



Critical water requirements for food, methodology and policy consequences for food security

P.W. Gerbens-Leenes ^{*}, S. Nonhebel

*Center for Energy and Environmental Studies (IVEM), University of Groningen, Nijenborg 4, 9747
AG Groningen, The Netherlands*

Abstract

Food security and increasing water scarcity have a dominant place on the food policy agenda. Food security requires sufficient water of adequate quality because water is a prerequisite for plant growth. Nowadays, agriculture accounts for 70% of the worldwide human fresh water use. The expected increase of global food demand requires a great deal of effort to supply sufficient fresh water. If a doubling of agricultural production goes along with a doubling of the use of water, current fresh water resources are probably not sufficient in the long run. The objective of this study is to develop a generally applicable method for the assessment of crop growth-related water flows or “transpirational water” requirements of agricultural crops. Traditionally, agricultural studies have made assessments of water requirements for specific situations to provide a yield. This study uses the agricultural information the other way around. Water had to be present for a growth to occur. Based on the strong linearity of processes taking place in all green plants, the study develops a method to calculate the growth-related factor of crop water requirements, assesses the impact of crop characteristics on water requirements, and evaluates options to reduce the use of water by changing food consumption patterns. The study calculates “transpirational water” requirements for a representative group of crops with different functions for human nutrition, such as staple

Abbreviations: CVF, conversion factor; FAO, Food and Agricultural Organization of the United Nations; H-crops, hypothetical crops; MJ, megajoule; MT, metric tons (1 metric ton = 1000 kg); RUE, radiation use efficiency

^{*} Corresponding author. Tel.: +31 50 3634611; fax: +31 50 3637168.

E-mail address: W.Gerbens@fwn.rug.nl (P.W. Gerbens-Leenes).

crops, vegetables, and livestock fodder. For C_3 crops in a temperate climate, 0.11 l are needed to produce 1 g of glucose; for C_4 crops in a tropical climate, 0.09 l. Water requirements per unit of dry mass differ by a factor of two. These differences arise from differences among harvest indices of crops and their chemical composition. Differences in requirements per unit of nutritional energy, however, are low. Therefore, options to reduce the use of water by qualitative changes of food consumption patterns are few.

The study distinguished between site-specific and crop growth specific water flows. In this way, it quantified a central flow of the hydrological system, the water flow that actually passes a crop and is directly related to the photosynthesis process. If yields increase, this water demand increases with the same factor. The results show critical water requirements in agriculture. However, these results are intended to improve the insight into hydrological systems and must always be used in combination with locally, variable water needs. The results have two important consequences for food policy issues. Firstly, the study shows only small differences in water requirements among crops. Secondly, results indicate that under rainfed conditions, a doubling of food production on existing land areas does not imply a doubling of water use but only of “transpirational water” use. This flow forms a minor part of total water requirements in agriculture.

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Introduction

Food security for a growing world population requires the availability of sufficient water of adequate quality. Increasing water scarcity and the need for more food have a dominant place on the food policy agenda (Pinstrup-Andersen, 2000). Today, irrigated agriculture requires 70% of total human fresh water use (FAO, 2003a; Falkenmark, 1989; Rosegrant and Ringler, 1998; Rockstrom, 1999). In some parts of the world, such as Eastern Asia and the former USSR, water is already a scarce resource (Penning de Vries et al., 1995). In these parts of the world, the use of water for agricultural purposes has to compete with other uses such as urban supply and industrial activities (Falkenmark, 1989). Moreover, projections for 2025 indicate that more than half of the world's population will live in regions dependent on food imports due to water scarcity (Falkenmark, 1997). Additionally, recent research has suggested that climate change will lead to major shifts in the spatial and temporal patterns of precipitation (IPCC, 2001). In Southern Europe, for example, long-term projections (2070s) indicate a decrease of water availability between 25% and 50%, while in large parts of France, an important producer of wheat, decreases lie between 10 and 25% (Lehner et al., 2001).

So far, the growth of global agriculture has been sufficient to meet the growth of demand (FAO, 2003a). By 2050, the United Nations' medium projection estimates global population to be 50% larger than in 2003 (United Nations Population Division, 2002), while FAO projections (FAO, 2003a) indicate that per capita food de-

demand increases by 9% in the next thirty years. Again, the resulting increase in demand requires large efforts from agriculture (Tilman et al., 2002) and implies huge challenges on the availability of sufficient water resources. The required growth of global food production can be achieved via three routes, an increase of agricultural land areas, an increase of yield levels per unit of land, or an increase in cropping intensities (i.e. increasing multiple cropping and shorter fallow periods). If agricultural land areas are increased, water inputs will probably increase with the same factor because input per unit of land (m^3 per m^2) remains the same. This large increase of water inputs in agriculture is probably not possible, implying that water scarcity is the reason that the provision of food for a growing world population must focus on a more efficient use of water per unit of crop (m^3 per kg) (Wallace, 2000). This requires a fundamental insight into the relationship between yield levels, crop types and related water requirements.

