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ANALYSIS

The water footprint of biofuel-based transport

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The EU target to replace 10 percent of transport fuels by renewables by 2020 requires additional water. This study calculates water footprints (WFs) of transport modes using first generation bio-ethanol, biodiesel or bio-electricity and of European transport if 10 percent of transport fuels is bio-ethanol. Results are compared with similar goals for other regions. It is more efficient to use bio-electricity and bio-ethanol than biodiesel. Transport by train or car using bio-electricity (8–19 and 11–13 litres per passenger km) is more water efficient than transport by car (36–212) or airplane (65–136) using bio-ethanol. For cars, there is a factor of ten between water-efficient cars using bio-ethanol and water-inefficient cars using biodiesel. Biofuel-based freight transport is most water-efficient by ship or train; airplanes are least efficient. Based on first generation biofuels, the EU goal for renewable transport energy results in a WF of 62 Gm^3 per year, 10 percent of the current WF. Differences in transport energy use and in production systems result in a broad range of annual transport-related WFs: from 60 m^3 per capita in Bulgaria to 500 m^3 in Finland. If similar targets are applied in other regions, the additional WF of North America and Australia will be 52 percent of the present regions WFs. The global WF for biofuel-based transport in this scenario will be 9 percent of the current global WF. Trends towards increased biofuel application enhance the competition for freshwater resources.

1. Introduction

In western societies, transport requires about one third of total energy use[1,2] and contributes substantially to greenhouse gas emissions. Energy for transport in transition countries, such as Romania and Bulgaria, and in developing countries, such as China and India, is still relatively small.[2] Along with economic growth in these countries, transport will also grow, increasing transport fuel needs. In many countries, policy aims to introduce renewable transport biofuels (biodiesel and bio-ethanol). For example, India promotes the introduction of biodiesel and aims to replace 20 percent of petro diesel by biodiesel.[3] In China, the National Development and Reform Commission promotes biofuel production, aiming for a 15 percent biofuel share for transport in 2020.[4] In the USA, the Energy Independence and Security Act of 2007 mandated to produce 36 billion gallons of biofuel from corn and cellulosic crops in 2022.[5] The European Union aims to replace 10 percent of transport fuels by renewables (biofuels, bio-electricity and hydrogen) in 2020.[6] It can be expected that on a short term, especially biofuels will become important in Europe.

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Broader context

Human activities consume much freshwater, mainly in agriculture that produces our daily food and natural fibres. Freshwater is increasingly becoming a global resource, driven by trade in water-intensive commodities, separating consumers and producers. Especially the concept of the water footprint (WF) has shown this connection by introducing the supply chain perspective and indirect water use. Today, a new demand for water comes from the bioenergy sector producing biofuels from agricultural crops, the so-termed first generation biofuels. The EU target to replace 10 percent of transport fuels by renewables by 2020 requires additional water. This study calculates WFs of transport modes using first generation bio-ethanol, biodiesel or bio-electricity and of European transport if 10 percent of transport fuels is bio-ethanol. It compares results with similar goals for other regions. A shift towards more biofuels increases water use up to ten percent of the current water use, increasing competition. Introducing more water efficient second generation biofuels will help to decrease competition. Efforts to make transport more water efficient, however, should also consider the large share of the transport sector in total energy use. This requires that not only the renewable fuel, but also transport systems as a whole are considered in western societies.

Replacing transport fuels, made from crude oil, by biofuels, made from crops, will take large efforts and will require substantial amounts of water. The aim of this study is to consider three types of biofuel, bio-ethanol, biodiesel and bio-electricity, for different types of transport and show the most efficient ways of transport from a water perspective. It provides information for the European countries about the increase of water use when the EU goals are met and puts results in a global perspective.

Many studies have addressed renewable energy advantages, such as decreased CO_2 emissions, increased energy supply security, resource diversification and absence of depletion.[7] At present there is a polarized global debate over biofuels. For the scientific community, biofuels can be conceived as a technological system encompassing complex interactions at local, national and global levels between positive claims, addressing rural poverty and economic development[3] and competing negative counter-claims linked to land use changes,[4,8] increasing food prices and decreasing food security[5,8,9] and increased water use. A challenge for the 21st century is to provide enough water along with the protection of the ecological quality of freshwater systems.[10] Humans already use more than half of the globally accessible water runoff[11] with agriculture accounting for 86 percent of human freshwater consumption.[12–14] The water footprint (WF) of biofuels is much larger than the WF of fossil fuels.[15–18] De Fraiture *et al.*,[19] for example, have shown that increased biofuel use at global scale will lead to a substantial increase in global agricultural water use, increasing water competition. Yang *et al.*[4] have demonstrated that Chinese government goals for biofuels increase water use, needing the annual discharge of the Yellow River. Galan-del-Castillo and Velazquez[20] have calculated that Spain's WF increases substantially if the goal for biofuels of 5.83 percent of gasoline and diesel consumption is met. Dominguez-Faus *et al.*[21] have shown large US biofuel water requirements and the impact on aquifers such as the Ogallala Aquifer. Chiu *et al.*[22] have shown large variation in irrigation water requirements for US ethanol. King and Webber[15] have calculated large water intensities of ethanol and biodiesel. King *et al.*[23] have shown large water requirements related to biofuel use for US transport in 2030. Van der Velde *et al.*[24] have shown large varieties in water use efficiencies for rapeseed, a crop commonly used for biodiesel, in Europe. In general, WFs of biofuels, including bio-ethanol, biodiesel and bio-electricity, show large variability.[25]

First generation biofuels are an important step to creating biofuels infrastructure for transport.[71] This study quantifies WFs of biofuel-based transport based on first generation biofuels. First, we calculate the WF for different modes of passenger and freight transport, distinguishing between biodiesel, bio-ethanol and bio-electricity use. Second, we calculate WFs related to the use of biofuels for European transport in the case that biofuels take a share of 10 percent of all fuels used in transport, assuming the EU goal for 2020 means that renewable transport fuels are biofuels. Finally, we compare results with 10 percent replacements in other regions (Africa, Asia, Latin America, the former USSR, Australia and North America). In this way, the study shows the consequences of changes in the transport system on freshwater resources.

