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Article

Saving the Planet's Climate or Water Resources? The Trade-Off between Carbon and Water Footprints of European Biofuels

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Abstract: Little information regarding the global water footprint of biofuels consumed in Europe is available. Therefore, the ultimate origin of feedstock underlying European biodiesel and bioethanol consumption was investigated and combined with the irrigation requirements of different crops in different countries. A (blue) water consumption of 1.9 m^3 in 12 countries per GJ of European biodiesel and 3.3 m^3 in 23 countries per GJ of bioethanol was determined. Even though this represents an increase by a factor of 60 and 40 compared to fossil diesel and gasoline, these figures are low compared to global average data. The assessment of local consequences has shown that the irrigation of sunflower seed in Spain causes 50% of the impacts resulting from biodiesel—even though it constitutes only 0.9% of the feedstock. In case of bioethanol production, the irrigation of sugar cane in Egypt, which constitutes only 0.7% of the underlying feedstock, causes 20% of the impacts. In a case study on passenger cars, it was shown that biofuels can reduce the global warming potential by circa 50% along the product life cycle. However, the price of this improvement is an approximate 19 times increased water consumption, and resulting local impacts are even more severe.

Keywords: water footprint; carbon footprint; biofuels; cars; transport

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1. Introduction

Taking into account the European Union's targets to reduce both CO_2 emissions and its dependency on fossil fuels, biofuels such as biodiesel and bioethanol gained increasing attention during the last years. Fixed in the Renewable Energy Directive (RED) [1], the European Commission committed itself to reach a share of 10% of energy in road transport coming from renewable sources in each of the member states by 2020. Even though this includes hydrogen or electricity produced from renewable sources as well, biofuels are expected to be the most relevant fuels to reach this goal [2].

While the RED demands certain sustainability criteria to be met, such as the ban of cultivation of energy plants on land with high biodiversity and high carbon stocks, the environmental sustainability of biofuels is debated. Biofuels are not 'carbon neutral' as the cultivation and harvesting of energy plants as well as the production of the biofuels requires fertilizers, agricultural machinery, processing equipment and chemicals which all cause fossil CO_2 emissions during their production. Taking into account these aspects, recent life cycle assessment [3] and carbon footprint [4] studies determined a reduction potential in the global warming potential (GWP) of up to ~50% for biodiesel (soy bean, US) and ~65% for bioethanol (sugar cane, Brazil) compared to their fossil alternatives [5]. Even though this study shows that the minimum GWP reduction of currently 35% (50% in 2017, 60% in 2018) required by the RED is met in many cases, some scientists predict lower GWP reduction rates when considering GHG emissions resulting from the indirect land use effect [6]. However, due to the lack of scientific robustness, international standards do not require the inclusion of these indirect effects [7].

Despite these discussions, biofuels tend to show a more or less distinct advantage when it comes to the reduction of GHG emission. However, in comparisons to fossil fuels, it is often forgotten that the production of biodiesel and bioethanol can require a lot of water, mainly in the cultivation of crops. Studies of Gerbens-Leenes and colleagues [8] have shown that up to 11,636 L of "green", "blue", and "gray" water is needed to produce 1 L of biodiesel from jatropha and the production of 1 L of bioethanol from sorghum can require up to 4254 L of water, even though these plants are not used as a source of European biofuel production. Taking into account the facts that water consumption grew twice as fast as the world's population during the past century and that more than 1 billion people live in water stressed areas, the neglecting of this aspect is a severe deficit in the discussion of international biofuel strategies. In a nutshell, this trade-off can be summarized as: Which water footprint increase do we need to accept for a carbon footprint decrease?

In order to tackle this question, this paper determines the water footprint of the European biodiesel and bioethanol consumption mixes and compares them to their fossil alternatives diesel and gasoline. On the inventory level, the volumes of blue water consumed in the global production of the underlying crops as well as in the crude oil production and refinery steps are investigated. As this study represents a water availability footprint according to ISO 14064 [9], green and gray water consumption are excluded here but can be reviewed in the works of Gerbens-Leenes and Hoekstra [10]. In order to allow for comparability, a functional unit of 1 GJ of fuel has been chosen, which equates to 31 L of biodiesel, 47 L of bioethanol, 28 L of diesel and 33 L of gasoline. Since the determination of water consumption volumes represents the first step in a water footprint analysis only [9], resulting local impacts are determined using recently developed impact assessment models. Finally, the influence of biofuels on the carbon and water footprint of a car is estimated taking into account the entire product life cycle.

2. Methodology

2.1. Water Inventory

Taking into account the findings of previous studies accomplished by Mekonnen and Hoekstra [11], it was assumed that relevant water consumption in the production of both biodiesel and bioethanol occurs only in the cultivation of the underlying crops resulting from irrigation. Here it should be noted, that water consumption refers to the fraction of total withdrawal which is not returned to the originating catchment area, mainly due to evapotranspiration [12]. As irrigation water needs highly depend on the crop and the location it is grown, the shares and origins of specific crops underlying the European consumption of biodiesel and ethanol need to be determined. Based on a study of Ecofys [13], Gerasimchuk [2] determined the ultimate origin of feedstock underlying the European biodiesel and bioethanol consumption in 2010 (Tables 1 and 2). The underlying surveys also acknowledge triangular trade, e.g., the import of biodiesel from Argentina and Indonesia via the US. Moreover, the figures presented relate to the ultimate origin of feedstock. Thus, it is considered that the underlying crops used for the production of biofuels in a certain country can come from other countries as well. In order to provide a higher spatial resolution, total amounts derived from the European Union have been disaggregated based on the production shares of the individual crops on member state level derived from FAO data [14].

Subsequently, the country specific production volumes underlying European biodiesel (Table 1) and bioethanol (Table 2) consumption mixes have been combined with information regarding their country specific irrigation requirements. For this, the blue water footprint of biodiesel (Table 3) and bioethanol (Table 4) produced from different crops in different countries derived from the WaterStat Database ([11] reference year1996–2005) has been used.

The average water consumption per GJ of European biofuel has been calculated by dividing the total volume of water consumed to irrigate the underlying crops by the total amount of biodiesel (Table 1) and bioethanol (Table 2).

The water consumption per GJ of fossil diesel and gasoline has been determined with the GaBi 6 database [15] by using the water consumption figures of the EU27 fuel mixes (reference year 2013).