Traditionally, agricultural research has assessed local water needs. This has resulted in large variation on the amount of water to produce a unit of food, even for equal food types. To grow 1 kg of potatoes, for example, Renault and Wallender (1999) calculate a requirement of 105 l of water, Pimentel and Houser (1997) 500 l of water, and Wallace (2000) 840 l of water. Variation of results is caused by variation among local hydrological systems and implies that information on water use obtained at a specific site cannot be used for other locations. General conclusions on surplus water requirements related to an increase of food production or differences in water needs among foods, therefore, must be obtained through another methodology. An important characteristic of the methodology should be that it does not take locally determined, highly variable water flows into account but focuses on similar processes in biomass production.

The objective of this study is to develop a methodology for the quantification of the amount of water that had been required to produce a unit of food. Based on the presence of a harvest, it argues that water had been available for growth to occur. This is the transpirational water flow summed over the complete growing season. This flow forms the absolute minimum or critical water requirement to provide a yield. In this way, the study provides information on the impact of crop characteristics on water requirements and on surplus requirements related to an increase of food production. The results provide a better understanding of the consequences of changes in food production systems on water requirements, and indicate the direction and magnitude of changes in water requirements. By improving the insight into hydrological systems, the study contributes to the information need relevant for the water scarcity and food security issue.

System description

Agricultural and hydrological systems are very complex. For the assessment of the amount of water needed for the production of a unit of food, this study strongly simplifies these systems. Firstly, it simplifies the agricultural system by defining seven hypothetical crops representing the globally most important crops for human nutri-

tion. Secondly, it neglects the locally determined water flows and focuses on the amount of water that has actually passed the biomass present after harvest, the transpirational water flow.

Food crops and their place in human nutrition

Globally, a large variety of food items is available for human consumption. Food items are products of animal or vegetable origin that form the end of a food production chain, often requiring several commodities deriving from primary or secondary production systems. Primary production grows crops, secondary production uses these crops for livestock products. Although the variety of foods is large, globally there is only a limited amount of crops that form the basis for human food consumption patterns. Food consumption patterns are repeated arrangements that can be observed in the consumption of food by a population group (Ivens et al., 1992) and concern the types and quantities of foods and their combinations into different dishes or meals.

The fifteen most important arable crops or categories of crops in order of decreasing annual production are: sugar cane, root crops, vegetables, maize, paddy rice, wheat, fruits, potato, sugar beet, cassava, soybean, barley, pulses, oil seed rape, and sorghum (FAO, 1999). The chemical composition of an arable crop determines its function for human nutrition. Staple crops, such as wheat and potatoes, are consumed for their carbohydrate content. Other crops are rich in proteins, such as pulses, or provide oil, such as oil seed rape. Grass can be considered as an important non-arable crop because it is significant for livestock fodder and therefore for human nutrition. Environmental research has demonstrated large differences in resource use of specific foods and food consumption patterns. Differences in the use of land resources, for example between potatoes and cereals, are already known from agricultural history. In Western Europe in the 18th century, potatoes were introduced on a large scale to prevent hunger because potatoes provided two to three times as much nutritional energy per unit of land area as cereals (Jobse-van Putten, 1995). An important question is whether changes in the use of crops for food cause changes in the use of water.

Crop production

The basis for primary production is the photosynthesis process in which solar photonic energy is converted into the chemical energy of glucose. The radiation on the ground surface available for photosynthesis is termed global radiation and is expressed in megajoules per unit of land area per day ($\text{MJ m}^{-2} \text{day}^{-1}$). The efficiency of photosynthesis shows large variation, but on the scale of a complete growing season and under conditions without shortage of water or nutrients, a linear relationship between intercepted global radiation and above ground biomass is observed (e.g. Goudriaan et al., 2001; Monteith, 1977a). This relationship exists for all plants, from agricultural crops to trees. In the Netherlands, for example, crops rich

in carbohydrates, such as wheat, potato, sugar beet, and maize, grown under near-optimal growth conditions, form dry matter at a rate of 200 kg per hectare per day (Sibma, 1968). Although the formation of glucose is the basis for all dry matter production, variation among crops is large and results in different functions of specific crops for human nutrition. Four important characteristics of crops are responsible for this variety: the chemical composition, the harvest index, the dry matter content, and the biochemical pathway of photosynthesis.

