm system, where productive water comprises those water flows that directly contribute to biomass generation via plant and animal metabolism. The specific technical water inflow quantifies the water inflow into the system by technical means relative to the farm area. The application of the methodology in a first case study for a mixed crop-livestock farm with 2869 ha in Germany results in a farm water productivity of 2.30 kg fresh mass per $\mathrm{m}^{-3}_{\mathrm{Winput}}$, 1.03 kg dry mass per $\mathrm{m}^{-3}_{\mathrm{Winput}}$, 5.96 GJ $\mathrm{m}^{-3}_{\mathrm{Winput}}$, and 0.25 € $\mathrm{m}^{-3}_{\mathrm{Winput}}$. The degree of water utilization is 0.56. The specific technical water inflow is 36.5 $\mathrm{m}^3\ \mathrm{ha}^{-1}\ \mathrm{year}^{-1}$. Factors that mainly effect these indicators and general approaches to optimize water use in farms are discussed as well as the further research required for practical implementation.

Introduction

Water is scarce in many regions of the world (e.g., Seckler et al. 1999; Molden et al. 2011). It is expected that global change will further aggravate the problem of water scarcity by increasing the water demand due to the growing world population combined with rising per capita water use, and by reducing water availability due to climate change (e.g., Arnell 1999; Rosegrant et al. 2002; Lotze-Campen et al. 2008; Rockström et al. 2009; de Fraiture and Wichelns 2010).

Water is indispensable for agricultural production. Worldwide, agriculture is and will be the major user of water resources (de Fraiture et al. 2007). Hence, ensuring water supply for agriculture and making the best use of it has been an issue of high relevance for stakeholders and scientists around the world for decades. Within this discussion, the question how to estimate and to assess water use for agricultural production has been covered extensively in scientific literature.

Depending on the objective of estimating water use in agriculture, various approaches at different scales have been developed. Agricultural scientists often work at the crop or field scale expressing the relation of water use to biomass generation in terms of water use efficiency or water productivity (see, e.g., Zoebl 2006; Bouman 2007) while the concept of livestock water productivity presents an approach that can be applied at the scale of animal, household, farming system, or basin (e.g., Descheemaker et al. 2010; Haileslassie et al. 2011). Most recently, an advanced methodology for evaluating water use efficiency at a range of spatial and temporal scales has been suggested, for example, for crop, crop rotation, field, farm, region, or landscape (Moore et al. 2011).

From a hydrological perspective, water flows are balanced mostly in a spatial context, for example, at the scale of basins or fields (e.g., Molden and Sakthivadivel 1999). Life cycle analysts aim at the assessment of environmental impacts of water use for agricultural products through the quantification of water use and subsequent estimation of impacts (e.g., Koehler 2008; Milà i Canals et al. 2009, 2010; Pfister et al. 2009; Peters et al. 2010). Similar to life cycle assessment in objective and partly in methodology is the concept of sustainability indicators applied at the scale of farms, farming systems, or regions. Only a few of the indicator sets consider water use (van der Werf and Petit 2002), and those that do, cover only parts of total water use such as irrigation water use (e.g., Zhen et al. 2005; Dantsis et al. 2010; Gómez-Limón and Sanchez-Fernandez 2010) or process water use in livestock husbandry (e.g., Meul et al. 2009) or they use very simple approaches for rough estimation of feed crop water demand (van Calker et al. 2004). The virtual water concept has been developed from an economical perspective and provides a basis for the estimation of the water demand for agricultural products and the derivation of the water footprint of nations from their agricultural production and food trade (e.g., Allan 1998; Hoekstra and Hung 2002; Chapagain and Hoekstra 2003).

From our point of view, the farm scale has been underrepresented in the development of conceptual framework as well as in case studies up to now. The current comprehensive and sophisticated concepts of water use estimation do not deal with the farm scale, whereas the majority of farm-scale approaches are deficient in methodology due to incompleteness and simplicity. However, it is primarily at the farm scale that farmers can be directly addressed and involved. Indicators for water use at farm scale would be most useful to assist farmers in understanding the water flows in their farms and in optimizing water use by agronomic measures and farm management.

The objective of this study is to develop a methodology to estimate water flows at the farm scale, to derive indicators for farm water use and to apply them in a first case study. First, the spatial system boundaries and the temporal frame are defined. Subsequently, all water flows into and out of the system are compiled. Afterward, we select those fractions of the water inflows that contribute to biomass production and assign them to the useful farm output. Then, three indicators for farm water use are derived and calculated in a case study for a farm in East Germany.

Conceptual Framework

System boundaries

The system regarded here is the farm. The spatial boundaries of the system are set from an institutional perspective in that sense that any physical feature that belongs to the farm also belongs to the system. The horizontal dimension of the system includes the fields managed by the farm and the areas covered with farm buildings. Hence, within a given area, the arable land, grasslands, and yards of the farm belong to the system, whereas anything else within that area (surface water, forest, settlements, and traffic infrastructure) does not. From an institutional perspective, farmers have their fields and yards at their exclusive disposal, whereas they cannot manage the other parts of the area exclusively or perhaps at all. The vertical dimension of the system includes the plant canopies and animals as well as farm buildings, machinery, equipment, and ancillary materials to their respective height and the soil to the depth of the roots. Again, this determination is made from an institutional perspective, although it results in permanently changing vertical dimensions of the system as crops are growing and being harvested and animals are moving. The criterion for assigning crops, animals, machinery, and buildings to the system is that they are at the farmers' exclusive disposal, whereas the air above the fields or the groundwater below are common goods without exclusive access for the farmers.

The temporal frame is set with the reference period comprising the farming year for crop production on arable land and the calendar year for grassland and animal husbandry. The reference period for arable land is determined at the single field scale. It begins with the day after harvesting the preceding main crop and ends with the day of harvest of the main crop in the calendar year regarded. Thus, the reference period comprises the period between tillage and harvest of the main crop plus the period of preceding fallows and/or cover crops. The reference period for grassland is the calendar year as the land is covered with the same type of vegetation permanently. Thus, the reference period in crop production is not uniform for the whole farm, but varies from field to field. Animal husbandry, in contrast to crop production, is not subject to that strong variation among seasons or years. The reference period is defined as the calendar year.

Water inflows and outflows

Once the system is defined, water flows into and out of the system can be determined (Fig. 1). The term water