In order to assess local consequences of water consumption, the volumetric inventory information is not sufficient and spatial information is the minimum requirement for all impact assessment methods [16]. In case of biofuels, spatial data is available as the inventories have been determined based on the underlying feedstock and its origin. For fossil fuels, the location of water consumption was determined in a top-down regionalization approach introduced by Berger and colleagues [17,18]. By means of the GaBi 6 database, the total water consumption of diesel and gasoline has been subdivided into the shares of water consumed at the crude oil production and at the refineries. These shares have been allocated to different countries based on the European crude oil consumption mix and on the location of European refineries [15].

In addition to the absolute water consumption volumes, the spatially explicit water inventories show the location of water consumption along the supply chains of biodiesel, bioethanol, fossil diesel, and gasoline.

Table 1. Origin of crops underlying the European biodiesel consumption mix in 2010 (10^3 GJ) [2,14]; gray color indicates exclusion from water footprint calculation as the origin is unknown or the feedstock is a waste.

	Rapeseed	Soybean	Oil palm	Sunflower	Tallow	RVO	Other	Total
European Union	171,583	3643	209	18,590	6657	49,490	126	250,299
Austria	-	288	-	-	-	-	-	392
Bulgaria	-	-	-	4043	-	-	-	4043
Croatia	-	387	-	273	-	-	-	659
Czech Republic	13,050	-	-	-	-	-	-	13,050
Denmark	6203	-	-	-	-	-	-	6203
France	39,516	383	-	3303	-	-	-	43,203
Germany	52,305	-	-	-	-	-	-	52,409
Greece	-	-	-	703	-	-	-	703
Hungary	4769	285	-	3068	-	-	-	8122
Italy	-	1641	-	467	-	-	-	2108
Lithuania	4962	-	-	-	-	-	-	4962
Poland	24,213	-	-	-	-	-	-	24,213
Romania	6349	521	-	4585	-	-	-	11,455
Slovakia	-	138	-	-	-	-	-	138
Spain	974	-	-	2,149	-	-	-	3123
United Kingdom	19,242	-	-	-	-	-	-	19,242
Argentina	-	49,867	-	-	-	-	-	49,867
Indonesia	-	-	34,082	-	-	-	-	34,082
Brazil	-	17,460	-	-	42	-	-	17,502
Canada	8876	1842	-	-	544	921	-	12,184
Ukraine	10,551	586	-	-	-	-	-	11,137
US	293	9253	-	-	502	209	-	10,258
Malaysia	-	-	8876	-	-	-	-	8876
Paraguay	126	7746	-	-	-	-	-	7872
Russia	3350	1884	-	-	-	-	-	5234
China	-	42	-	-	-	2805	-	2847
Others	4145	586	544	-	-	42	-	5317
Total	198,924	92,910	43,712	18,590	7746	53,468	126	**415,476**
Share	48%	22%	11%	4%	2%	13%	0%	

Table 2. Origin of crops underlying the European bioethanol consumption mix in 2010 (10^3 GJ) [2,14]; gray color indicates exclusion from water footprint calculation as the origin is unknown.

	Wheat	**Maize**	**Barley**	**Rye**	**Triti-cale**	**Sugar Beet**	**Wine**	**Sugar Cane**	**Others**	**Total**
European Union	24,326	14,403	2428	3391	837	30,691	4229	-	1382	81,688
Austria	-	382	-	-	-	1119	-	-	-	1501
Belgium	-	-	-	-	-	1430	-	-	-	1430
Bulgaria	1072	536	-	-	-	-	-	-	-	1609
Croatia	-	437	-	-	-	-	-	-	-	437
Czech Republic	989	-	72	-	-	1209	-	-	-	2270
Denmark	871	-	179	199	-	-	-	-	-	1249
Finland	-	-	86	-	-	-	-	-	-	86
France	8124	3511	467	-	-	10,852	-	-	-	22,953
Germany	5264	1023	468	1775	-	7370	-	-	-	15,900
Greece	334	510	-	-	-	-	-	-	-	843
Hungary	1072	1568	-	-	-	-	-	-	-	2640
Ireland	-	-	75	-	-	-	-	-	-	75
Italy	1475	1517	-	-	-	-	-	-	-	2991
The Netherlands	-	-	-	-	-	1849	-	-	-	1849
Poland	1992	943	132	1272	-	3419	-	-	-	7758
Portugal	-	198	-	-	-	-	-	-	-	198
Romania	1535	2646	70	-	-	-	-	-	-	4251
Spain	1599	1132	455	145	-	860	-	-	-	4190
Sweden	-	-	88	-	-	-	-	-	-	88
United Kingdom	-	-	321	-	-	2583	-	-	-	2904
Brazil	-	335	-	-	-	-	-	9798	-	10,133
USA	84	5108	-	-	-	-	-	-	-	5192
Peru	-	-	-	-	-	-	-	1089	-	1089
Switzerland	1047	-	-	-	-	-	-	-	-	1047
Bolivia	-	-	-	-	-	-	-	837	-	837
Ukraine	209	293	-	-	-	84	-	-	-	586
Egypt	-	-	-	-	-	-	-	628	-	628
Guatemala	-	-	-	-	-	-	-	586	-	586
Argentina	-	84	-	-	-	-	-	209	-	293
Cuba	-	-	-	-	-	-	-	251	-	251
Other	419	293	-	-	-	-	-	670	84	1465
Total	26,085	20,516	2412	3391	837	30,774	4229	14,068	1465	**103,780**

Table 3. Specific irrigation water consumption of crops (1996–2005) underlying the European biodiesel consumption (m^3/GJ) [11].

	Rapeseed	**Soybean**	**Oil Palm**	**Sunflower**
European Union				
Austria	-	0.00	0.00	-
Bulgaria	-	-	-	0.38
Croatia	-	0.00	-	0.00
Czech Republic	0.00	-	-	-
Denmark	0.00	-	-	-
France	0.43	71.54	-	1.55
Germany	0.00	-	0.00	-
Greece	-	-	-	90.94
Hungary	3.87	0.98	-	0.21
Italy	-	20.95	-	9.60
Lithuania	0.00	-	-	-
Poland	0.00	-	-	-
Romania	0.00	103.10	-	16.44
Slovakia	-	24.19	-	-
Spain	6.02	-	-	128.06
United Kingdom	0.00	-	-	-
Argentina	-	0.85	-	-
Indonesia	-	-	0.00	-
Brazil	-	0.13	-	-
Canada	0.00	0.00	-	-
Ukraine	0.00	0.00	-	-
US	1.76	14.79	-	-
Malaysia	-	-	0.00	-
Paraguay	0.00	0.00	-	-
Russia	0.00	0.00	-	-
China	-	39.89	-	-

Table 4. Specific irrigation water consumption of crops (1996–2005) underlying the European bioethanol consumption (m^3/GJ) [11].