The chemical composition of a crop determines the amount of dry matter formed per unit of radiation. Groups of organic compounds are, for example, lipids, lignin, proteins, carbohydrates, and organic acids. Although the synthesis of glucose per MJ of intercepted global radiation is a uniform process for all plants, the amounts of glucose required for a unit of dry mass differ among plants and depend on their chemical composition. For fats, the amount is relatively large, for carbohydrates relatively low. The conversion factors (CVFs in g product per g glucose) have been calculated with great accuracy (Penning de Vries, 1983). The value for fats is 0.31, for proteins 0.52, and for complex carbohydrates 0.78.

In general, crops are grown for their reproductive or storage organs that have an economic value. For example, cereals are grown to produce grains and potatoes to produce tubers. Other crops, such as vegetables, are grown for their leaves or stems. The growth of these organs, however, requires the preceding growth of complete plants with stems and foliage. Fig. 1 shows the harvest index, the ratio of the economic yield and the total biomass production, that determines the fraction of a yield available for human consumption. The difference between the total biomass production and the economic yield is the rest fraction. A low harvest index implies that crops make large glucose investments in this fraction of non-edible biomass and have a small economic yield. Data on harvest indices are available from literature.

The dry matter contents of economic yields and rest fractions show large variation among crops. Potatoes, for example, have a dry matter content of 25%, while wheat has a dry matter content of 85% (Goudriaan et al., 2001). The third crop character-

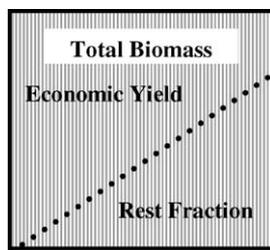


Fig. 1. The two components of the total biomass production, the economic yield and the rest fraction. Crops show a biological yield, i.e. the total biomass produced. This yield consists of an economic yield: that part of the total yield that can be traded on the food commodity market and is suitable for human consumption, and a non-food part or rest flow that has little economic value and is not edible for humans. The ratio of the economic yield and the total biological yield is termed the harvest index and depends on crop characteristics.

istic, the dry matter content, determines the amount of fresh biomass produced per unit of radiation.

The biochemical pathway of photosynthesis takes place via two different routes, which are characterized by the length of the C-skeleton of the first stable product, comprising either three or four carbon atoms. Since these pathways are species specific, typical C₃ and C₄ plants are distinguished. For example, potato and wheat are C₃ species and maize is a C₄ species. C₄ plants have a higher optimum temperature for photosynthesis than C₃ plants. Under optimal conditions, the efficiency of solar energy conversion is 40% higher for C₄ than for C₃ species (Monteith, 1977b).

Water flows at a crop field

Crop growth requires water in the root zone of plants. The hydrological system of a crop field comprises six main water flows, precipitation, drainage, run-off, evaporation from the soil, transpiration from the crop leaves, and irrigation. These flows interact and can therefore not be assessed independently. Moreover, local hydrological systems are highly variable in space and time, and sensitive to land use and its change (Schulze, 2000). In the Netherlands, for example, rainfall varies between 400 and 1200 mm per year (Buishand and Velds, 1980). At a field level, a water balance approach distinguishes between vertical and horizontal components of root zone water flows. Fig. 2 shows a simplified overview of the two stocks, the crop root zone and the above ground crop mass distinguished at the field level. Flow 1 represents the total supply composed of precipitation (vertical) and exogenous inflow (horizontal). Flow 2 represents the

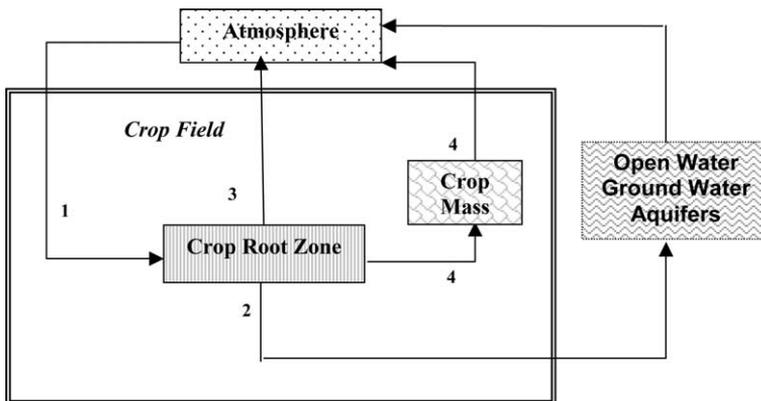


Fig. 2. Simplified overview of the two water stocks, the crop root zone and the crop mass in a crop field. Flow 1 represents the total supply composed of precipitation (vertical) and exogenous inflow (horizontal). Flow 2 represents the horizontal output of water lost to aquifers and rivers, and the vertical downward flow leaving the root zone of plants to lower layers (groundwater and eventually to open water). Flow 3 is the water evaporated from the soil and flow 4 represents the water flow that actually passes through crops and is related to plant growth. Flow 3 and flow 4 are termed evapotranspiration.