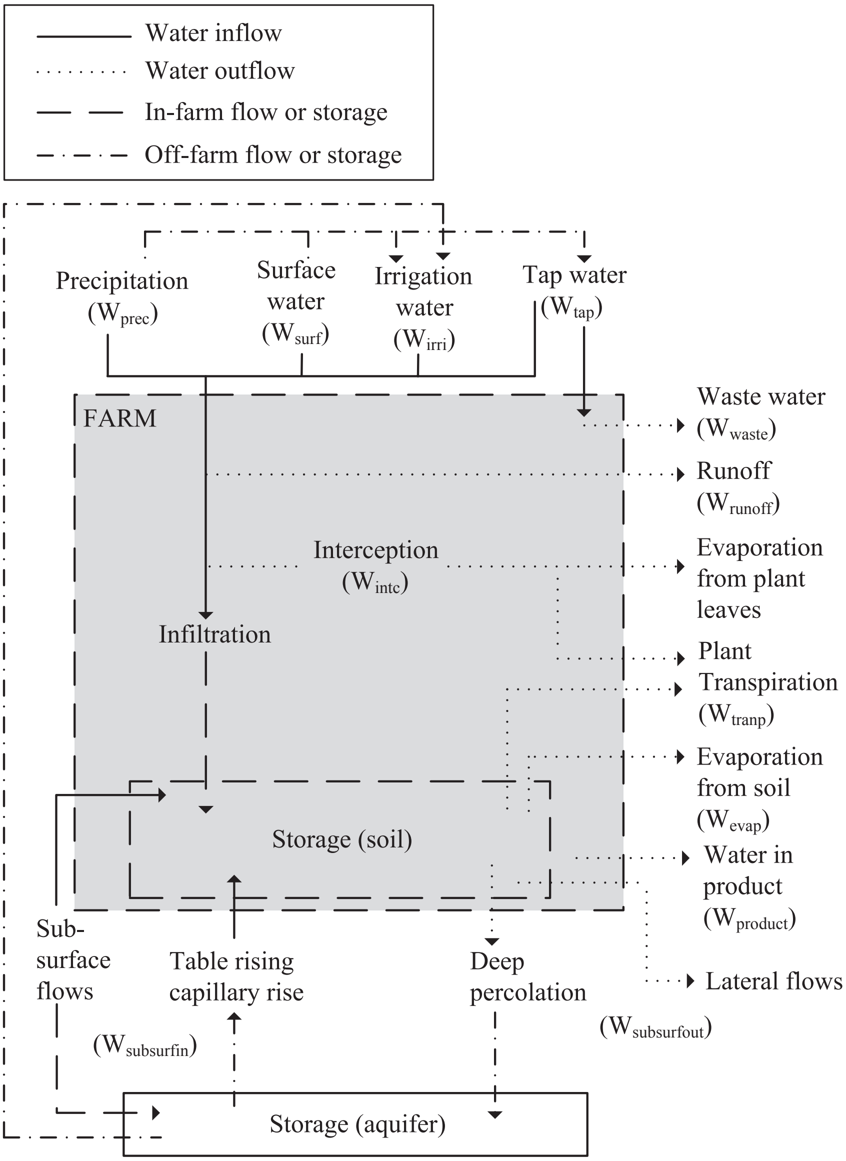


Figure 1. System boundary, water flows, and storages at farm scale.

flow is perceived from a hydrological perspective here. It comprises all water that enters or leaves the farm system regardless of whether it is used for agricultural production.

Water inflows W_{inflow} (m^3) may enter the system

- via air as precipitation W_{prec} (m^3),
- via ground as surface flows W_{surf} (m^3) and subsurface flows $W_{subsurfin}$ (m^3),
- via technical means W_{tech} (m^3) as irrigation water W_{irri} (m^3) and tap water W_{tap} (m^3).

$$W_{inflow} = W_{prec} + W_{surf} + W_{subsurfin} + W_{tech} \tag{1}$$

where:

$$W_{tech} = W_{irri} + W_{tap} \tag{2}$$

Water outflows $W_{outflow}$ (m^3) may leave the system

- via air as water vapor from interception W_{intc} (m^3), soil evaporation W_{evap} (m^3), plant transpiration W_{transp} (m^3), and animal perspiration and exhalation $W_{persp+exh}$ (m^3),
- via ground as liquid water flows comprising surface runoff W_{runoff} and subsurface flows $W_{subsurfout}$ (m^3) as deep percolation and lateral flows,
- via pipe as wastewater W_{waste} (m^3), and
- via water content in farm products $W_{product}$ (m^3).

$$W_{outflow} = W_{intc} + W_{evap} + W_{transp} + W_{persp+ex} + W_{runoff} + W_{subsurfout} + W_{waste} + W_{product} \tag{3}$$

According to the system boundaries, precipitation W_{prec} enters the system when it reaches the plant canopies or the soils. Surface flows W_{surf} enter the system as runoff from areas adjacent to the farm or as water from temporary inundations. Technical water W_{tech} is made up of tap water W_{tap} and irrigation water W_{irri}, which can be withdrawn from surface or groundwater. The source may be located within the farm's territory and only the farmer himself manages withdrawal and distribution. In other cases, irrigation water may be conveyed over large distances. Irrigation water is considered to enter the system at that point where the farmer is responsible for distribution and, thus, able to control the process.

Tap water W_{tap} comprises water flows that are provided by all technical means other than irrigation water. It may originate from technically captured and stored precipitation from surface or from ground water. Tap water is mainly used in animal husbandry for drinking, cleaning, disinfection, regulation of housing climate (heating, cooling, moistening), and temperature regulation during intermediate storage of animal products. Tap water may further be used in crop husbandry for spraying herbicides and pesticides.

Subsurface water $W_{subsurfin}$ may enter the system by lateral flows, increases in groundwater levels and capillary rise.

Water flows entering the system "from above" divide into runoff, interception, and infiltration. Runoff W_{runoff} and evaporated interception water W_{intc} leave the system rapidly and without contributing to biomass production. Part of the interception water W_{intc} is taken up by the plants and transpired. This water outflow is included in W_{transp}, which encompasses plant transpiration regardless of source.. The water fraction infiltrated into the soil divides further into soil evaporation W_{evap}, plant transpiration W_{transp}, and subsurface outflows $W_{subsurfout}$ via deep percolation and lateral subsurface flows. Also, the water having entered the system "from below" may leave via soil evaporation and plant transpiration or via deep percolation and lateral flows. Only the fraction that is used for plant transpiration contributes to biomass production. A minor part of this fraction is incorporated into the plant tissue. This part may be consumed within feed for the farm's livestock or leave the system in products as part of $W_{product}$.

Water within feed and drinking water is metabolized by the livestock and leaves the system as water vapor from animal perspiration and exhalation $W_{persp+exh}$ or incorporated in livestock products and included in $W_{product}$. The water contained in excreta partly evaporates during storage and partly is returned to the fields where it may infiltrate or evaporate. Tap water used for cleaning and disinfection immediately leaves the system as wastewater W_{waste} or it is added to the excreta. Tap water used for regulation of the housing climate may cycle within the installation, and finally leaves the system as well.

Indicators

The indicators we propose are intended to characterize the efficiency of the water use at the farm scale. Hence, they are derived from the general economic principle aiming at the best relationship of input and output (e.g., Mühlbradt 2007). In the case of farm water use, the economic maximum principle applies, meaning that a maximum useful farm output with the limited water resources should be achieved. Consequently, we change perspectives here from the hydrological perspective of water inflows and outflows to the economic perspective of input and useful output. From the economic point of view, the water outflows are not relevant. We have to define the useful farm output in other terms. Furthermore, we have to select only those water inflows that contribute to the generation of the useful farm output.

We suggest the following indicators to characterize farm water use:

Farm water productivity (*FWP*)	(on a fresh mass (FM) base in $\mathrm{kg_{FM}}\ m^{-3}_{\mathrm{Winput}}$, on a dry mass (DM) base in $\mathrm{kg_{DM}\ m^{-3}_{Winput}}$, on a food energy base in $\mathrm{MJ\ m^{-3}_{Winput}}$, on a monetary base in € $\mathrm{m^{-3}_{Winput}}$)
Degree of water utilization (*DWU*)	(dimensionless)
Specific technical water inflow (*STW*)	($\mathrm{m^{3}_{Wtech}\ ha^{-1}\ year^{-1}}$)

Productivity in general is an economic term describing the relation of output to input and aimed at the quantification how much useful output is obtained per unit of resource input (e.g., Mühlbradt 2007). Similarly, the term water use efficiency originates in the economic concept of productivity (Tate 1994). Both water productivity and water use efficiency are often used in the context of physiology, agronomy, hydrology, or ecology at different scales and with different variables regarding the output (see, e.g., Bessembinder et al. 2005; Zoebl 2006; Moore et al. 2011).

For estimating farm water productivity, a water input is related to a mass or nutritional or monetary output. Input and output have to be defined. The output here is expressed with respect to several categories: (i) in physical terms as the total fresh or dry mass of farm products, (ii) under nutritional aspects as the total food energy contained in the products of the farm, and (iii) on a monetary basis as total farm revenues.

Although external output such as ecosystem services or social effects of running a farm are important as well, we will not include them here (for discussion of externalities see the livestock water productivity concept, e.g., Peden et al. 2007; Descheemaker et al. 2010). We will focus on output that is relevant to the farmer as our objective is to support farmers in better understanding and managing the water flows in their farms with respect to their products. Only if biomass production is not the main purpose of the farm, it could be appropriate to consider different output categories. For instance, if farmers would receive their income mainly from environmental programs for maintaining high-diversity semi-natural grassland by keeping cattle, it could be reasonable to regard the hectares of grassland biotopes conserved as the farm output.