	Wheat	Maize	Barley	Rye	Sugar beet	Sugar cane
European Union						
Austria	-	0.00	-	-	1.40	-
Belgium	-	-	-	-	0.01	-
Bulgaria	0.00	1.65	-	-	-	-
Croatia	-	0.03	-	-	-	-
Czech Republic	0.00	-	0.00	-	0.00	-
Denmark	0.62	-	0.02	0.00	-	-
Finland	-	-	0.00	-	-	-
France	0.13	9.00	0.40	-	0.48	-
Germany	0.00	0.21	0.00	0.00	1.04	-
Greece	2.83	49.38	-	-	-	-
Hungary	0.18	0.11	-	-	-	-
Ireland	-	-	0.00	-	-	-
Italy	1.58	10.75	-	-	-	-
The Netherlands	-	-	-	-	0.08	-
Poland	0.04	0.37	0.00	0.02	0.22	-
Portugal	-	86.00	-	-	-	-
Romania	4.47	1.93	0.00	-	-	-
Spain	4.68	40.43	8.23	0.00	21.63	-
Sweden	-	-	0.00	-	-	-
United Kingdom	-	-	0.00	-	0.33	-
Brazil	-	0.05	-	-	-	2.32
USA	9.04	6.31	-	-	-	-
Peru	-	-	-	-	-	26.09
Switzerland	0.00	-	-	-	-	-
Bolivia	-	-	-	-	-	3.92
Ukraine	1.85	8.66	-	-	1.02	-
Egypt	-	-	-	-	-	61.93
Guatemala	-	-	-	-	-	5.40
Argentina	-	1.40	-	-	-	11.70
Cuba	-	-	-	-	-	21.53

2.2. Impact Assessment

After the water inventory was determined, an impact assessment has been conducted in order to evaluate the local consequences resulting from the water consumption in the different regions.

For this, the water accounting and vulnerability evaluation (WAVE) model [19] and the impact assessment model of Pfister and colleagues [20] have been applied. Both methods rely on local freshwater scarcity which is calculated by relating annual water use (in case of WAVE water consumption) to annual freshwater availability (groundwater recharge and surface run-off). Such ratios have been determined for more than 11,000 river basins on a global level by means of the hydrological model WaterGAP2 [21] which provides annual average hydrological information based on the climate normal period (1961–1990). Based on these scarcity ratios and further hydrologic parameters, the WAVE model determines regional water depletion indexes (WDI) which denote the risk that water consumption leads to freshwater depletion (Figure 1).

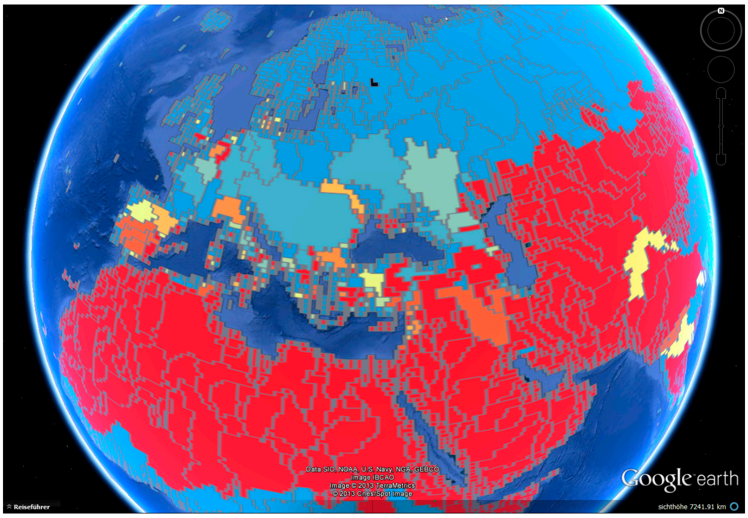


Figure 1. Water depletion index (WDI), which denotes the risk that water consumption leads to freshwater depletion, ranging from 0.01 (blue) to 1.00 (red)—Google Earth layer can be downloaded free of charge at http://www.see.tu-berlin.de/WAVE.

The model of Pfister and colleagues also provides a general scarcity based indicator (water stress index) and additionally assesses damages resulting from water consumption specifically for human health, ecosystems, and resources according to the procedure described in ref. [20]. While all impact factors have been developed on the spatial resolution of river basins, national average factors have been derived by creating water consumption weighted averages for each country.

The overall impacts per GJ of biodiesel, bioethanol, fossil diesel, and fossil gasoline have been determined by multiplying their spatially explicit water inventories by the corresponding national impact factors and aggregating the local impacts.

2.3. Influence of Biofuels on Carbon and Water Footprint of Cars along the Life Cycle

In order to compare the carbon and water footprint of cars run by fossil fuels and biofuels, GHG emissions and water consumption of a car's production and recycling phases have been estimated based on existing studies [17,22,23]. Assuming a mileage of 200,000 km and an average fuel consumption of 9 L gasoline per 100 km (and 13.8 L bioethanol, both equals 369 MJ) the global warming potential and the water consumption of a car's use phase has been estimated. An average emission of 2.5 kg CO_2 per L gasoline and a reduction of 60% [24] have been assumed. For water, the consumption figures determined for gasoline and biofuels in this paper have been used. In addition to the volumetric information, impacts resulting from water consumption along the product life cycle have been assessed by means of the WAVE model [19].

3. Results and Discussion

3.1. Water Inventories

By connecting the information regarding the crops and their origins underlying European biodiesel and bioethanol consumption (Tables 1 and 2) with the crop-specific national irrigation requirements (Tables 3 and 4), the total volume of water consumed around the globe for the provision of European biofuels has been determined (Tables 5 and 6).

Table 5. Total (blue) water consumption of crops underlying the European biodiesel consumption (10^6 m^3).

