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WATER USE OF OIL CROPS: CURRENT WATER USE AND FUTURE OUTLOOKS

REPORT

Commissioned by the ILSI Europe Environment and Health Task Force

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By Fulco Ludwig, Hester Biemans, Claire Jacobs, Iwan Supit,
Kees van Diepen and John Fawell

With additional research support provided by
Ettore Capri and Pasquale Steduto

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COMMISSIONED BY THE ILSI EUROPE ENVIRONMENT AND HEALTH TASK FORCE

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1. SUMMARY

Many parts of the world are considered to be water stressed through a combination of decreasing reliability in rainfall and growing population. Agriculture is one of the biggest users of water and it is therefore essential that water for food production is used efficiently and sustainably. The main aim of this study is to evaluate globally grown oil crops in terms of rain and irrigated water use, and discuss how to improve sustainable water use in the agricultural sector.

Several models and data sources were used to determine the water status for production of sunflower, rapeseed, groundnut, soybean and palm oils. The concept of green water (evaporated rainfall) and blue water (water evaporated originating from irrigation using rivers and groundwater) was incorporated in order to make the distinction between rainfed production and production relying on irrigation. The objective of the study was to estimate crop water requirements and actual water use in relation to crop yield for the selected oil crops.

Sunflower and rapeseed are primarily grown in Europe and, due to climatic differences, show a higher water demand in southern Europe than in the north. Therefore, the total water requirements to meet optimum yield is greater in southern Europe, although there is variability from year to year throughout the region. Rapeseed is grown mainly in northern Europe where not much irrigation is needed and where there is little water scarcity. Sunflowers, however, are grown in parts of southern Europe where significant irrigation is needed for optimal production and where water scarcity is or might become an important issue.

Soybean is currently grown primarily in the USA, Brazil and Argentina. Differences in crop water use are the highest for soybean, and in some countries twice as much water per unit of crop area is used than in the countries with lowest water use. In terms of water productivity, the differences are even larger. Soybean production in the USA is apparently much more water efficient than in Brazil. However, in most of the regions in Brazil there is little shortage of rainfall, which has a positive impact on water sustainability. Groundnut is grown in widely differing regions but there is little use of irrigation because it makes only a marginal difference to yield. There is a large sustainability issue for palm oil, which is not directly related to unsustainable water use, but to carbon loss from drained tropical peatlands.

In assessing the most sustainable sources of oil crops there are several different issues that need to be considered. The simple equation that rainfed is always good and irrigated always unsustainable is not correct and may lead to inappropriate decisions. For a first-order assessment of sustainable oil crop sourcing, six different considerations were developed. Considerations include the use of water, sources of and efficiency of irrigation water and possible impact on water quality and land use. To assist in deciding whether crop production is sustainable or not, we have developed a decision tree. This decision framework can be used to make an initial scan in relation to sustainable water use in oil crop production.

2. INTRODUCTION

2.1 Water use in agriculture

The agricultural sector is by far the biggest user of freshwater. According to estimates made in the year 2000, agriculture accounted for 67% of the world's total freshwater abstraction, and 86% of its consumption (UNESCO, 2000).

In developing countries, around 60% of food crops are grown with rainfed agriculture, which takes place on 80% of the arable land. Consequently irrigated agriculture produces about 40% of the food crops on 20% of the arable land. In the future, it is predicted that much of the increased demand in food production will need to be supplied by irrigated crops from developing countries.

FAO estimates that world food production needs to increase by around 60% to feed a growing world population (OECD, 2003). Agricultural water use will be a key element for increasing food production, especially in many developing countries. Currently, some 20% (around 205 million hectares) of agricultural land in developing countries is irrigated and provides about 40% of crop production in these countries. Developing countries are expected to expand their irrigated area by 40 million hectares by 2030 (OECD, 2003).

The water availability for food production is likely to change in the future due to increased demands from other sectors and climate change. Climate change has an impact on the amount and distribution of rainfall, which has an effect on the amount and timing of water availability for food production. In the sub-tropical regions, rainfall is likely to be reduced due to climate change, and higher temperatures also increase evaporative demand. However, higher atmospheric CO_2 concentrations increase yield potential and water use efficiency.

Water use in agriculture is recognised as one of the major drivers of ecosystem degradation, potentially causing habitat loss, drying up of rivers and reduction in groundwater levels. Clearly, regulating and potentially limiting agricultural water use is one of the key issues for environmental sustainability. Growing more food with less water, i.e. increasing water productivity, can help to reduce future demand for water, thus easing both competition for water and environmental degradation (International Water Management Institute, 2007).

2.2 Rethinking global water use: a better use of rain

Water use for food production includes both blue water resources in irrigated agriculture (diverted water) and green water resources (soil moisture from infiltrated rainfall) in rainfed agriculture. The consumptive water use in agriculture is in the order of three and a half times larger than generally stated if green water use is also included. Total agricultural water use is estimated to be in the order of 7000 km^3/year. Compared to 110 000 km^3/year of precipitation over the world's land areas, only 6% of the total freshwater resource is used for agricultural production (Falkenmark and Rockström, 2008).

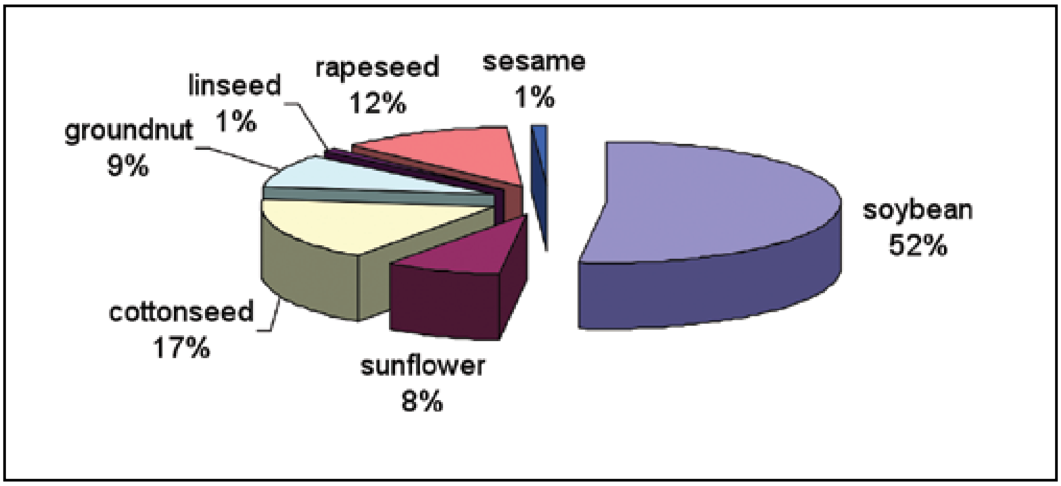
In general, current approaches to water management consider mostly blue water, i.e. river discharge and groundwater. This limits the options to meet changing water needs in response to the impacts of climate change and a rapidly growing population. A recent study by a team of Swedish and German scientists quantified for the first time the opportunities of effectively using both green and blue water to adapt to climate change and to feed the future world population (Rockstrom *et al.*, 2009). When only blue water is taken into account, over three billions of the current world population are estimated to suffer from severe water scarcity. The new analysis, which additionally accounts for green water, suggests that the actual number is fewer than one billion. It also shows that wise water management can lift billions out of water poverty. It is concluded that many water-stressed countries are able to produce enough food if green water is considered and managed well.

This conclusion is in line with more recent recommendations from the scientific community for proposing a shift in land and water management approaches, e.g. to seek opportunities to increase infiltration and retention of rainfall in the soil (increasing natural moisture reserves) instead of increasing dependence on irrigation.

2.3 Oil crop production

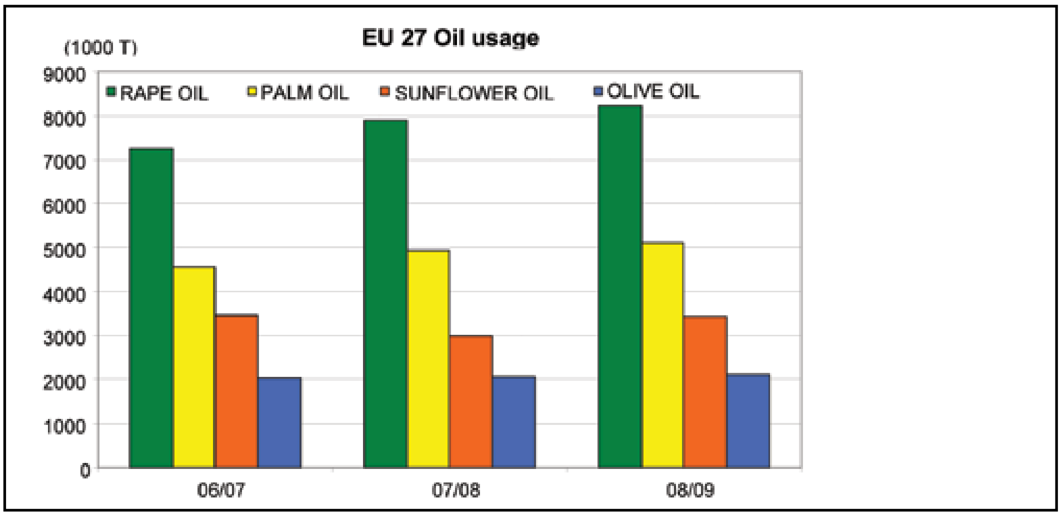
Until now most of the work on agricultural water use has focussed on crops like wheat, rice and maize. The current report has a focus on water use in (vegetable) oil crops, with the percentage world production for the major oil crops shown in Figure 1.

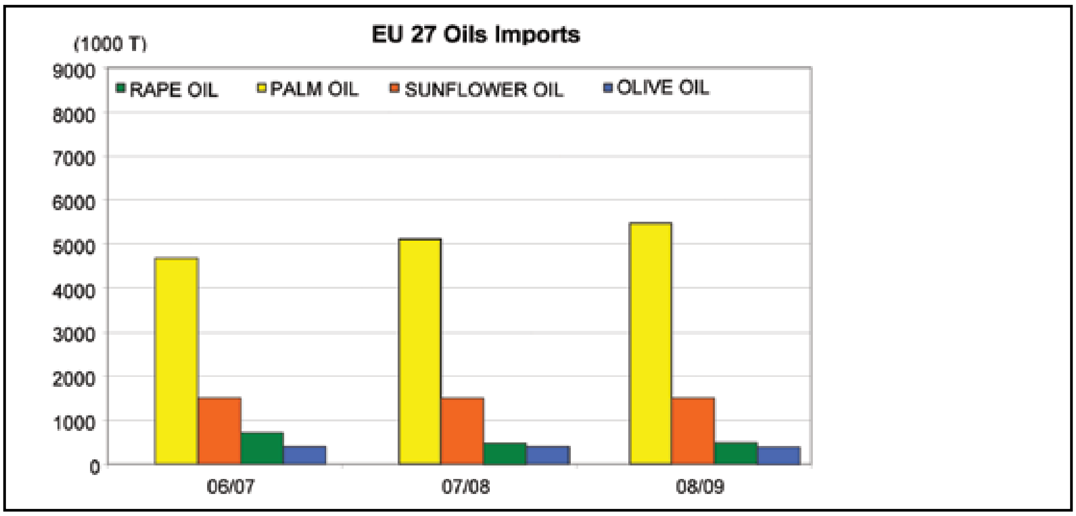
Figure 1. World production of seven major oilseed crops in 2005. (Source: FAO Statistics, http://faostat.fao.org/) Note that this graph does not include palm oil



Vegetable oil crops have gained in importance during the past few decades, resulting in a doubling of the world oil crop production in the last 25 years. Figure 2 illustrates recent usage (production and consumption) and imports for Europe.

Figure 2. Usage and import of main vegetable oil types





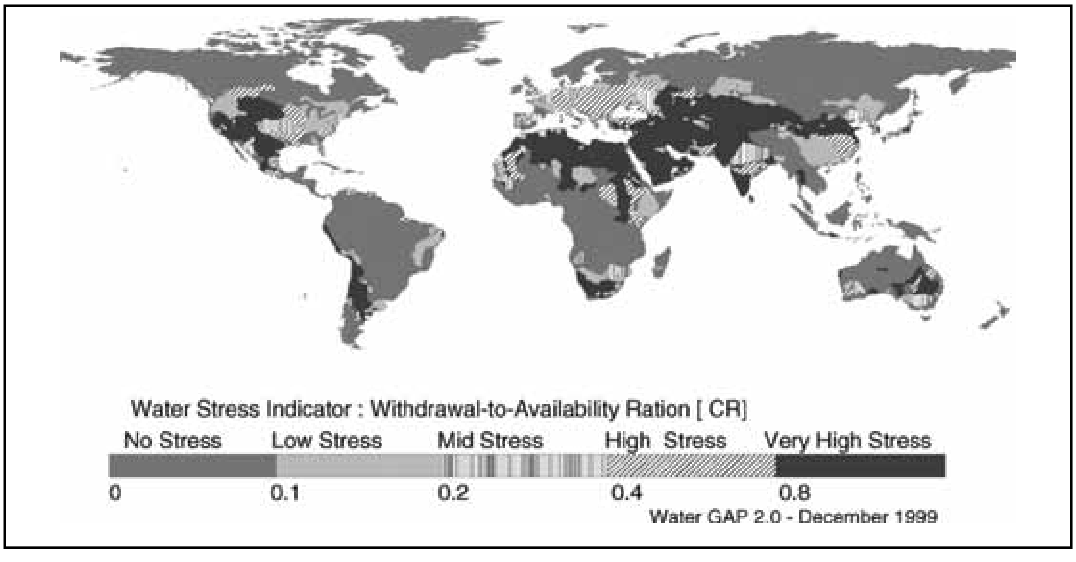
Both consumers and producers of vegetable oils show an increasing recognition of the importance of sustainable production of their food products. For the production of oil crops, significant amounts of freshwater are used, and in some areas this is unsustainable due to use of non-renewable ground water sources and over-exploitation of surface water. Worldwide, there is an increased interest in oil crop production, but not much information is available on the actual water requirements and water use of these crops.