The nutritional output of the farm is focused on food energy in order to avoid splitting-up the farm output into too many parameters, for example, food protein, vitamins, etc. For simplification, we assume here that the farm produces biomass only for food and not for energy or material use.

For calculating the water input, we have to identify those water flows that shall be assigned to the generation of output. We define water input W_{input} (m^3) as the sum of plant transpiration originating from precipitation $W_{prec-transp}$ (m^3), which is the fraction of precipitation that contributes to crop growth, plus all water inflows via technical means W_{tech} (m^3) plus an additional quantity of water used in the prechains, that is, indirect water use $W_{indirect}$ (m^3):

$$W_{input} = W_{prec-transp} + W_{tech} + W_{indirect} \tag{4}$$

The particular issue how to deal with soil evaporation and plant transpiration from infiltrated precipitation is highly controversial among scientists who deal with the estimation of water use in agricultural production. Depending on the objective of the study, different approaches for estimating water use have been developed. Hydrologists balance water inflows and outflows at different scales such as fields or watersheds and, thus, have to include evapotranspiration (e.g., Molden and Sakthivadivel 1999). From an agricultural perspective, many scientists consider either evapotranspiration (e.g., Peden et al. 2007; Descheemaker et al. 2010) or transpiration only (e.g., Bouman 2007; Moore et al. 2011) as input for evaluating water use efficiency or water productivity at various scales. The virtual water concept generally includes evapotranspiration from precipitation (e.g., Hoekstra and Hung 2002; Chapagain and Hoekstra 2003, 2007; Chapagain et al. 2006). Life cycle analysts aim at environmental impact assessment and generally exclude precipitation (for case study and further references, see Peters et al. 2010) or include only the difference between evapotranspiration of the crop and a reference vegetation (Milà i Canals et al. 2009, 2010).

For calculating the farm water productivity, we include in the water input that fraction of precipitation that contributes to plant biomass generation, that is, transpiration. The total amount of precipitation is a natural process, on which farmers have no influence. They only can affect, within certain limits, the fraction of precipitation that is infiltrated into the soil and how much of this fraction will be transpired by plants. Soil evaporation is excluded from the water input as it is not involved in biomass generation and should be minimized. We explicitly state that we do not consider plant transpiration (or soil evaporation) to be a water "consumption" or a water "loss" as evaporated water is neither consumed nor lost, but transformed into a gaseous state, a natural step in the water cycle. Consistent with the terminology used here, plant transpiration is an input into the production process, where input is used as a neutral expression without the connotation of something disappearing and being lost.

For farms with irrigated crops, the technical water inflow W_{tech} is mainly made up of irrigation water. In contrast to the procedure described above for dealing with water input from precipitation, we include all water withdrawn for the farm's sake as water input in W_{irri}, not just transpiration. With this approach, we again deviate intentionally from several common methods for estimating water use that include only the fraction of irrigation water that is subject to infiltration or evapotranspiration (e.g., Chapagain and Orr 2009). Irrigation water withdrawal, distribution, and application are technical processes partly or entirely controlled by the farmers. Consistent with the system boundaries, all irrigation water managed by the farmers themselves is input into the production process. Farmers have to pay for all the withdrawn water, not only for the fraction available to the plants, and it is in their hands to reduce the percentages of unproductive irrigation water. Furthermore, in contrast to precipitation, irrigation water is distracted from its natural flow, which might cause environmental impacts and gives reason to fully account for all irrigation water.

With the term indirect water use, we denote the volume of water used to produce feed purchased from outside the farm and all the other farm input such as building materials, machinery, energy, fertilizer, pesticides, herbicides, ancillary materials, and so on. Indirect water use is introduced here in correspondence to the methodology in energy and greenhouse gas balancing (ISO 2006a,b). Indirect water use was not listed among the water flows as it is not a physical water flow in the farm and most likely spatially decoupled from the hydrological cycle of the region the farm is located in. The water used in prechains has been withdrawn and discharged elsewhere, most likely rather far away. Although farmers cannot control how much water is used to produce the farm inputs, from the institutional perspective, all these things belong to the farm and it is their decision to purchase them and to make sound use of them.

Finally, farm water productivity can be expressed using the following formulae:

$$FWP_{mass} = \frac{Mass_{output}}{W_{input}} \tag{5}$$

$$FWP_{energy} = \frac{Energy_{output}}{W_{input}} \tag{6}$$

$$FWP_{mon} = \frac{Revenues}{W_{input}} \tag{7}$$

where FWP_{mass} is water productivity on mass base (kg$_{\mathrm{FM}}$ m$^{-3}_{\mathrm{Winput}}$, kg$_{\mathrm{DM}}$ m$^{-3}_{\mathrm{Winput}}$); FWP_{energy} is water productivity on food energy base (MJ m$^{-3}_{\mathrm{Winput}}$); FWP_{mon} is water productivity on monetary base (€ m$^{-3}_{\mathrm{Winput}}$); W_{input} is water input (m^3 year^{-1}); $Mass_{output}$ is mass output (kg$_{\mathrm{FM}}$ year^{-1}, kg$_{\mathrm{DM}}$ year^{-1}); $Energy_{output}$ is food energy output (GJ year^{-1}); and *Revenues* indicates total farm revenues (€ year^{-1}).

The farm water productivity can be calculated for the whole farm, for a single subsystem of the farm such as crop production and livestock husbandry, as well as for individual products. This allows us to assess the productivity of the whole system as well as the contribution of the single components and to investigate the effects of measures to increase water productivity.

While farm water productivity tells how much output a farm produces per unit water input, it is also important to know the water fraction that becomes available for biomass production in relation to the total water inflow of the farm.

To characterize the water fraction directly committed to biomass generation, we will introduce the degree of water utilization *DWU* (−) as the relation of productive water W_{prod} (m^3) to the total water inflow W_{inflow} (m^3):

$$DWU = \frac{W_{prod}}{W_{inflow}} \tag{8}$$

Productive water W_{prod} (m^3) refers to water directly involved in biomass generation through plant and animal metabolism and comprises water taken up and transpired by plants W_{transp} (m^3), drinking water for animals W_{drink} (m^3), and water taken in by animals with feed W_{feed} (m^3):

$$W_{prod} = W_{transp} + W_{drink} + W_{feed} \tag{9}$$

While the water transpired by plants and the drinking water for livestock completely originate from physical water inflows, the water within feed is an in-farm flow for that part of feed that is provided by the farmers themselves. The drinking water W_{drink} may be a part of the tap water W_{tap} or directly taken from surface waters by the livestock.

Note the differences between total water inflow, water input, and productive water and their use in the indicators. The total water inflow W_{inflow} comprises all water physically entering the system via the natural water cycle or by technical means. Water input W_{input} is that fraction of total inflow that is used in the farm's production process plus indirect water input. However, it would not be appropriate to relate the degree of water utilization to the total water input W_{input} as the total water input contains indirect water as well as unproductive irrigation water and ancillary water. Unproductive irrigation water refers to that part of irrigation water that does not become available to the plants. Ancillary water is tap water minus drinking water, that is, water used for cleaning, disinfection, heating, cooling, and application of pesticides and herbicides. Unproductive irrigation water and ancillary water should be minimized. Thus, we exclude them from the degree of water utilization and restrict this indicator to the productive water, which is the fraction that directly contributes to biomass generation through plant and animal metabolism.

An approach similar to the degree of water utilization is known from Moore et al. (2011) who define the indices of rainfall capture efficiency (the total amount of water that enters the soil profile and hence is available to be transpired), and the soil water utilization efficiency (the total amount of water transpired by plants that contribute to the production of grain, grazed forage, or conserved fodder).

The two indicators introduced in this article reflect the two basic options farmers have to increase farm output with a given total water inflow: (i) to enhance the percentage of water that flows into biomass generation, that is, to increase the degree of water utilization and (ii) to make a more efficient use of this productive water, that is, to increase farm water productivity. Both options can be combined (Fig. 2).