2. Method and data

2.1 Water footprint

The water footprint (WF) of a product, such as a biofuel, is the volume of freshwater used for production at the place where it was actually produced.[14] Actual water contents of products are generally negligible compared to their WF. Often, agricultural production dominates water use in product life cycles. The WF includes three components: green, blue and gray WFs.[26] Green WFs refer to rainwater evapotranspired and blue WFs to surface and groundwater evaporated during production. The gray WF concerns water that becomes polluted during production and is defined as the amount of water needed to assimilate pollutants discharged into the natural water system so that the quality of the ambient water remains above agreed water quality standards.

2.2 Fuels for transport

Different transport modes, such as cars, lorries or airplanes, use different fuels. Cars use gasoline, but also diesel or electricity, lorries mainly diesel, while airplanes apply jet fuel and trains diesel or electricity.[27–34] Large ships use bunker fuel, also termed 'Number 6 fuel oil'. Bunker fuel is a high-viscosity residual oil requiring preheating before use. Bunker fuel is a fossil derived fuel left over after distillation of crude oil. Fuels with relatively low boiling points, *e.g.* gasoline and jet fuel, are removed at the start of the fractional distillation process. Heavier petroleum products, *e.g.* diesel oil, are less volatile and distill out more slowly, while bunker oil, the heaviest fuel, is left behind.[61] Today, consumption of bunker fuel is about 320 million tons per year.[62] It is expected that global energy use for transport increases. The energy scenarios developed by Shell indicate that in 2050 energy consumption for transport doubles and that the share of biofuels increases to one third of total energy use.[63] This means that in 2050 still large quantities of bunker fuel are available. Sustainability issues in shipping include emissions to air, ballast water discharge and energy use.[64,65] It is expected that in 2050 energy efficiency in shipping will have increased substantially and that half of the energy for shipping will be derived from renewable sources like wind, sun and waves, and the other half from biogas.[64] Also, there are initiatives to use biofuels for sustainable shipping.[66–68] Airplanes use jet fuel.[69] In general, first-generation biofuels, *e.g.* biodiesel from rapeseed and ethanol from sugar crops, are not suitable for aircraft. At present, the aviation industry focuses on second and next generation biofuels derived from non-food crop sources, for example jatropha, camelina, algae, or halophytes.[69] It is theoretically possible to use ethanol for aviation[73] and there are also initiatives to apply ethanol for aviation. In 2004, a Brazilian airspace company certified an aircraft for flying on alcohol fuel.[72]

2.3. Energy for transport

Different transport modes, such as cars, lorries or airplanes, have different energy requirements. Differences originate from energy requirements of the transport mode itself, but also from factors like the load factor. For example, in 2000, the average passenger load factor for airplanes was 70 percent.[27] Other factors include size and geography of the country, congestion, or urbanisation.[28]

For instance, mountainous countries have larger energy requirements for lorries. These factors cause differences in energy requirements for transport among countries. For the assessment of the average energy requirement per passenger km and per ton freight per km, a literature search was done.

We estimated the average energy requirement per passenger km for airplanes, buses and trains based on data from several sources.[27–31] For trains, direct energy requirements in the form of electricity were calculated adopting an efficiency of electric power generation of 59 percent.[25] For electric cars, we adopted the energy use per km from ref. 32–34. For fuel-based cars, we distinguished between petrol and diesel fuel use. The amount of different car types is very large, however. To make an estimate of the range of energy use for cars, we selected three different car types: cars with low, medium and high energy use (litre fuel per 100 km). Data were derived from the Dutch RDW,[35] which gives an overview of fuel use of cars available in the Netherlands. The higher heating values (HHV) of petrol (36.7 MJ per litre) and diesel (38.3 MJ per litre) were derived from SenterNovem.[36] To convert energy use of a car per km to energy use per passenger km, we adopted a load factor of 1.66 passengers per car.[37] For walking and biking, we calculated additional energy requirements for a person of 60 kg at a speed of 5 and 16 km per hour respectively, using data from Breedveld *et al.*[38]

We calculated average energy requirements for freight transport using data from several sources.[28,39–42] In the Appendix, Table 5 gives an overview of the energy requirements of passenger transport modes (MJ per passenger km). Table 6 gives a more detailed overview of energy requirements of cars (MJ per passenger km). Table 7 gives the data for freight transport (MJ per 1000 kg km^{-1}).

2.4 The water footprint (WF) of biofuel-based transport

The WF of biofuel-based transport, expressed in litres of water per passenger km or per 1000 kg of freight per km, is a function of transport energy requirements (MJ km^{-1}), the load factor (number of passengers transported) and WFs of bio-energy type applied (litre per MJ). The WF of biofuels depends on the crop used and the circumstances under which the crop is grown, both climate and agricultural practice.[43] For biodiesel we considered rapeseed, the most water-efficient crop for that purpose in Europe. For bio-ethanol and sugar, we focused on sugar beet and for bio-electricity on maize. Per biofuel type, we assessed the weighted average WF in Europe (litres per MJ). The calculation was done for the European countries that make a substantial contribution to global agricultural production. These countries were: the Czech republic, Denmark, France, Germany and the UK (for rapeseed); Austria, Belarus, Belgium-Luxembourg, Czech republic, Denmark, France, Germany, Greece, Hungary, Ireland, Italy, Moldova, the Netherlands, Poland, Romania, Serbia and Montenegro, Slovakia, Sweden and the UK (for sugar beet); and France, Germany, Italy, Romania and Spain (for maize). Data on national WFs per biofuel were obtained from Mekonnen and Hoekstra.[70]

The WF of a certain mode of passenger transport was calculated based on the weighted average water footprint (litre MJ^{-1}) for the fuel of that transport mode and its energy requirement:

$$WF[m,\ e,\ c] = E[m,\ e] \times \sum_{n=1}^{i} \frac{P[n,\ c] \times WF[n,\ e,\ c]}{\sum_{n=1}^{i} P[n,\ c]}$$

in which WF[m,e,c] is the weighted average water footprint of transport mode m based on energy source e from crop c (litre per passenger km), E[m,e] the energy requirement of transport mode m based on energy source e (MJ per passenger km), P[n,c] the production of crop c in country n (tons per year), and WF[n,e,c] the water footprint in country n of the energy source e derived from crop c (litre per MJ). A standard deviation for the average European water footprint was calculated based on the variation of national values for the European countries. In our calculation, we assumed that energy requirements for transport using biofuels are the same as for transport using the traditional fuels. For biking and walking, we assumed that the required additional nutritional energy is obtained from sugar from sugar beet.