horizontal output of water lost to rivers and aquifers, and the vertical downward flow leaving the root zone of plants to lower layers (groundwater) and eventually to open water. Flow 3 is the water evaporated from the soil and flow 4 represents the water flow that actually passes through crops and is related to plant growth. Transpiration and evaporation from the soil surface are termed evapotranspiration (Buishand and Velds, 1980; FAO, 1992). Transpiration efficiency has been widely investigated at the leaf and the plant levels, but rarely of a crop at the field level owing to the difficulty in directly measuring transpiration or in separating transpiration from evapotranspiration (Zhang et al., 1998). Under rainfed conditions, crops are grown using natural water flows only. Sometimes the availability of water is a limiting factor for crop growth and irrigation is applied resulting in higher yields. This study distinguished variable, site-specific water flows (flow 1, 2 and 3) and a crop growth-related flow (flow 4). The size of the site-specific flows is determined by local factors and expressed in liters per unit of land area; the size of flow 4 (i.e. transpiration) is determined by crop growth and expressed in liters per unit of mass. The study terms this flow passing crops “transpirational water”. Evapotranspiration, therefore, consists of a variable, site-specific water flow and a growth-related flow.

Solar radiation is the principal driving force for the evaporation of water but also for the photosynthesis process. If water is limited, plant growth is limited with the same ratio. Agriculture uses this relationship to assess water requirements during crop growth. The relationship between growth and water requirements can also be applied the other way around, however. There are many equations available to estimate potential evapotranspiration requiring the input of meteorological data (Smith et al., 1991). The FAO (1992), for example, used such an equation to develop the computer program CROPWAT, a useful tool for farmers for irrigation planning and management.

Materials and methods

Starting points

Traditionally, agricultural studies have assessed water requirements for specific situations to provide a yield. This study started from the other side, the availability of a yield, and related the presence of biomass to the availability of water for plant growth. It argued that water had to be present for a growth to occur. Based on the strong linearity of processes taking place in all green plants, the study developed a method to calculate the growth-related factor of crop water requirements and assessed the impact of crop characteristics on these requirements. By assessing water losses related to photosynthesis, it was possible to quantify one of the flows of the hydrological system in a generally applicable way.

From physics, a linear relationship between the evaporation of water and radiation is known, while agricultural research has shown a linear relationship

between the synthesis of dry matter and radiation (e.g. Goudriaan, 1982; Monteith, 1977a; Goudriaan et al., 2001). The gain in dry weight per unit of water loss has been described for the first time by Woodward (1699) and has been confirmed by the standard reference of De Wit (1958). If water is limited, photosynthesis is limited with the same ratio. This implies that one of the water flows of the hydrological system of a crop field, the transpirational water flow that actually passes a crop, is linearly related to yield levels. Within carefully known conditions, this study calculated the amount of water transpired from the amount of above ground biomass using equations from meteorology and agricultural science. This theoretical approach made it possible to separate transpiration from evapotranspiration and to assess the transpirational water flow by combining data on dry matter produced per unit of radiation, information on CVFs of crop organic matter, and data on transpiration. Data on the forming of dry matter (g per MJ) and CVFs (g product per g glucose) were available from agricultural studies. Data on transpiration were calculated using a model adopted from meteorological studies requiring input of climate data.

Hypothetical crops as representatives for crop types

The study calculated “transpirational water” requirements for a representative group of crops with different functions for human nutrition, such as staple crops, vegetables, and livestock fodder. The four crop characteristics of the sixteen globally most important crops show variation. Based on this variety, the study distinguished ten categories of crops. These categories show: (i) a low harvest index, (ii) a high harvest index, (iii) a low water content, (iv) a high water content, (v) a relatively low content of carbohydrates, (vi) a relatively high content of carbohydrates, (vii) a relatively low content of proteins, (viii) a relatively high content of proteins, (ix) a relatively low content of fats, (x) a relatively high content of fats. C₃ and C₄ crops are found in every category.