Farmers will pay special attention to the water inflows by technical means, that is, irrigation water and tap water. While access to precipitation and subsurface flows is assured by access to the land and does not cause additional costs, technical water has to be purchased and requires expenditures for withdrawal, distribution, and application. Furthermore, access to irrigation water often is regulated and limited. As water supplied by technical means is diverted from its natural course, the amount of technical water may also be of environmental relevance. Thus, as a third indicator we will use the specific technical water inflow STW, describing the relation of the annual water inflow by technical means W_{tech} to the area of the farm land A_{farm}:

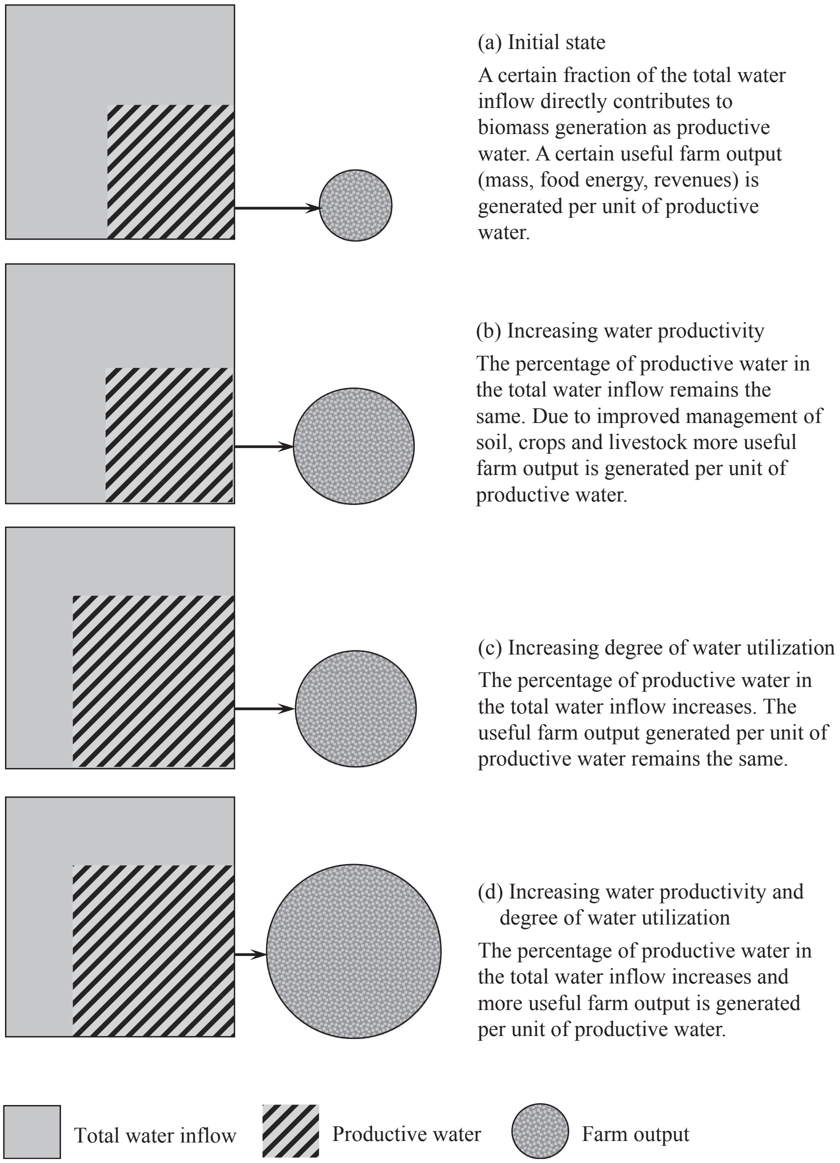
$$STW = \frac{W_{tech}}{A_{farm}} = \frac{W_{irri} + W_{tap}}{A_{farm}} \tag{10}$$

The water inflow by technical means is related to the area of the farm for making farms comparable.

Case Study

Database

For the first application of the concept in a case study, a farm in the central plains of East Germany was selected. The farm is located close to the river Neiße that marks the border between Germany and Poland. This region


(a) Initial state

A certain fraction of the total water inflow directly contributes to biomass generation as productive water. A certain useful farm output (mass, food energy, revenues) is generated per unit of productive water.

(b) Increasing water productivity

The percentage of productive water in the total water inflow remains the same. Due to improved management of soil, crops and livestock more useful farm output is generated per unit of productive water.

(c) Increasing degree of water utilization

The percentage of productive water in the total water inflow increases. The useful farm output generated per unit of productive water remains the same.

(d) Increasing water productivity and degree of water utilization

The percentage of productive water in the total water inflow increases and more useful farm output is generated per unit of productive water.

Figure 2. Options to increase farm output with a given total water inflow.

was chosen as water availability and water productivity gain in importance in the central plains of East Germany. For example, the East German state of Brandenburg has a temperate continental climate with a mean annual temperature varying locally between 7.8°C and 9.5°C and mean annual precipitation between 470 and 710 mm. Climate change will probably lead to higher temperatures with increasing evapotranspiration, whereas precipitation is expected to not only decrease in total but also to shift to an unfavorable temporal pattern, with less precipitation during the vegetation period to more in autumn and winter (Gerstengarbe et al. 2003; UBA 2007). Thus, water supply becomes a more and more pressing problem for farmers, causing them to consider irrigation and how to make a better use of the available water.

The farm size is 2869 ha, consisting of 2605 ha arable land and 264 ha grassland. Large farms are typical in East Germany (e.g., MIL 2010; SMUL 2011). The main crops are wheat, rye, barley, rapeseed, and maize (Table 1). The majority of the potato fields (74 ha) are under drip irrigation or hose reel irrigation. The farm keeps 340 dairy cows plus heifers and calves for reproduction in stables all year. The year regarded in this study is 2010. All farm data were collected in personal interviews.

The following data were used in this study:

- *Climate:* Data from the next station of the German Weather Service (distance from farm 10 km), daily temperature, precipitation, relative air humidity, sunshine duration, wind speed
- *Cropping:* For all fields, the main crop with the dates of agronomic measures, the yield, and its use (sale or feed), if applicable the volume of irrigation water applied, preceding crop, and its harvesting date
- *Livestock husbandry:* Animal species and utilization, livestock numbers and age, amount of products
- *Technical water inflow:* Volume of water withdrawn for irrigation, volume of water taken from taps
- *Indirect water:* Water used to produce the feed purchased from outside the farm

Table 1. Farm data (2010).

Parameter	Value
Climate (2009–2010)	
Mean annual temperature (°C)	8.47
Mean annual precipitation (mm)	801
Farm size (ha)	2869
Arable land (ha)	2605
Winter wheat	660
Winter barley	461
Spring barley	49
Winter rye	666
Winter rapeseed	335
Pea	111
Maize	158
Potato	88
Sugar beet	77
Grassland (ha)	264
Permanent grassland	193
Sown grassland	71
Livestock numbers	
Dairy cows	340
Heifers (1–2 years)	146
Heifers (0.5–1 year)	81
Calves	81

Calculations

Total water inflow

The total water inflow comprises precipitation, irrigation water, tap water, soil surface flows, and subsurface flows (eq. 1).

Water inflow via precipitation W_{prec} (m^3) is calculated as the total precipitation received by all fields *f* of the farm within their respective reference periods. Precipitation received by a single field W_{prec_f} (m^3) is obtained by adding up precipitation per day *d* W_{prec_d}(m^3) within the reference period:

$$W_{prec} = \sum_{f=1}^{n} (\sum_{d=1}^{m} W_{prec_{f,d}}) \tag{11}$$

Precipitation received by fallows is assigned to the following main crop. The farm regarded here does not grow cover crops. In general, precipitation received by cover crops will be assigned to the following main crop in case the cover crop solely contributes to agronomic improvements, such as soil erosion reduction and humus accumulation. If the cover crop is used for feed or bioenergy and, thus, yields a self-contained product water flows of the cover crop are balanced separately.

Water inflow via irrigation is the total volume of water withdrawn by the farmer or delivered to the farmer during the reference period. It is measured by water meters. Tap water is the total volume of water taken off from pipes within the reference period and measured by water meters. In case no water meters are installed at animal housings, the demand of drinking and process water is calculated according to KTBL (2008). This refers to one of the two stables in the farm studied here.