Freight can be transported in several ways. In general, transport of bulk freight by large sea container shipping requires less energy per unit of freight than transport by airplane.[28] For the calculation of the WFs of freight, we combined information on energy requirements of freight (MJ per 1000 kg km^{-1}) from several sources[28,40–42,44] with data on WFs of biofuels.[43] We assumed that ships and lorries use biodiesel as a renewable fuel. For airplanes, at present research is done concerning second generation bio-derived oils. In this process, plants are converted by chemical processes to make high-quality jet fuels.[69] We assumed the use of European rapeseed with an average green WF of 99 ± 15 (m^3 per GJ) and a blue WF of zero. Also we calculated the use of ethanol as a jet fuel, as is proposed in Brazil.[72] For trains, we calculated the use of bio-electricity and biodiesel. The WF of freight transport was calculated in a similar way as in the case of passenger transport.

2.5 The water footprint of transport in Europe

The European Union (EU) aims to reach a share of 20 percent of total energy supply from renewable sources in 2020.[6] In order to reach this target, the EU also sets targets for various sectors in the economy, including the transport sector. It aims at 10 percent renewable energy for this sector in 2020. We calculated the effects on the WF of a shift towards a contribution of 10 percent renewable energy from biofuels to total energy supply in the European transport sector for 25 countries of the EU (excluding Cyprus and Malta), and for Norway, Switzerland and Iceland. Currently, countries mostly rely on national biofuel production (IEA, 2006). Assessments were based on energy use in 2005 and national biofuel production. For each country, we combined data on transport energy consumption from the IEA[2] with biofuel WFs from Mekonnen and Hoekstra.[70] For each country, we selected the crop that has the lowest WF per unit of biofuel. Results are presented as national WFs (Gm^3 per year) and as per capita WFs per country (m^3 per year).

2.6 The water footprint of transport for the main global regions

In order to put results for Europe in a global perspective, we assessed the WF of transport for seven other world regions: Africa, Australia, Asia (excluding China), China, the former

USSR, Latin America and North America. We assumed similar targets for renewable energy for these regions, *i.e.* 10 percent of total energy for transport. This was done using the method described above. The WF of biofuels in a specific region was calculated by assessing the regional weighted average. For all regions, bio-ethanol is the most water-efficient biofuel.[70] For the assessment of the WF of transport in the seven regions, we assumed that the most water-efficient biofuel, *i.e.* bio-ethanol, and the most water-efficient crop (different per region) are applied for biofuel production.

2.7 Assumptions

The calculations have been based on seven assumptions.

(1) Transport energy requirements (MJ km^{-1}) remain constant when switching from fossil fuels to biofuels. Currently, biofuels give the same energy efficiency (km MJ^{-1}) only when added in relatively marginal amounts to fossil fuels. Ethanol has solvent characteristics that, in high concentration blends, can cause metal corrosion or deterioration of rubber or plastics. The major automobile manufacturers warranty their cars to run on petrol ethanol blends with up to 10 percent ethanol, while cars sold in Brazil have components that are resistant to the solvent characteristics of ethanol in blends up to 25 percent of ethanol.[55] This means that the calculated WFs per km may be conservative.

(2) We considered current volumes of fuel needed for transport. The expectation is that energy use will grow.[45] This assumption implies that we underestimate the 2020 conditions.

(3) All countries and regions have similar goals for renewable energy for transport. For comparison, the study has taken a goal of 10 percent biofuels in transport for all countries and regions, but actual goals may differ. Countries with high potential for bio-ethanol may have other goals for adopting biofuels than countries without potentials. For example, the Brazilian Alcohol Program aimed to produce bio-ethanol from sugar cane was already established during the 1970s with the intention to reduce oil imports.[46] The USA also stimulates bio-ethanol for transport.[47]

(4) Transport fuels are produced in the most water-efficient way. The study has taken optimistic assumptions by either taking theoretical minimum values or values that refer to best available technologies and assumed that countries apply the most water-efficient biofuel, which means that resulting WF figures are conservative. Gerbens-Leenes *et al.*[43] have shown that, at present, bio-ethanol is the most water-efficient biofuel. Some countries, for example Germany, promote biodiesel from rapeseed,[48] a fuel with a relatively large WF. For Germany, the green WF of biodiesel from rapeseed is 86 and the blue WF 0 m^3 GJ^{-1}, whereas the green WF of bio-ethanol from sugar beet amounts 23 and the blue WF 1 m^3 GJ^{-1}.

(5) Agricultural water productivities remain constant. Data for WFs of bio-ethanol are based on actual yields, which may increase in the future without increasing water use per hectare. This means that in some cases WFs per unit of energy can be lowered.

(6) For estimating the biofuel-related WF per country and region we have taken the agricultural water productivities as in the country or region considered, implicitly assuming that the biomass is grown domestically. Today, most countries are mostly self-sufficient in biofuels.[45] When demand increases, this situation may change because countries with few opportunities will have to import biofuels. Then, the WF will press in other countries and water productivity data, as in the other countries, will have to be applied when estimating the biofuel-related WFs of the importing countries.

And (7) biofuels have a substantially higher WF per unit of energy than fossil fuels, so that the WF of the latter can be ignored compared to the former. Gerbens-Leenes *et al.*[16] have shown that the WF of bio-energy is indeed much larger than the WF of fossil energy.