In general, biological systems show natural variation. Even for a specific crop type, the chemical composition of the dry matter, the harvest index, and the water content vary. Habekotté (1996), for example, has demonstrated that carbohydrate, protein, and oil contents of the seeds of winter oil seed rape are variable. Since these macronutrients all have different CVFs, natural variability results in varying glucose requirements per unit of weight. For the provision of general information on transpirational water requirements, natural variation forms a complication. This study, therefore, defined seven hypothetical crops (H-crops) that were considered representative for the 10 crop categories and were derived from existing crops. These were: potato (*Solanum tuberosum* L.), wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), field pea (*Pisum sativum* L.), winter oil seed rape (*Brassica napus* L.), grass (*Gramineae*), and spinach (*Spinacia oleracea* L.). The study added H-maize as a representative of C₄ crops, spinach as a representative of vegetables, and H-grass for its importance as a livestock fodder. Table 1 shows the main characteristics of the H-crops.

Table 1

Main characteristics for seven hypothetical crops (H-crops) for 10 categories: (i) low harvest index, (ii) high harvest index, (iii) low water content, (iv) high water content, (v) relatively low content of carbohydrates, (vi) relatively high content of carbohydrates, (vii) relatively low content of proteins, (viii) relatively high content of proteins, (ix) relatively low content of fats, (x) relatively high content of fats

Crop	Category	Harvest index	% Water economic yield	% Water rest fraction	Carbohydrates product (g kg ⁻¹)	Fats product (g kg ⁻¹)	Proteins product (g kg ⁻¹)	Nutritional energy (kJ kg ⁻¹)
H-potato	ii, iv, vi, vii, ix	0.70 ^a	75.0 ^a	87 ^h	190	0	20	3570
H-wheat	i, iii, vi, ix	0.42 ^a	15.0 ^a	15 ^h	693 ^f	2 ^f	117 ^f	14364
H-maize	ii, iii, vi	0.45 ^a	15.0 ^a	87 ^h	710 ^f	38 ^f	92 ^f	14450
H-field pea	i, viii, ix	0.51 ^b	34.5 ^b	87 ^h	430 ^g	15 ^g	210 ^g	11319
H-winter oil seed rape	i, x	0.32 ^c	26.0 ^c	87 ^h	100 ^c	420 ^c	220 ^c	21252
H-grass	ii, v, vii, ix	1.00 ^d	92.0 ^d		54 ^d	0 ^d	30 ^d	1411 ^d
H-spinach	ii, v, vii, ix	0.90 ^h	92.0 ^e	92 ^e	40 ^e	0 ^e	20 ^e	510 ^e

The characteristics were derived from existing crops.

^a Goudriaan et al. (2001).

^b Lecoeur and Sinclair (2001).

^c Habekotté (1997).

^d Centraal Veevoederbureau (1997).

^e Voedingscentrum (1998).

^f Catsberg and Kempen-van Dommelen (1997).

^g Voorlichtingsbureau voor de Voeding (1973).

^h Estimated value.

Radiation use efficiency and glucose for growth

Radiation use efficiency (RUE) is the conversion factor between the amount of radiation intercepted or absorbed by a plant canopy and the amount of carbon dioxide fixed or biomass produced (Arkebauer et al., 1994; Monteith, 1994). This study considered global radiation, the flux of solar radiation reaching the surface of the earth ($\text{MJ m}^{-2} \text{day}^{-1}$). The RUE is often based on field studies assessing the relationship between the formation of dry matter and global radiation (Monteith, 1994). This study defined the RUE as the amount of glucose produced per unit of global radiation (g MJ^{-1}) that was calculated using data of field studies of Monteith (1977a) and the CVF of carbohydrates from Penning de Vries (1983). Based on the chemical composition of the attained yields of the H-crops, the study used the RUE and CVFs to calculate the amount of glucose required for producing a unit of mass of the economic yield and of the rest fraction. Based on data of harvest indices, the study allocated the amount of glucose required to produce the rest fraction to the economic yield.

The transpiration of water

For the calculation of evaporation, several estimation methods have been developed requiring meteorological data (Smith et al., 1991). A simple equation adopted here is a modified version of the Makkink equation (KNMI and CHO, 1988). It uses global radiation and the slope of the saturation vapor temperature curve as input data. Transpiration was calculated by

$$T \text{ (K)} = 0.65 \frac{s}{s + \gamma} \frac{K}{\lambda},$$

where T is the transpiration of a crop ($1 \text{ m}^{-2} = \text{mm}$), s is the slope of the saturation water vapor temperature curve ($\text{hPa } ^\circ\text{C}^{-1}$), γ is the psychrometric constant = $0.67 \text{ hPa } ^\circ\text{C}^{-1}$ (Buishand and Velds, 1980), λ is the latent heat of vaporization of water = 2.26 MJ kg^{-1} (Verkerk et al., 1986) and K is the global radiation (MJ m^{-2}).

