The water footprint of bioenergy

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Edited by David Pimentel, Cornell University, Ithaca, NY, and accepted by the Editorial Board April 20, 2009 (received for review December 12, 2008)

All energy scenarios show a shift toward an increased percentage of renewable energy sources, including biomass. This study gives an overview of water footprints (WFs) of bioenergy from 12 crops that currently contribute the most to global agricultural production: barley, cassava, maize, potato, rapeseed, rice, rye, sorghum, soybean, sugar beet, sugar cane, and wheat. In addition, this study includes jatropha, a suitable energy crop. Since climate and production circumstances differ among regions, calculations have been performed by country. The WF of bioelectricity is smaller than that of biofuels because it is more efficient to use total biomass (e.g., for electricity or heat) than a fraction of the crop (its sugar, starch, or oil content) for biofuel. The WF of bioethanol appears to be smaller than that of biodiesel. For electricity, sugar beet, maize, and sugar cane are the most favorable crops [50 m^3/gigajoule (GJ)]. Rapeseed and jatropha, typical energy crops, are disadvantageous (400 m^3/GJ). For ethanol, sugar beet, and potato (60 and 100 m^3/GJ) are the most advantageous, followed by sugar cane (110 m^3/GJ); sorghum (400 m^3/GJ) is the most unfavorable. For biodiesel, soybean and rapeseed show to be the most favorable WF (400 m^3/GJ); jatropha has an adverse WF (600 m^3/GJ). When expressed per L, the WF ranges from 1,400 to 20,000 L of water per L of biofuel. If a shift toward a greater contribution of bioenergy to energy supply takes place, the results of this study can be used to select the crops and countries that produce bioenergy in the most water-efficient way.

sustainability | climate change | energy | biomass | natural resource use

In the coming decades humanity will face important challenges, not only to meet the basic human need for water (1, 2), but also to ensure that extraction of water from rivers, streams, lakes, and aquifers does not affect freshwater ecosystems performing ecological functions (3). With a world population of 9.2 billion by 2050, as projected by the United Nations (4), there are reasons for concern over whether the food and fiber needs of future generations can be met in regions with limited water resources (3, 5–8).

The scientific as well as the international political community often consider global change in relation to climate change. It is generally recognized that the emission of greenhouse gases is responsible for anthropogenic impacts on the climate system. To reduce emissions, a shift toward renewable energy, such as bioenergy, is heavily promoted. Other advantages of renewable energy are an increase in energy supply security, resource diversification, and the absence of depletion risks (9). The sources of bioenergy can be crops specifically grown for that purpose, natural vegetation, or organic wastes (10). Many of the crops used for bioenergy can also—alternatively, not at the same time—be used as food or feed. Biomass can be burnt to produce heat and electricity, but it can also be used for the production of bioethanol or biodiesel, which are biofuels that can displace fossil energy carriers in motor vehicles (11).

At present, the agricultural production of biomass for food and fiber requires ≈86% of worldwide freshwater use (12, 13). In many parts of the world, the use of water for agriculture competes with other uses, such as urban supply and industrial activities (14), although the aquatic environment shows signs of degradation and decline (1). An increase in demand for food in combination with a shift from fossil energy toward bioenergy puts additional pressure on freshwater resources. For the future, scarcely any new land will be available so all production must come from the current natural resource base (15), requiring a process of sustainable intensification by increasing the efficiency of land and water use (16).

Globally, many countries explore options for replacing gasoline with biofuels (11). The European Union and the U.S. even have set targets for this replacement. When agriculture grows bioenergy crops, however, it needs additional water that then cannot be used for food. Large-scale cultivation of biomass for fossil fuel substitution influences future water demand (17). An important question is whether we should apply our freshwater resources to the production of bioenergy or to food crops. The Food and Agriculture Organization (FAO) estimated that in 2007 alone, before the food price crisis struck, 75 million more people were pushed into undernourishment as a result of higher prices, bringing the total number of hungry people in the world to 923 million (18). Moreover, the FAO reports that biofuels increase food insecurity (19). The World Bank recognizes biofuel production as a major factor in driving up food prices. It estimates that 75% of the increase in food prices in the period from 2002–2008 was due to biofuels (20). The current financial crisis may diminish purchasing power and increase the risk of a drop in food intake. As a result, more people are likely to fall below the hunger threshold. Households may make decisions to have fewer meals or eat cheaper foods of lower nutritional value, decisions that can have particularly severe consequences for infants and children (21).

The replacement of fossil energy with bioenergy generates the need for detailed information on water requirements for this new energy source. A concept for the calculation of water needs for consumer products is the water footprint (WF) (12, 13, 22), defined as the total annual volume of fresh water used to produce goods and services for consumption.

The objective of this study is to give a global overview of the WF per unit of bioenergy [m^3/gigajoule (GJ)], including heat, electricity, bioethanol, and biodiesel. This study covers the 12 main crops that together form 80% of global crop production. In addition, this study includes jatropha, a plant species often mentioned in the context of bioenergy. Research questions are: (*i*) what are the WFs (m^3/GJ) for heat and electricity derived from the combustion of biomass per crop per country and (*ii*) what are the WFs (m^3/GJ) for transport fuels (bioethanol and biodiesel) per crop per country. The study excludes organic wastes, such as manure or crop residues, biogas, and energy from algae. This study builds upon 2 earlier studies: one that estimated the WFs of a large variety of food and fiber products (12, 13), and one that estimated the WF of heat from biomass (23). This study

Author contributions: W.G.-L. and A.Y.H. designed research; W.G.-L. performed research; A.Y.H. contributed new reagents/analytic tools; W.G.-L., A.Y.H., and T.H.v.d.M. analyzed data; and W.G.-L. and A.Y.H. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission. D.P. is a guest editor invited by the Editorial Board.