	Rapeseed	**Soybean**	**Oil palm**	**Sunflower**	**Total**	**Share**
European Union	41.3	119.1	0.0	426.2	586.7	76%
Austria	-	0.0	-	-	0.0	0%
Bulgaria	-	-	-	1.5	1.5	0%
Croatia	-	0.0	-	0.0	0.0	0%
Czech Republic	0.0	-	-	-	0.0	0%
Denmark	0.0	-	-	-	0.0	0%
France	17.0	27.4	-	5.1	49.5	6%
Germany	0.0	-	-	-	0.0	0%
Greece	-	-	-	63.9	63.9	8%
Hungary	18.5	0.3	-	0.6	19.4	3%
Italy	-	34.4	-	4.5	38.9	5%
Lithuania	0.0	-	-	-	0.0	0%
Poland	0.0	-	-	-	0.0	0%
Romania	0.0	53.7	-	75.4	129.1	17%
Slovakia	-	3.3	-	-	3.3	0%
Spain	5.9	-	-	275.2	281.0	36%
United Kingdom	0.0	-	-	-	0.0	0%
Argentina	-	42.4	-	-	42.4	6%
Indonesia	-	-	0.0	-	0.0	0%
Brazil	-	2.3	-	-	2.3	0%
Canada	0.0	0.0	-	-	0.0	0%
Ukraine	0.0	0.0	-	-	0.0	0%
US	0.5	136.9	-	-	137.4	18%
Malaysia	-	-	0.0	-	0.0	0%
Paraguay	0.0	0.0	-	-	0.0	0%
Russia	0.0	0.0	-	-	0.0	0%
China	-	2	-	-	1.7	0%
Total	41.8	302.3	0.0	426.2	**770.4**	100%
Share	5%	39%	0%	55%	100%	

Table 6. Total (blue) water consumption of crops underlying the European bioethanol consumption (10^6 m^3).

	Wheat	**Maize**	**Barley**	**Rye**	**Sugar beet**	**Sugar cane**	**Total**	**Share**
European Union	19.5	142.6	3.9	0.0	34.8	0.0	200.9	59%
Austria	-	0.0	-	-	1.6	-	1.6	0%
Belgium	-	-	-	-	0.0	-	0.0	0%
Bulgaria	0.0	0.9	-	-	-	-	0.9	0%
Croatia	-	0.0	-	-	-	-	0.0	0%
Czech Republic	0.0	-	0.0	-	0.0	-	0.0	0%
Denmark	0.5	-	0.0	0.0	-	-	0.5	0%
Finland	-	-	0.0	-	-	-	0.0	0%
France	1.1	31.6	0.2	-	5.2	-	38.0	11%
Germany	0.0	0.2	0.0	0.0	7.7	-	7.9	2%
Greece	0.9	25.2	-	-	-	-	26.1	8%
Hungary	0.2	0.2	-	-	-	-	0.4	0%
Ireland	-	-	0.0	-	-	-	0.0	0%
Italy	2.3	16.3	-	-	-	-	18.6	5%
The Netherlands	-	-	-	-	0.1	-	0.1	0%
Poland	0.1	0.3	0.0	0.0	0.8	-	1.2	0%
Portugal	-	17.0	-	-	-	-	17.0	5%
Romania	6.9	5.1	0.0	-	-	-	12.0	4%
Spain	7.5	45.8	3.7	0.0	18.6	-	75.6	22%
Sweden	-	-	0.0	-	-	-	0.0	0%
United Kingdom	-	-	0.0	-	0.9	-	0.9	0%
Brazil	-	0.0	-	-	-	22.7	22.7	7%
USA	0.8	32.2	-	-	-	-	33.0	10%
Peru	-	-	-	-	-	28.4	28.4	8%
Switzerland	0.0	-	-	-	-	-	0.0	0%
Bolivia	-	-	-	-	-	3.3	3.3	1%
Ukraine	0.4	2.5	-	-	0.1	-	3.0	1%
Egypt	-	-	-	-	-	38.9	38.9	11%
Guatemala	-	-	-	-	-	3.2	3.2	1%
Argentina	-	0.1	-	-	-	2.4	2.6	1%
Cuba	-	-	-	-	-	5.4	5.4	2%
Total	21	178	4	0	35	104	**341.3**	100%
Sahre	6%	52%	1%	0%	10%	31%	100%	

Dividing the total water consumption by the total biofuel consumption, an average water consumption of 1.9 m^3/GJ for biodiesel and 3.3 m^3/GJ for bioethanol has been determined. It should be noted that in both cases, the specific water consumption can be very diverse depending on the underlying crop and country. While no irrigation is needed to cultivate crops for biodiesel in the UK, Poland, and Germany, on average 90 m^3 of irrigation water are consumed to produce 1 GJ of biodiesel in Spain or from Spanish crops. Bioethanol or underlying crops can be produced without irrigation in Czech Republic and Switzerland. In contrast, the production of bioethanol or underlying crops in Portugal consumes 86 m^3/GJ.

The analysis of water consumption for fossil fuels resulted in water consumption figures of 0.032 m^3/GJ for diesel and 0.081 m^3/GJ for gasoline. Hence, biodiesel causes about 70 times and bioethanol 44 times the water consumption compared to their fossil alternatives (Figure 2). Taking into account these significant differences, it is assumed that data availability related differences in the reference years (origin of feedstock 2010, water consumption of biofuels 1996–2005, and fossil fuels 2013) do not change the general finding from this study.