In this equation, transpiration mainly depends on global radiation because the sensitivity of T to air temperature is small. Between 15 and 35 °C, the term $s/(s + \gamma)$ varies between 0.6 and 0.8. Assuming air temperatures in the growing season between 15 and 25 °C, an average value of 0.7 was taken for crops grown in a temperate climate. For crops grown in a tropical climate, the value of 0.8 was used.

Transpirational water requirements

Without limiting factors other than water, transpiration losses and the ability of roots to take up water determine final yields. For the calculation of total transpiration related to an attained yield, this study used a step-by-step approach. Information on the amount of glucose produced per unit of global radiation was combined with data on transpiration. This provided data on amounts of glucose produced per unit of water. Next, the amount of glucose required for producing an at-

tained yield was assessed. Finally, the amount of water required to produce this yield could be calculated. Fig. 3 shows the flow chart, the six calculation steps, and inputs for the calculation.

Based on data of carbohydrate production of C₃ crops per unit of radiation (1.4 g per MJ global radiation) that was derived from field studies of Monteith (1977a) and the CVF of carbohydrates (Penning de Vries, 1983), Step 1 calculated the amount of glucose per MJ global radiation available for the growth of C₃ crops. For C₄ crops grown in a tropical climate, a 40% increase in efficiency was assumed (Monteith, 1977b). This study calculated transpiration by using the Makkink equation. Step 2 assessed the amount of water transpired (liters per MJ global radiation). Step 3 combined the results of step 1 and 2, and calculated the amount of water needed to produce glucose available for crop growth (liters per g). Based on the harvest index, Step 4 calculated the total amount of biomass required to produce a crop. Based on the chemical composition of the H-crops as shown in Table 1 and data on CVFs (Penning de Vries, 1983), Step 5 assessed the amount of glucose required for the total biological yield (g per g). Finally, Step 6 assessed the transpirational water requirement for the crop (liters per kg) by combining the results of step 3 and 5.

The transpirational water requirement for maize was calculated for two climatic regions, a temperate climate with maximum temperatures between 15 and 25 °C, and a tropical climate with temperatures between 30 and 40 °C.

Results

The first three steps shown in Fig. 3 provided general information, step 4 the transpirational water requirements of crops. Step 1 provided the amount of glucose available for crop growth: for C₃ crops, 1.8 g glucose per MJ global radiation; for C₄ crops, the amount is larger: 2.5 g per MJ. Step 2 provided the amount of water transpired. Potential crop transpiration is 0.20 l per MJ global radiation in temperate climates and 0.23 l per MJ in tropical climates. Step 3 provided water requirements of glucose production. For C₃ crops in a temperate climate, 0.11 l are needed to produce 1 g of glucose; for C₄ crops in a tropical climate, 0.09 l. Table 2 shows the “transpirational water” requirements for the seven H-crops provided by step 4 in liters per kg economic yield, liters per kg dry mass and liters per kJ nutritional energy. For H-maize results are given for two climatic conditions, a temperate and a tropical climate.

Differences among transpirational water requirements for crops depend on specific glucose requirements for crop biomass determined by crop characteristics such as biomass composition and harvest indices. Crops showing relatively large water contents, for example, use little glucose for biomass production resulting in low transpirational water requirements. Table 2 demonstrates that the large water contents of H-grass, H-spinach (92%), and H-potato (75%) result in low transpirational water requirements in liters per kg product. In general, grains have small water contents and therefore relatively large transpirational water requirements. The requirement for H-wheat, for example, is a factor of fifteen larger than for H-grass. Proteins

