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The water footprint of second-generation bioenergy: A comparison of biomass feedstocks and conversion techniques

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ABSTRACT

Bioenergy is the most widely used type of renewable energy. A drawback of crops applied for bioenergy is that they compete with food and use the same natural resources like water. From a natural resources perspective, it would be more efficient to apply the large potential of available crop residues. In this paper, we calculate the water footprint (WF) of ten crop residue types and a few other second-generation bioenergy feedstocks (miscanthus, eucalyptus and pine). Further we estimate the WF of energy carriers produced through different conversion techniques (heat or electricity from combustion and gasification, bioethanol from fermentation and oil from pyrolysis), using the global WF standard. The WFs of crop residues, miscanthus and wood show a large variation. Crop residues have a smaller WF than miscanthus and wood. Given a certain feedstock, the WF of pyrolysis oil is smaller than the WF of bioethanol from fermentation. The WFs of heat from combustion or gasification are similar. The WF of electricity by combustion ranges from 33 to 324 m^3/GJ and the WF of electricity by gasification from 21 to 104 m^3/GJ. This research concludes that it is relatively water-efficient to apply crop residues, and that the production of miscanthus and wood for bioenergy is less favourable. Crop residues can best be converted to oil rather than to ethanol. Electricity from gasification has a smaller WF than electricity form combustion; heat from combustion has a smaller WF than heat from gasification. By showing the water efficiency of different feedstocks and techniques to produce second-generation bioenergy, the study provides a useful basis to wisely choose amongst different alternative forms of second-generation bioenergy.

1. Introduction

Currently, bioenergy is the most widely used type of renewable energy, contributing about 10% to the global primary energy supply (IEA, 2012a). In 2010, global energy demand was about 550 EJ, with 80% derived from fossil fuels and 11% from bioenergy (mainly from wood combustion), while the contribution of nuclear energy, hydropower, sun and wind was small (Smil, 2010). In the European Union projections for 2020, biomass contributes to two-thirds of the overall renewable energy share of 20% (European Commission, 2009). Therefore, bioenergy production must consider the use of all available resources, including crop residues (Scarlat et al., 2010). Bioenergy production converts various types of feedstock of organic origin, such as food crops, agricultural residues, forest residues or municipal solid waste, to energy carriers, like bioethanol, biodiesel or pyrolysis oil or directly to energy (heat and electricity) (IEA, 2012b). Biofuels have been critically described as a commodity feeding fuel hungry cars of the rich at the cost of food production for the poor. Positive claims include that biofuels are carbon neutral or at least have a lower carbon footprint than fossil fuels and that biofuel production can reduce rural poverty. Negative counter-claims relate to the impact of biofuels on land use, forest loss, biodiversity, soil degradation, and water use. Especially the application of food crops for energy purposes, so-called first-generation bioenergy, is criticised and has turned the attention to alternative organic feedstocks (IEA, 2010). Alternative feedstocks, often referred to as second-generation feedstocks, are recovered

Abbreviations: FAO, Food and Agriculture Organization; HHV, Higher heating value; HI, Harvest index; IEA, International Energy Agency; WF, Water footprint.

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organic material (Cuellar and Straathof, 2015), e.g. lignocellulosic feedstocks like straws, wood and stalks (IEA, 2010).

First-generation bioenergy has limited ability to meet the targets of energy demand because of the direct competition with land and water resources used for food (IEA and OECD, 2008). Pacetti et al. (2015), for example, have shown the importance of the water-energy nexus in Italy when food crops are applied for biogas. Various studies have been published concerning the water footprint (WF) of biomass and bioenergy. Gerbens-Leenes et al. (2009a), for example, made a global assessment of the water footprint of bioenergy. The more recent study by Mekonnen and Hoekstra (2011) has yielded a global database of WFs of crops and derived crop products, which formed the basis for the study into the WFs of first-generation biofuels derived from sugar and starch (Gerbens-Leenes and Hoekstra, 2012) and a study into the WF of electricity and heat (Mekonnen et al., 2015). Another study was carried out regarding the WF of biofuels derived from algae (Gerbens-Leenes et al., 2014). These studies indicate the large impact of bioenergy on the demand for water resources. To make bioenergy more sustainable, the attention should shift towards the use of second-generation feedstocks, the most abundant form of biomass available (FAO, 2008). Global energy demand is projected to increase by 37% over the period 2014–2040 (IEA, 2014). Considering this demand, crop residues could become a relevant source of energy. Montforti et al. (2013), for example, show that in the EU-27 crop residues could provide 1.5 EJ of bioenergy per year. Wood is another biomass source that can be converted to energy (Möller and Nielsen, 2007). Srirangan et al. (2012) indicate that there are still large challenges related to the production of second-generation bioenergy. Technical issues remain, in particular the recalcitrant nature of the second-generation feedstock and the limited substrate range, resulting in low yields of biological conversion technologies. Liu et al. (2016) show the importance of pretreatment of wastes before combustion. After microwave drying, energy from the combustion of leaves increased by 35% compared with electrically dried leaves. Lin and Huber (2009) have high expectations for biomass conversion by catalysis, showing that it is highly cost-effective to develop new approaches to convert biomass to biofuels.