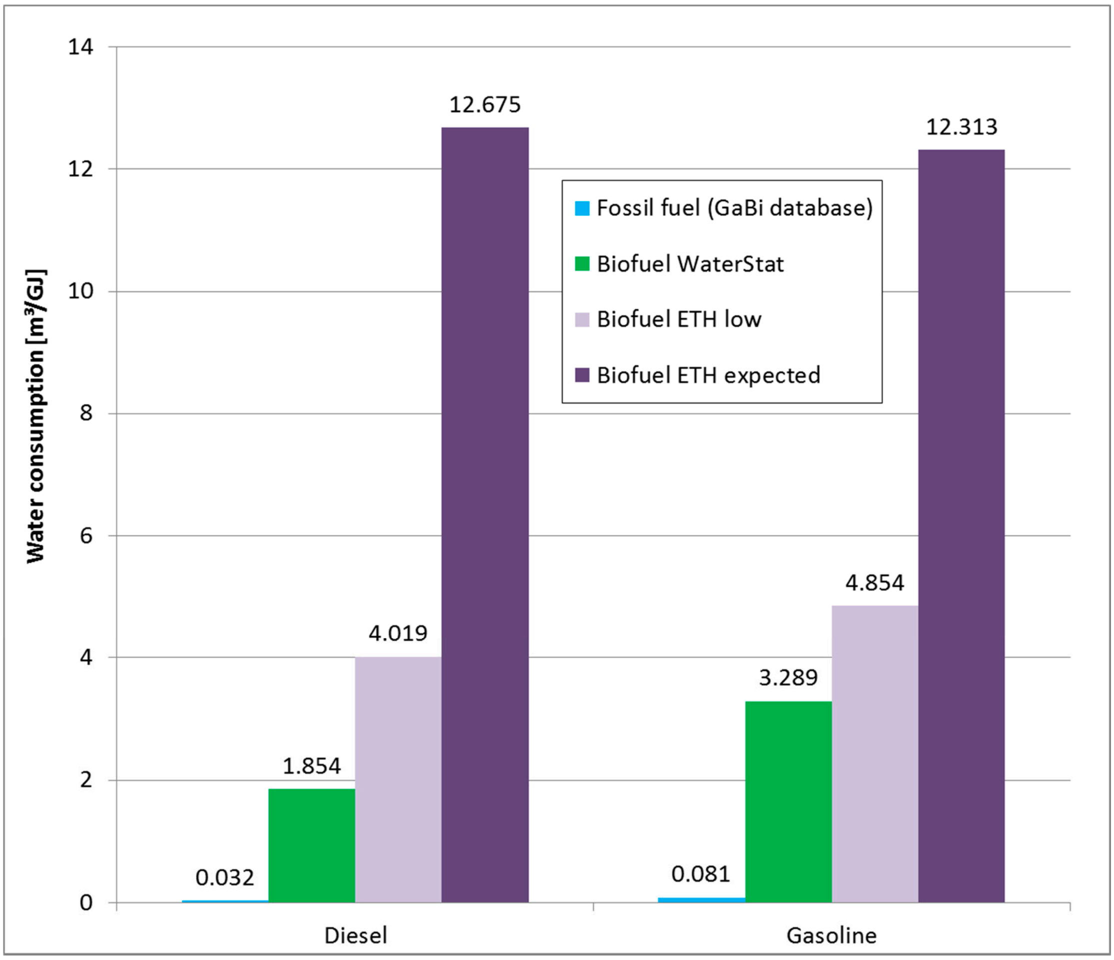


Figure 2. Water consumption per unit of energy derived from average fossil diesel, biodiesel, fossil gasoline, and bioethanol consumed in Europe. The figure includes the estimate form the WaterStat database [11], and the ETH database low [25] and normal estimate [26] included as a sensitivity check.

3.2. Uncertainties in Volumetric Results

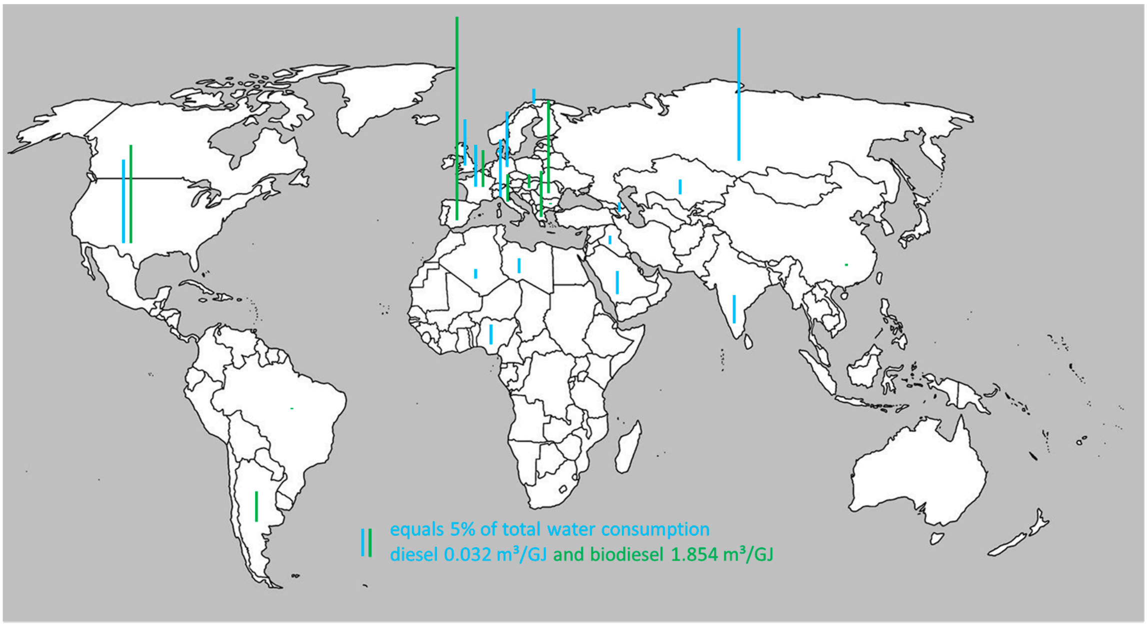
Since irrigation water consumption data is based on global models, uncertainties in the estimates should be analyzed. Therefore, additional irrigation water consumption data from the ETH databases [25,26] has been applied which provides an expected and a low estimate for the blue water footprint of biofuels. As shown in Tables S1–S4 in the supporting information, the water consumption estimates per biofuels or specific origin can vary considerably, depending on the model used: Spain is getting a lower share in the blue water footprint of EU's biofuel consumption, while France, Romania and Argentina get a higher percentage. This is based on differences in the underlying ETH model which shows relatively high differences in water consumption for some regions compared to WaterStat. While the ETH data is based on spatially explicitly modeled yields, WaterStat calculates the yields as a function of water availability (and therefore a function of modeled irrigation). ETH data corrects calculated theoretical irrigation water demand based on a spatially explicit irrigation dataset, while WaterStat calculates water availability of precipitation and irrigation in soil moisture as a function of a different irrigation model. Since both approaches have advantages and disadvantages and cannot reflect the real water consumption, the observed difference can be expected, since all the input data required for the models are uncertain, especially since they are available on high spatial resolution (~10 km) on global coverage.

However, total global agricultural water consumption of the WaterStat database is between the ETH expected and low estimates, so there is no general trend between the two databases—which appears to be the case according to the results shown in this paper. Based on the analysis in this paper, the average water consumption for EU results to 4.0–12.7 m^3/GJ for biodiesel and 4.9–12.3 m^3/GJ for bioethanol, which is considerably higher than the numbers based on WaterStat (Figure 2). This variability among different data also indicates that the difference of EU bioethanol and biodiesel consumption is not significant and more detailed assessment of specific origins is needed to compare two specific options. Uncertainty is even more relevant since the variability of blue water consumption for a crop within one country can be very high as reported for the ETH model [21]: for soybean production, the coefficient of variation (CV) is 2.9 for Argentina and 2.7 for the US, while for Spain, the CV of sunflower and maize production is 0.9.