3. Results

3.1 The water footprint of transport modes using biofuels

Table 1 gives weighted average green, blue and total WFs for biodiesel, bio-ethanol, bio-electricity and sugar (m^3 per GJ) in Europe, including the standard deviation (SD). Bio-electricity (for trains and electric cars) obtained from maize has an average total WF of 17 ($\pm$3) m^3 GJ^{-1}. Sugar from sugar beet (as an energy source for walking and biking) requires 35 ($\pm$10) m^3 GJ^{-1}. Bio-ethanol from sugar beet requires little more, 36 ($\pm$11) m^3 GJ^{-1}. The most water-inefficient biofuel is biodiesel from rapeseed, with a total WF of six times the WF of bio-electricity. For biodiesel from rapeseed, the blue WF is zero, but for bio-electricity from maize and bio-ethanol and sugar from sugar beetthere is a small blue WF.

Table 2 gives the green, blue and total WF, energy source and crop choice for different transport modes in the EU (litres per passenger km). When biking and walking are excluded, the electric train and electric car are the most water-efficient transport modes, airplanes using biodiesel the most water-inefficient. The table shows the large variability in WFs caused by differences in energy requirements per passenger km among transport modes and differences in WFs of fuels. For airplanes, the difference between lowest and highest WF per passenger km is a factor 10. For cars, the difference is even larger (factor 12). This is caused by the large variability in energy use of cars. Although diesel cars are more efficient in terms of energy use than petrol cars, cars using biodiesel generally have a larger WF than cars using bio-ethanol, because biodiesel is less water-efficient than bio-ethanol. The WF of electric cars applying bio-electricity is much smaller than the WF of biofuelled conventional cars, depending on which conventional car is used for comparison. Table 3 gives the average green, blue and total WF of freight transport in the EU.

When using bio-energy, the most water-efficient way of transporting freight over long distances overseas is by ship using biodiesel; the most inefficient way is by airplane using biodiesel, with

Table 1 Weighted average water footprint of four different sources of energy in the EU

		(Weighted average EU water footprint/m^3 per GJ or litres per MJ) $\pm$ SD[a]		
Energy source	Crop source	Green	Blue	Total
Biodiesel	Rapeseed	99 $\pm$ 15	0	99 $\pm$ 15
Bio-ethanol	Sugar beet	36 $\pm$ 11	2 $\pm$ 2	36 $\pm$ 11
Sugar	Sugar beet	32 $\pm$ 10	3 $\pm$ 3	35 $\pm$ 10
Bio-electricity	Maize	14 $\pm$ 0	3 $\pm$ 1	17 $\pm$ 3

[a] First generation biofuels.

Table 2 Green, blue and total WF for different modes of passenger transport in the EU, energy source and crop choice

			WF[a]/litre per passenger km		
Transport mode	Energy source	Crop source	Green	Blue	Total
Airplane	Biodiesel	Rapeseed	142–403	0	142–403
	Bio-ethanol	Sugar beet	42–79	1–10	42–89
Car (large)	Biodiesel	Rapeseed	214–291	0	214–291
	Bio-ethanol	Sugar beet	136–257	2–32	138–289
Car (small efficient)	Biodiesel	Rapeseed	65–89	0	65–89
	Bio-ethanol	Sugar beet	23–44	0–5	24–50
Bus	Biodiesel	Rapeseed	67–126	0	67–126
	Bio-ethanol	Sugar beet	20–52	0–5	20–58
Train	Biodiesel	Rapeseed	15–40	0	15–40
Electric train	Bio-electricity	Maize	3–8	0–3	3–12
Electric car	Bio-electricity	Maize	4–5	1–2	4–7
Walking	Sugar	Sugar beet	3–5	0–1	3–6
Bike	Sugar	Sugar beet	1–2	0	1–2

[a] Results are based on first generation biofuels.

Table 3 Average WF for different modes of freight transport in the EU

			WF[a]/litre per 1000 kg of freight per km		
Transport mode	Energy source	Crop source	Green	Blue	Total
Airplane	Biodiesel	Rapeseed	576–1023	0	576–1023
	Bio-ethanol	Sugar beet	169–419	2–52	169–471
Lorry	Biodiesel	Rapeseed	142–330	0	142–330
Ship (inland)	Biodiesel	Rapeseed	38–68	0	38–68
Ship (sea, bulk)	Biodiesel	Rapeseed	8–11	0	8–11
Train	Biodiesel	Rapeseed	15–40	0	15–40
Train	Bio-electricity	Maize	2–5	0–2	2–7

[a] Results are based on first generation biofuels.

a difference of a factor of 80. For transport over land, the electric train is the most water-efficient way of transport, about 35 times as efficient as a lorry using biodiesel or an airplane using bio-ethanol.

3.2 The WF of European transport if 10 percent of fuels is bio-ethanol

Fig. 1 shows national green and blue WFs for European transport if 10 percent of transport fuels derive from bio-ethanol. The European transport-related WF is 60 Gm^3 per year (95 percent green, 5 percent blue). Spain, Germany, Italy and the UK show the largest WFs, followed by France, Sweden, the Netherlands and Poland. Especially the southern European countries Spain, Portugal and Greece depend on irrigation showing large blue WFs. Differences among countries are large and depend on total transport energy use per country and on transport fuel WFs. For example, although total German transport energy use is 50 percent larger than in Italy, the WF is similar. This is caused by differences in WFs of bio-ethanol. In Italy, the most favourable crop for bio-ethanol in terms of water is sugar beet (WF 39 m^3 GJ^{-1}), in Germany potato (WF 30 m^3 GJ^{-1}). Slovenia, Latvia, Estonia and Iceland have the lowest transport WF, mainly due to small total energy use of their transport sector.

3.3 European per capita transport WFs

Fig. 2 gives European per capita green and blue transport WFs if 10 percent of transport fuels derive from bio-ethanol.

Most countries show WFs between 60 and 200 m^3 per capita per year. Differences are caused by differences in energy use and specific WFs of bio-ethanol. For example, Switzerland, Denmark and Austria combine relatively large annual per capita energy use for transport (42–43 GJ) with small WFs for bio-ethanol (20–24 m^3 GJ^{-1}), whereas Romania combines small energy use (8 GJ) with a large WF for bio-ethanol (89 m^3 GJ^{-1}). Results for Luxembourg differ from results for the other countries, caused by large per capita energy use compared to other countries.

3.4 The European WF compared to WFs of other regions

Table 4 gives the most favourable crops from a WF point of view for bio-ethanol for eight world regions including weighted average WFs and standard deviations (SD).