Water inflow via soil surface flows, subsurface water inflow via lateral flows, and capillary rise are not considered here. We assumed a negligible water inflow via soil surface flows and capillary rise due to the fact that the sandy texture of the soils results in high infiltration capacity and a low rise of water above the water table through the action of capillarity. Predominately, sandy or loamy–sandy soils with low contents of organic matter in the topsoil are characteristic for the state of Brandenburg. The subsurface water inflow via lateral flows was assumed to be equal to the lateral outflow, and therefore negligible as well. The groundwater level is low due to the local granulite rock aquifer. The igneous rock basin in the northwest of Saxony is separated from the Erzgebirge basin by this hard rock unit (Jordan and Weder 1995). Hence, capillary rise into the root zone can be excluded.

Water input

Water input is the sum of precipitation water transpired by plants, water supplied by technical means, and indirect water. The water supplied by technical means is already known from the calculation of the total water inflow. Indirect water input for machinery, fertilizer, buildings, and so on could not be included due to the lack of data. Thus, indirect water input was considered only for feed purchased from outside the farm. This applies to soy bean meal. According to the fact that most of the German imports originate from Brazil and Argentina (ZMP 2008), the water input for producing soy bean meal in these two countries was calculated. It was assumed that 95% of the water input originates from transpired precipitation and 5% from irrigation. Plant transpiration from precipitation $W_{prec-transp}$ was calculated as described below for the farm crops.

Total plant transpiration from precipitation $W_{prec-transp}$ was estimated as the cumulated plant transpiration from precipitation of all fields of the farm. Plant transpiration from precipitation of the single fields with their crops was calculated based on the FAO 56 dual crop coefficient method (Allen et al. 1998) where the actual crop transpiration T_{act}. is equal to the term $W_{prec-transp}$ used here. The effect of the differences in crop height, leaf, and stomata properties of different crops on their transpiration are reflected in different coefficients. These representative plant specific values for the different development stages for the basal crop coefficient (K_{cb}), the Leaf Area Index (*LAI*), the rooting depth (Z_r), the average fraction of available soil water (p), and for the plant height (h) of each specific crop were used for the calculations (Table 2).

A three-step approach was used:

(1) Potential evapotranspiration of a grass reference surface ET_0 (mm) was derived from climatic data measured near the investigated farm using the FAO Penman–Monteith equation (Allen et al. 1998). For the calculation of the potential evapotranspiration of a grass reference surface ET_0 in the countries Brazil and Argentina, the database of climatic parameters from the Environment and Natural Resources Service of the FAO (FAO-SDRN) in Bauro (Brazil) and Pejuaho (Argentina) was used.

Table 2. Crop-related model parameterization.

Crop	K_{cb} (–)	*LAI* (–)	Z_r (m)	p (–)	Plant height (m)
Spring barley	0.55[1]	1.80[2]	1.25[1]	0.55[1]	1.00[1]
Winter barley	0.55[1]	1.80[2]	1.25[1]	0.55[1]	1.00[1]
Grassland	0.93[1]	2.06[3]	0.10[1]	0.55[1]	0.70[1]
Winter rape	0.61[1]	2.00[4]	1.25[1]	0.60[1]	1.00[1]
Winter rye	0.59[5]	2.61[6]	1.50[5]	0.55[5]	1.30[5]
Winter wheat	0.60[1]	2.70[3]	1.65[1]	0.55[1]	1.00[1]
Peas	0.77[1]	4.00[7]	0.80[1]	0.35[1]	0.50[1]
Potatoes	0.63[1]	3.40[8]	0.50[1]	0.35[1]	0.60[1]
Sugar beet	0.62[1]	4.10[9]	0.80[1]	0.50[1]	0.40[1]
Maize	0.53[1]	5.03[3]	0.47[10]	0.55[1]	2.00[1]
Soy bean	0.70[1]	3.18[3]	0.95[1]	0.50[1]	0.50[1]

[1] Allen et al. (1998).
[2] Liu et al. (2010).
[3] Scurlock et al. (2001).
[4] Lemaire et al. (2008).
[5] Bodner et al. (2007).
[6] Feyereisen et al. (2006).
[7] Béasse et al. (2000).
[8] Särekanno et al. (2010).
[9] González-Sanpedro et al. (2008).
[10] Timlin et al. (2001).

(2) The potential evapotranspiration of the individual crop ET_c (mm) can be calculated based on the single crop coefficient approach proposed by Allen et al. (1998):

$$ET_c = K_c ET_0 \tag{12}$$

where K_c is a plant specific crop coefficient. For calculating the transpiration of the farm crops, the dual crop coefficient approach was applied. For this purpose, the potential crop transpiration T_c (mm) was adjusted for the individual crops using a basal crop coefficient K_{cb} (mm).

$$T_c = K_{cb} ET_0 \tag{13}$$

The basal crop coefficient is defined as the ratio of T_c over ET_0 under optimal wetting conditions of the soil. The basal crop coefficient K_{cb} allows for the calculation of the transpiration component of T_c. The values for K_{cb} are presented in Table 2.

(3) The tabular values of K_{cb} are applicable for optimal wetting conditions. For water limiting conditions, the coefficients of equation (14) must be multiplied with a reduction factor K_s (–) incorporating water stress. The method for calculating K_s is described below. The final equation for the actual crop transpiration T_{act} (mm) applied here was as follows:

$$T_{act} = K_s K_{cb} ET_0 \tag{14}$$

The basal crop coefficient is affected mainly by the changing characteristics of the crop over its growing season. Three fixed crop coefficients can be taken into account to reflect this development: one at initial stage, one at midstage, and one at late stage. At the beginning of the growing season, the plants are small and the value of the respective initial stage crop coefficient is low. With the further growing of the culture during a development stage, the coefficient increases constantly. The following mid-season stage is associated with one, larger crop coefficient. The late-season stage is characterized by aging and senescence of the plants and associated with a constantly decreasing crop coefficient ending with one crop coefficient at harvest, called late stage crop coefficient. The crop coefficient in this stage is smaller than the antecedent coefficient. The length of the different stages varies for the different cultures. As mean basal crop coefficients for cover crops are not available in literature, a calculation procedure to estimate K_{cb} adapted from the method presented by Allen et al. (1998) was used. As a representative value for the three stages was needed, the weighted arithmetic mean using the number of days of each stage was calculated. The following equation was used to estimate K_{cb}:

$$K_{cb} = \frac{K_{c,ini} \times n_{ini} + K_{cb,mid} \times n_{mid} + K_{cb,late} \times n_{late}}{n_{cb}} \tag{15}$$

where $K_{cb,ini}$ (–) is the crop coefficient at the initial stage of transpiration of the plants, n_{min} the number of days of this initial stage, $K_{c,mid}$ the midvalue, n_{mid} the number of days of the middle stage $K_{cb,\ late}$ (–) the plant height-based estimate of the K_{cb} value for full ground cover, n_{late} the number of days of the late stage, and n_{cb} the number of growing days of the crop. Similarly, to the crop coefficients $K_{c,}$ the values of K_{cb} and the related number of days of the three different growing stages are readable from tables presented by Allen et al. (1998).

For adjustment on specific climatic conditions, the calculated K_{cb} values were improved using the formula of $K_{cb,adj}$:

$$K_{cb,adj} = K_{cb} + [0.04 \times (u_2 - 2) - 0.004 \times (RH_{\min} - 45)] \times \left(\frac{h}{3}\right)^3 \tag{16}$$

where RH_{min} is the minimum relative humidity, u_2 is the wind speed at 2 m height (m sec^{-1}), and h is the mean plant height during the mid- or late-season stage (m) for 20% $\leq RH_{min} \leq$ 80%.

The tabular values of K_{cb} are applicable for optimal wetting conditions. If the amount of soil water drops below a critical value, the crop is water stressed (Bodner et al. 2007). To calculate the water stress coefficient, values of total available soil water in the root zone, readily available soil water in the root zone, and the root zone depletion are needed. K_s is given by:

$$K_s = \frac{TAW - D_r}{TAW - RAW} \tag{17}$$

where K_s is the transpiration reduction factor dependent on available soil water (0–1), D_r is the root zone depletion (mm), TAW is the total available soil water in the root zone (mm), and RAW is the readily available soil water in the root zone (mm). The maximum value of K_s of 1 shows the absence of soil water stress.