Given the potential of second-generation feedstock to provide bioenergy, combined with the increasing demand for this type of renewable energy, it is important to investigate the possibilities to convert these feedstocks into useful energy (e.g. heat or electricity) and energy carriers (e.g. bioethanol or oil) and to study the efficiency in terms of output per unit of natural resource use, e.g. water use. The authors of the studies on the WF of crops and bioenergy mentioned above have calculated the WF of first-generation energy from crops, showing the large water footprint of this type of energy. There are some studies available that have made an analysis of the WF of second-generation bioenergy. Chiu et al. (2015) have assessed the WF of second-generation bioethanol in Taiwan, concluding that the WF of second-generation bio-ethanol is considerably smaller than the WF of first-generation bio-ethanol, mainly because the WF of the feedstock, bagasse and rice straw, is allocated to the main product, rice and sugar cane. Renouf et al. (2013) studied the use of sugar cane residues for the production of ethanol and electricity in Australia. They emphasize that when bagasse is used for ethanol or electricity, it cannot be used for animal feed anymore, requiring the production of other feed. González-García et al. (2014) analysed bioenergy production chains in Southern Europe and show that residues have smaller environmental impacts than energy crops, indicating the potential of residues for bioenergy. Chiu et al. (2015), Renouf et al. (2013) and González-García et al. (2014) performed case studies, assessing environmental impacts of second-generation bioenergy for specific situations. To add a holistic approach to the existing body of knowledge, Aivazidou et al. (2016) anticipate that future research will focus on supply-chain oriented WF assessment. The current study contributes to the existing knowledge by adding an analysis of the WF of the most important crop residues that together contribute to 60% of globally available residues, and comparing residues with energy crops and wood. The study includes the main conversion techniques available to produce useful energy. The novelty of the study is that it provides an overview of the impact of different types of residue feedstocks and conversion techniques on water consumption.

There are two main conversion pathways for biomass feedstocks, thermochemical and biochemical conversion, which have different efficiencies. Thermochemical processes include three alternative processes: combustion, pyrolysis and gasification. Combustion produces heat (Abuelnuor et al., 2014) or electricity (Evans et al., 2010). Pyrolysis decomposes biomass, generating heat, volatile gases, pyrolysis oil and solid carbon. Pyrolysis and gasification are two promising utilization methods for the conversion of biomass toward a clean fuel source (Bahng et al., 2009). Pyrolysis oil has a relatively large oxygen content, larger than oil extracted from oilseeds, so that the energy content of pyrolysis oil is smaller than the energy content of oils from first-generation feedstocks (Lehto et al., 2013). Gasification is a form of thermochemical conversion of biomass that generates synthesis gas (syngas). Syngas primarily consists of hydrogen and carbon monoxide (Higman and Van der Burgt, 2011), with some other compounds like carbon dioxide. Syngas can be used for heat or electricity generation (Evans et al., 2010) and forms a basis for methanol production (Mathers, 2012).

Biochemical conversion is the process in which bacteria or enzymes break down biomass molecules into smaller molecules (Basu, 2013), e.g. fermentation or anaerobic digestion. To ferment biomass, the biomass is converted into sugars using acids or enzymes, producing bio-ethanol (Mood et al., 2013) or biogas (Sawatdeenarunat et al., 2015). All thermochemical and biochemical conversions have different efficiencies and different resource use, such as water use.

Plants need land and water to grow. While water and land resources are already scarce today, they will be increasingly scarce in the future (FAO, 2012). The IEA expects a more water-intensive power generation and biofuel production in 2035 (IEA, 2012b). Cramer et al. (2007) introduced sustainability criteria related to biofuel production and water consumption, e.g. the criterion that for the production and processing of biomass the quality of surface water and groundwater must be retained. There are various ways to measure water use, e.g. to assess gross or net water withdrawal, or to calculate the green, blue and grey water footprint (Hoekstra et al., 2011). The water footprint (WF) is an indicator of freshwater appropriation that includes the water consumption and pollution along product supply chains (Hoekstra et al., 2011). The *green* WF refers to rainwater consumed (evaporated). The *blue* WF refers to surface water and groundwater volumes consumed (evaporated), thus showing the net blue water withdrawal. The *grey* WF refers to the volume of freshwater required to assimilate a load of pollutants based on ambient water quality standards. It has appeared to be instrumental in analysing water use along supply chains and in identifying hotspots and priority areas for action. The WF can be measured for various entities, like products (e.g. food, energy), consumers or national consumption as a whole. There are studies for the WF of nations (Hoekstra and Chapagain, 2007) or animal products (Mekonnen and Hoekstra, 2012). Concerning biomass, data on the WF for various crops and crops products are available (Mekonnen and Hoekstra, 2011). Also, studies are available for the WF of heat and electricity obtained through combustion of biomass assuming 100% efficiency, based on the higher heating value (HHV) of the feedstock (Gerbens-Leenes et al., 2009a). Available WF studies for electricity from biomass consider electricity from combustion (Gerbens-Leenes et al., 2009b), while electricity production may be generated with other conversion techniques like gasification as well.