Total WFs range from 37 (Europe) to 114 m^3 GJ^{-1} for Africa. Blue WFs are particularly large for bio-ethanol from sugar cane in Asia (excluding China) and in Australia. The green WF of bio-ethanol is especially large for bio-ethanol from cassava from Africa; the blue WF in Africa is zero. Fig. 3 shows green and blue transport WFs per world region if 10 percent of transport energy derives from bio-ethanol. This requires globally 400 Gm^3 per year of green water and an additional 60 Gm^3 of blue water.

Differences among regions are large, however, and result from differences in total transport energy use in combination with different WFs for bio-ethanol. North America, for example, has a two times greater transport energy use than Europe, while the

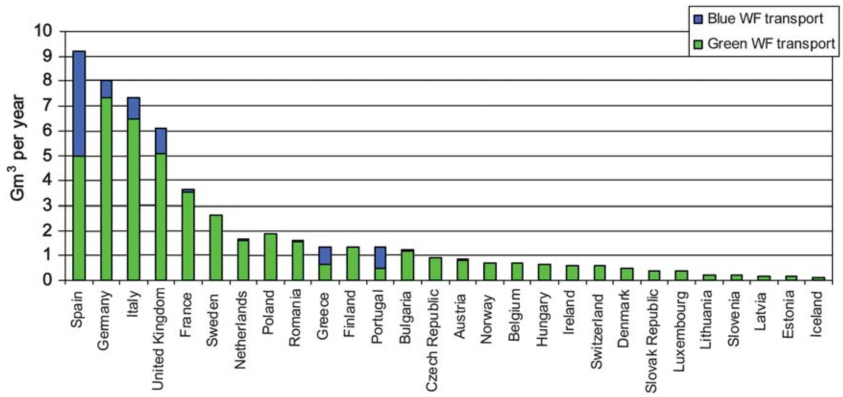

Fig. 1 The WF of the European transport sector if 10 percent of all transport fuels derive from bio-ethanol (first generation biofuel).

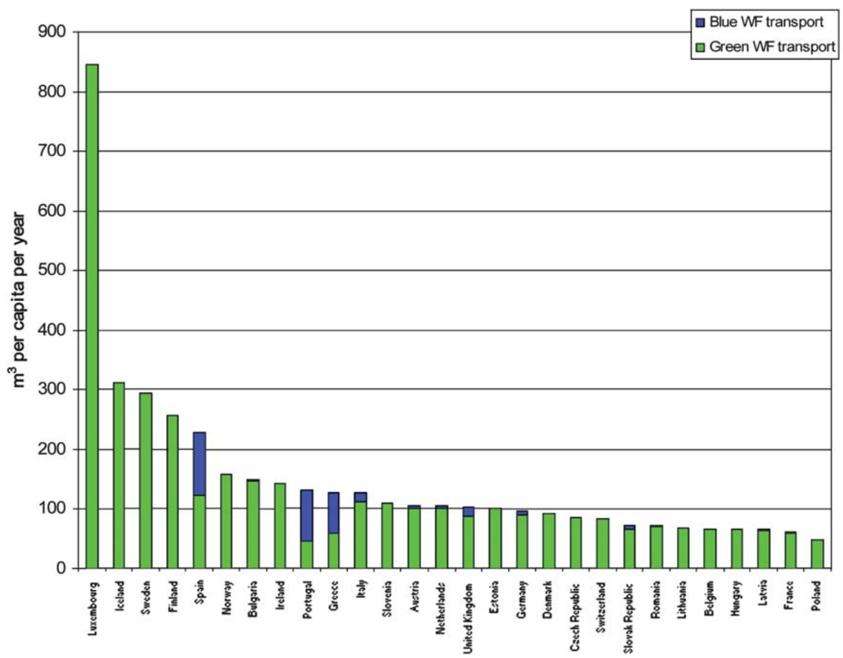

Fig. 2 WF per capita related to consumption of biofuels when in each European country 10 percent of all transport fuels are derived from bio-ethanol (first generation biofuel).

WF of bio-ethanol from maize in North America is 58 m^3 GJ^{-1} and the WF of bio-ethanol from sugar beet in Europe is 37 m^3 GJ^{-1}. These factors cause the difference of a factor three between WFs of North America and Europe. The WF in the former USSR is relatively large given its energy use for transport, which is only half of energy use in Europe. This is caused by the disadvantageous WF of bio-ethanol produced in the former countries of the USSR.

4. Discussion

4.1 Comparison with other studies

Although methods of calculation, assumptions and scenarios among studies estimating relations between biofuels and freshwater differ, all studies have in common that expansion of crop production for biofuels leads to a large increase of freshwater use along with an increase of water stressed situations in some countries. Compared to the study of Berndes[18] our results are conservative. We considered transport only, assumed constant global transport energy use of 90 EJ per year as in 2005, 10 percent biofuel and the most favourable biofuel in terms of water, bio-ethanol produced from the most water-efficient crop, and arrived at a global WF of 450 Gm^3 y^{-1}, compared to 6700 Gm^3 y^{-1} green and blue water for food and cotton.[70] Based on a bio-energy use of 300 EJ in 2100, Berndes[18] has arrived at a doubling of evapotranspiration from global croplands from 6800 to 13 600 Gm^3 that even increases with 370 Gm^3 if irrigation is applied. De Fraiture *et al.*[19] have estimated for 2030 evapotranspiration from croplands for biofuels of 262 Gm^3 y^{-1}, based on a much more modest expectation of biofuel growth.

For China, we assumed energy use for transport of 0.5 EJ, where Yang *et al.*[4] have estimated the use of 10 million tons of bio-ethanol and 2 million tons of biodiesel in 2000 (0.4 EJ) and have arrived at a water requirement between 31.9 and 71.7 Gm^3 y^{-1}. Based on the most water-efficient crop, sugar cane, we calculated a WF of 40 Gm^3 y^{-1}. For 0.4 EJ, this would

Table 4 Most favourable crops for bio-ethanol production for eight world regions including the weighted average WF

Region	Crop for bio-ethanol	(Weighted average WF bio-ethanol/m^3 GJ^{-1}) ± SD[a]		
		Green	Blue	Total
Europe	Sugar beet	36 ± 11	2 ± 2	37 ± 11
Australia	Sugar cane	31	23	54
North America	Maize	52 ± 2	6 ± 3	58 ± 6
Latin America	Sugar cane	59 ± 10	6 ± 6	65 ± 14
Former USSR	Sugar beet	66 ± 9	3 ± 3	69 ± 9
China	Sugar cane	72	3	75
Asia (excluding China)	Sugar cane	60 ± 17	52 ± 21	111 ± 15
Africa	Cassava	114 ± 37	0	114 ± 37

[a] First generation biofuel.