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This article contains supporting information online at www.pnas.org/cgi/content/full/0812619106/DCSupplemental.

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refines the work of Hoekstra and Chapagain (13) by taking precise production locations into account for the calculation of crop water requirements and by using local estimates for the start of the growing season based on an analysis of when weather conditions at specific locations are most favorable. An additional refinement is that this study differentiates between blue and green water. This study also extends the study by Gerbens-Leenes, et al. (23), which focused on the WF of heat from biomass, to the WF of bioelectricity and biofuels.

Bioenergy. Energy derived from biomass is termed bioenergy. The FAO (24) defines biomass as material of organic origin, in nonfossilized form, such as agricultural crops and forestry products, agricultural and forestry wastes and by-products, manure, microbial matter, and industrial and household organic waste. Biomass is used for food or feed (e.g., wheat, maize, sugar), materials (e.g., cotton, wood, paper), or for bioenergy (e.g., maize, sugar, jatropha). Figure S1 shows that biomass can provide different forms of bioenergy: heat, electricity, and biofuels such as ethanol and biodiesel. First-generation biofuels are presently available biofuels produced using conventional technology, i.e., fermentation of carbohydrates into ethanol, and extracting and processing oil from oil crops into biodiesel. Biomass not only contains starch, sugar, and oil that can be processed into biofuel; it also contains large amounts of cellulosic matter. To date, the cellulosic fraction has been used for energy by burning it to provide heat and produce electricity. It is expected that these cellulosic fractions will form an attractive source for the production of next-generation biofuels. Next-generation biofuels are biofuels available in the future, produced using new technology, now under development, that aims to also convert cellulosic fractions from crops into biofuels, e.g., ethanol (25). In this way, biofuel produced per unit of crop can be increased substantially.

WF. The WF of a product is defined as the volume of freshwater used for production at the place where it was actually produced (13). In general, the actual water content of products is negligible compared with their WF, and water use in product life cycles are dominated by the agricultural production stage. The WF consists of 3 components: the green WF, the blue WF, and the gray WF (13). The green WF refers to rainwater that evaporated during production, mainly during crop growth. The blue WF refers to surface and groundwater for irrigation evaporated during crop growth. The gray WF is the volume of water that becomes polluted during production, defined as the amount of water needed to dilute pollutants discharged into the natural water system to the extent that the quality of the ambient water remains above agreed water quality standards.

Crops Considered in This Study. Globally, a limited number of crops determines total production. Theoretically, all crops can be used for bioenergy, but in practice some crops dominate production: sugar cane, sugar beet, maize, rapeseed, and soybean (25). Because this study aims to provide a global overview of the WFs of the main crops that can be used for bioenergy, it includes the 12 crops that contribute 80% of total global crop production. Table S1 shows these crops in decreasing order of annual production. Additionally, this study includes jatropha curcas, a tree species with seeds from which oil can be extracted (26).

The composition of biomass determines the availability of energy from its specific type, resulting in differences in combustion energy and options for biofuel production. This study includes 4 categories of biomass: starch crops [cereals (barley, maize, rice, rye, sorghum, and wheat) and tubers (cassava and potato)]; sugar crops (sugar beet and sugar cane); oil crops (rapeseed and soybean); and trees (jatropha).

Table 1. Total weighted-global average WF for 13 crops providing electricity (m^3/GJ)

	m^3 per GJ electricity		
Crop	Total WF	Blue WF	Green WF
Sugar beet	46	27	19
Maize	50	20	30
Sugar cane	50	27	23
Barley	70	39	31
Rye	77	36	42
Paddy rice	85	31	54
Wheat	93	54	39
Potato	105	47	58
Cassava	148	21	127
Soybean	173	95	78
Sorghum	180	78	102
Rapeseed	383	229	154
Jatropha*	396	231	165

It is assumed that not only crop yields, but total biomass yields are used for the generation of the electricity.

*Average figures for 5 countries (India, Indonesia, Nicaragua, Brazil, and Guatemala).

Results

Crop Production, Crop Water Requirements, and Irrigation Requirements. Some countries make a large contribution to global production. For example, Brazil produces 27% of globally available sugar cane; the U.S. has almost half of the global soybean production, 40% of the maize, and one quarter of the sorghum production; and China provides 18% of all wheat, one third of the paddy rice, one fifth of the potatoes, and 27% of the rapeseed production. Half of the global production of rye takes place in Russia and Germany, whereas Nigeria shows the largest contribution to cassava production. For other crops, such as sugar beet and barley, production is distributed more evenly among countries.

Irrigation is required at almost every crop location. The exceptions are sugar beet grown in Japan; maize from South Africa; wheat from Australia; cassava from Nigeria, Angola, Benin, Guinea, the Philippines, Vietnam and India; potato from Bangladesh, Peru, and Japan; sorghum from Nigeria, Ethiopia, Chad, and Venezuela; and rapeseed from Bangladesh. In some countries crop water requirements are completely or almost completely accounted for by irrigation water. These crops and countries are sugar cane from Argentina (96%) and Egypt (92%); wheat from Argentina (100%), Kazakhstan (98%), and Uzbekistan (98%); potato and barley from Kazakhstan (100%); sorghum from Yemen (100%); and soybean from Brazil (95%). For the other crops and production locations, irrigation requirements are between these 2 extremes.

The WF of Biomass. WFs show large variations for similar crop types, dependent on agricultural production systems used and climate conditions. Table S2 shows extreme values of total and blue WFs per crop. Most total WFs show variations of a factor of 4 to 15, with 2 exceptions. These exceptions are the values for wheat and sorghum, with a difference of a factor of 20 and 47, respectively. Kazakhstan occurs 3 times as the country with the largest total and blue WF for a crop (barley, potato, and wheat).