The total available soil water TAW (mm) can be calculated by the difference between water content at field capacity θ_{FC} (m^3 m^{-3}) and water content at wilting point θ_{WP} (m^3 m^{-3}). This value is multiplied by the effective rooting deep Z_r (mm).

$$TAW = (\theta_{FC} - \theta_{WP}) \times Z_r \tag{18}$$

We generally used a sandy soil with water content at wilting point of 0.05 (m^3 m^{-3}) and water content at field capacity of 0.13 (m^3 m^{-3}) (Allen et al. 1998).

The readily available soil water content is described as follows:

$$RAW = p \times TAW \tag{19}$$

where p is a tabular value (Table 2) describing the average fraction of TAW that can be depleted from the root zone, without causing moisture stress for the crop. It can be adjusted with the formula

$$p_{adi} = p + 0,04 \times (5 - T_c) \tag{20}$$

The transpiration component of T_c includes a residual diffusive evaporation component supplied by soil water below the dry surface and by soil water from beneath dense vegetation.

In order to determine water availability for evapotranspiration, a root zone depletion D_r was calculated using a daily water balance using a simple tipping bucket approach:

$$D_{r,i} = D_{r,i-1} - P_i + T_{act,i} + DP_i + I_i \tag{21}$$

where $D_{r,i}$ (mm) is the root zone depletion at the end of day i, $D_{r,i\text{-}1}$ (mm) is the root zone depletion at the end of the previous day i–1, P_i (mm) is the precipitation on day i, $T_{act,i}$ (mm) is the actual transpiration on day i, I_i the interception on day i (mm), and DP_i (mm) is the water loss out of the root zone by deep percolation on day i.

After heavy precipitation or irrigation, the soil water content in the root zone might exceed field capacity. The difference between the content, which exceeded the field capacity and the soil water at field capacity, is called deep percolation. Deep percolation is given by

$$DP_i = P_i - I_i + Ir_i T_{act,i} - D_{r,i-1} \quad \text{with } DP_i \geq 0 \tag{22}$$

with P_i as precipitation on day i (mm), I_i for interception on day i (mm), DP_i for deep percolation on day i (mm), $D_{r,i\text{-}1}$ for water content in the root zone at the end of the previous day, $i-1$ (mm), Ir_i for irrigation on day i, and $T_{act,i}$ for transpiration on day i. For the instant calculation, the values of DP and D_r for day i = 1 were set to zero.

The rainfall interception calculation used here is based on work of von Hoyningen-Huene (1983) and Braden (1985). The approach was implemented in several agrohydrological models of different complexity for the estimation in particular of the interception for agricultural crops, for example, the physical-based model SWAP (Kroes and van Dam 2003) or the bucket model (Baroni and Gandolfi 2009). The authors measured interception of precipitation for various crops. The general formula for canopy interception proposed is

$$I = a \times LAI \times \left(1 - \frac{1}{1 + \frac{cf \times P}{a \times LAI}}\right) \tag{23}$$

where I is the intercepted precipitation (mm), P is the gross precipitation (mm day^{-1}), a is an empirical coefficient (mm day^{-1}), and cf is the soil cover fraction ($1 - e^{-0{,}385 \ \mathrm{LAI}}$ [−]). For increasing precipitation amounts, the amount of intercepted precipitation asymptotically reaches the saturation amount $a \times LAI$. We assumed a = 0.25 (mm day^{-1}) for the agricultural crops.

Table 2 shows the input parameters and state variables used for the basal crop coefficient calculation procedure. All parameters were derived from specific literature.

Productive water

Productive water is the sum of all water transpired by plants, drinking water for animals, and water taken in by animals with feed (eq. 9).

Water transpired by plants comprises the fractions of both precipitation and irrigation water that are subject to transpiration. Calculation of transpired precipitation water has been described in the section about estimation of water input. Transpired irrigation water is derived in the same way from total irrigation water. Given water distribution via subsurface pipes and the short distances from the wells to the fields, possible water losses by leakage were considered to be low and neglected.

The drinking water intake of lactating cows $W_{drink\text{-}cow}$ (l day^{-1}) is calculated from the average ambient temperature T (°C), the milk production Y_{milk} (l day^{-1}), the body weight m_B (kg), and the sodium intake In_{Na} (g day^{-1}) with a regression function according to Meyer et al. (2004):

$$W_{drink-cow} = -26.12 + 1.516T + 1.299Y_{milk} + 0.058m_B + 0.406In_{Na} \tag{24}$$

According to Drastig et al. (2010), the values adopted in this study are T = 15°C (KTBL 2008), Y_{milk} = 24 l day^{-1} (farm value), m_B = 650 kg (Kraatz et al. 2009), and In_{NA} = 3.85 g day^{-1} (Kirchgeßner 2004).

To obtain the volume of water in feed, the amount of every feedstuff produced within the farm and purchased from external suppliers is recorded. In-farm feed supply is derived from the collected field data including yield and utilization for feed or sale. Feed purchased from external suppliers is taken from the farm documents. Typical mean water contents of every feedstuff are taken from literature or as reported by the farmer or supplier (Table 3). Subsequently, the volume of water contained within each feedstuff and consumed by animals with feed can be determined.

Farm output

The farm output is calculated on the basis of biomass, food energy, and revenues. The mass output is estimated from the farm data on the amount of sold crop and animal commodities, that is, biomass that leaves the farm system. The sold crop biomass is obtained from the total harvested crop biomass minus the biomass used for feeding the farms' livestock. The food energy output is calculated from the amount of sold food commodities and their food energy content. Revenues are derived from the amount of sold commodities and their producer prices. It is assumed that feed produced beyond the farm's own needs is sold as well. Losses occurring in the process chain after the products have left the farm are not considered here as they happen outside the farm system.

Some crop commodities yield several products. For example, rapeseed is processed to the main product rapeseed oil and the coproduct rapeseed meal or sugar beet to sugar, molasses and dried sugar beet chips. For such crops, the mass output and the revenues refer to the sold biomass while the food energy output considers only

Table 3. Data for calculation of output from crops and livestock products.

Commodity	Utilization[1] (% of original matter) Feed	Food	Industry	Dry matter content (% in FM)	Food energy content[2] (MJ t_{FM}^{-1})	Producer price[3] (€ t^{-1})
Wheat	41	35	21	14	12.937	111
Rye	41	35	21	14	12.267	98
Feed barley	97	–	–	14	13.188	95
Brewers barley	–	–	97	14	–	103
Rapeseed	70	6	24	9	–	263
Rapeseed meal	70	–	–	–	–	–
Rapeseed oil	–	6	24	100	38.937	–
Peas	–	100	–	14	11.639	139
Potato	–	100	–	23	2.931	107
Sugar beet	80	20	–	22	–	35
Dried sugar beet chips	21	–	–	90	–	–
Sugar	–	16	–	100	16.957	–
Molasses	–	4	–	80	11.639	–
Maize	100	–	–	28	–	46
Grass	100	–	–	30	–	42
Milk	–	100	–	12.5	2.680	252

[1] Diepenbrock et al. (1999), Bringezu et al. (2008), BMELV (2011).
[2] Based on data from Klever-Schubert and Endres (2010).
[3] KTBL (2010).

the mass portion of those single products that can be used for alimentation.

Furthermore, a number of crop products are used for several purposes. For instance, grain can be used for food, feed, and industrial purposes, such as bioenergy and materials. For estimation of the food energy output, it is necessary to determine the mass portion that is used for human alimentation. For those crops the farmer grows and sells without specification of further use, we assign the national distribution to the different options of utilization. In the farm regarded here, this applies, for example, to wheat and rye. For other crops dedicated to a specific purpose already in the field, we assume that the yield is fully utilized as intended. For instance, if the farmer grows and sells potatoes for human alimentation, a 100% food use is adopted.

Data used for farm output calculation are given in Tables 3 and 4.