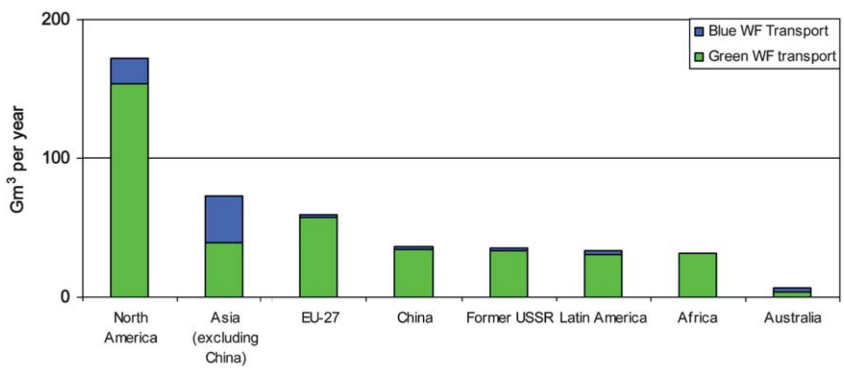

Fig. 3 Green and blue WF per world region related to the consumption of biofuels in the transport sector for the situation that 10 percent of transport fuels are derived from bio-ethanol (first generation biofuel).

require 32 Gm^3 y^{-1}, a result in line with the study of Yang *et al.*[4] That study is also in line with our finding that in China sugar cane is the most favourable crop in terms of water and that rapeseed and soybean are unfavourable.

King and Webber[15] have estimated water requirements for US light duty vehicles using ethanol from maize and have arrived at 15 to 260 litre per km. That study only considered irrigation water (blue water) and expressed water requirements per km. For cars, we arrived at a blue WF based on bio-ethanol from European sugar beet between 0 and 32 litre per passenger km (0–51 litre per km). When also the larger blue WF of ethanol from US maize (6 m^3 per GJ) compared to the average European value for sugar beet of 2 (±2) m^3 per GJ is taken into account, our results fall in the range found by King and Webber.[15] Our analysis is in line with King *et al.*[23] if it comes to the conclusion that US water use for biofuels is substantial if compared to total water consumption. We agree with King *et al.*[23] who conclude that is important to understand the full life cycle of transport and not only the fuel. At present, energy use in the transport sector is heavily dominated by cars. Our study showed that there are large differences among WFs per passenger km of cars, especially electric cars have low WFs. This result gives options to use water in the most efficient way. Also a shift from transport using cars to trains is more favourable in terms of water.

The study of Galan-del-Castillo and Velazquez[20] into the WF of transport in Spain also shows the large impact of differences in crops used for biofuels on WFs. In the case of self-sufficiency, a target of 5.58 percent of biofuel use and a mix of ethanol from wheat and barley and biodiesel from sunflower and rapeseed, Spanish transport requires 600 m^3 per capita per year. Importing biofuels based on more water-efficient crops from elsewhere could substantially reduce the WF of biofuels in Spanish transport. Our study showed a WF of 227 m^3 per capita per year in Spain, based on the use of bio-ethanol from Spanish potato. These comparisons show that differences in biofuel type (bio-ethanol or biodiesel), crop type and country of origin have a large impact on the final results.

In order to put results in perspective, we compared the transport related WF with the WF of food and cotton.[14] If 10 percent of the fuel used in the transport sector is replaced by first generation bio-ethanol, biofuel-based transport in Europe will require a water volume equal to 10 percent of the European WF of food and cotton consumption. If the same biofuel target is applied in other regions as well, the additional water consumption in China would be equivalent to 5 percent of the WF for food and cotton consumption, in the rest of Asia 3, in Africa 4, in Latin America 6, in the former USSR 9 and both in North America and Australia 40 percent. The global water consumption related to biofuel-based transport in this scenario would be 7 percent of the current global water consumption for agriculture.

4.2 Uncertainties and sensitivities

We assumed that biofuel crops will be grown domestically to meet exactly 10 percent of the total transportation fuel demand in a given country. However, in today's global market it is unlikely that the WF will be uniformly exerted in the same country where the biofuels are consumed. Probably, the situation in 2020 might differ from our assumption. At present, South East Asia is ramping up palmoil agriculture to supply biodiesel to Europe, and the US imports a significant portion of its ethanol demand from Brazil. This means that in some countries the biofuel WF might be much larger than calculated in here.

Next, we assumed that the increase in water demand is an extrapolation of the current water demand exerted by existing biofuel crops, in proportion to the increase in biofuels demand. At present, however, there is uncertainty about whether the increased biofuel demand would be met through intensification, involving irrigation or extension of irrigated land, or changes in land use causing changes in evaporation baseline conditions. Another development could be that presently produced first generation biofuels are replaced by the second generation biofuels made from agricultural waste.

For the calculation of WFs, our study used the method of the WF that defines blue water as water for irrigation that actually evaporated during crop production. In this way it does not take the efficiency of irrigation into account, nor the water that is returned to the regional water cycle.

Data used for this study are based on rough estimates of freshwater requirements in crop production and on theoretical maximum conversion efficiencies in biofuel production. Data on the WF of biofuels are based on information from several sources, each of which adds a degree of uncertainty. Crop water requirements, for example, are sensitive to input of climatic data and assumptions concerning the start of the growing season. This means that results presented in this study are indicative and show directions of change.