The WF of Heat and Electricity from Biomass. Table 1 shows the total weighted global average WF for 13 crops providing electricity. It is assumed that not only crop yields, but total biomass yields are used for the generation of electricity. The largest difference of WF is found between jatropha and the sugar beet; the beet is almost 10 times more water efficient. The WF of heat is at all

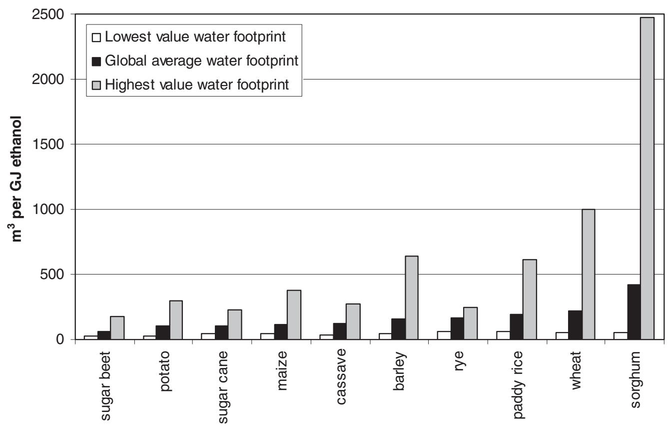

Fig. 1. Lowest value, highest value, and weighted-average global value of the WF for energy for 10 crops providing ethanol.

times 59% of the WF of electricity, as shown in Table 1, based on the energy efficiency assumed in this study (see *Methods*).

The WF of First-Generation Biofuels. Table S3 shows energy provided by ethanol [higher heating value (HHV) ethanol in megajoule/kg fresh weight of the crop] from 2 sugar and 8 starch crops included in this study. There are 3 groups: sugar crops and 1 starch crop with relatively low values for energy provided by ethanol (sugar beet, sugar cane, and potato), starch crops with relatively large values for energy provided by ethanol (sorghum, maize, wheat, barley, paddy rice, and rye), and 1 crop in between (cassava). These variations are caused by differences in the water content of the crops, where a large water content relates to relatively low energy values from ethanol. Table S3 also shows the energy provided by oil from the 3 oil crops included in this study. The HHV of oil from soybean is the lowest, about half the value of rapeseed or jatropha.

The WF of Bioethanol: Biofuel Energy Production per Crop Unit. Fig. 1 shows the lowest value, the highest value, and the weighted-average global value of the WF for energy of 10 crops providing ethanol, showing the enormous variation in the total WF among crops. This is especially true for sorghum, mainly caused by unfavorable conditions in Niger and highly efficient production in Egypt.

Fig. 2 gives weighted global average green and blue WFs for 10 crops providing ethanol. It shows that there are large differences among crops.

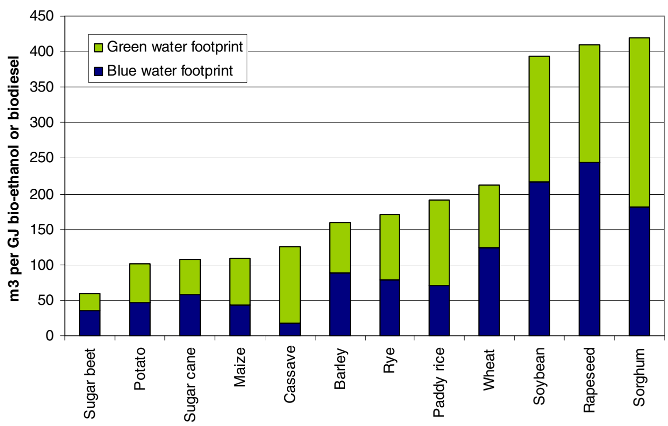

Fig. 2. The weighted global average WF for 10 crops providing ethanol and for 2 crops providing oil for biodiesel.

Currently, sugar beet is the most favorable crop and sorghum the most disadvantageous, with a difference of a factor of 7 in terms of the size of the WF. When data for the 2 main ethanol producing countries, Brazil and the U.S., are compared, Brazilian ethanol from sugar cane is more efficient than maize (99 against 140 m^3/GJ ethanol); however, in the U.S., maize is more attractive than sugar cane (78 against 104 m^3/GJ ethanol). Fig. 2 also shows the distinction between green and blue water. As a global average, the blue WF of cassava is smallest. Other efficient crops are sugar beet, potato, maize, and sugar cane. In terms of blue water, sorghum is unfavorable.

Table 2 shows the total weighted global average WF for 10 crops providing ethanol, as well as their blue and green WF. Table 2 also shows the amount of water needed for a specific crop to produce 1 L of ethanol.

On average, to produce 1 L of ethanol from sugar beet takes ≈1,400 L of water, production from potato takes 2,400 L, production from sugar cane takes 2,500 L, and production from maize takes 2,600 L. Sorghum is the most inefficient crop, needing 9,800 L of water for 1 L of ethanol. Irrigation is least for cassava, at 400 L of blue water for 1 L of ethanol, followed by 800 L for sugar beet and 1,000 L for maize. Sorghum is the crop showing the largest blue WF, with 4,250 L per L of ethanol. As can be seen from a comparison of Tables 1 and 2, sugar beet is most efficient in terms of both ethanol and electricity. The other crops are in different order regarding the efficiency at which electricity and ethanol are produced. In general, the production of ethanol from only part of the crop is less water efficient than the production of electricity from total biomass.

The WF of Biodiesel. The WF of biodiesel derived from soybean, rapeseed, and jatropha shows differences among the main producing countries. For rapeseed, Western Europe has the smallest WFs and Asia has the largest (especially in India, where rapeseed has a large, blue WF). For soybean, Italy, Paraguay, and Argentina have the smallest WFs and India has the largest. Biodiesel from jatropha is produced in the most water-efficient way in Brazil and inefficiently in India. Table 2 shows the total weighted global average WF for biodiesel from soybean and rapeseed, and the average WF for biodiesel from jatropha, as well as their blue and green WF. Table 2 also shows the amount of water needed to produce 1 L of biodiesel; on average, it takes ≈14,000 L of water for soybean or rapeseed, and 20,000 L for jatropha.