The main aim of this study is to evaluate globally grown oil crops in terms of sustainable or unsustainable water use.

2.4 Water scarcity and oil crops

Alcamo *et al.* (2000) estimated that more than half of the world population would be living in countries facing high water stress by the year 2025. Figure 3 illustrates projected future water stress on a global scale as the ratio of withdrawal to availability, quantified by the WaterGAP model. In this respect, water stress relates not only to rainfall and actual amounts of water available but also to the population density and competing needs for water.

Figure 3. Water stress by 2025, based on withdrawal-to-availability ratio (Alcamo et al., 2000)



Rijsberman (2006) concluded that water will be a major constraint for agriculture in the coming decades. Particularly in Asia and Africa this will require major institutional adjustments. Focus should, therefore, be on improvement of overall water productivity rather than just seeking new supplies, as an appropriate response to water scarcity.

Currently, there is already absolute water stress in North Africa and the Middle East. When taking into account the water needs of ecosystems, there are already considerable parts of Europe, North America and parts of Asia and Africa suffering from water scarcity.

The current and increasing water stress will have a significant impact on oil crops. High stress is expected to occur in the regions where soybean and groundnut are grown (Asia, Africa). In Europe, water scarcity will affect sunflower production in Mediterranean parts, i.e. in Spain, Italy and Greece and possibly further north.

2.5 Objective and approach of the study

The objective of this study is to quantify oil crop water use to allow for an improved comparison of globally grown oil crops in terms of sustainable or unsustainable water use. A framework is developed that can be used to make an initial scan in relation to sustainable water use in oil crop production.

Various models[1] are used to quantify water use and productivity for the following oil crops:

- Sunflower and rapeseed (European level)
- Soybean, groundnut and oil palm (global level)

It should be noted that for oil palm no global data sets exist at the moment. Therefore, for this crop a qualitative assessment was made.

In the next section, a short description of the crops is given, followed by information of the modelling systems used. In Section 4e, the modelling results are presented, listing water use and productivity at the European or global level. The final sections discuss the results, including some general conclusions, and provide a decision framework for sustainable water use of crops.

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[1] Unfortunately one single model could not be used to model all the oil crops. This is because at the moment validated datasets (e.g. crop characteristics) for different oil crops occur in separate models and exist at specific scales (European, global). For oil palm, no global data sets are available.

3. METHODS

3.1 Description of the major oil crops

Sunflower

Sunflower (*Helianthus annuus*) is a species that is native to North America. It is an annual, broadleaf plant with a strong taproot and prolific lateral spread of surface roots. Sunflower is grown in many semi-arid regions. Within Europe it is mainly grown around the Mediterranean because lots of sun is needed for optimal productivity and it is relatively tolerant to drought conditions. Outside Europe, sunflower is grown in large parts of North America, parts of Africa and Australia.

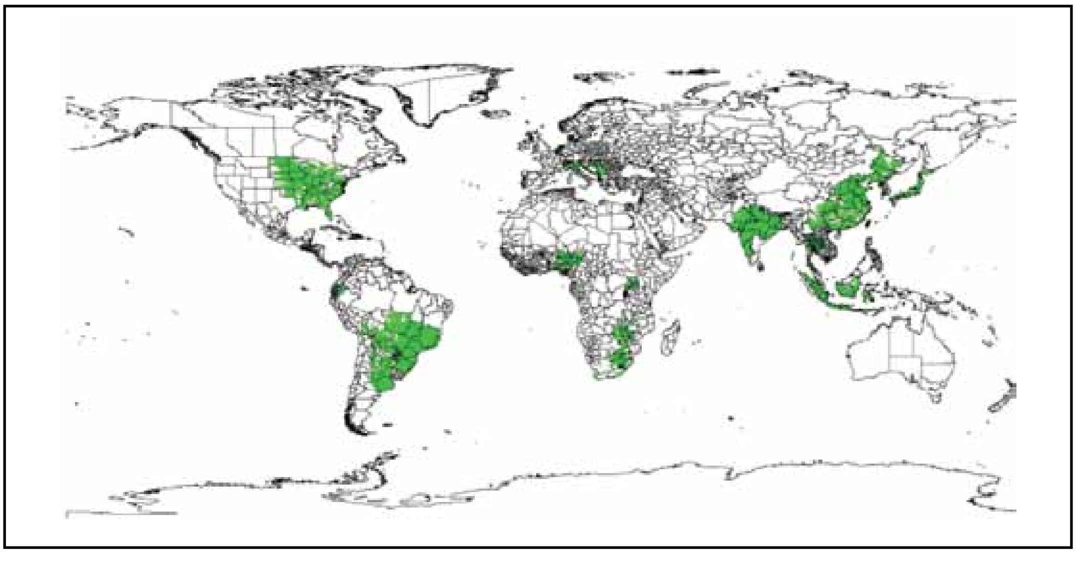
Rapeseed

Rapeseed (*Brassica napus*) is also known as rape, oilseed rape and canola. It is a bright yellow flowering member of the Brassicacea family, the mustard or cabbage family. It is a mustard crop grown primarily for its seed, which yields about 40% oil and is a high-protein animal feed. Although rapeseed can be grown in a wide range of environments it is particularly adapted to cool and temperate zones. Within Europe it is particularly grown in the central zone, in countries like Poland, Germany and France.

Soybean

Soybean (*Glycine max*) is a species of legume native to East Asia. Soybeans are the primary ingredient in many processed foods, including dairy product substitutes. Soybeans are an important source of vegetable oil and protein worldwide. The main producers of soybeans are the United States, Brazil, Argentina, China and India. The area under soybean cultivation is outlined in Figure 4.

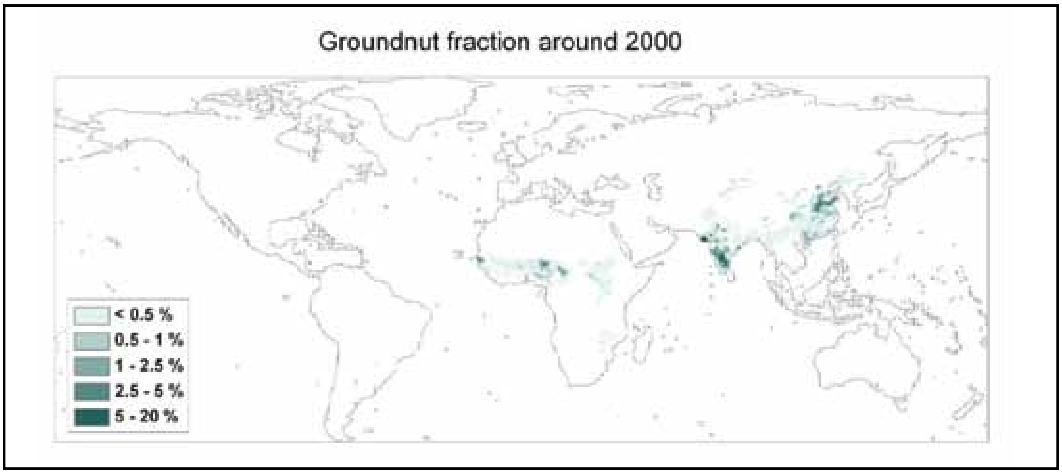
Figure 4. Map illustrating where soybean was planted in 2005 (source: FAO Statistics, www.fao.org/corp/statistics/en/)



Groundnut

Groundnut (*Arachis hypogaea*) is a species in the legume family (Fabaceae) native to South America, Mexico and Central America. Groundnut is also known as peanut, earthnut, groundnut, goober, goober pea, pinda, jack nut, pinder, manila nut, g-nut and monkey nut. Groundnut currently covers only a very small fraction of the global agricultural area and is mainly grown in India, South East Asia and West Africa, (Portmann *et al.*, 2010), see Figure 5.

Figure 5. Fraction of land covered with groundnut according to Portmann et al (2010)



Palm oil

Palm oil is an edible plant oil derived from the fruit and kernels (seeds) of the oil palm *Elaeis guineensis*. Palm oil is one of the few vegetable oils that is relatively high in saturated fats (like coconut oil) and thus semi-solid at room temperature. The oil is widely used as cooking oil, as an ingredient in margarine and as a component of many processed foods. It is also an important component of many soaps and personal care products. Although it is produced throughout Asia, Africa and South America, around 80% of global exports come from just two countries: Malaysia and Indonesia (Table 1). Due to their tropical climate with year-round temperatures ranging from 25 to 33°C and evenly distributed rainfall of 2000 mm/year, Malaysia and Indonesia have emerged as major producers of palm oil.

Table 1. Top 10 countries for oil palm production (source: FAO Statistics: http://faostat.fao.org/)

Top 10 Countries for Oil Palm Production	
1. Malaysia (44%)	6. Côte d'Ivoire (1%)
2. Indonesia (36%)	7. Ecuador (1%)
3. Nigeria (6%)	8. Cameroon (1%)
4. Thailand (3%)	9. Congo (1%)
5.Colombia (2%)	10. Ghana (1%)

3.2 Modelling systems applied

The approach in the present water use assessment for oil crops is based on quantifying the effect of drought on crop yield by a model-based estimation of both soil and water availability, crop water use and crop water requirements. The water availability is conceived as the amount of water originating from rainfall stored in the rooted soil, and represents the actual supply of water from the soil to the plant roots. The water requirements represent the actual demand by the crop under the given weather conditions. As long as sufficient water is available from rainfall or irrigation and in the absence of other growth-limiting constraint, the crop water use equals the water requirements. The water use under purely rainfed conditions (also called a water-limited production situation) may be limited by drought and, consequently, water use drops below the requirements for optimum yield.

The modelling procedure combines two major model components, one for the soil water system and one for the cropping system. At the global level, a limited number of models are available. At Wageningen UR a well-developed modelling system at the European level is available, which was used for sunflower and rapeseed. A similar system is not available at the global level; therefore, we used different modelling systems for soybean and groundnut. The global systems are not as well tested and are based on rougher parameter estimations than the European model.

The purpose of the present study is to estimate crop water requirements and actual water use in relation to crop yield for some selected oil crops. Based on the availability of modelling tools and access to databases, three different modelling systems have been applied. It would have been ideal to use a single modelling system for the comparison of the different crops. However, within the scope of this project we did not have the time available to develop a new single modelling system that included all the major oil crops. Therefore, different existing models were applied for each oil crop, as appropriate.

To estimate water use by sunflower and rapeseed for Europe, the European Commission´s Joint Research Center (JRC)-Agri4Cast MARS Crop Growth Monitoring System (CGMS model) was used. The JRC-MARS-Food's Global Water Satisfaction Index system (GWSI) was used for soybean at a global level and the Lund-Potsdam-Jena managed Land Dynamic Global Vegetation and Water Balance Model (LPJmL) model was used for global estimates of water use by groundnut.

GWSI is a relatively simple model and its inputs are a mix of rather detailed weather data and generalized country-scale crop data. For the European assessment, JRC's results of CGMS were used, which contain a relatively complex WOFOST (WOrld FOod STudies) crop–soil model and uses much more detailed weather, crop and soil data. The crop model within LPJml is somewhat less complex than WOFOST whereas the soil model is comparable. LPJml is currently being expanded with dam modules within a hydrological river-basin-based component, allowing the model to estimate irrigation water availability. The GWSI and CGMS apply only a vertical water balance for each land unit. Each model relies on a mixture of universally valid biophysical parameters and specific local data sets, e.g. on crop calendars and reference yield levels. Details of the models are given in Table 2.

Table 2. Specification of models used in the study

Model name	**Crop species**	**Spatial coverage**	**Climate data used**	**Reference**
GWSI	Soybean	Global	CRU (New *et al.* 2002)	–
LPJmL	Groundnut	Global	CRU (Österle *et al.* 2003)	Bondeau *et al.* 2007
CGMS	Sunflower and Rapeseed	Europe	CGMS climate data (Micale and Genovese, 2004)	Supit *et al.* 2010

3.2.1 GWSI model

The most widely applied and therefore classic method of estimating crop water use and related crop yield is the "crop yield response to water procedure" described in FAO Irrigation & Drainage Paper no. 33 (Doorenbos and Kassam, 1979). The approach is based on the quantification of cumulative crop evapotranspiration during the crop-growing season. The maximum evapotranspiration (per day or per 10 days) is the water requirement for the crop, defined as:

$$ET_m = K_c \times ET_0$$

Where:

K_c	Crop coefficient according to Doorenbos and Pruitt
ET_0	Potential evaporation and transpiration in mm/day or mm/10 days according to Penman-Monteith

This maximum evapotranspiration rate ET_m is realized when the root zone is well watered and the soil surface is wet. The values of the K_c coefficients depend on crop type and canopy cover. When water supply to the crop roots is insufficient, the actual evapotranspiration ET_a is reduced, and a water deficit develops in the crop, often called crop water stress, whereby the growth of the crop will be reduced proportionally.