4.3 Sustainability criteria

The European Union outlined sustainability criteria for biofuels in its European Renewable Energy Directive.[50] The criteria focus on the protection of untouched nature and on greenhouse gas savings. Biofuels should not be made from raw materials from tropical forests or recently deforested areas, drained peatland, wetland or highly biodiverse areas. And, biofuels must deliver greenhouse gas savings of at least 35 percent compared to fossil fuels, rising to 50 percent in 2017 and to 60 percent, for biofuels from new plants, in 2018. The criteria now enter into national laws. Water is not included in these European criteria. It is mentioned though in the Dutch Cramer criteria for biofuels that state that competition for water should be avoided and include an indicator that aims to improve the quantity and quality of surface and groundwater[51]. Industry in the Netherlands has recently adopted these criteria.

Water footprint research has recently formulated criteria for the sustainable use of freshwater that are related to the geographic context and the characteristics of the production process itself.[52] A WF is unsustainable when the process is located in a so termed hotspot, a catchment where during a certain period of the year the total WF is unsustainable. For the evaluation of hotspots, it is assumed that environmental flow requirements are 80 percent of available water. When more water is withdrawn, this will affect nature. For example, when ethanol from sugar cane is produced in North India, an area where water stress occurs, this is unsustainable. Next, a WF is unsustainable when the WF of the process can be reduced or avoided altogether. Agriculture can reduce green WFs by increasing the land productivity, blue WFs can be reduced by more efficient irrigation or the selection of other crops. Grey WFs can be reduced by the application of less chemicals. We have shown the large differences in WFs among countries and among crops. Including the water sustainability criteria in the EU sustainability indicators for biofuels would contribute to the protection of nature and decrease competition for water.

An example that increased production of feedstock for biofuels could decrease sustainability is rapeseed production in Germany. In Germany, renewable water resources are 154 Gm^3 per year.[53] Blue water availability is 20 percent of the renewable water resources, because 80 percent is defined as the environmental flow requirement.[52] The German blue water footprint is 5 percent of the sum of industrial, domestic and agricultural water withdrawal,[53] in total 4.7 Gm^3.[13] Present rapeseed yield levels are 4.3 tons per ha,[53] where potential yields are between 4.7 and 5.7 tons per hectare[54] leaving some room for intensification, probably also needing additional irrigation, fertilizer and agrochemical application. Increasing rapeseed production would imply intensification of the existing production, probably leading to greater water use and probably also to larger water pollution.

4.4. Future developments

Future developments in the area of biofuels are, for example, the development of so termed next generation biofuels and biodiesel from algae. For next-generation biofuels, all cellulosic biomass is applied as a feedstock. There are two basic conversion technologies, thermo-chemical conversion, *e.g.* pyrolysis, and biochemical conversion, *e.g.* biological conversion into ethanol.[55] At present, research is done to develop next-generation biofuels from agricultural waste, such as pyrolysis oil and ethanol. Pyrolysis oil, however, still misses the quality of first-generation biodiesel, because it contains hundreds of different components formed during the decomposition of the cellulosic biomass in the feedstock. Pyrolysis oil has a low quality, is unstable, has a high acidity and viscosity and it has a relatively low energy content. Moreover, it is not miscible with petrol and is corrosive to engines.[56] Another problem is the instability of pyrolysis oil, especially during storage, referred to as "aging".[57] Aging causes greater viscosity and a possibly unwanted change in chemical composition of pyrolysis oil. Biological conversion into ethanol, *e.g.* by fermentation, also finds itself in an experimental stage.[55,58] When the production of next-generation biofuels is technically and economically possible, large amounts of feedstocks are available. A second interesting development is the production of biodiesel from algae. To date, microalgae-based biofuel production has not yet been commercialized to large scale, but there is a wide interest for this new biofuel, for example from the US army for aviation[59] and from the aviation industry.[71]

Biodiesel from algae can reduce WFs to one fourth of values of presently applied biodiesel.[60]

4.4 Policy implications

Governments reconsider the use of fossil energy, such as oil, coal, and natural gas, because resources are limited and carbon dioxide emissions are considered as negative effects that need to be decreased. Moreover, many countries have become dependent of less stable oil and gas providing countries. Agriculturally produced biomass and biowaste are renewable sources and can serve as ingredient for the growing demand of carbonaceous materials reducing emissions and dependency. Presently available biofuels are the so termed first generation fuels produced using conventional techniques. Transforming biomass into so termed second generation biofuels takes place in three stages: decentralized pyrolysis (liquifaction), upgrading using hydrogen and centralized refinery. Currently, researchers are working to up-scale the technology of conversion of biomass into biofuels to an industrial size, so that biofuels may substitute fossil fuels at gas and power stations without transformation of local infrastructure (*e.g.* power stations, gas stations and cars). This new option is consumer friendly and energy efficient, but it requires substantial quantities of raw biomass.

This study has shown the differences in WFs among different transport modes. In general it is far more efficient to apply electricity rather than biofuels. This will require a transformation of the transport system, however. If biomass provides 10 percent of our transport energy demand, some countries might require heavy biomass imports, with several negative effects like increasing food prices, land use changes or water depletion in biomass producing countries. The study of Van Lienden *et al.*[49] into future water shortages has shown that only Brazil and Canada can provide large quantities of biomass without compromising their water resources.

To enable a sustainable transition in the transport sector that also takes social and environmental impacts of producing biomass into account, policy needs to make choices. This study has given new scientific insight into possibilities of large scale biomass production for energy purposes and the implications this will have on the water system.

5. Conclusions

The WF of transport per passenger km shows differences among transport modes and depends on the fuel. In general, it is more efficient to use bio-electricity or bio-ethanol than biodiesel. Transport per train using bio-electricity (3–12 litres per passenger km) is more water-efficient than transport by car (24–289). Theoretically, if an airplane would use first generation bio-ethanol, this would require between 42 and 89 litres per passenger km, which is more favourable than water use of some inefficient cars. For cars, WFs have large differences. A small car using bio-ethanol has a twelve times smaller WF than a large car using biodiesel (24 *versus* 291 litres per passenger km). An electric car fed by bio-electricity is a favourable alternative using 4–7 litres of water per passenger km. Freight is transported in the most water-efficient way by ship or train, airplanes are the most water-inefficient way of transport.