The WF of Next-Generation Biofuels. For next-generation biofuels, total biomass of a crop can be used. When we optimistically assume that their production will be as efficient as the production of electricity from biomass (in terms of GJ/ton), the results shown in Table 1 form a lower limit for the WF of these next-generation biofuels. Another factor that has to be taken into account is the water use of biomass processing, fermentation, and distillation of these next-generation biofuels. On the other hand, agricultural water use is much larger than the processing water use. In the *SI Methods*, it is argued that water is predominantly used during the first link of the production chain—agriculture. This study, therefore, only took water requirements in agriculture into account and ignored water use in the industrial links of the production chain.

Discussion

Assumptions. Similar to earlier studies (12, 13, 27), the calculations have been based on the assumption that crop water use is equal to crop water requirements. When actual water availability is lower and water stress occurs, this study overestimates the crop water use. With respect to agricultural yields, we have taken

Table 2. Total weighted-global average WF for 10 crops providing ethanol and 3 crops providing biodiesel (m³/GJ), as well as their blue and green WF

Crop	Total WF	Blue WF	Green WF	Total water	Blue water	Green water
Ethanol		m^3 per GJ ethanol			L of water per L of ethanol	
Sugar beet	59	35	24	1,388	822	566
Potato	103	46	56	2,399	1,078	1,321
Sugar cane	108	58	49	2,516	1,364	1,152
Maize	110	43	67	2,570	1,013	1,557
Cassava	125	18	107	2,926	420	2,506
Barley	159	89	70	3,727	2,083	1,644
Rye	171	79	92	3,990	1,846	2,143
Paddy rice	191	70	121	4,476	1,641	2,835
Wheat	211	123	89	4,946	2,873	2,073
Sorghum	419	182	238	9,812	4,254	5,558
Biodiesel		m^3 per GJ biodiesel			L of water per L of biodiesel	
Soybean	394	217	177	13,676	7,521	6,155
Rapeseed	409	245	165	14,201	8,487	5,714
Jatropha*	574	335	239	19,924	11,636	8,288

The table also shows the amount of water needed for a specific crop to produce 1 L of ethanol or 1 L of biodiesel.
*Average figures for 5 countries (India, Indonesia, Nicaragua, Brazil, and Guatemala).

actual yields, which in many cases can be increased in the future without increasing water use per unit of product. This future yield increase means that in some cases WFs per unit of energy can be significantly lowered. For the efficiency of obtaining electricity or biofuels from biomass, we have made optimistic assumptions by taking theoretical maximum values or values that refer to the best available technology. These assumptions mean that the resulting WF figures are conservative.

Sensitivities. The results of this study are based on rough estimates of freshwater requirements in crop production and on theoretical maximum conversion efficiencies in the production of bioelectricity and biofuels. For the assessment of the WF of bioenergy, the study integrated data from several sources, each of which adds a degree of uncertainty. For example, the calculations using the FAO model CROPWAT (28) required input of meteorological data that are averages over several years rather than data for a specific year. The data presented thus do not reflect annual variations. Estimated crop water requirements are sensitive to the input of climatic data and assumptions concerning the start of the growing season. In the most extreme cases, this study found crop water requirements that were a factor of 2 different from earlier studies (12, 13, 27), whereas at other times the results were similar. The aspects mentioned above imply that results presented here are indicative. However, the differences in calculated WFs are so great that general conclusions with respect to the WF of bioethanol vs. the WF of biodiesel can be drawn and that conclusions also can be drawn about the relative WFs of different crops.

Gross vs. Net Production of Bioenergy. There is a distinction between gross and net production of bioenergy (29, 30). In assessing the WF of heat, electricity, and fuels from biomass, we looked at the WF of the gross energy output from crops. We did not study energy inputs in the production chain, such as energy requirements in the agricultural system (e.g., energy use for the production of fertilizers and pesticides) or energy use during the industrial production of the biofuel. Neglecting energy inputs means that this study underestimates the WF of bioenergy, most particularly so in cases where agricultural systems have a relatively large energy input. For example, if energy input equals 50% of the energy output—something common in bioenergy production systems (30)—the WF of the net bioenergy production would be twice the WF of the gross energy production.

Conclusions

The WF of bioenergy is large when compared to other forms of energy. In general, it is more efficient to use total biomass, including stems and leaves, to generate electricity than to produce a biofuel. For most crops, the WF of bioelectricity is about a factor of 2 smaller than the WF of bioethanol or biodiesel. This difference is caused by the crop fraction that can be used. For electricity, total biomass can be used; for bioethanol or biodiesel, only the starch or oil fraction of the yield can be used. In general, the WF of bioethanol is smaller than that of biodiesel. The WF of bioenergy shows large variation, depending on 3 factors: (*i*) the crop used, (*ii*) the climate at the location of production, and (*iii*) the agricultural practice:

i. For electricity generation, sugar beet, maize, and sugar cane with WFs of ≈50 m^3/GJ are the most favorable crops, followed by barley, rye, and rice with WFs of ≈70–80 m^3/GJ. Rapeseed and jatropha, typical energy crops showing WFs of ≈400 m^3/GJ, are the least water-efficient. For the production of ethanol, 2 crops grown in a temperate climate (sugar beet and potato) with WFs of ≈60 and 100 m^3/GJ, respectively, are most efficient, followed by a crop typical for a warm climate, sugar cane, showing a WF just below 110 m^3/GJ. Values for maize and cassava are larger than for sugar beet, sugar cane, and potato at 110 and 125 m^3/GJ, respectively. With a WF of >400 m^3/GJ, sorghum is by far the most disadvantageous crop. For biodiesel production, soybean and rapeseed, crops mainly grown for food, show the best WF at ≈400 m^3/GJ; jatropha has the least favorable WF of ≈600 m^3/GJ.

ii. Results show large differences in crop water requirements among countries, caused by differences in climate. The crop water requirement of sugar beet grown in Iran, for example, is twice the weighted global average value.

iii. Agricultural practice determines yields and thus differences among WFs of crops, even where there is a similar climate. If yield levels are relatively low, WFs are high and vice versa. For example, in Kazakhstan yields of barley, potato, and wheat are relatively low. In combination with unfavorable climatic factors this results in high values for the WFs. Conditions in Denmark are favorable for wheat resulting in relatively low crop water requirements.