The calculation of ET_a requires data on soil moisture status, which is changing daily. The effective mean value of the ratio ET_a/ET_m over the entire growth period can be quantified as the WSI value (water satisfaction index) as the output of a dynamic soil water balance model (FAO, 1986). Next, the FAO CSWB model (crop soil water balance model) can be transformed from a soil water model into a crop yield model by applying this WSI value in a crop yield function. In the present global assessment, the maximum yield is estimated directly on the basis of national yield statistics. The calculation procedure is valid for a homogeneous crop field. For application at the scale of a farm, region, country or continent the agricultural area is subdivided in calculation units, defined by crop type, crop calendar, weather and soil conditions, possibly split by management level, and into irrigated and rainfed areas.

The original crop response procedure is a water-driven crop model that requires a relatively low number of parameters and input data to estimate the yield response to water of the major field crops. The 'crop yield response to water procedure' has been applied for the assessment of both irrigation requirements and of crop yield reduction due to drought.

The FAO WSI is a qualitative index, expressed as a percentage of maximum yield, which can be used independently, or combined with other models. In addition, the CWSB method requires the calculation of the soil water storage and evapotranspiration deficit, and provides an estimate of the duration that the soil has been dry, which themselves can be used as qualitative indicators of the outcome of the regional cropping season.

The Global WSI model (GWSI) developed by JRC Mars-Food is applied to the whole world with a resolution of 1×1 degree climatic grid cells, which are subdivided into smaller agricultural land areas (0.1×0.1 degrees). The output variables of GWSI at the end of the growing season are cumulated values (since planting date) for WSI, water deficit (D), water surplus (WS), ET_a, rainfall and yield (on regional level). As a reference, the long-term average of these indicators is used, usually based on the 15 most recent and complete years.

The WSI is a qualitative index expressing the percentage of the crop water requirements that have been met. It is calculated on the basis of 10-day values of D. These values of D are summed and divided by the total seasonal water requirement of the plant. Specific crop parameters for soybean were used in GWSI calculations for each country where soybean is a major crop, including the duration of the growing season and mean planting date. The crop is grown during one season per year only. The actual planting date in any given year may be up to 30 days earlier or later, depending on sufficient rainfall during the planting period. The target maximum yield is taken from FAO national statistics and, for example, is set at 2711 kg/ha for Brazil and at 1236 kg/ha for India. The K_c factor is given as a function of the progress index, which runs from 0 at planting to 100 at harvest (see Table 3).

Table 3. Relationship between progress index and K_c factor

Progress index (%)	**K_c factor**
0	0.4
20	0.4
40	1.15
80	1.15
100	0.5

3.2.2 *The Crop Growth Monitoring System*

The WOFOST crop model

The WOFOST model is the weather-driven crop engine of the Crop Growth Monitoring System (CGMS) of the JRC-Agri4Cast action (Figure 6). The WOFOST model is one of the crop models developed by the school of CT de Wit with the aim of determining the upper limits of production, as determined by climatic conditions and the genetic potential of the crop. These models are based on a number of crop physiological responses to weather and soil conditions. The principles of the WOFOST crop growth simulation model have been discussed by van Keulen and Wolf (1986) and van Diepen *et al.*, (1989). Its implementation in CGMS and its structure is described by Supit *et al.* (1994), and its application by Vossen and Rijks (1995).

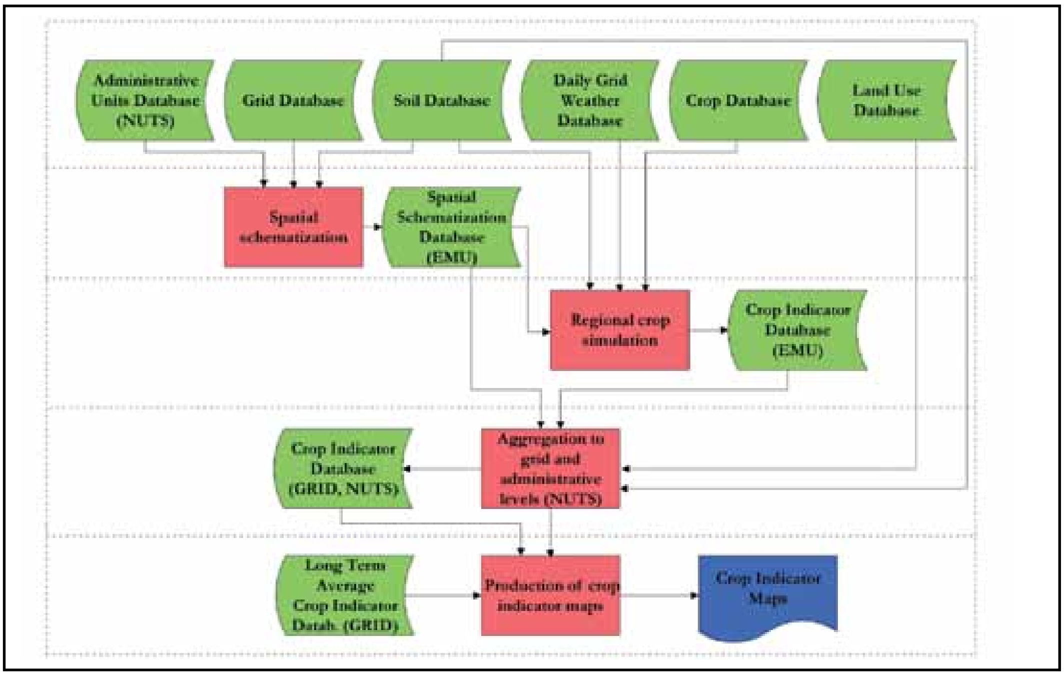
In WOFOST, the first, instantaneous photosynthesis, calculated at three depths in the canopy for three moments of the day, is integrated over the depth of the canopy and over the light period to arrive at daily total canopy photosynthesis. After subtracting maintenance respiration, assimilates are partitioned over roots, stems, leaves and grains as a function of the development stage, which is calculated by integrating the daily development rate, described as a function of temperature and photoperiod. Assimilates are then converted into structural plant material, taking into account growth respiration. Leaf area growth is driven by temperature and limited by assimilate availability. The dynamically simulated leaf area index is one of the most crucial crop state parameters in the model, as it controls the rates of both photosynthesis and crop water use.

Above ground dry matter accumulation and its distribution over leaves, stems and grains on a per hectare basis are simulated from sowing to maturity on the basis of physiological processes, as determined by the crop's response to daily weather (rainfall, solar radiation, photoperiod, minimum and maximum temperature and air humidity), soil moisture status (i.e. the ratio of actual transpiration to potential crop transpiration, similar to the FAO models) and management practices (i.e. sowing density, planting date, etc.). Water supply to the roots, infiltration, runoff, percolation, capillary rise and redistribution of water in a one-dimensional profile are derived from hydraulic characteristics and moisture storage capacity of the soil. Within CGMS, parameters describing the specific growth potentials of individual crops are described for winter wheat, spring wheat, barley, rice, potato, sugar beet, field beans, soybean, rapeseed and sunflower (Boons-Prins *et al.*, 1993).

Soil data in CGMS

The need for soil data in CGMS is twofold. Rooting depth and water retention characteristics determine the maximum available water that can be stored by the soil. Important system aspects like initial available water at the start of the growing season and the soil capacity to buffer infiltrated rainfall are influenced by these soil properties. Further, soil data are used to define whether a crop can be grown for a given soil type. For instance, shallow soil types are not suitable for cropping. The current CGMS is based on the Soil Geographical Database of Europe (SGDBE), version 4 covering pan Europe. The SGDBE contains a list of soil typologic units (STU), characterizing distinct soil types and the properties of these soils, such as texture, moisture regime and stoniness. As it is not technically feasible to delineate each STU on the map, the STUs are grouped into soil mapping units (SMU) to form soil associations. Soil attributes like rooting depth and water retention required in the crop water model of CGMS have been derived from basic properties like soil name and texture, applying so called pedotransfer rules.

Figure 6. Schematic overview of the Crop Growth Monitoring System (CGMS)



Weather data in CGMS

CGMS-Europe contains a meteo-database with historical daily meteorological data from weather stations. For the EU15 and neighbouring countries, data from approximately 380 stations with data since 1976 are available, in some cases back to 1930. Since about 1990, the data set was extended with stations from Eastern Europe, Western Russia, Maghreb and Turkey, while the station density increased over the entire area. At present, data from nearly 7100 stations is available. Of these stations, about 2500 receive daily meteorological information. The historical data were converted into consistent units and scanned for inconsistencies and non-realistic values. Variables covered are global radiation, air temperature, dew-point temperature (humidity), pressure at sea level, wind speed, precipitation, cloudiness and sunshine duration. Although CGMS can be applied at station level, CGMS runs on a 50×50 km grid for the following reasons: irregular spatial distribution of the meteorological stations, spatial variability of the crop and land use and of crop and soil information. The weather variables needed as input are: precipitation, minimum and maximum temperature, global radiation, wind speed and vapour pressure. The data interpolation is based on the averaging of values from weather stations surrounding a given grid cell.

CGMS output for estimating mean regional yield and water use

To determine the present irrigation water requirements of the field crops, the potential and water-limited yield, and the amount of water directly used by the crops for transpiration under differing potential conditions have been extracted from the database of the CGMS of the MARS project of the Joint Research Center. The data have been collected for oil seed rape and sunflower at NUTS2 (Nomenclature of Units for Territorial Statistics) level. EU29 has 258 NUTS2 regions. A NUTS2 region roughly equals a province in most countries. CGMS uses grid cells of 50×50 km as a basic climatic grid on which daily weather data are available as a time series over many years. In this study, the 30-year period of 1976–2005 has been used as the input for the simulation of crop growth and water use with CGMS. The simulations have been carried out for all regions where the agricultural statistics mention that the crop is grown. The final simulated values of yield and water use at the end of the season have been averaged over 30 years, and aggregated over NUTS2 regions. Water use is the total of plant transpiration and soil evaporation.

Estimation of irrigation requirements in CGMS

In CGMS, irrigation is not considered; however, with the available simulation results it can easily be determined. The net amount of water needed to produce one unit of crop biomass has been determined by dividing potential crop water use by the amount of biomass. This is the crop water use efficiency (WUE), expressed in cubic meters of water per ton dry matter (m^3/kg). It has been determined per crop in each NUTS2 region. The net amount of required irrigation water has been quantified as follows:

Net crop irrigation water requirement = (potential biomass yield – water-limited biomass yield) × WUE

When taking into account field water evaporation from soil surface, the net irrigation requirements may be 10–20% higher. The water requirements at field level take into account the field water application efficiency, which depends on the irrigation technique, timing, weather conditions and field water losses due to irregular distribution involving excess applications.

The field water application efficiency has been taken from NUTS2 level data compiled by Wriedt *et al.* (2008). These, however, only refer to the field level efficiency. It would be better to use efficiency data covering the whole trajectory from river and groundwater extraction to field level application. If this was the case an additional water transport loss above field level application should be accounted for (e.g. another 70% water transport efficiency).

3.2.3 The LPJmL model

The LPJmL global scale vegetation and water balance model solves the carbon and water balances at the earth's surface at a 0.5° spatial resolution. Originally, the model was developed as a dynamic global vegetation model, simulating changing patterns of natural vegetation on the basis of soil properties and climate (Sitch *et al.*, 2003). In recent years, the model has been extended with several new modules, including a crop model that simulates the growth and production of major crops (Bondeau *et al.*, 2007), and a global routing and irrigation module (Rost *et al.*, 2008), including reservoir operations (Biemans *et al.*, 2011). The model system can be used to estimate the available surface water that can be used for irrigation. LPJmL also simulates crop growth based on the available irrigation water as well as the effect of water shortage on crop yields. The consistent framework consisting of a coupled water resource and crop model of LPJmL makes this model unique in its possible application for crop–water interaction studies.

The LPJmL model is comparable to other global hydrological models in its simulation of stream flow, and has been analysed by Biemans *et al.* (2009). The performance of the LPJmL crop model for maize and temperate cereals has recently been validated by Fader *et al.* (2009).

Inputs to the model are climate, soil and land use information at a 0.5° resolution. For each crop type within the grid cell, a sowing date is simulated on the basis of climate and soil characteristics and crop-specific requirements regarding temperature and soil moisture. Crop growth is then simulated on the basis of climate and available additional water resources (if the crop is irrigated). The crop is harvested when mature, or when the maximum number of growing days is reached. Water stress affects crop yields through the effect on LAI (leaf area index) development and the distribution of biomass to the different carbon pools (roots, leaves, storage organs and reservoirs). More information on the crop model of LPJmL can be found elsewhere (Bondeau *et al.*, 2007; Fader *et al.*, 2009).