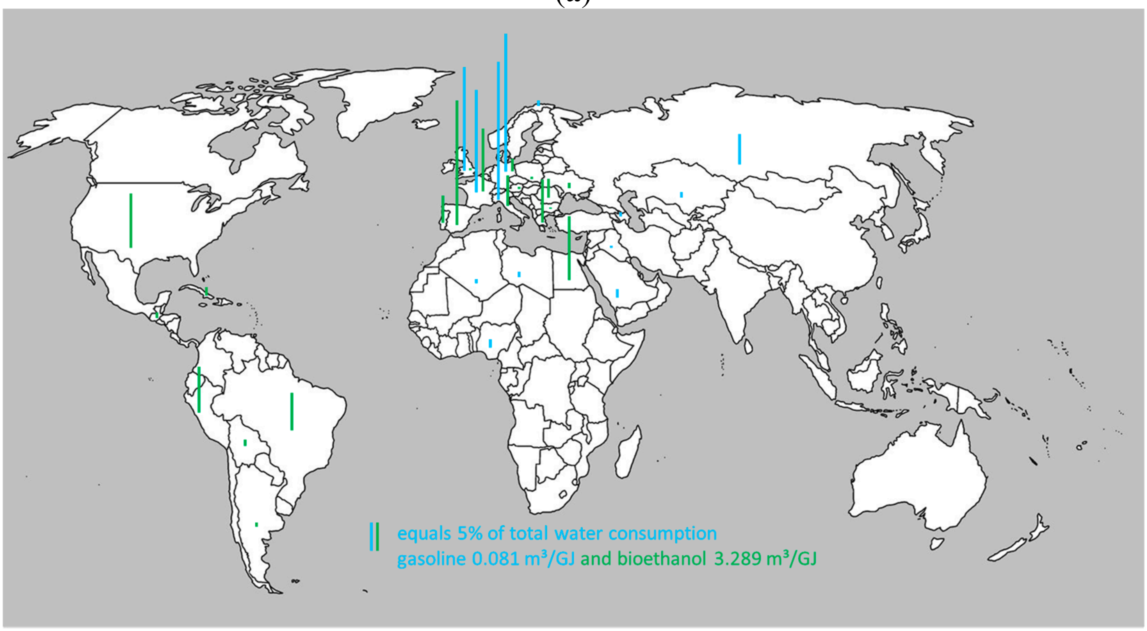
However, the results based on the two databases agree that the blue water footprint of biofuels is ~2 orders of magnitude higher compared to their fossil alternatives.

The average water consumption caused by European biofuel consumption is significantly lower than the world average water consumption of biofuels. Based on ETH data, the global average biofuel production has roughly 2–2.5 times the water consumption of EU consumption (Table S5). Based on WaterStat data, the global average is around two orders of magnitude higher for biodiesel (217 m^3/GJ for soybean to 335 m^3/GJ for jatropha) and one order of magnitude for bioethanol (18 m^3/GJ for cassava to 182 m^3/GJ for sorghum) [8]. This can be explained by the fact that 60% and 79% of the crops underlying European biodiesel and bioethanol consumption are grown within the European Union where, except for Southern European countries, irrigation demand is relatively low. Moreover, as it can be seen in Tables 3 and 4, also the imported crops are derived from countries with mainly low irrigation needs, such as Soybean from Argentina or sugar cane from Brazil. However, the enormous difference between European and global average water consumption might also be a result of the high model uncertainty as discussed above.

Since absolute volumes do not allow for an assessment of local impacts, a regionalized water inventory has been established for both fossil and biofuels according to the methodology described in the previous chapter. The following maps show the relative local shares of water consumed in the production of average biodiesel and fossil diesel (Figure 3a) and bioethanol and fossil gasoline (Figure 3b). Taking into account the relative presentation, the maps allow for a comparison of local water consumption per individual fuel only. Hence, the bars of different fuels cannot be compared to each other since they are based on different absolute water consumption figures per GJ of fuel.



(**a**)



(**b**)

Figure 3. Relative local water consumption occurring in the production of (**a**) fossil diesel (blue bars) and biodiesel (green bars) and (**b**) gasoline (blue bars) and bioethanol (green bars) consumed in the European Union.

As it can be seen from the maps, water consumption in biodiesel and diesel production takes place in 12 and 16 countries, respectively. The production of bioethanol and gasoline consumes water in 23 and 14 countries. For biodiesel, 72% of the water consumption occurs in Spain (sunflower seed), the US (soybean), and Romania (sunflower seed and soybean). For bioethanol, water consumption is distributed more homogeneously. Nevertheless, Spain (22%, mainly maize and sugar beet), Egypt (11%, sugar cane), France (11%, mainly maize), and the US (10%, mainly maize) can be regarded as the main contributors. The relative spatial distribution for biofuel based on the alternative database is shown per country in the supporting information (Figure S1) indicating differences in relative importance.

3.3. Impact Assessment

By multiplying the spatially explicit water inventories shown in Figure 3 with the corresponding regional characterization factors provided by the WAVE model [19] and the model of Pfister and colleagues [20], impacts from water consumption in these countries have been assessed (Figure 3). It should be noted that for biofuels only the consumption figures determined based on WaterStat are considered in this impact assessment. Since only water consumption but no water pollution is considered in this work, this study represents a water availability footprint according to ISO 14046 [9].

Comparing biodiesel and fossil diesel, it has been shown that the differences on the inventory level (varying by a factor of 60) are in a similar range on the impact assessment level (factor 55–74). The only exception from this trend is the impact category damage to human health. Here, biodiesel causes similar impacts as fossil diesel despite the significantly higher water consumption. This can be explained by the locations of water consumption in biodiesel production. As shown in Figure 3a, water consumption occurs mainly in Europe and in the US. Even though physical water scarcity is relevant in many of those countries, their high degree of development avoids health damages resulting from water stress.

Concerning bioethanol, Figure 4 shows that differences on the impact assessment level are significantly higher (factor 64–246) than on the inventory level (factor 40). The reason for this can be found in the origin of the feedstock (Figure 3b) and the local water scarcity which leads to higher differences on the impact than on the volumetric level compared to gasoline. For instance, crops grown for European bioethanol consumption cause irrigation water consumption in water stressed countries like Egypt or Spain, while gasoline production has main water consumption in North-Western Europe (Figure 3b) with low water scarcity and no human health impacts.