Theoretically, all crops can be used for energy, including crops such as rice and rye that are currently mainly used for food. Water use for a specific crop does not depend on whether the crop is for energy or for food. Some food crops, including rice, are more water-efficient in producing a unit of ethanol, biodiesel, or electricity than some typical energy crops, such as rapeseed or jatropha. The ethical discussion on whether food crops can be used for energy should be extended to a discussion on whether we should use our limited water resource base for food or for energy.

The scientific and the international political communities promote a shift toward renewable energy sources, such as biomass, to limit the emission of greenhouse gases. This study has shown that biomass production goes hand in hand with large water requirements. There are already reasons for profound concern in several regions and countries with limited water resources about whether the food and fiber needs of future generations can be met. If a shift toward a larger contribution from bioenergy to total energy supply takes place, results of this study can be used to select the crops and countries that (under current production circumstances) produce bioenergy in the most water-efficient way.

Methods

The calculation of the WF of bioenergy is done in several steps including the calculation of (*i*) the WF of crops, (*ii*) energy yields of bioethanol, biodiesel, heat, and electricity per crop, and (*iii*) the WF of heat, electricity, and first-generation and next-generation biofuels. The method is presented in detail in the *SI Methods*.

Calculation of the WF of Crops. For the assessment of the WF of bioenergy, the study follows the method of Hoekstra and Chapagain (13) to arrive at estimates of the WF of crops. WF calculations were made by adding up daily crop evapotranspiration (mm/day) using the model CROPWAT 4.3 (28) over growing periods distinguishing between the green and the blue WF. These calculations provided information on the crop water requirements for the 12 crops shown in Table S1 and for jatropha. Calculations were performed for the main producing countries, deriving data from the FAO (3). In general, yields show variations over the years. The study, therefore, calculated average yields over 5 production years (1997–2001) by using data from the FAO (31).

Calculation of the WF of Heat and Electricity from Biomass. For the calculation of the WF of heat from biomass, the study has followed the method of Gerbens-Leenes, et al. (23), which calculated the energy yield of a crop (GJ/ton) by combining data on the heat of combustion of plant components with information on composition, harvest index, and dry-mass fraction of a crop, as shown in Tables S4 and S5. The WF of heat from a crop (m^3/GJ) was calculated by dividing the WF of the total crop biomass, including stems and leaves, (m^3/ton) by the total heat content (GJ/ton). The WF of biomass electricity (m^3/GJ) was calculated by dividing the WF of the total crop biomass (m^3/ton) by the electricity output per crop unit (GJ/ton).

Calculation of the WF of First-Generation Biofuels. The WF of ethanol-energy from a crop (m^3/GJ) was calculated by dividing the WF of the crop yield (m^3/ton) by the ethanol-energy yield (GJ/ton). The WF of biodiesel-energy (m^3/GJ) was calculated in a similar way. Table S6 gives the HHVs of ethanol and biodiesel. For first-generation biofuels, this study fully allocated the WF of the crop to the biofuels derived, assuming that the value of the residues of production is much lower than the value of the biofuel.

Calculation of the WF of Next-Generation Biofuels. It is expected that wastes, including cellulose, will form an attractive source for the production of liquid, next-generation biofuels so that industry can use total biomass. For the WF of next-generation biofuels, this study assumes that the WF of next-generation biofuels will never be lower than the WF of the total crop biomass (m^3/ton) divided by the energy content (GJ/ton), where the latter is expressed in terms of its HHV.

ACKNOWLEDGMENTS. We gratefully acknowledge the valuable comments of David Pimentel on an earlier version of this paper.

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Supporting Information

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SI Methods

Calculation of the Water Footprint (WF) of Crops. For the calculation of the WF of crops, this study used the methodology of the WF concept (1). There is an extensive database that includes the WF of almost all crops produced worldwide (m^3/ton), based on average national meteorological data (2). This study, however, assessed the WFs of crops more specifically by production location. WF calculations were made by adding up daily crop evapotranspiration (mm/day) over growing periods, thus providing information on crop water requirements. The start of the growing season depends on climatic conditions in the production location and on the individual choices of farmers. For the start of the growing season, this study took the first option for sowing after winter or after a dry season, assuming that growing seasons start when mean monthly maximum temperatures are above 10 °C and when sufficient rain and global radiation is available.

This study calculated crop water requirements in the main producing countries for the 12 crops shown in Table S1 and for jatropha, distinguishing between the green and the blue WF, but excluding the gray WF. Next, the main producing countries, deriving data from the Food and Agriculture Organization (FAO), were selected (3). For jatropha, it considered production in Brazil, Guatemala, Indonesia, and Nicaragua, countries whose data were available (4). Next, agricultural production locations were selected. Information was obtained from the Madison Center for Sustainability and the Global Environment of the University of Wisconsin (5). For these areas, weather stations providing climatic data, that were used as input for the calculations, were selected. Data were drawn from Müller and Hennings (6).