Total estimates by LPJmL of irrigated water requirement are higher than the water actually consumed by the plants, because irrigation systems are never 100% efficient. On the basis of soil moisture deficits, the model estimates a net irrigation requirement, which is translated into water withdrawals by accounting for country-specific irrigation efficiencies (described in Rohwer *et al.*, 2007). Subsequently, part of the withdrawn water is assumed to get lost during transport, depending on the conveyance system (also estimated in Rohwer *et al.*, 2007). The remaining water is then supplied to the fields.

4. RESULTS

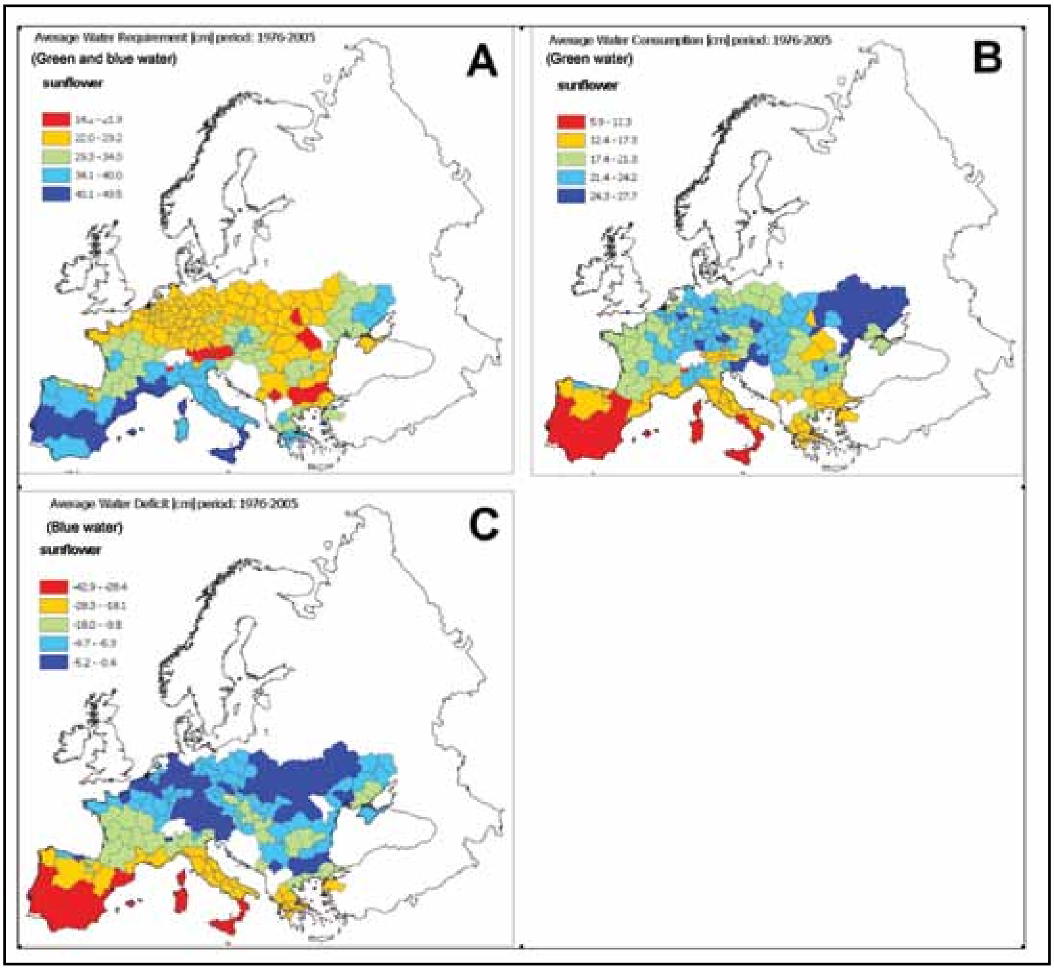
4.1 Water use of sunflower (European level)

To estimate the water use of sunflower, the CGMS model was used. CGMS analyses water use at the European level. Crop duration is variable because it depends on the temperature. The crop calendar is derived from Narisco *et al.* (1992) and Eurostat (1989). The presented results are based on meteorological data and planted area data from the period 1976–2005. The average area of sunflower cultivation as used in the CGMS calculations and the simulated water use are presented in Table 4. The most important countries in sunflower production in terms of cultivated area are Romania, France, Spain, Hungary and Bulgaria.

Table 4. Green (actual) water use and cultivated area for sunflower and rapeseed in Europe, as simulated using the CGMS model (average 1976–2005). WUE (water use efficiency) is calculated as kg water/kg dry matter

	Sunflower					**Rapeseed**				
Country	Actual water use	Water deficit	Cultivated area	WUE - no water stress	WUE - rainfed	Actual water use	Water deficit	Cultivated area	WUE - no water stress	WUE - rainfed
	10^5 m^3	10^5 m^3	10^3ha	g/g	g/g	10^5 m^3	10^5 m^3	10^3ha	g/g	g/g
AT	473	152	15.9	843	1114	744	30	33.7	695	756
BE						93	1	3.9	681	679
BG	14035	3737	546.5	827	1057	207	4	9.6	685	733
CZ	840	203	26.7	719	962	5933	161	281	645	709
DE	1556	391	51.6	766	885	22878	710	1049.5	616	645
DK						3735	567	145.1	583	692
ES	17365	28893	937	1204	6619	544	147	26	668	830
FR	18590	8808	653.6	863	1361	17998	535	721.7	700	731
GR	552	327	26.2	889	1606	283	9	15.3	573	582
HR	773	336	28.2	777	899	2205	26	101.3	706	738
HU	14516	3436	444.7	817	1118	49	3	1.6	733	761
IT	2936	2906	126.6	1096	2900	398	61	16.9	646	698
LT						788	15	35.2	549	569
LU						43	1	1.7	693	696
LV						296	5	12.8	558	580
NL						146	2	5.7	671	679
PL	45	10	1.5	774	935	9453	128	459.2	605	673
PT	751	1947	50	1477	18760					
RO	28136	6445	921.5	834	1267	1002	15	45.4	715	768
SE						2444	429	94.1	636	704
SI	6	1	0.2	705	756	28	0	1.3	699	711
SK	2485	578	74.3	775	1111	1997	24	88.9	721	766
UK						7861	332	308	626	672

Figure 7. Potential water consumption (mm) (green and blue water) (A), actual water consumption (green water) (B) and water deficit (blue water requirement) (C) as yearly averages for sunflower, based on CGMS results (period: 1976–2005)



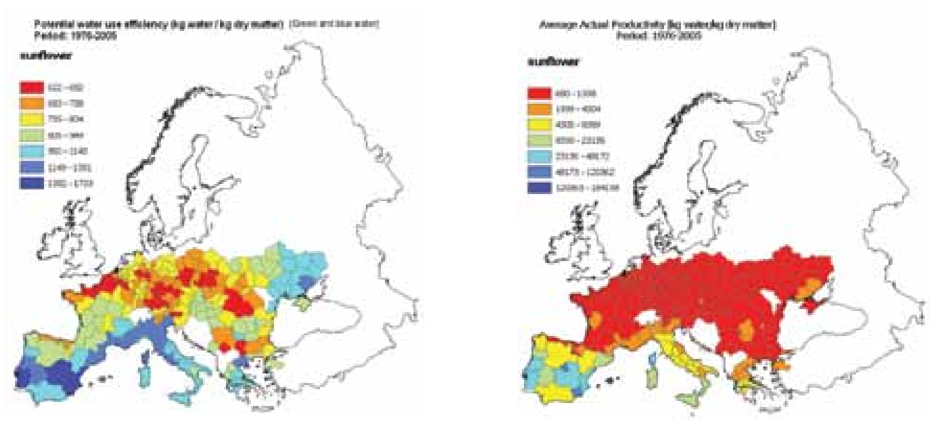
The difference between the potential (green and blue water use) and actual water consumption (green water) is defined in CGMS as the "water deficit" (i.e. the irrigation requirement; blue water use) is also shown in Figure 7. Potential water consumption is the water consumption by the crop if sufficient water is available throughout the growing season, i.e. if the crop is fully irrigated. The actual water consumption is the water use if the crop is not irrigated; the difference is the water deficit. From Figure 7 it can be seen that the actual water consumption (i.e. the rainfed situation) is lowest in Spain, Italy, southern France and Greece. This is the result of limited rainfall during the growing season. Since the amounts of irrigation water needed to reach the potential production are also highest in these regions it is clear that the highest deficits can be found in these regions as well.

In northern and eastern Europe, as a result of the higher rainfall amounts during the growing season in combination with lower summer temperatures (than southern Europe), the actual water consumption is higher and the water deficit is lower in these regions.

The potential and actual water productivity in terms of kg water/kg dry matter for sunflower is shown in Figure 8. The actual productivity refers to rainfall use, where the potential productivity refers to a situation when the crop water requirements are fully met, thus including irrigation. The most efficient potential productivity can be found in northwestern France and in some areas in central and eastern Europe. In these regions, crops may profit the most from the weather patterns. In southern Europe and eastern Russia the efficiency is less. Due to the high temperatures observed during the growing season, the water amounts required to reach the full crop potential are much higher than in northern Europe. Consequently, lower efficiencies are observed in southern Europe and eastern Russia.

The efficiency in the actual situation is also highest in northern Europe. Note that the range is large. This is caused by the fact that under rainfed conditions crop yields may drop dramatically, causing a reduction in the efficiency.

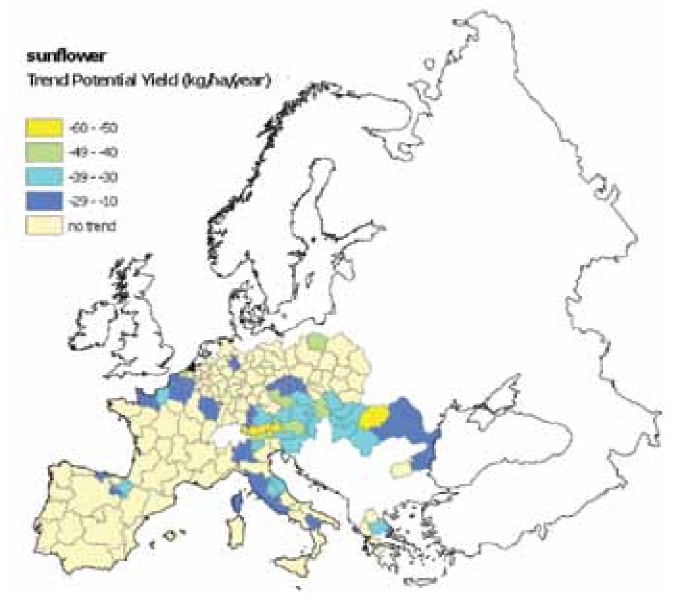
Figure 8. Potential water use efficiency when the crop is fully irrigated for sunflower, based on CGMS results



Trends

Figure 9 shows the trend in yield for Europe, as an average for the years 1976–2005. In some central, western and southern European regions there has been a decline in yield as a result of increasing temperatures during this period.

Figure 9. Trend in sunflower yield for Europe (average for the years 1976–2005), based on CGMS results



4.2 Water use of rapeseed (European level)

To estimate the water use of rapeseed in Europe, the CGMS model was used. The average area of sunflower cultivation (as used in the CGMS calculations) and the simulated water use are presented in Table 4. As for sunflower, the rapeseed crop duration is temperature-dependent. The presented results are based on meteorological data and planted area data from the period 1976–2005. The crop data are derived from van Diepen and de Koning (1990). Major countries for rapeseed production in terms of cultivated area are Germany, France and Poland.

Figure 10 shows the potential and actual water consumption for rapeseed, as average yearly values for the period 1976–2005.