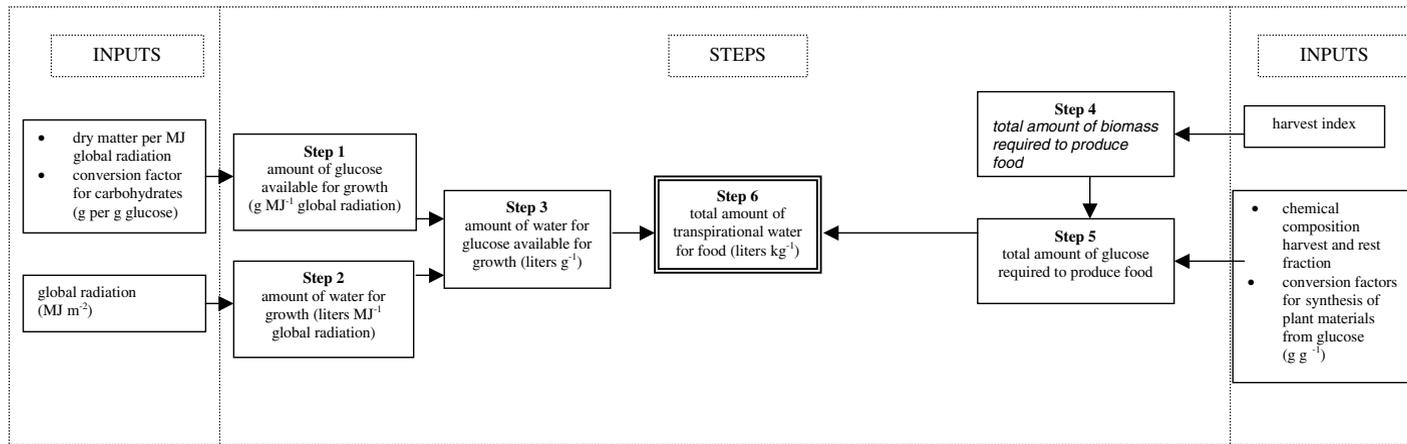


Fig. 3. Flow chart and necessary inputs for the calculation of transpirational water requirements for crops. Agricultural data are combined with meteorological data. The output of one step is the input of the next one. This results in the value for “transpirational water” requirements (l kg^{-1}) for a specific crop.

Table 2
 “Transpirational water” requirements for the seven hypothetical crops (H-crops)

Crop	“Transpirational water” requirement		
	Liters per kg product	Liters per kg dry mass	Liters per kJ nutritional energy
H-potato	38	150	0.011
H-wheat	204	240	0.014
H-maize (temperate climate)	145	171	0.010
H-maize (tropical climate)	120	142	0.008
H-field pea	121	185	0.011
H-winter oil seed rape	224	303	0.011
H-grass	14	176	0.010
H-spinach	11	140	0.022

and fats require more glucose than complex carbohydrates and thus more water. The large oil content of H-winter oil seed rape, therefore, requires a relatively large amount of glucose so that despite its relatively large water content (32%), water requirements of H-winter oil seed rape are in the same order as of wheat. The harvest index is another crop characteristic that has a high impact on transpirational water use. If crops show large investment in crop biomass, but have low yields water requirements are large. Due to their large harvest indices, H-spinach, H-potato, H-maize (temperate climate), and H-grass show relatively low water requirements while H-wheat shows an intermediate water requirement. In general, relatively small harvest indices, small water contents or large fat contents correspond with a relatively large water requirement, of which the requirement of winter oil seed rape forms a good example.

Water requirements per unit of nutritional energy provided by the crop are all in the same order of magnitude. H-maize (temperate climate), H-potato, H-grass, H-winter oil seed, and H-field pea have an average requirement of 0.011 l per kJ; H-wheat has an intermediate requirement of 0.015 l per kJ, and H-spinach a relatively large requirement of 0.022 l per kJ. If the vegetable group, represented here by H-spinach, is excluded, requirements vary by a factor of 1.5.

H-maize grown in a tropical climate shows a 40% increase in energy efficiency but, on the other hand, transpiration per MJ global radiation is also larger. As a result, H-maize grown in the tropics shows a 17% lower transpirational water requirement compared to H-maize grown in temperate regions.

Discussion

Applicability

Agricultural scientists have studied water needs of crops for specific situations and have provided useful tools for farmers for irrigation planning and water management. Those studies, however, do not separate water demand directly related to plant growth from site-specific losses. Temporal and spatial variation and

the use of different system boundaries explain the large variation of water requirements found in literature. This study quantified one of the six relevant flows of the hydrological system, the transpirational water flow, under optimal conditions, with sufficient nutrients. The present study, therefore, gives low values compared to results of other studies that include the site-specific flows. The results should be considered as the absolute minimum water requirements to provide a yield. For practical situations, site-specific flows, such as soil evaporation or drainage, must always be taken into account. Although the results cannot be used to assess local water requirements in agriculture, they improve the insight into hydrological systems, demonstrate differences and similarities among crops, and provide a tool to evaluate the effect of an increase of global agricultural production on existing water resources. The calculations were done for hypothetical crops but, provided necessary data are available, transpirational water requirements can be calculated for any crop.