The calculation of crop water requirements (mm/day) was performed by major production region, by using the calculation model CROPWAT 4.3 (7) based on the FAO Penman–Monteith method, to estimate reference crop evapotranspiration (8) and a crop coefficient that corrects for the difference between actual and reference crops.

Calculations for green and blue WFs (m^3/ton) were performed by using Hoekstra and Chapagain's method (1). Green water use (m^3/ha) over the length of the growing period was calculated as the sum of daily volumes of rainwater evapotranspiration. This green water use is equal to the crop water requirement except when effective precipitation is less than the requirement, in which case rainwater evapotranspiration is equal to effective precipitation. Blue water use (m^3/ha) over the length of the growing period was calculated as the sum of daily volumes of irrigation-water evapotranspiration. This blue water use is equal to the irrigation requirement, if this requirement is actually met, and otherwise to actual effective irrigation. The irrigation requirement is defined as the crop water requirement minus effective precipitation. In doing so, it has been assumed that irrigation requirements are actually met. The green WF of a crop (m^3/ton) is the total green water use over the length of the growing period (m^3/ha) divided by the crop yield (ton/ha). The blue WF (m^3/ton) is the total blue water use over the length of the growing period (m^3/ha) divided by the crop yield (ton/ha). In general, yields show variations over the years. This study, therefore, calculated average yields over 5 production years (1997–2001) by using data from the FAO (3).

Calculation of the WF of Heat and Electricity from Biomass. The energy content of biomass is expressed in terms of combustion values. Energy analysis defines the energy content of a substance as the amount of heat produced during combustion at 25 °C at 1 bar. It distinguishes between the higher heating value (HHV) and the lower heating value (LHV) (9). For the HHV, energy analysis measures the heat content of water that is the product of the combustion process in the liquid form; in the case of LHV, energy analysis measures the heat content of water that is the product of the combustion process in the gaseous form. For the calculation of the WF of heat from biomass, this study has followed the method of Gerbens-Leenes, et al. (10), which calculates the energy yield of a crop [gigajoule (GJ)/ton] by combining data on the heat of combustion of plant components with information on composition, harvest index, and dry-mass fraction of a crop as shown in Tables S4 and S5:

$$E_{heat}(c) = HI(c) \times DMF_y(c) \times \sum_{i=1}^{5}(f_{y,i} \times HHV_i) + (1 - HI(c)) \times DMF_r(c) \times \sum_{i=1}^{5}(f_{r,i} \times HHV_i)$$

$E_{\mathrm{heat}}(c)$ is the energy yield of crop c in the form of heat (GJ/ton), $HI(c)$ the harvest index of crop c (g/g), $DMF_{\mathrm{y}}(c)$ the dry-mass fraction of the crop yield (g/g), $DMF_{\mathrm{r}}(c)$ the dry-mass fraction in the rest fraction (i.e., in the residue biomass), $f_{y,i}$ the fraction of component i in the dry mass of the crop yield (g/g), $f_{r,i}$ the fraction of component i in the dry mass of the rest fraction (g/g), and HHV_i the higher heating value of component i [kilojoule (kJ)/g].

For the generation of electricity from biomass, industry can use the heat that becomes available from the combustion of total biomass. The energy in the form of electricity from crop c (GJ/ton) depends on the efficiency with which energy in the form of biomass-heat can be transformed into electricity:

$$E_{electr}(c) = \eta \times E_{heat}(c)$$

For the value of the efficiency η, this study applied a value of 59%, based on the maximum efficiency derived from Carnot (11) and the technology of "Biomass fired Integrated Gasifier Combined Cycle" operated at a temperature of 720 K (9, 12).

The WF of heat from a crop c (m^3/GJ) was calculated by dividing the WF of the crop (m^3/ton) by the heat content of the crop (GJ/ton). The WF of biomass electricity from a crop c (m^3/GJ) was calculated by dividing the WF of the crop (m^3/ton) by the electricity output per crop unit (GJ/ton):

$$WF_{heat}(c) = \frac{WF(c)}{E_{heat}(c)}; \qquad WF_{electr}(c) = \frac{WF(c)}{E_{electr}(c)}$$

Calculation of the WF of First-Generation Biofuels. Currently, bioethanol is produced from sugars that come from sugar cane or sugar beet, or from starch hydrolysed into sugars derived from maize, wheat, or cassava (13). Under anaerobic conditions, sugar naturally ferments into acids and alcohols (mainly ethanol). For thousands of years people have used yeast to hasten fermentation. The main metabolic pathway involved in ethanol fermentation is glycolysis, through which 1 molecule of glucose is metabolized and 2 molecules of pyruvate are produced (14, 15). Under anaerobic conditions, pyruvate is further reduced to ethanol, with the release of CO_2. The overall reaction is $C_6H_{12}O_6 \rightarrow 2\ C_2H_5OH + 2CO_2$. Theoretically, the maximum yield of ethanol is 511 g of ethanol and 489 g of carbon dioxide per kg of glucose metabolized (or 530 g of ethanol per kg of starch). Often, various by-products are also produced, for example, glycerol (15). During ethanol fermentation, yeast cells suffer from stresses, such as ethanol accumulation, inhibiting yeast cell growth and ethanol production. The final ethanol concentration is ≈10–12% (15, 16). The fermentation industry, therefore, uses a tanks-in-series system to alleviate product inhibition. Currently, it can reach a yield of 90–93% of the theoretical value of glucose to ethanol (17).