Figure 10. Potential water consumption (green and blue water) (A), actual water consumption (green water) (B) and water deficit (blue water requirement) (C) as yearly averages for rapeseed, based on CGMS results

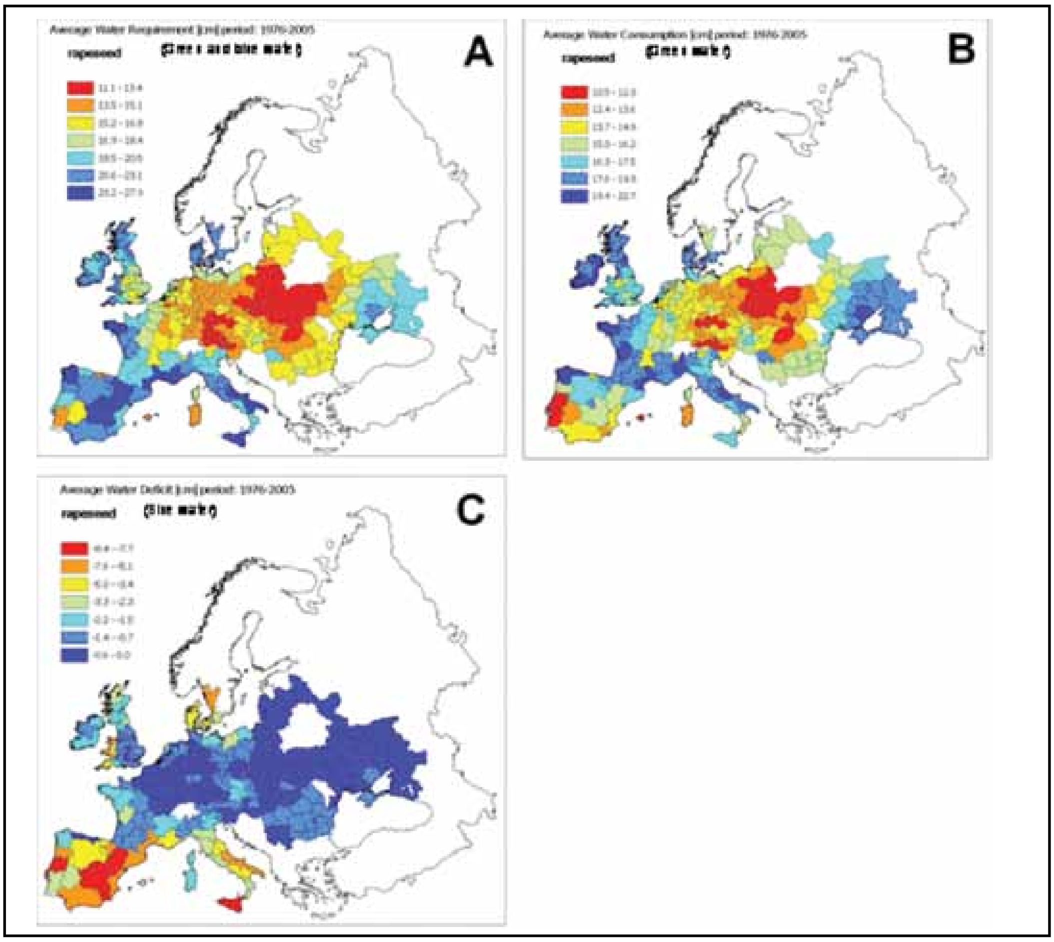
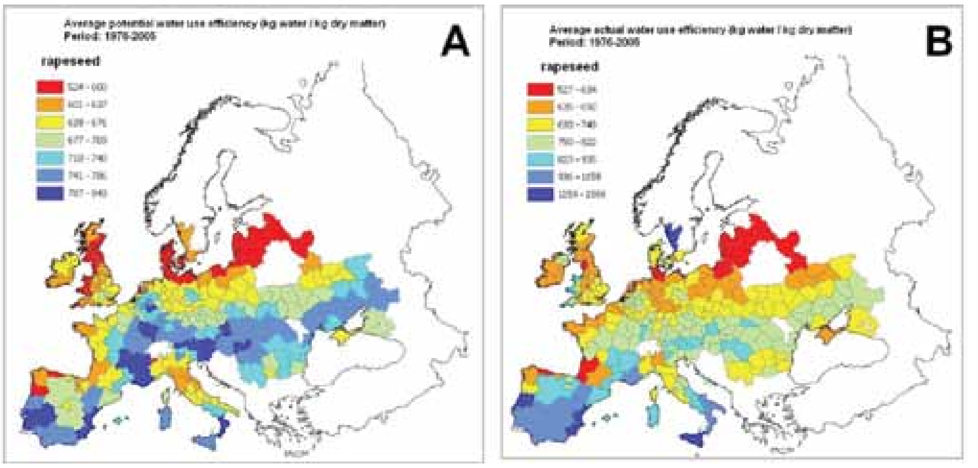


Figure 10 shows that the actual water consumption (i.e. green water use situation) is highest in southern France, Italy, the British Isles and in eastern Europe, southern Russia and the Ukraine. Note however, that rapeseed is hardly grown in southern France and Italy. In northern and central Europe the green water use is very modest. The irrigation amounts needed to reach the potential production are highest in north western and eastern Europe. Since rapeseed is grown more in temperate countries than is sunflower, the water deficit (or irrigation dependence) is much less.

The most efficient potential productivity (i.e. amount of water used per kilogram yield) can be found in northern Europe (i.e. the Baltic area and Denmark) and in some areas of the British Isles (Figure 11). Further south, the efficiency becomes less as the temperatures observed during the growing season increase. Consequently, lower efficiencies are observed.

The efficiency in the actual situation is also highest in northern Europe. In southern Europe the efficiency is lowest; however, the area planted with rapeseed in this region is limited.

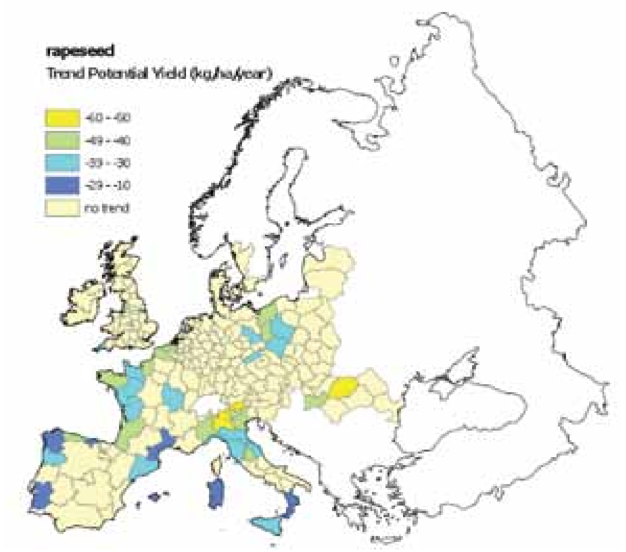
Figure 11 Potential (blue water) (A) and actual (when only green water is used) (B) water use efficiency for rapeseed, based on CGMS results



Trends

For most regions in Europe the yield and water use in rapeseed shows no trend over the last 30 years. In some regions, a drop in potential yield is simulated (Figure 12). These regions are mostly located in Spain, France, Italy and Poland. In southern Europe the decreasing potential yield is caused by rising temperatures in the period 1976–2005. In Poland, the decreasing potential yield is related to decreasing global radiation in the same period as a result of increasing atmospheric turbidity.

Figure 12. Trend in yield for rapeseed, based on CGMS results for 1976–2005



4.3 Water use of soybean (global level)

To estimate the water use of soybeans, the GWSI model has been run for all the countries in the world where soybean is a major crop. For each country, fixed crop growth duration and planting date window are used, taken mainly from FAO data. Within each country, the arable land mask has been applied to select only the agricultural regions, and climatic rules have been applied to avoid modelling soybean in climatically unsuited regions. The total water use at field level (expressed in mm water layer) over the main growing season has been quantified for both rainfed and irrigated conditions, and the difference between these two water use levels can be considered as the net crop irrigation requirement (Figures 13, 14, 15).

The map of soybean water use without irrigation shows the actual evapotranspiration (ETa) in millimeters for soybean under rainfed conditions over the growing season as mean values per country (Figure 13). These can be considered as the crop water requirement, to be provided by rainfall through the soil moisture reservoir filled with rainwater.

All results are based on data from GWSI, JRC-MARS FOODSEC, which are based on current crop calendars and crop growth durations and represent averages over 8 years; so in a single year the irrigation need might be much higher. The map shows that in most regions that traditionally produce soybean, the crop can be grown under rainfed conditions, without, or with only limited, supplementary irrigation. Usually, no irrigation is needed in typical monsoon climates like Southeast Asia and the southern part of West Africa. A limited amount of irrigation would be needed in China, Brazil and Argentina, and somewhat more in the USA, India and Indonesia. The highest irrigation requirements are found for Mediterranean climates and savannah climates with a short rainy season like in southern Africa. In more detail, the lowest water use without irrigation (230–400 mm per season) is found in regions with growing seasons that are humid and with rather low temperatures, such as in tropical mountains or higher latitudes (Nepal, Bhutan, Korea, Japan), especially when the crop cycle is short (100–120 days); or in tropical lowlands with a pronounced rainy season (coastal West Africa, Vietnam, Thailand). Higher water use (500–600 mm per season) and negligible irrigation requirements (under 5 mm) are found for humid regions that are warmer and/or have longer growth cycles (Central America).

When the growing season becomes drier, warmer or longer, the water use and irrigation requirements increase. The most drought-prone areas in need of irrigation water are found in southern Africa, southern Europe and Pakistan, with crop water use of 500–600 mm per seasons, of which 200–250 mm should come from irrigation. In Pakistan, as much as 450 mm per season is needed because the cropping area is in the semi-arid zone (Figure 14). The long-season varieties (150–170 days) are grown in South America and southern Africa. Unreliable rainy seasons are found in East and southern Africa. Continental climates have warm summers with dry spells (USA, China). Mean irrigation requirements increase to up to 50 mm for China and Brazil, and up to 100 mm for India and USA (Figure 15).

There are large differences in water use and water productivity between the main soybean producing countries (Figure 16), the USA producing more soybeans per hectare with less water compared to Brazil and Argentina. As a result, the water productivity is much higher in the USA and the amount of water needed to produce a kilogram of soybean is less than one fifth of that needed on average in Brazil.

Figure 13. Average annual soybean water use without irrigation (green water only) for the period 2001–2007

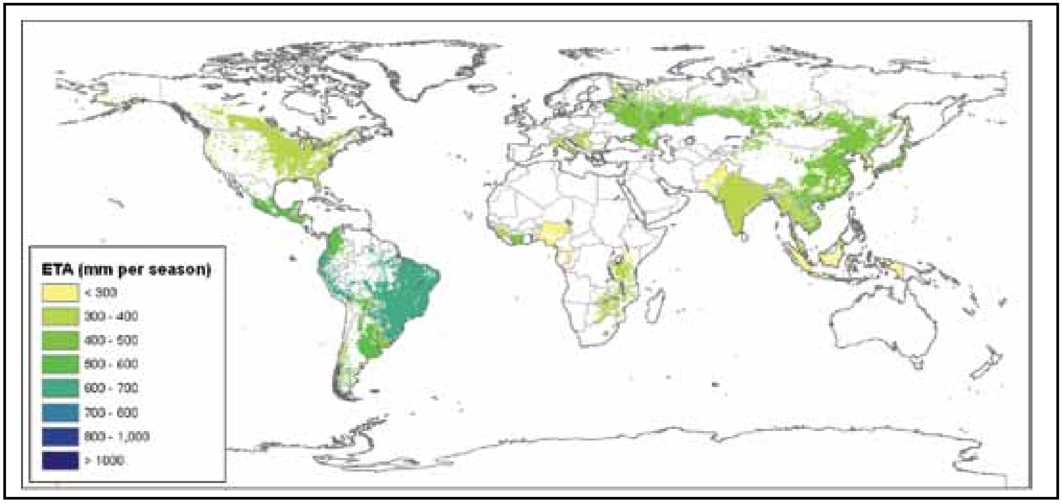


Figure 14. Average annual soybean water use assuming full irrigation (green and blue water) for the period 2001–2007, excluding irrigated water losses

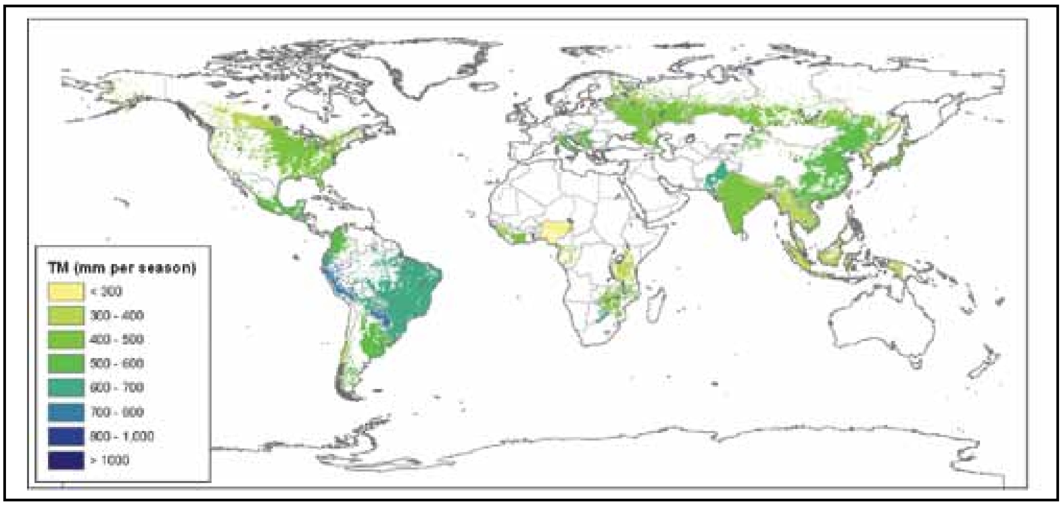


Figure 15. Average net irrigated water demands for soybean for the years 2001–2007 (blue water)