It is stressed that the data derived in this paper are based on rough estimates of the environmental consequences of changes in the food production system and should not be interpreted at face value but as tools to better understand the system. The data show the direction of the changes and give an indication of their magnitudes. Although many rough estimates are used, the analysis provides new insights into the functioning of the system.

Options to reduce water requirements by changing food consumption patterns

If the fresh weight of crops is considered, large differences can be shown for the transpirational water requirements. However, if nutritional energy is considered, requirements are all in the same order of magnitude, except for vegetables, represented here by H-spinach. Crops having a small dry matter content, such as vegetables, make relatively large glucose investments in plant structural matter without nutritional energetic value for humans. In the calculations for the water requirements, fibers were included, but in the calculations of nutritional energy they are excluded. The relatively large fiber content of vegetables compared to their macronutrient content explains the large water requirements per unit of nutritional energy.

For two reasons, differences in water requirements among crops hardly form a basis for reduction options. Firstly, differences per unit of nutritional energy are low, so that there are only small differences among foods with the same function in human nutrition. Secondly, food consumption patterns must show variation to comply to nutritional constraints. A healthy diet provides nutrients in a balanced way, including vegetables with relatively large water requirements per unit of nutritional energy.

Increasing global food production

The expected growth of the world population and the increase of per capita food demand in the coming decades might require a doubling of global food pro-

duction. Under rainfed conditions, about 11 l of “transpirational water” is needed for the production of a MJ of nutritional energy. A doubling of global food demand implies in the first place a doubling of the marginal requirements or “transpirational water”. If the doubling is achieved via the route of the doubling of agricultural land areas, not only transpirational water but also site-specific losses increase, implying a doubling of total water requirements. The agricultural land area is limited, however. Given the potential production capacities (Penning de Vries et al., 1995), a doubling of yield levels is more likely. This means that globally only “transpirational water” requirements, a minor part of total losses, double. On a global scale level, average evapotranspiration is 470 mm per year (Goudriaan et al., 2001). The average global wheat yield in 2002 was 2.7 tons per hectare (FAO, 2003b). Based on the results of this study presented in Table 2, this global yield requires 55 mm of transpirational water or 12% of the average yearly evapotranspiration. A doubling of wheat yields requires 110 mm of transpirational water, or 23% of the average yearly evapotranspiration. The example shows that the demand for water expressed per unit of land area increases with increasing yield levels but also that transpirational water flows are a minor part of total yearly evaporation losses. The possibility to increase yields depends on local factors that determine the availability of sufficient water. In some regions this surplus will not be available, so that for the satisfaction of demand, yield levels in other regions must rise more than twice. In the light of the predicted future water scarcity, the replacement of foods of vegetable origin by foods with lower water requirements is no option to reduce the overall use of water. Better options are the increase of yield levels and harvest indices, or the reduction of waste flows and losses in the life cycle. This requires further research from various disciplines, especially the agricultural and hydrological sciences.

Conclusions

Site specific water flows are highly variable in time and among locations and form the major part of the hydrological system. The growth related water flow is a minor part of the system but quantifiable from a crop yield perspective. The linearity between this flow and attained yields provides a new insight into the food production system. Although “transpirational water” requirements per unit of fresh weight differ considerably among crops, requirements per unit of nutritional energy show minor variation. The main reason is that all green plants use the same basic strategy, photosynthesis, to produce biomass transpiring water at the same time. Differences in the efficiency to use glucose for the economic yield, therefore, is the main reason for variation in “transpirational water” requirements among crops. This efficiency is mainly determined by the harvest index and the chemical composition of the dry matter. Crops rich in proteins have relatively large water requirements per unit of dry mass. Crops rich in oil show large water requirements but this is compensated by their large nutritional energy content. Qualitative changes in food consumption

patterns, therefore, do not result in substantial changes in annual per capita requirements for water.

By distinguishing between site-specific and crop growth specific water flows, this study quantified a central flow of the hydrological system, the water flow that actually passes a crop and that is directly related to the photosynthesis process. If yields increase, this water flow increases with the same factor. The results differ from results of traditional agricultural studies because they show the critical water requirements. These requirements are the only quantifiable, constant flows of a hydrological system. However, they must always be used in combination with locally, variable water needs. The results have two important consequences for food policy issues. Firstly, the study shows only small differences in water requirements among crops. Secondly, results indicate that under rainfed conditions, a doubling of food production on existing land areas does not imply a doubling of water use but only of “transpirational water” use. This flow forms a minor part of total water requirements in agriculture. The assessment of transpirational crop water requirements provides insight into essential characteristics of the hydrological system and makes an important contribution to the information need relevant for global food security.

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