Results and Discussion

The water flows on the farm investigated are shown in Table 5. Total water inflow is 19,642,853 m^3. Precipitation contributes 99.5% to the total water inflow. The remaining 0.5% is the technical water inflow comprising 0.4% of irrigation water and 0.1% of tap water.

The water input into the farm is 12,074,220 m^3, that is, 61% of the total water inflow. Transpiration from

Table 4. Data for calculation of output from sale of living animals.

Commodity	Live weight (kg)	Carcass weight (kg)	Food energy content (carcass) (MJ t_{FM}^{-1})	Producer price[1] (carcass) (€ kg^{-1})
Veal calves[2]	50	27	5.488	2.31
Heifers[3]	440	239	7.317	2.63
Slaughter cows[4]	650	338	7.517	2.36

FM, fresh mass.
[1] KTBL (2010).
[2] Calves are sold within 14 days after birth, carcass weight 54% of live weight (Specht et al. 1994), food energy content 75% of heifers (assumed).
[3] Carcass weight 54% of live weight (assumed), gross energy content after Ferrell et al. (1975).
[4] Carcass weight 52% of live weight (Gresham et al. 1987; O'Mara et al. 1998), food energy content derived from Gresham et al. (1987) and Wagner et al. (1988).

Table 5. Water flows in the farm investigated (2010).

Water flow	Volume (m^3)
Water inflow (W_{inflow})	19,642,853
Precipitation (W_{prec})	19,538,167
Technical water (W_{tech})	104,686
Irrigation water (W_{irri})	77,771
Tap water (W_{tap})	26,915
Water input (W_{input})	12,074,220
Transpiration from precipitation ($W_{prec-transp}$)	10,953,185
Technical water (W_{tech})	104,686
Indirect water (purchased feed only) ($W_{indirect}$)	1,016,349
Productive water (W_{prod})	11,045,986
Plant transpiration (W_{transp})	10,996,382
Drinking water (W_{drink})	14,624
Water in feed (W_{feed})	4980

precipitation accounts for 90.7% of the water input while indirect water input by purchased feed contributes 8.4%, and the technical water amounts to 0.9%.

The productive water accounts for 11,045,986 m^3, with 99.82% of this transpired by plants, 0.14% used for drinking water, and 0.04% contained in feed.

The farm output in 2010 in terms of biomass, food energy and revenues for crop, and livestock products is given in Table 6. Crop products amount to 91% of the dry matter food biomass output, 88% of the food energy output, and 69% of the revenues. Grains and potatoes mainly contribute to the crop output. Output from livestock products is dominated by milk accounting for 98% of the mass output, 96% of the food energy output, and 86% of the revenues.

The resulting farm water indicators are shown in Table 7. The farm water productivity is given for the whole farm, for food crops, and for livestock. Farm water productivity of the whole farm on a mass base accounts for 2.30 $kg_{FM}\ m^{-3}_{Winput}$ and for 1.03 $kg_{DM}\ m^{-3}_{Winput}$. In the farm studied, the farm water productivity is 2.2 times higher for food crop production than for animal

Table 6. Biomass production and farm output in 2010.

	Biomass yield	Total harvest/production[1]	Biomass leaving the farm[2]		Food biomass[3]		Total food energy[4]	Revenues[5]
	(t_{FM} ha^{-1})	(t_{FM})	(t_{FM})	(t_{DM})	(t_{FM})	(t_{DM})	(GJ)	(€)
Crops								
Winter wheat	5.3	3509	3509	3018	1128	1056	15,888	389,477
Winter barley	5.0	2298	1974	1698	0	0	0	187,546
Spring barley	1.5	76	76	66	0	0	0	7847
Winter rye	4.3	2707	2707	2328	947	815	11,622	265,265
Winter rapeseed	3.4	1125	675	615	71	64	2761	177,623
Pea	3.2	354	354	305	354	305	4124	49,252
Potato	60.2	5272	5272	1213	5272	1213	15,452	564,155
Sugar beet	55.4	4238	2299	506	848	814	13,470	80,480
Maize	40.3	6375	3155	884	0	0	0	145,144
Permanent grassland	31.9	6154	3999	1200	0	0	0	167,970
Sown grassland	38.7	2730	575	173	0	0	0	24,154
Crops total	–	**34,838**	**24,595**	**12,006**	**8720**	**4267**	**63,317**	**2,058,913**
Livestock and products								
Milk	–	3084	3084	386	3084	386	8265	778,558
Veal calves	–	10	10	5	5	3	29	12,225
Heifers	–	11	11	5	6	3	44	15,714
Slaughter cows	–	80	80	38	42	22	312	98,115
Livestock total	–	**3185**	**3185**	**434**	**3137**	**414**	**8650**	**904,612**
Farm total	–	**38,023**	**27,780**	**12,440**	**11,857**	**4681**	**71,967**	**2,963,525**

FM, fresh mass; DM, dry mass.

[1] Total harvest refers to all the crop biomass that was harvested in the farm during the reference period.

[2] Biomass leaving the farm is the mass of crops, livestock, and livestock products that is sold, and hence leaves the farm system as useful output. For crops, it is the total harvest minus the animal feed produced and used in the farm.

[3] Food biomass is that fraction of the produced biomass that is used for human alimentation. For crops, it is obtained from the total harvest and the respective mass percentage used for food (Table 3). For livestock, it is calculated from the live weights and carcass weights of the respective animals (Table 4).

[4] The farm output in terms of food energy is obtained from the food biomass and the food energy contents of crop and livestock products (Tables 3 and 4).

[5] The farm output in terms of revenues is obtained from the biomass leaving the farm and the respective producer prices (Tables 3 and 4).

Table 7. Farm water indicators.

Indicator	Unit	Whole farm[1]	Food crops[2]	Livestock[3]
Farm water productivity				
Mass basis	$\text{kg}_{\text{FM}}\ \text{m}^{-3}_{\text{Winput}}$	2.30	2.89	1.32
	$\text{kg}_{\text{DM}}\ \text{m}^{-3}_{\text{Winput}}$	1.03	1.42	0.17
Food energy basis	$\text{GJ}\ \text{m}^{-3}_{\text{Winput}}$	5.96	21.32	3.63
Monetary basis	$€\text{m}^{-3}_{\text{Winput}}$	0.25	0.30	0.38
Degree of water utilization	–	0.56	–	–
Specific technical water inflow	$\text{m}^{3}_{\text{Wtech}}\ \text{ha}^{-1}\ \text{year}^{-1}$	36.5	–	–

FM, fresh mass; DM, dry mass.

[1] The whole farm output is the total biomass leaving the farm system, the total food energy produced, and the total revenues from sale of crop and livestock commodities. The whole farm water input is the total water input into crop and livestock production.

[2] The farm output in terms of mass, energy, and revenues as well as the water input refers to the food crops only. Feed crops (both used in the farm itself and sold) and livestock are excluded.

[3] The farm output refers to livestock products only. The water input comprises feed supply (both grown at the farm and purchased from outside the farm), drinking water, and tap water. The feed consumed by the farm's livestock in the reference year 2010 was 3918 t of grass silage, 2727 t of maize silage, 208 t of hay, 324 t of wheat barley, 200 t of corn, 315 t of rapeseed meal, 322 t of soy bean meal, 407 t of dried sugar beet chips.

husbandry on a fresh matter basis and 8.1 times higher on a dry matter basis. The food energy-based farm water productivity amounts to 5.96 GJ $\text{m}^{-3}_{\text{Winput}}$ and is 5.9 times higher for food crops than for livestock. Farm water productivity on a monetary basis is 0.25 € $\text{m}^{-3}_{\text{Winput}}$. In contrast to the mass and energy-based farm water productivity, the revenue-based value is higher for livestock than for food crops (1.3 times). The degree of water utilization is 0.56, and the specific technical water inflow is 36.5 $\text{m}^3\ \text{ha}^{-1}\ \text{year}^{-1}$.