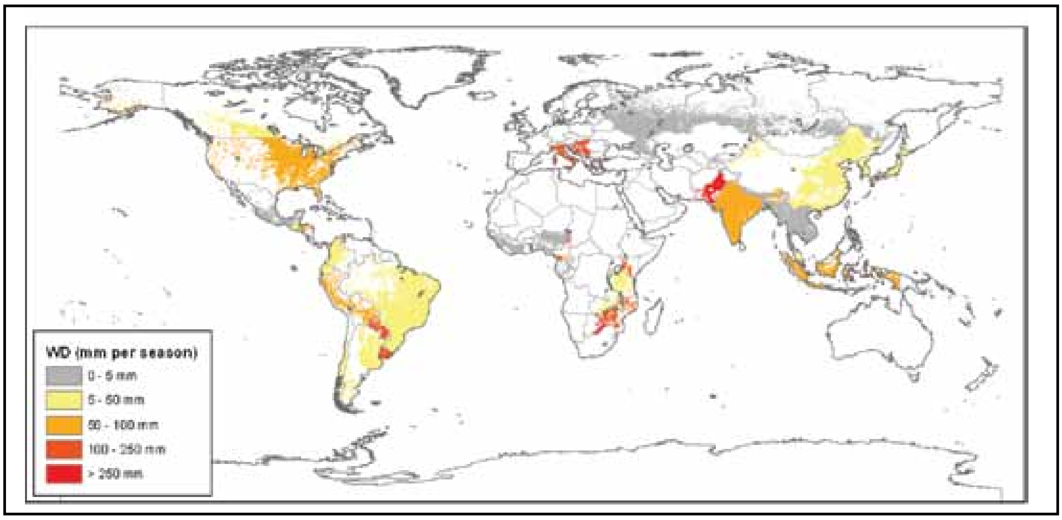
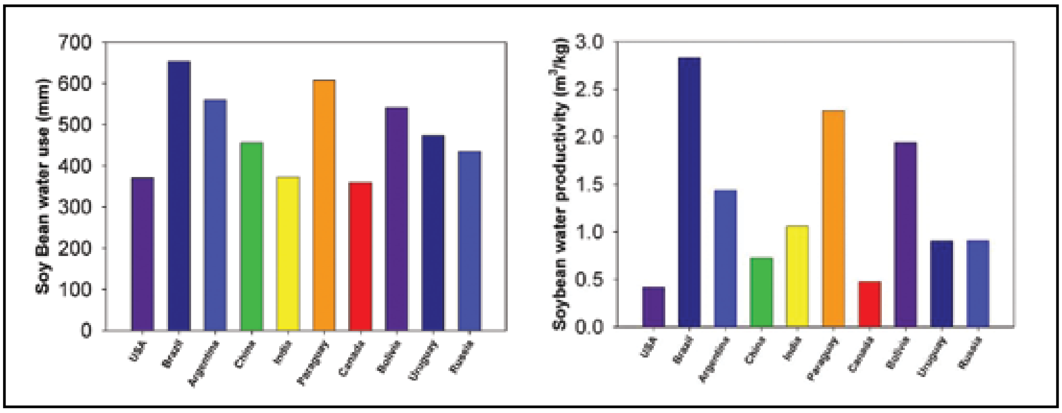


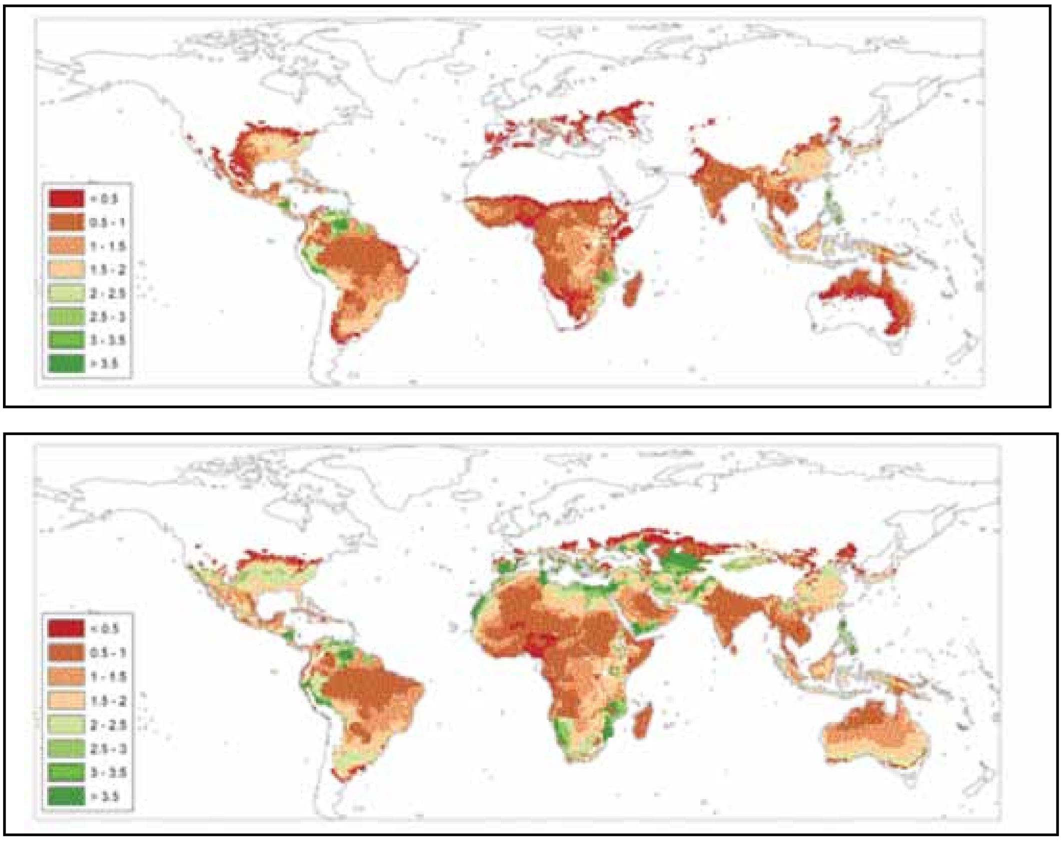
Figure 16. Average soybean water use (left panel) and water productivity (right panel) in the main soy producing countries



4.4 Water use of groundnut (global level)

To estimate the water use of groundnut, the LPJmL model has been run for the whole world, assuming complete coverage of groundnut. This has been done to see spatial differences between water use and yields. A distinction is made between water use based on climate input, adding no extra water, and water use where full irrigation is applied, assuming that all water needed is available. The results are shown in Figures 17, 18, 19.

Figure 17. Simulated yields in ton dry matter (DM)/ha for a simulation with only precipitation water supply (upper panel) and with unlimited additional irrigation water supply (lower panel). Areas with simulated yields below 0.2 ton DM/ha are excluded. The figure shows average yields for 1991–2000 climate conditions.



To interpret the results it is also important to take into account where groundnut is mostly grown (see Figure 17). Total groundnut production is relatively modest in most groundnut growing regions like India, Southeast Asia and West Africa. Considering these regions, green water use is the lowest in India in comparison to East Asia and Africa. In most of the areas, the irrigation requirements are relatively modest (less than 300 mm/year). Only in drier parts of India does groundnut water requirement increase to up to 500 mm. But, in India groundnut is mostly grown in the wetter regions of central and southern India. These limited irrigation requirements also explain the small difference in production between irrigated and dry land in India and in West Africa. In China, some gain in production can be made by irrigating groundnut.

Figure 18. Water consumption (mm/year) consisting of total evaporation, transpiration and interception during the entire growing period. (A) Total consumption for the simulation without irrigation (green water), (B) total consumption for the simulation with irrigation (green and blue water) and (C) total consumption only originating from additional irrigation water supply (the blue part). Areas with yields under 0.2 ton dry matter/ha are excluded.

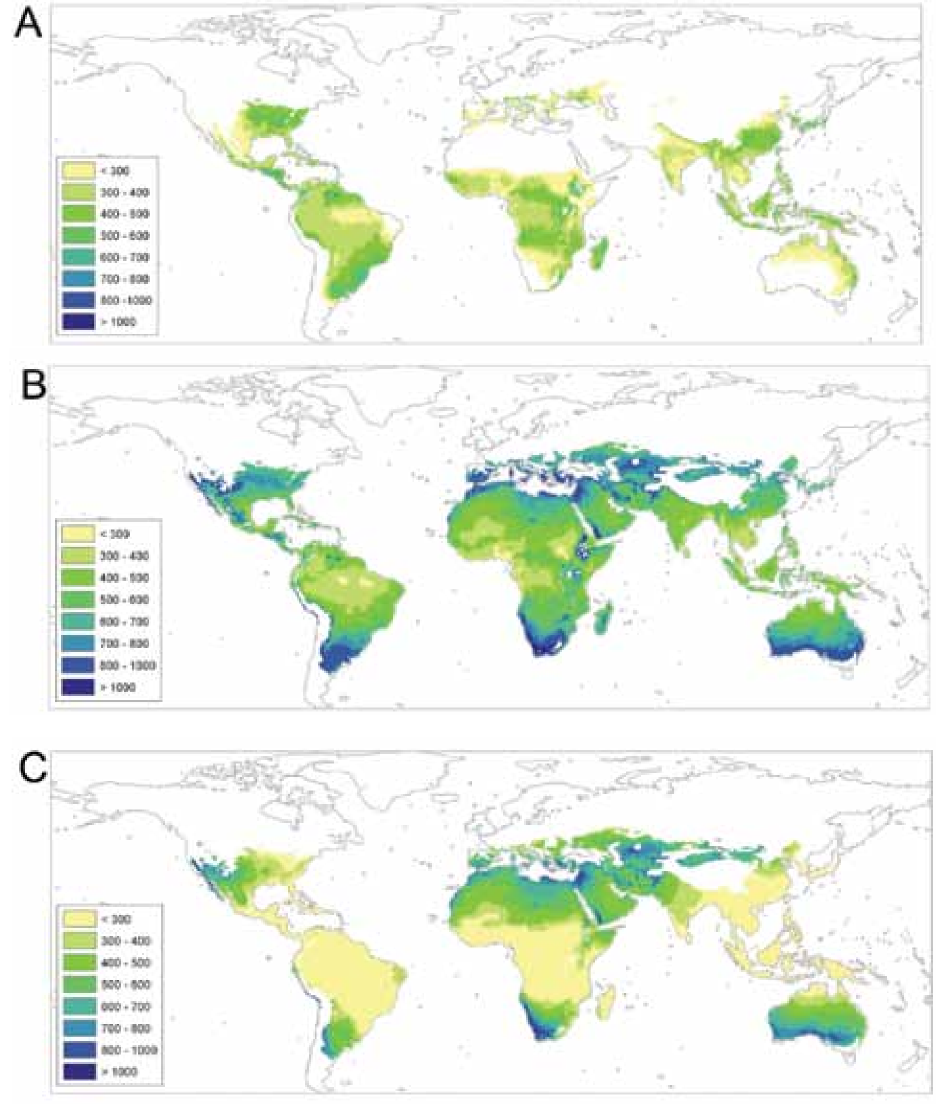
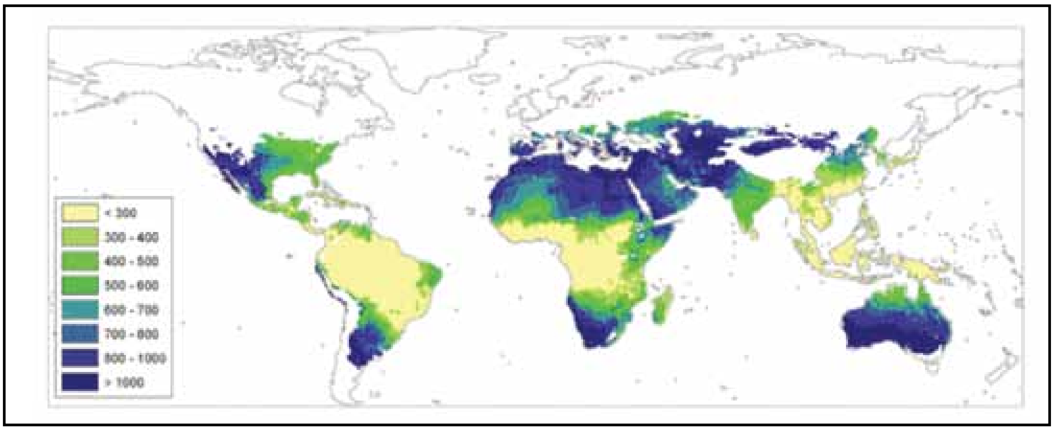


Figure 19. Estimate of the total irrigation water requirements (blue water) for groundnut under unlimited conditions.



4.5 Water use of oil palms (global level)

Palm oil is the world's leading fruit crop and is grown primarily in tropical climates where it has become the building block of several developing world economies. Due to their tropical climate with year-round temperatures of 25–33°C and evenly distributed rainfall of 2000 mm/year, Malaysia and Indonesia have emerged as major producers of palm oil.

The oil palm is a highly productive crop. No other crop is capable of producing such high yields. A single hectare of oil palm produces as much as 6000 L of crude palm oil (to compare: soybeans yield around 446 L/ha). The comparatively low price of palm oil continues to drive its demand as cooking oil and as an ingredient in other products.