The EU goal of 10 percent renewables for transport in 2020 means that the transport-related WF will grow to 60 Gm^3 per year (95 percent green, 5 percent blue) a conservative estimate, assuming that the most water-efficient crops for making bio-ethanol are used. The volume is to be compared with the current WF of European consumption of food and cotton of about 600 Gm^3 per year. If a mix of biodiesel and bio-ethanol is used, or if fuels are imported from outside the EU, the transport-related WF increases.

Per capita WFs for renewable transport are a function of energy use and WFs of transport fuels. Both show large differences. In Europe, there is a difference in per capita transport energy use between the western European countries showing energy use above 40 GJ per capita per year (*e.g.* Austria 43 GJ, the UK 41 GJ, the Netherlands 41 GJ) and the eastern countries with energy use below 25 GJ per capita per year (*e.g.* Bulgaria 15 GJ, Romania 8 GJ). WFs of transport fuels also differ. Currently, the western European countries have the lowest WF per unit of bio-ethanol and the eastern European countries the highest. Differences in per capita energy use for transport among European countries, together with differences in production systems, result in a broad range of transport-related WFs: from 50 m^3 per year per capita in Poland to 300 m^3 per year per capita in Iceland and Sweden (excluding Luxembourg and assuming 10 percent first generation biofuels in transport).

If the EU target is applied in other regions as well, the additional water consumption in China would be equivalent to 5 percent of the WF for food and cotton consumption, in the rest of Asia 3, in Africa 4, in Latin America 6, in the former USSR 9 and both in North America and Australia 40 percent. The global water consumption related to first generation biofuel-based transport in this scenario would be 7 percent of the current global water consumption for agriculture. In regions where water is limited and where energy use for transport is large, the trend towards biofuels is a significant factor for total agricultural water use and increases the competition for freshwater resources. Efforts to make transport more water efficient should consider the large share of the transport sector in total energy use. This requires that not only the renewable fuel, but also the transport system as a whole is considered in western societies.

Appendix

Table 5 Overview of energy requirements for different modes of passenger transport

Transport mode	Energy source	Energy/MJ per passenger km
Airplane	Kerosene[a]	1.7–3.5
Car	Petrol	1.0–5.5
Car	Diesel	0.8–2.6
Bus	Diesel	0.8–1.1
Train	Electricity	0.2–0.6
Car	Electricity	0.3–0.4
Walking	Sugar	0.1
Bike	Sugar	0.1

[a] In the further analysis we assume that the energy requirement for airplanes using bio-ethanol or biodiesel is the same as the requirement for airplanes using kerosene.

Table 6 Energy requirements for different car types using petrol or diesel

		Car type	Energy/MJ per passenger km
Petrol	Low energy use	Toyota IQ 1.o '99	1.0
		Nissan Pixo 1.0	1.0
		Smart	1.0
		Suzuki Alto 1.0	1.0
		Daihatsu Cuore 1.0	1.0
	Medium energy use	Peugeot 206 1.1 LHFXA	1.3
		Toyota Corolla 1.3 '133'	1.3
		Opel Astra 14–16 v (Z14XEP) '146'	1.3
		Volkswagen Golf B 59 KW H5 149 32	1.4
		Ford Focus 1.4I 59kW	1.4
		Renault Megane 1.6 16V 100 (159)	1.5
	High energy use	Subaru legacy 30 spec	2.7
		Alfa 3.2 ITS	2.7
		Renault Espace	2.7
		Rolls Royce Phantom	3.5
		Jeep Grand Cherokee	3.6
		Bentley continental	3.7
		Bugatti Veyron 16.4	5.5
Diesel	Low energy use	Smart 451	0.8
		VW Polo	0.9
	Medium energy use	Ford focus 1.6TDCi 66kW cDPF	1.0
		Toyota Corolla 1.4 D-4D DPF '125′	1.1
		Opel Meriva A 1.3CDTi (Z1.3DTJ-DPF) '134'	1.2
	High energy use	Alfa 2.4 JTD	1.8
		Dodge Nitro	2.1
		Land Rover Discovery 3	2.4
		Land Rover Discovery sport	2.6

Table 7 Overview of energy requirements for different modes of freight transport

Transport mode	Energy source	Energy/MJ per 1000 kg km^{-1}
Airplane	Kerosene	6.90–9.00
Lorry	Diesel	1.70–2.90
Ship (inland shipping)	Diesel	0.40–0.80
Ship (sea, bulk)	Diesel	0.09–0.10
Train	Electricity	0.18–0.35[a]

[a] Based on the use of electricity. For comparison of energy use with other transport modes, the efficiency to convert primary energy into electricity has to be taken into account.

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Additions and corrections

The water footprint of biofuel-based transport

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Some of the data in the original abstract is incorrect. The corrected abstract is as follows:

The EU target to replace 10 percent of transport fuels by renewables by 2020 requires additional water. This study calculates water footprints (WFs) of transport modes using first generation bio-ethanol, biodiesel or bio-electricity and of European transport if 10 percent of transport fuels is bio-ethanol. Results are compared with similar goals for other regions. It is more efficient to use bio-electricity and bio-ethanol than biodiesel. Transport per train or car using bio-electricity (3–12 and 4–7 litres per passenger km) is more water efficient than transport by car (24–289) or airplane (42–89) using bio-ethanol. For cars, there is a factor of ten between water-efficient cars using bio-ethanol and water-inefficient cars using biodiesel. Biofuel-based freight transport is most water-efficient by ship or train; airplanes are least efficient. Based on first generation biofuels, the EU goal for renewable transport energy results in a WF of 60 Gm^3 per year, 10 percent of the current WF. Differences in transport energy use and in production systems result in a broad range of annual transport-related WFs: from 50 m^3 per capita in Poland to 300 m^3 in Sweden. If similar targets are applied in other regions, the additional WF of North America and Australia will be 40 percent of the present regions WFs. The global WF for biofuel-based transport in this scenario will be 7 percent of the current global WF. Trends towards increased biofuel application enhance the competition for fresh water resources.

The rest of the article is not affected by this mistake.

The Royal Society of Chemistry apologises for these errors and any consequent inconvenience to authors and readers.

Additions and corrections can be viewed online by accessing the original article to which they apply.