Oilseed crops, such as rapeseed, soybean, and jatropha, are used to produce either straight vegetable oil or biodiesel. Straight vegetable oil is oil extracted from an oilseed crop and directly used for energy purposes (13). An example is olive oil for lighting. Because of its chemical properties, such as the high viscosity at low temperatures, it is often difficult to use straight vegetable oil as a biofuel in diesel engines (13). In countries with warm climates, the relatively high temperatures prevent the oil from thickening and straight vegetable oil is a viable fuel. In countries with temperate climates, the oil needs additional treatment to make a biodiesel that is less sensitive to lower temperatures. Biodiesel is manufactured in a chemical reaction termed transesterification, in which oil reacts with an alcohol resulting in an alkyl ester of the fatty acid, with glycerine molecules as the primary coproduct. In Europe, rapeseed oil is the dominant feedstock for biodiesel, with some sunflower oil also used. In the U.S., the main feedstock is soybean oil, and in tropical and subtropical countries, palm, coconut, and jatropha oils are used (13).

When calculating natural resource use, the whole life cycle of a product should be taken into account. The use of water, however, is predominantly during the first link of the production chain—agriculture. Ethanol production, for example, requires ≈21 L of water per L of ethanol, but this water is often reused (18). This study, therefore, only took water requirements in agriculture into account and ignored water use in the industrial links of the production chain.

The ethanol-energy yield of a crop (in GJ/ton) was calculated as follows:

$$E_{ethanol}(c) = DMF_y(c) f_{carbohydr}(c) f_{ethanol} \times HHV_{ethanol}$$

where $DMF_y(c)$ is the dry-mass fraction in the crop yield (g/g), $f_{carbohydr}(c)$ the fraction of carbohydrates in the dry mass of the crop yield (g/g), $f_{ethanol}$ the amount of ethanol obtained per unit of carbohydrate (g/g), and $HHV_{ethanol}$ the higher heating value of ethanol (kJ/g). For the amount of ethanol per unit of sugar, we assumed the theoretical maximum value of 0.51 g/g, and for starch, 0.53 g/g (17).

The biodiesel-energy yield of a crop (in GJ/ton) was calculated as follows:

$$E_{diesel}(c) = DMF_y(c) \times f_{fat}(c) \times f_{diesel} \times HHV_{diesel}$$

where $DMF_y(c)$ is the dry-mass fraction in the crop yield (g/g), $f_{fat}(c)$ the fraction of fats in the dry mass of the crop yield (g/g), f_{diesel} the amount of biodiesel obtained per unit of fat (g/g), and HHV_{diesel} the higher heating value of biodiesel (kJ/g). For the fraction biodiesel per fat weight, we assumed the value of 1. The fractions of carbohydrates and fats in the dry mass of crop yields are given in Table S5. Table S6 gives the HHVs of ethanol and biodiesel.

The WF of ethanol energy from a crop c (m^3/GJ) was calculated by dividing the WF of the crop (m^3/ton) by the ethanol energy yield of the crop (GJ/ton). The WF of biodiesel energy from a crop c (m^3/GJ) was calculated in a similar way:

$$WF_{ethanol}(c) = \frac{WF(c)}{E_{ethanol}(c)}; \qquad WF_{diesel}(c) = \frac{WF(c)}{E_{diesel}(c)}$$

For the calculation of the WF of first-generation biofuels, this study fully allocated the WF of the crop to the biofuels derived, assuming that the value of the residues of production was much lower than the value of the biofuel.

Calculation of the WF of Next-Generation Biofuels. Biomass not only contains starch, sugar, and oil that can be processed into biofuels, it also contains large amounts of cellulosic matter. Thus far, the cellulosic fraction could be used for energy only by burning it to provide heat and produce electricity. It is expected that these cellulosic fractions will form an attractive source for the production of liquid, next-generation biofuels for which industry can use total biomass, including wastes. It is not yet clear what efficiency will be achieved in converting total biomass into biofuel. It is safe, however, to assume that the WF of next-generation biofuels will never be lower than the WF of the crop (m^3/ton) divided by the energy content of the crop (GJ/ton), where the latter is expressed in terms of its HHV.

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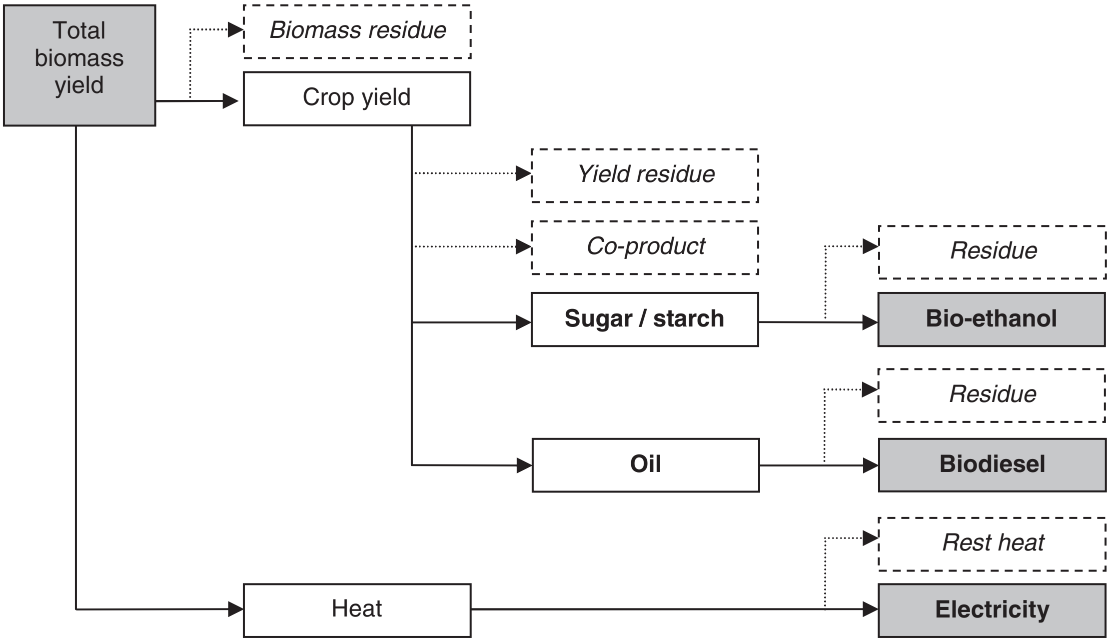

Fig. S1. From biomass to bioenergy. Total biomass yield can be converted into heat and subsequently into electricity. Alternatively, the crop yield, which is part of the total biomass, can be converted into bioethanol (in the case of starch and sugar crops) or biodiesel (in the case of oil crops). In every step in the production chain, residues or rest heat are generated.