Palm oil crops in Asia are rainfed and suit the heavy to moderate rainfalls found in Malaysia and Indonesia. Some supplemental irrigation during periodic droughts might help to increase yields.

The actual water requirement of oil palm is relatively unknown. So far few studies have been done on water use in palm oil production, some examples are:

- Palm Information Centre, Malaysian Palm Oil Board (Research on oil production process)
- Unilever Sustainable Agriculture Advisory Board SAAB (Good Agricultural Practice Guidelines developed for palm oil)

The use of palm oil as a biofuel is gaining momentum. Given its cost and yield advantages over soybean and corn, palm oil could be a solution for the world's energy problems, even though it is difficult to predict where the supply will come from because 93% of the global supply is already in use as a food source.

Sustainable oil palm cultivation

Due to the high yields and steady demand for palm oil, vast amounts of rainforest have been turned into farmable acreage and treated with large amounts of chemical fertilizers. Many NGOs are now actively petitioning palm oil producing nations to regulate further deforestation efforts. Additionally, much of the land that was used to increase the size of existing palm oil plantations required the draining of peat land. Peat is a natural sponge that absorbs and retains water and carbon. When it is drained for palm farming, the result is a dramatic spike in carbon emissions and a drop in the water retention capacity of the land.

4.6 Comparison of water use for different oil crops

Europe

Due to the climatic differences in Europe, both sunflower and rapeseed show a higher water demand in southern Europe than in northern regions. On average, sunflower requires around 430 mm of water for optimal crop growth in southern Europe and 300 mm in central Europe. Rapeseed requires around 230 mm water in southern Europe and 160 mm in central Europe.

Looking at water deficits, both sunflower and rapeseed demonstrate a water deficit in the southern parts of Europe, indicating that rainfall is not sufficient to meet the crop water demand. Additional supplies from irrigation are, therefore, needed in these parts of Europe. In absolute terms, blue water requirements are much higher for sunflower than for rapeseed (e.g. 350 mm deficit for sunflower versus 70 mm deficit for rapeseed in the south of Spain). This can be explained by the fact that sunflower is a summer crop, with a growing period during the hot, dry summer months. Rapeseed is a winter crop that is grown when temperatures are more moderate and when more rainfall is available. This also explains why sunflower is more prevalent in Mediterranean countries, whereas rapeseed is grown mostly in the middle parts of Europe.

The result is that rapeseed is mostly grown further north in Europe where water scarcity is not a major issue. For sunflower the situation is different. This crop is also grown in southern Europe where water scarcity is a major issue and irrigation is necessary to obtain an economic yield. In many parts of France, sunflower is also irrigated during dry spells in the summer. Water scarcity in Mediterranean Europe is likely to become much more severe in the future, which would affect the water available for sunflower and will push farmers to become more efficient in terms of water use.

Global

Soybean

Compared to other crops, the variability in crop water use for soybean is much higher. The national water requirements of irrigated soybeans range between the extremes of 230 and 770 mm/season while most values are between 300 and 600 mm/season. In about half of the soybean-growing countries the mean irrigation needs (blue water) are below 50 mm/season, whereas in 25% of the countries (situated in southern Europe, southern Africa and South America) the calculated irrigation needs are above 100 mm/season. Most differences in crop water use and irrigation requirements for soybean around the globe can be related to differences in climatic conditions during the growing season and to differences in the length of the crop growth cycle.

The USA and Brazil are the two major soybean-producing countries. Soybean water use is twice as high in Brazil as in the USA. When comparing water productivity, the difference is even larger. Farmers in Brazil use six times more water to produce one kilogram of soybean compared to US farmers. This does not mean that farmers in the USA are much more efficient in their use of water or that their water use is more sustainable. In Brazil, water scarcity is hardly an issue whereas in the west of the USA water scarcity is a very significant problem. So, in this case, the highest water use is observed in the country with the lowest water scarcity problem. This makes it particularly hard to compare the water sustainability of the different countries.

Groundnut

In the regions where groundnut is mostly grown (China, India and West Africa) the total water consumption is between 300 and 600 mm/season. Yields are the highest in North America and China and considerably lower in India and West Africa. Water use is the highest in the southern USA and China, whereas the lowest water use is observed in Nigeria and parts of India. In the main groundnut cropping regions, irrigation increases water use by between 100 and 300 mm; however, the yield increase from irrigation in the important groundnut cropping countries is marginal.

Palm Oil

Palm oil is grown in tropical regions with very high rainfall, and therefore there are no significant issues with the sustainable use of water resources in these regions. However, there are other sustainability issues associated with palm oil production, in particular deforestation and the large-scale carbon emissions released when tropical peatlands are drained to make them suitable for palm oil.

4.7 Model limitations, data gaps and uncertainty

All three modelling systems make various assumptions and simplifications. In general, the models assume that weeds, diseases and pests are controlled and that all nutrients are optimally available. The ability of plants to adapt to low resource conditions by modifying their morphology and physiology is not accounted for, so that the models, especially CGMS, may overestimate the effects of drought. Sowing date variations or occurrence of re-sowing in response to droughts may occur at regional or even national level. However, since no information on these phenomena is available, an average sowing date per crop and per region has to be assumed.

The main limitation of the water use simulated by GWSI is the sensitivity of the crop factor (K_c). The outcome of the model depends heavily on the value of Kc. For each country, one value is calculated and that is unrealistic, especially in the larger countries. Also, in several countries limited data are available for accurate calculation of this factor, which make the value and the corresponding water use uncertain. In addition, the crop water requirements calculated with GWSI are based on current crop calendars and crop growth durations in countries where soybean is currently a major crop. This is in contrast to a crop water use assessment based on one standard reference crop, and to a reconnaissance of regions where the crop is not yet cultivated as a major crop, e.g. New Zealand, Australia, France and many African countries. These were not included in the GWSI system, because GWSI is designed as a monitoring and drought early warning system for the present situation, rather than for assessment of production potential. In addition, it should be noted that in large countries (Brazil, India, USA) or countries with contrasting or varying climates (countries with mountains or with two or three rainy seasons) there might be a mismatch between the applied average national crop calendar and the regional climatic conditions. In addition, the basic assumption that soybean is grown in the main rainy season may not be correct, as in some regions it is grown mainly as a second crop in the dry season in rotation with the main crop, rice. This implies that the GWSI system can be improved by adding spatially explicit crop input data, which is underway.

The groundnut results calculated with the LPJmL model should also be used with some caution. Although LPJmL has the functionality of calculating groundnut yields and water use, the representation of this crop in the model has not yet been validated. Simulated sowing dates for temperate cereals agree well with reported cropping calendars (Bondeau *et al.*, 2007), but have not yet been validated for other crops. The yields of temperate cereals and maize have recently been calibrated at the country level (Fader *et al.*, 2009), but for other crops this calibration has not yet been finished. Therefore, results for yields and water productivity do reveal country boundaries (e.g. Egypt), because some estimate has been made on country-level management efficiencies (based on FAO reported yields).

Other uncertainties in the results presented are gaps and errors in the available data, including meteorological data, planted areas, planting dates etc. A major limitation for making more precise analyses of water use of crops is the lack of irrigation data. Data on when, where and how much water is used for irrigation is still rarely available, even in developed countries. Data on the extent of an irrigated area is also difficult to obtain. Siebert *et al.* (2005) produced a detailed map of irrigated areas. The problem with using this map is that it represents the area that is currently equipped for irrigation; it is not certain whether the area is actually irrigated nor how much water is used. Irrigation efficiency is an important determining factor for how much water is used. Part of the irrigation efficiency can be determined from the type of irrigation. For example, drip irrigation is the most efficient whereas sprinkler irrigation of crops with high leaf area such as sunflower can be very inefficient. There is also a large range in efficiency associated with the transport of water to the irrigation point if surface water is used for irrigation.

5. DECISION FRAMEWORK FOR SUSTAINABLE WATER USE FOR OIL CROPS

Water management and the problems arising from drought and flooding, resulting in a lack of water or contamination of existing supplies, increasing population, increased domestic and industrial use, and agricultural use for irrigation are creating conflicts over water use in many parts of the world. Climate change is likely to exacerbate these problems and few countries are taking adequate steps to mitigate the risks to society from these threats. Agriculture is often seen as one of the villains in this scenario because agriculture apparently uses a significant proportion of the available water. Whether this is fair or not, it is the widespread perception and so the food industry must consider its approach to sourcing crops and foodstuffs to try and minimise its impact on the availability of water. This is complex because it not only relates to the amount of water used in a particular location for a particular crop but it also relates to agronomic and water management practices, including maintenance of the overall water budget of the area, which is influenced by soil type as well as rainfall.

In some countries there is much tighter regulation of water use than in others. Where water use and abstraction is regulated, the regulatory authority will often have data and information that would be helpful in making judgements regarding water sustainability in a specific region or locality. Where there is little or no regulation, information must be gathered from other sources such as local or national university departments and meteorological offices.

In assessing the most sustainable sources of oil crops there are several different issues that need to be considered. This means that the simple equation that rainfed means good and irrigated means bad is simply not correct and may lead to inappropriate decisions. As a starting point, it is assumed that in each situation the crop quality is appropriate for the proposed use.

The considerations are:

1. Is the crop grown in a water-stressed area? (Is the region able to readily meet its water needs for all users and the environment?)
2. Is the crop grown without the need for irrigation, i.e. only rainfed (green water)?
3. If there is a requirement for irrigation, is this efficient? (Is there little loss of water and is the water applied just sufficient for the crop, e.g. spray irrigation suffers from high interception loss?)
4. Can husbandry be improved to increase efficiency, i.e. to improve the relation between input of blue water (irrigation) and the yield?
5. Is the source of water for irrigation sustainable? (Is there a plentiful supply of water so there is no pressure on other users or the environment and will the introduction of contaminants through leaching and run-off be minimal, resulting in no adverse impacts on other users or the environment?)
6. Has the growth of the crop resulted in a change in local vegetation that has adversely disturbed the local water balance? (For example, has the removal of natural vegetation and its replacement with oil crops impacted on the local water balance? This can be the case for peat soils, which dry out resulting in a loss of carbon and natural capacity to retain water. In semi-arid regions the removal of natural vegetation can cause dry land salinity).

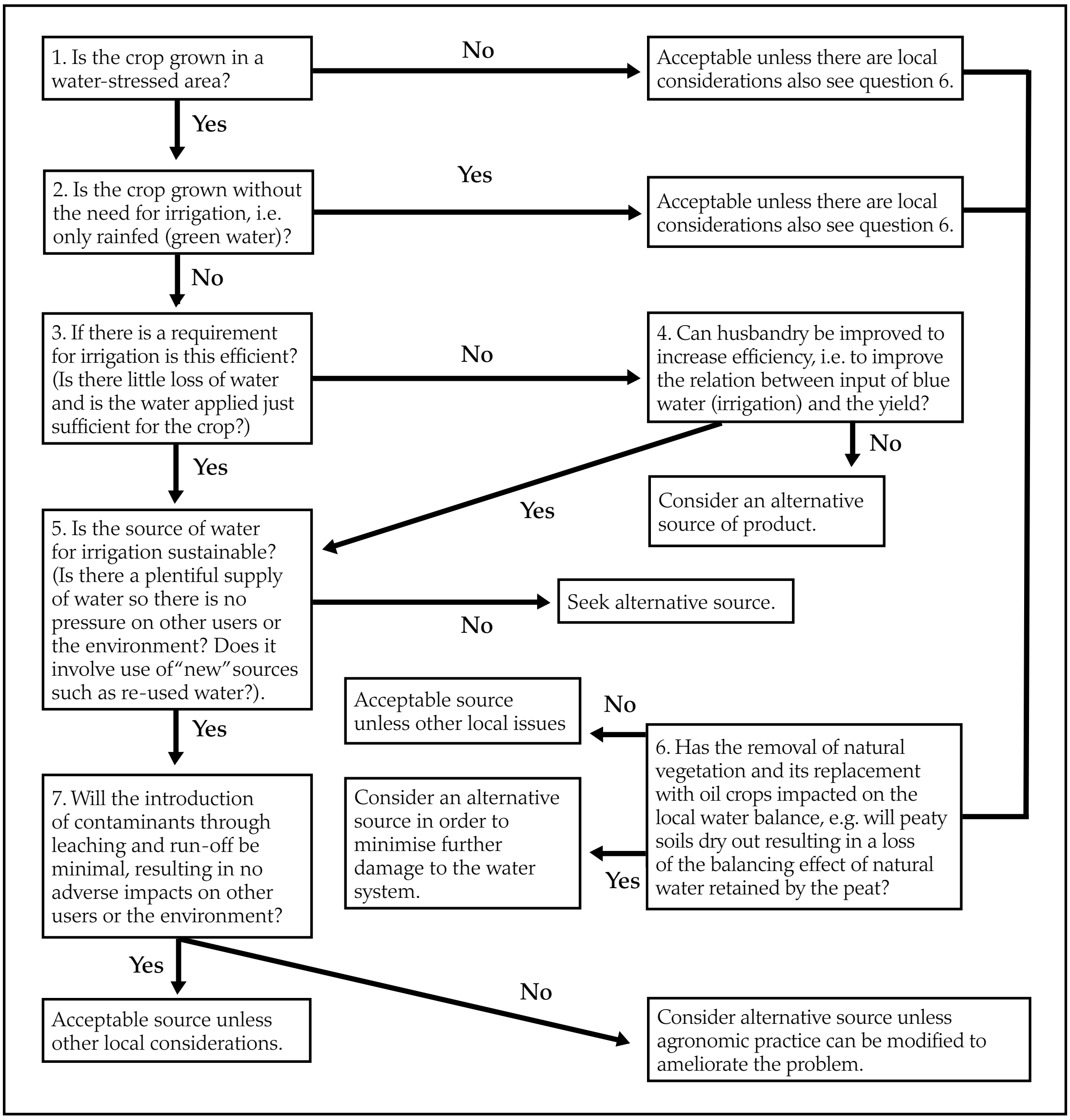
However, there are also considerations that are important on a more local level, particularly in relation to climate variability. In regions with high climate variability, irrigation requirements and water availability vary widely from year to year. As a result, water scarcity will be an issue intermittently and may not be constant from year to year.