Due to diverse novel approaches in the methodological framework (such as scale, new indicators, including or excluding evaporation, and transpiration), it is difficult to compare the results to those of other authors. The most commonly applied approaches – the water footprint concept and life cycle assessment – consider the product scale, not the farm scale. Furthermore, the water footprint includes evapotranspiration, while life cycle analysts exclude it. In contrast, we exclude evaporation and include transpiration. Hence, the numbers for the water productivity are not comparable. Nor can the farm water productivity be compared to the rainfall use efficiency for grain and for gross margin according to Moore et al. (2011), as they relate the crop biomass produced and the monetary-based gross margin to the total rainfall. The degree of water utilization resembles a combination of the rainfall capture efficiency and soil water utilization efficiency defined by Moore et al. (2011). The numbers given there for wheat grown on a heavy red soil in Australia would be close to a degree of water utilization of 0.36–0.44, which is lower than the value of 0.56 found for the farm studied here.

Table 8 shows the weighted average water productivities for the single crops of the farm and their ranges that represent the fields with the minimum and maximum water productivity. There is a strong variation between and within the crops. The differences between the crops on a mass base can be attributed mainly to differences in the yields (Table 6) and to a lesser extent to the varying reference periods and crop-specific coefficients (Table 2). High-yielding crops such as sugar beet, potatoes, maize, or grasses are characterized by high water productivities from 9.4 to 12.8 $\text{kg}_{\text{FM}}\ \text{m}^{-3}_{\text{Winput}}$, and vice versa water productivity is in a much lower range from 0.39 to 1.59 $\text{kg}_{\text{FM}}\ \text{m}^{-3}_{\text{Winput}}$ for crops with lower biomass production, such as grains, peas, or rapeseed.

The food energy-based water productivities of the crops in addition vary due to the food energy contents: for sugar beet, the high yields of food biomass in combination with the high food energy contents result in energy-based water productivities that are about 6–20 times higher than those of the other crops. Potatoes with even slightly higher yields achieve much lower energy-based water productivities owing to their low food energy contents. The low yields of rapeseed are counterbalanced by the high food energy contents of rapeseed oil. The food energy-based water productivities of grains are in the lower range. The food energy-based water productivity of the farm's livestock products is about a third of the crop with the lowest water productivity.

The monetary-based water productivity of the crops is dominated by the yields and producer prices. The high-yielding crops achieve water productivities from 0.39 to 1.21 € $\text{m}^{-3}_{\text{Winput}}$, whereas the water productivity of crops with lower yields is in the range from 0.04 to 0.23 € $\text{m}^{-3}_{\text{Winput}}$.

The farmer's decision on which crops to grow and which livestock to keep mainly depends on natural conditions and general economic framework. Neither from a nutritional nor from an agronomic perspective would it be meaningful to improve the total farm water productivity by growing crops with high water productivities preferably. The focus

Table 8. Water productivity for single crop products.[1]

	FWP_{mass}		FWP_{energy}		FWP_{mon}	
	Mean	Min–Max	Mean	Min–Max	Mean	Min–Max
	$kg_{FM}\ m^{-3}_{Winput}$		$GJ\ m^{-3}_{Winput}$		$€\ m^{-3}_{Winput}$	
Winter wheat	1.24	0.85–2.31	16.0	11.0–30.0	0.14	0.09–0.26
Winter barley	1.59	0.98–2.26	–	–	0.15	0.09–0.22
Spring barley	0.39	0.27–0.47	–	–	0.04	0.03–0.05
Winter rye	1.06	0.71–1.56	13.0	8.7–9.1	0.10	0.07–0.15
Winter rapeseed	0.87	0.70–1.07	33.8	27.4–41.9	0.23	0.18–0.28
Pea	0.76	0.48–0.78	9.4	5.7–9.8	0.11	0.07–0.11
Potato	11.32	9.58–13.98	33.2	28.1–41.0	1.21	1.02–1.50
Sugar beet	12.79	9.13–16.89	203.3	145.1–268.4	0.45	0.32–0.59
Maize	10.23	8.79–11.78	–	–	0.47	0.40–0.54
Permanent grassland	9.45	4.39–17.51	–	–	0.40	0.18–0.74
Sown grassland	12.55	3.60–17.51	–	–	0.53	0.17–0.74
All crops	3.16	0.27–17.51	21.3	5.7–268.4	0.25	0.03–1.50

FWP, farm water productivity; FM, fresh mass.

[1] Means are weighted means; minima and maxima refer to the single fields.

for improving the farm water productivity has to be put on the large differences in water productivity between the fields with the same crops (Table 8). They can be attributed to a strong variation in the yields that are reflected in a varying output of biomass, food energy, and revenues. As all fields received the same amount of precipitation per hectare, this fact illustrates that the farm output and thus water productivity is determined not only by water but also by many other factors such as soil quality and management practices as has been discussed in literature before (e.g., Zoebl 2006; Bossio et al. 2010; Molden et al. 2010). Improving the farm water productivity hence means a mutual optimization of water use and other factors that influence yields (Drastig et al. 2011). The effectiveness of single and combined agronomic measures for improving the farm water productivity and the degree of water utilization has to be investigated.

Improving water productivity in livestock husbandry has to focus on efficient feedstock production and conversion of feedstock into livestock products. In this case study, only 1% of the water input into livestock husbandry is technical water used in the stables, whereas 99% of the water is needed for in-farm and external feed crop growing. Hence, it is obvious that improving water productivity in feed crop growing, optimizing livestock diets, and measures to increase the amount of livestock products from the feedstock will be the most effective approaches to optimize water use in livestock husbandry. However, measures to reduce water use in stables should not be neglected due to the particular relevance of technical water.

The case study presented here is the first application of the methodology we introduced. This methodology needs further development and application. It has to be applied to a multitude of farms with diverse climatic conditions and soils, farming systems, and structures as well as for different periods. It is necessary to explore the regional and temporal variation in the indicators and their range depending on the farming system. For instance, it seems obvious that the indicators will have different values for rainfed or irrigated agriculture and for cash crop farms compared with mixed crop-livestock systems. The aim of further research will be to classify farming systems and to assign regional target ranges of the farm water productivity and the degree of water utilization.

For the first step, we restricted the methodology to farms with food production only. In the future, the approach should be extended for the inclusion of farming systems with bioenergy and biomaterial production.

A multifunctional system as the mixed crop-livestock farm in the case study yields several products. Although the water input to produce a single crop product can easily be assigned, it is difficult to separate the water input of single livestock products, such as milk and meat in the case study. Allocation rules to distribute the water input between coproducts are required. Different approaches of allocation are known from literature, such as monetary allocation in the virtual water methodology (Chapagain and Hoekstra 2003; Chapagain et al. 2006), water partitioning by harvest index and feed metabolizable energy for estimating livestock water productivity (Haileslassie et al. 2011) and mass allocation, monetary allocation, or system expansion within life cycle assessment (ISO 2006a,b). The different approaches need to be examined and compared.

Research is needed to estimate the indirect water use in prechains of farming. Although comprehensive databases exist for calculating the energy demand or greenhouse gas emissions in prechains of agricultural production, these data are lacking for the water demand. Currently, estimation of indirect water input is only possible for purchased feed as the methodology of calculating water input for crop production can be applied.

The indicators suggested here are of economic nature and intended to assist farmers in understanding and optimizing their water use in terms of productivity. Future research should be directed at developing environmental indicators for water use at the farm scale, considering aspects of water availability and depletion and enabling farmers and stakeholders to assess environmental impacts of water use.

Conclusions

A methodology to assess water use at the farm scale by the indicators farm water productivity, degree of water utilization, and specific technical water inflow has been developed and applied in a first case study. The results indicate factors that mainly effect these indicators and general approaches to optimize water use in farms.

Research is needed for further development and application of the methodology including

- to apply the methodology to a multitude of farms with diverse climatic conditions, farming systems, and structures;
- to classify farming systems and to establish regional target ranges of the indicators;
- to investigate the effectiveness of single and combined measures of farmers for improving water productivity and degree of water utilization;
- to include farming systems with bioenergy and biomaterial production;
- to examine approaches of allocation;
- to estimate indirect water use in prechains;
- to develop environmental indicators for water use at the farm scale.

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