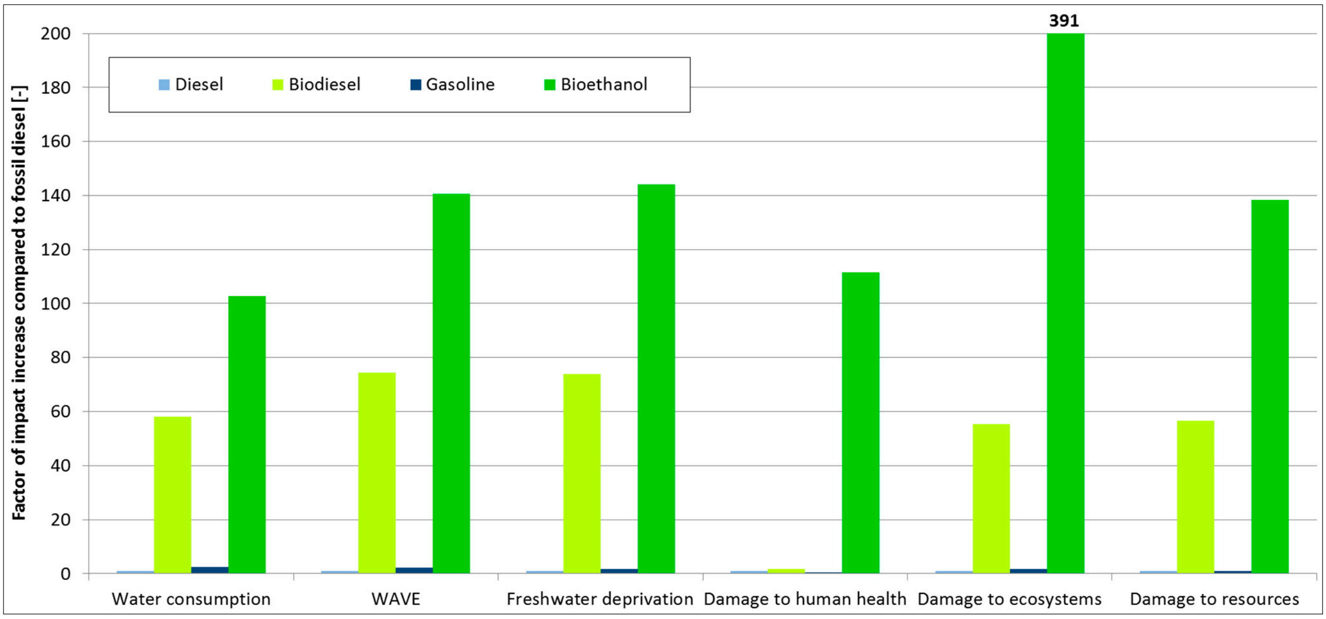
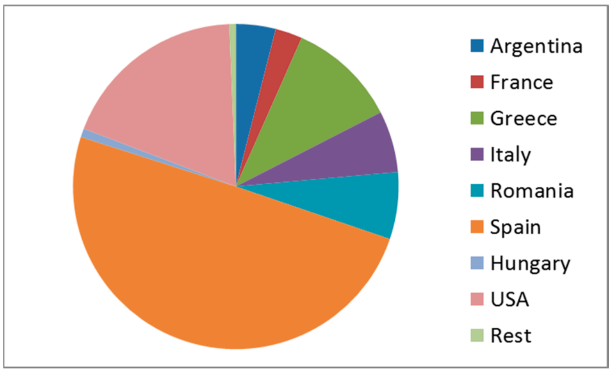
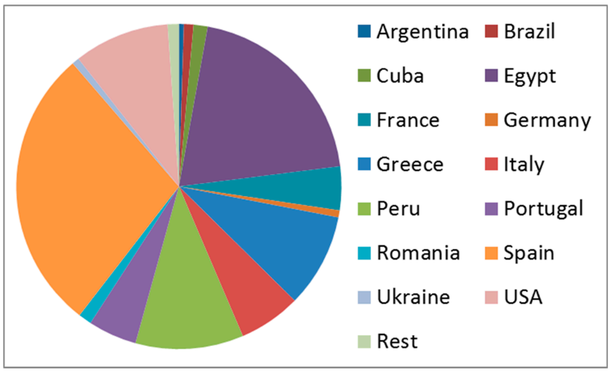


Figure 4. Water consumption and resulting local impacts presented in relation to fossil diesel, *i.e.*, factor of increase compared to fossil diesel in each category.

In order to identify the most relevant crops and countries, the origin of the impacts resulting from water consumption have been analyzed in more detail by means of the impact category freshwater depletion from the WAVE model [19]. As it can be seen from Figure 5a, the irrigation of mainly sunflower seed in Spain causes 50% of the impacts, even though it constitutes less than 0.9% of the feedstock in European biodiesel production. In case of bioethanol production, the irrigation of sugar cane in Egypt, which constitutes only 0.7% of European bioethanol production, causes 20% of the impacts. For agricultural products, where blue water consumption is largely depending on climate this effect is generally observed: places with high irrigation typically show higher water scarcity. However, it should be noted that average country factors have been used for both water consumption figures and characterization factors. Especially in large countries like the US or China, an evaluation on the level of river basins is more adequate. Moreover, considering the uncertainty of blue water estimates discussed above, the distribution of impacts should be considered as indicative rather than absolute shares.



(**a**)



(**b**)

Figure 5. Relative contribution of countries to the results of the impact category freshwater depletion from the WAVE model [19] for (**a**) biodiesel and (**b**) bioethanol.

3.4. Influence of Biofuels on Carbon and Water Footprint of Cars along the Life Cycle

So far, water consumption and related impacts have been analyzed for fossil fuels and biofuels solely. Yet, taking a holistic perspective, the influence of biofuels on the water footprint of a car along its entire lifecycle is more relevant. In order to address this aspect and to compare a car's carbon and water footprint, the global warming potential (Figure 6a), the volumetric water consumption (Figure 6b) and the resulting impacts (Figure 6c) of a car run by gasoline and bioethanol has been determined throughout the life cycle as described in Section 2.2. It should be noted that fuel production is assigned to the use phase of a car.

As it can be seen in Figure 5a, bioethanol can reduce the carbon footprint of a car by about 50% compared to a car run by fossil gasoline. However, taking into account the 40 times higher water consumption of bioethanol compared to fossil gasoline, the life cycle based water consumption increases from about 105 to 1979 m^3 (Figure 6b). On the impact assessment level (Figure 6c), the increase in freshwater depletion is even more significant which can be explained by the local water scarcity in the countries providing the underlying crops.