Table S1. The 12 crops that contribute 80% of total global crop production

Crop	Average global production for 1997–2001, 10^6 ton/yr
Sugar cane	1,258
Maize	603
Wheat	594
Paddy rice	593
Potato	309
Sugar beet	253
Rye	220
Cassava	172
Soybean	160
Barley	140
Sorghum	59
Rapeseed	38
Total	4,401
Total global crop production (1997)	5,513

See ref. 19.

Table S2. Overview of the extreme values of total WFs and blue WFs per crop, m^3/ton

Crop	Country	Extreme values total WF, m^3/ton	Country	Extreme values blue WF, m^3/ton
Barley	Ireland	448	India	147
	Kazakhstan	6,540	Kazakhstan	6,510
Cassava	India	191	India/Vietnam	0
	Côte d'Ivoire	1,437	Côte d'Ivoire	1,437
Jatropha	Brazil	3,222	Brazil	1,170
	India	21,729	India	14,344
Maize	Spain	407	South Africa	0
	Nigeria	3,783	Nigeria	2,267
Rapeseed	Germany	1,482	Bangladesh	0
	India	9,900	Pakistan	4,130
Paddy rice	Egypt	634	Bangladesh	19
	Nigeria	6,471	Nigeria	4,629
Potato	Spain	85	Japan	0
	Kazakhstan	922	Kazakhstan	922
Rye	Sweden	637	Austria	245
	Russia	2,620	Russia	1,220
Sorghum	Egypt	525	Venezuela/Chad	0
	Niger	24,700	Sudan	14,117
Soybean	Italy	1,442	Paraguay	546
	India	7,540	Indonesia	2,583
Sugar beet	Morocco	56	Japan	0
	Russia	455	Russia	376
Sugar cane	Peru	108	Peru	8
	Cuba	524	Pakistan	217
Wheat	Denmark	513	Australia	0
	Kazakhstan	10,178	Kazakhstan	9,989

Table S3. Energy provided by ethanol from 2 sugar and 10 starch crops that were included in this study, as well as the energy provided by oil from the 3 oil crops

Crop	Megajoule of biofuel per kg of fresh weight crop
Ethanol from sugar	
Sugar cane	2.3
Sugar beet	2.6
Ethanol from starch	
Potato	3.1
Cassava	5.2
Sorghum	10.0
Maize	10.0
Wheat	10.2
Barley	10.2
Paddy rice	10.5
Rye	10.5
Biodiesel from oil	
Soybean	6.4
Rapeseed	11.7
Jatropha	12.8

Table S4. HHV for 6 major groups of plant components

Plant component	HHV, kJ/g
Carbohydrates	17.3
Proteins	22.7
Fats	37.7
Lignins	29.9
Organic acids	13.9
Minerals (K,Ca,P,S)	0.0

See ref. 9.

Table S5. Main characteristics for 12 crops

	Cassava	Barley	Maize	Paddy rice	Potato	Rapeseed	Rye	Sorghum	Soybean	Sugar cane	Sugar beet	Wheat
Harvest index	0.70[a]	0.42[a]	0.45[a]	0.42	0.70[a]	0.32[a]	0.42	0.42	0.40[a]	0.60[a]	0.66[a]	0.42[a]
Economic yield	tuber[b]	ear + grain[b]	whole tops[b]	inflor + grain	tuber [b]	inflor + seed[d]	ear + grain[b]	ear + grain[b]	beans[a]	whole tops[a]	beet[a]	ear + grain[b]
Dry mass[b]	0.38	0.85	0.85	0.85	0.25	0.74	0.85	0.85	0.92	0.27	0.21	0.85
Composition dry mass, g/100 g[c]												
Carbohydrates	87	76	75	76	78	7	76	76	29	57	82	76
Proteins	3	12	8	8	9	22	12	12	37	7	5	12
Fats	1	2	4	2	0	42	2	2	18	2	0	2
Lignins	3	6	11	12	3	2	6	6	6	22	5	6
Organic acids	3	2	1	1	5	1	2	2	5	6	4	2
Minerals (K, Ca, P, S)	3	2	1	1	5	26	2	2	5	6	4	2
Rest fraction	leaves	shells	stems	stems	leaves	leaves	stems	stems	leaves	stems	leaves	stems
Dry mass[b]	0.38	0.85	0.85	0.85	0.13	0.13	0.85	0.85	0.15	0.27	0.21	0.85
Composition dry mass, g/100 g[c]												
Carbohydrates	52	62	62	62	52	52	62	62	52	62	52	62
Proteins	25	10	10	10	25	25	10	10	25	10	25	10
Fats	5	2	2	2	5	5	2	2	5	2	5	2
Lignins	5	20	20	20	5	5	20	20	5	20	5	20
Organic acids	5	2	2	2	5	5	2	2	5	2	5	2
Minerals (K, Ca, P, S)	8	4	4	4	8	8	4	4	8	4	8	4

[a]See ref. 20; [b]See ref. 21; [c]see ref. 22; [d]see ref. 23; [e]Assumption; [f]see ref. 24.

Table S6. HHV of ethanol and biodiesel

	HHV, kJ/g
Biodiesel	37.7
Ethanol	29.7

See refs. 12 and 14.