In developing a framework for identifying the different levels of sustainability from different sources it is important to consider the above-mentioned reflections. But finally, the extent to which the framework can be used in particular cases will often depend on the availability of data.

With regard to the six considerations listed above, the answers will probably lead to further questions and actions. In the case of the first question (is the crop grown in a water-stressed area), the answers to subsequent questions take on a greater importance because there will be a need to manage water for agriculture more carefully. This will also relate to the crop type and its particular needs. Sunflower, for example, requires high levels of sun and is relatively drought tolerant so will withstand the short periods of drought that are common in the regions in which it is currently grown. Sustainability can also be improved by the introduction of novel agronomic practices. For example, in the dryer areas near large cities, there is the potential for using"new" sources of water, such as treated wastewater effluent.

Incorporating the considerations above in a framework can assist in selecting the most sustainable sources. The framework below (Figure 20) provides a first pass assessment. The answers only provide a high level view and will require more detailed examination, but it provides a means of establishing a first level of priority.

Figure 20. Framework identifying the different levels of water sustainability from different sources



5.1 Wider issues

There are a number of wider issues that may impact on the decision with regard to the suitability and sustainability of a source. These may relate to the local economy and ecology and whether this will have a wider impact on sustainability. Often these questions arise at a local level and impact on the process of refining any decision. They can also include considerations of energy input in relation to yield. While these may be outside the consideration of water management and sustainability, there may be energy requirements associated with pumping, and agronomic practice related to water.

An additional issue is that of the contamination of surface and groundwater sources by nutrients and other chemicals, such as pesticides. Where irrigation is excessive, this can lead to enhanced loss of contaminants into both surface and groundwater. So, sustainable use of water reduces the pollution of water bodies and could provide additional benefits in this respect.

5.2 Future issues

The future will inevitably pose more questions and may well provide important answers. The impact of climate change remains uncertain, particularly at a local level. The way in which governments and societies manage climate change will be important. For example, those regions that put in place the means of capturing intermittent heavier rainfall and of mitigating uncontrolled flooding may well become more important for the production of a range of food crops. Equally, those regions that begin to develop the infrastructure for the use of "new" sources of water may also be well placed to take advantage of climate change.

The development of biotechnology plants for more efficient use of water or resistance to short-term drought or short-term flooding may also provide opportunities for improving the sustainability of existing sources in the long term or provide the means of moving into new regions that are otherwise unsuitable for crop growth. For example, the developing conflict between biofuel crops and food crops would benefit from such technology if this resulted in a separation between the areas suitable for both types of crop.

6. FUTURE OUTLOOK AND CONCLUSIONS

6.1 Sustainable use of water resources

Water footprint

With water becoming scarcer due to higher demands and more variability, the sustainable use of water resources becomes even more important. Not only is maximising productivity important but also the sustainable use of resources, including water. Following on from the concept of a carbon footprint, a water footprint has also been recently developed as an indicator for how much water is used for different products (Hoekstra and Chapagain, 2007). However, we need to be aware that, unlike fossil fuels, water is a renewable resource with only a limited amount of water used for human activities (Oki and Kanae, 2006) and water scarcity is mostly a regional problem. In terms of sustainability it is therefore important to link water use to water availability and, especially in regions where water is scarce, water productivity should be as high as possible so that enough water is left for other users, including the environment. This indicates that in terms of sustainability the crops grown with the least amount of water are not necessarily the most sustainable. An alternative approach would be to use a stress-weighed water footprint as suggested by Ridoutt and Pfister (2010). In the stress-weighed water footprint the water use is corrected for the amount of water stress in a particular basin. Water stress is calculated as the amount of water available divided by the water demands.

Best practices

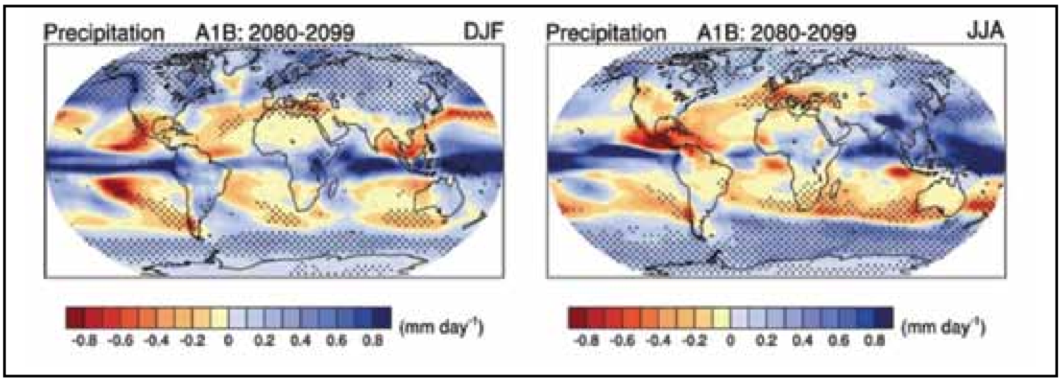
In this study, the largest difference in terms of water use and water productivity between different regions was observed for soybean. Large differences in water use per hectare and per kilogram yield are seen in the USA and Brazil, the two largest producers of soybean. So, is soybean produced in the USA more sustainable in terms of water use compared to Brazil? Not necessarily. Both countries have regions that could be considered water stressed. For the USA this is especially the western part of the country, whereas in Brazil water stress occurs in the northeast. In general, improving the water use efficiency of soybean is not yet an issue in Brazil, because enough water is available. Therefore, instead of just choosing the lowest water use in order to consider a crop "sustainable" it is important to define some best practices, especially in relation to the water used for irrigation. A set of minimal efficiencies should be defined on the basis of the local climate and water scarcity situation. For example, irrigation efficiency targets could be defined for different crops and regions.

The numbers presented in this report give a good first indication of how much water is used globally to produce oil crops in the different regions. The numbers cannot be transformed one to one into a sustainability indicator yet. Whether water use is sustainable or not depends on regional factors, for example whether enough water is available for environmental flows and whether the groundwater resources used are renewable or non-renewable.

6.2 Future outlook

Climate change in combination with increased population and food demands will have a large impact on agricultural water use and availability. Climate change will have an impact on agricultural water use as a result of higher temperatures, changing rainfall patterns and through the direct impact of elevated CO_2 concentrations (Asseng *et al.*, 2009). Higher CO_2 concentration has a positive impact on production potential and generally increases water use efficiency (Ludwig and Asseng, 2006). Higher temperatures affect plant water use and potential photosynthesis and growth rates. Especially in temperate regions, higher temperatures result in higher growth rates and longer potential growing seasons. However, using the same cultivar, warmer temperatures also reduce the length of the crop growing season, which could potentially reduce seasonal water use (Supit *et al.*, 2010). Higher temperatures also increase evaporative demand, which could increase water use. Due to climate change, rainfall will decrease in certain regions, mainly the mid-latitudes, while around the tropics and near the poles precipitation is projected to increase (Figure 21). However, not only the amount of rainfall will change but also the distribution, and there is a tendency for more variable rainfall, which will increase the number of both floods and droughts. These changes in rainfall will directly impact green water availability and use, and blue water availability will also significantly change due to global warming (Milly *et al.*, 2005). Important crop-producing regions such as Mediterranean Europe and western USA are expected to have lower rainfall and higher temperatures in the future, leading to increase evaporative demand. In some regions, such as Spain, North Africa and Western Australia, these changes in climate might result in more than 40% decrease in run off (Milly *et al.*, 2005). These changes will have large impacts on water available for irrigation and other uses.

Figure 21. Changes in precipitation (mm/day) for December–February (DJF) (left) and June–August (JJA) period (right). Changes are given for the SRES A1B emission scenario, for the period 2080–2099 relative to 1980–1999 (IPCC 2008).



The total water demand of oil crops is also projected to increase, especially in Asia. In Asia the population is growing rapidly, which increases the food and oil demands. Economic growth is also likely to increase meat consumption, which increases the demand for oil crops as animal feed. Also, water demand for other sectors is likely to increase on most continents due to economic growth, which is likely to reduce the amount of water available for agriculture. This means that water scarcity will probably increase across the globe, especially in semi-arid regions where rainfall is projected to decrease.

6.3 Conclusions

The results of this study show that there are considerable differences in the green and blue water requirements of the different oil crops for different regions. The differences are the highest for soybean where, in some countries, twice as much water per unit of crop area is used compared with the countries using least water. In terms of water productivity, the differences are even larger. The differences in water use are mostly due to differences in the local climate. In warm and dry climates the blue water use is much higher than in temperate climates with high rainfall.

Global anthropogenic water use is still increasing and in some areas this has a large impact on environmental quality and biodiversity. Therefore, it is becoming increasingly important that water is used in a more sustainable way. To raise awareness and to stimulate lower water use the concept of water footprint was introduced, which compares the water use of different products. The problem with the water footprint is that it ignores where the water is used and how much water is available, although there are future plans to include some measure of water scarcity. High water use in dry, water-scarce regions has much more impact on the environment than water use during a tropical monsoon period. It is therefore important to compare water use to the local water scarcity situation.

Rapeseed production is unlikely to cause unsustainable water use. The total water use is low and it is mostly grown in regions where water scarcity is not an issue. Sunflower is produced in regions where water scarcity is or will become a major issue. Until now most irrigation practices in relation to sunflower production are inefficient and could be considered unsustainable in some areas, although data on the amount of irrigated water use is limited, which makes a proper quantitative analysis difficult. This is, therefore, an important area for future development.

For soybean, the water use efficiency is much higher in the USA than in Brazil. This may reflect differences in farming methods and hence yield, as well as water use. Whether the water use in Brazil is unsustainable depends on the local situation. In general, enough water is available in Brazil but the northeast has significant water scarcity and quality problems. However, the difference in water use efficiency between the two countries is so large that it should be possible to reduce water use, or increase yield, in Brazil. To a lesser extent this also is the case for Argentina. It must be noted that all our results are based on total soybean production and that soybean production for oil is not separate from the soybean that is used for animal feed.

In general, the water use efficiency of groundnut production is low. This is mostly caused by improper management. Improved management could drastically improve groundnut productivity in many developing countries (Naab *et al.*, 2009; Licker *et al.*, 2010). For palm oil, the main sustainability issue is the drainage of tropical wetlands and not the crop water use.

In conclusion, this report presents quantitative data on water use of different oil crops. This data can be used to further develop sustainability indicators. It is important when focusing on sustainability that water use and water availability become more integrated. As we recognise that water use is not only the indicator for a sustainable crop we have developed an initial framework for the sustainable water use of oil crops. This framework can be used as an initial assessment. It indicates where potential issues might arise and which elements would require further attention. This framework requires further testing and should be first used in some example projects. Based on these experiences, the framework should be adapted and further optimised before it can be widely used.

7. GLOSSARY

Blue water	Water that is available for crop growth and development via irrigation
CGMS	Crop Growth Monitoring System
CSWB model	Crop Soil Water Balance model
Green water	Water that is available for crop growth and development via precipitation
ET_a	Actual evapotranspiration
ET_m	Maximum evapotranspiration
JRC	Joint Research Centre of the European Commission
LAI	Leaf Area Index
GWSI	Global Water Satisfaction Index
LPJmL	Lund-Potsdam-Jena managed Land Dynamic Global Vegetation and Water Balance Model, i.e. a global scale vegetation and water balance model that solves the carbon and water balances at the earth's surface at a 0.5° spatial resolution
NGO	Non Governmental Organisation
NUTS2	Nomenclature of Units for Territorial Statistics
Rainfed agriculture	Crop production system where the required water comes from precipitation
SGDE	Soil Geographical Database of Europe
STU	Soil Typologic Units, i.e. characterizing distinct soil types and soil properties
SMU	Soil Mapping Units, i.e. grouped STUs
T_a	Actual crop transpiration
T_m	Maximum transpiration
Water deficit	Difference between the actual and potential transpiration
WUE	Water use efficiency, i.e. the amount of water needed to produce 1 kilogram of dry matter
WOFOST	World Food Studies, i.e. a crop growth simulation model
WSI	Water Satisfaction Index, i.e. a qualitative index, expressed as a percentage of maximum yield

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