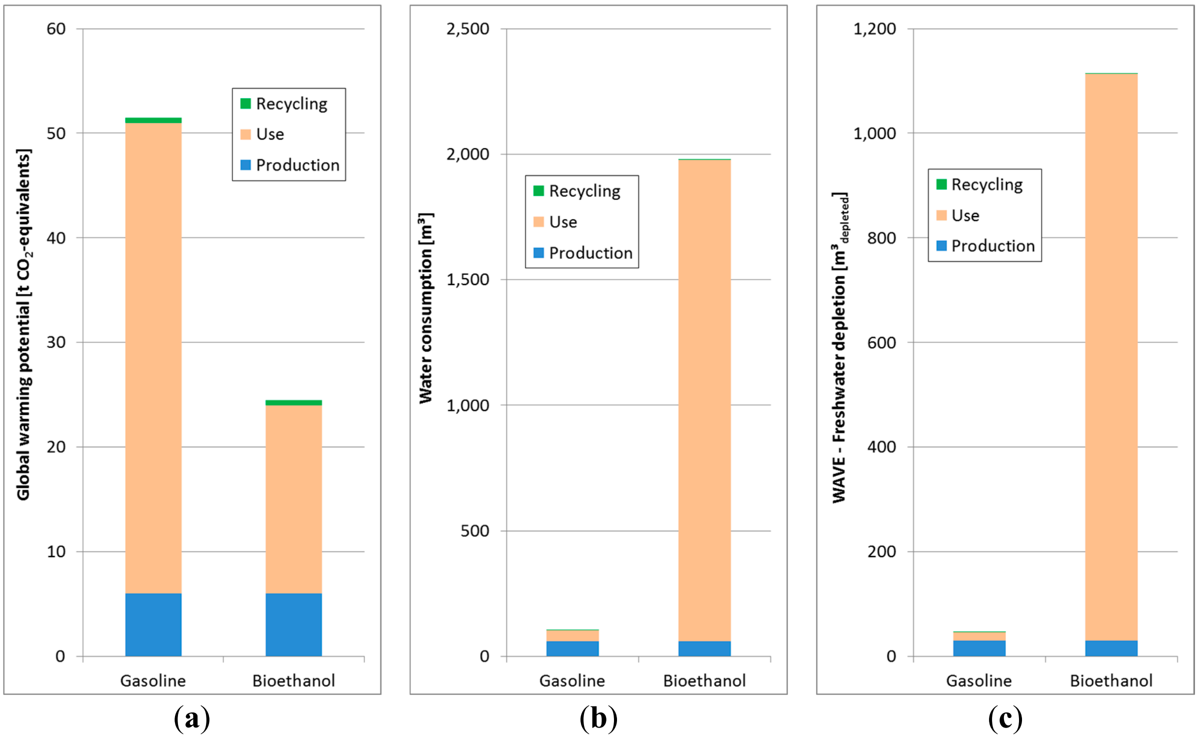


Figure 6. (**a**) Global warming potential (**b**) Volumetric water consumption (**c**) Impacts of water consumption (WAVE–freshwater depletion) along the life cycle of an average passenger car run by gasoline and bioethanol.

Even potential uncertainties in the water consumption figures of the car's production, fuel production, and recycling phase are not expected to affect the main finding of this work: European biofuels cause significantly higher water consumption in car transportation than their fossil alternatives. Thus, a reduction in a car's carbon footprint achieved by the use of biofuels is accompanied by a significant increase in its water footprint.

4. Conclusions

While biofuels are promoted to decrease the carbon footprint of car transportation, little information regarding the global water footprint of biofuels consumed in Europe is available. This study compares the water consumption and associated impacts resulting from the production of 1 GJ fuel of average European biodiesel, diesel, bioethanol, and gasoline.

The ultimate origin of feedstock underlying European biodiesel and bioethanol consumption has been combined with the irrigation requirements of different crops in different countries. As a result, a (blue) water consumption of 1.9 m^3 per GJ of European biodiesel and 3.3 m^3 per GJ of bioethanol has been determined. Even though this represents an increase by a factor of 60 and 40 compared to fossil diesel and gasoline, these figures are low compared to global average water consumption data for biofuels. However, the estimates are quite uncertain as a comparison with an alternative database resulted in higher water consumption (by a factor 1.5 to 6.8).

In order to assess potential local impacts resulting from this water consumption regional information on where the water consumption occurs is required. This analysis revealed that average European biodiesel causes water consumption in 12 countries and bioethanol is responsible for water consumption in 23 countries. In contrast, fossil diesel and gasoline are responsible for water consumption in 16 and 14 countries, respectively.

These regional water consumption figures have been multiplied by local characterization factors derived from the WAVE model [19] and the impact assessment method developed by Pfister and colleagues [20]. While the difference between biodiesel and fossil diesel is similar on the inventory and the impact assessment levels (factor 55–74, except human health impacts), bioethanol shows larger differences compared to gasoline on the impact level (factor 64–246) than on the volumetric level (factor 40). The reason for the significantly higher impacts of biofuels compared to fossil fuels can be found in the fact that relatively large shares of water consumption in the production of biofuels are caused in relatively dry countries. For instance, the irrigation of mainly sunflower seed in Spain causes 52% of the impacts, even though it constitutes only 0.5% of the feedstock in European biodiesel production. In case of bioethanol production, the irrigation of sugar cane in Egypt, which constitutes only 0.4% of European bioethanol production, causes 20% of the impacts. Yet, it should be noted that these conclusions are attenuated when considering the ETH databases.

By means of a case study on passenger cars, the trade-off between water and carbon footprints has been illustrated. While biofuels generally cause less greenhouse gas emissions than fossil fuels (factor ~0.5), the water consumption (factor ~19) and especially the resulting local impacts (factor ~24) are more severe.

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Author Contributions

Markus Berger accomplished the survey and wrote a draft of the manuscript. Stephan Pfister added an analysis and discussion by using alternative ETH databases for the irrigation water consumption needed to produce the crops used for biodiesel and bioethanol production. Vanessa Bach developed the software tool which creates the spatially explicit water inventories used as a base for the impact assessment of this work. Matthias Finkbeiner reviewed the manuscript and provided valuable comments to deepen the discussion and conclusion.

Conflicts of Interest

The authors declare no conflict of interest.

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