The aim of this study is to assess the WF of various forms of second-generation bioenergy using the method of Hoekstra et al. (2011). The results of this study can be applied to compare the implications for water resource use when different types of crop residues and biomass feedstocks are used and when different energy conversion techniques are chosen. This makes it possible to identify feedstocks and conversion techniques that are efficient from a water perspective. This is relevant given the increasing importance of water scarcity and competition over limited freshwater resources to the global economy. The World Economic Forum puts water crises in the top-3 of largest global risks for human societies in terms of potential impact in all of its annual global risk reports since 2012 (WEF, 2017).

2. Method and data

For the assessment of the WF of second-generation bioenergy, we applied the global WF standard (Hoekstra et al., 2011), which among the alternative WF methods is the most common one for estimating water consumption and pollution (Jeswani and Azapagic, 2011) The earlier study of Mekonnen and Hoekstra (2011) allocated water consumption and pollution in crop production fully to the crop yields. In the current study, we distribute the WF of crop production over the crop and the residue fraction. We selected crops based on three criteria. First, the crop has a significant global production, contributing at least 0.5% to the total annual global crop production. Second, the crop residue weight fraction is large enough for energy conversion purposes. For instance, crops like potato have a huge global production, but a relatively small residue fraction (Alva et al., 2002). Third, crop residues have bioenergy applications. We derived data on global crop production from FAO (2013). Ten crops meet the criteria: sugar cane, corn (maize), paddy rice, wheat, sugar beet, cassava, soybean, rapeseed, cotton and sunflower. Together, these crops represent 60% of the total annual global crop production. When sugar is produced from sugar cane or sugar beet, by-products are generated that can be used for producing second-generation bioenergy: sugar cane bagasse and sugar beet pulp. We included these residues too. Next, we selected wood and energy crops. We used two criteria to select wood: the wood has a relatively high heating value (HHV) so that it is applied for bioenergy and WF data are available. Two wood types meet the criteria: pine and eucalyptus. We included wood core, but excluded bark. We also included miscanthus, an energy crop with a high growth rate and without an edible yield (Walsh and Jones, 2013).

We allocated the WFs of crops obtained from Mekonnen and Hoekstra (2011) over the crop yields and crop residues using weight and value fractions. Fig. 1 shows that we calculated the WF of second-generation bioenergy in six steps: (1) calculation of crop residue weight fractions; (2) calculation of value fractions; (3) assessment of the WF of residues (m^3/t); (4) calculation of the WF of pyrolysis oil and bioethanol per unit of weight (m^3/tonne); (5) calculation of the WF of pyrolysis oil and bioethanol per unit of energy (m^3/GJ) and (6) assessment of the WF of bio-based electricity and heat (m^3/GJ).

Fig. 2 shows the selected conversion pathways. We included three thermochemical biomass conversion pathways, gasification, combustion and pyrolysis, electricity production after gasification or combustion and a biochemical conversion pathway. All selected crop residues can be converted thermochemically, except sugar beet pulp, which has a high moisture content (Akram et al., 2015). For the biochemical conversion pathway, we included bioethanol production from fermentation.

The heat produced after combustion is considered as energy output. The energy input is the HHV of the biomass feedstock. For gasification, we considered as energy output the heat produced including the HHV of the syngas and gasification is considered as a heat production conversion process. Despite combusted syngas is considered in the energy output, we define this process as gasification. For electricity production by combustion or gasification, heat is produced and used to generate electricity. The energy output is electricity and the energy input the HHV of the converted biomass.

Step 1 calculates the crop residue weight fractions. Fig. 3 shows that the total biomass yield (T) provides a crop yield (y) and a crop residue (x). The crop yield generates the primary product (p), but also by-products (b1 − bn). The ratio of the crop yield to the biomass yield is the harvest index (HI) (Scurlock et al., 1985). A low HI implies that crops make large investments in the fraction of non-edible biomass and have a small crop yield. The harvest index (HI), y/T, not only varies among crops, but also differs for the same crop depending on the variety and country where the crop is grown. We selected HIs from the countries with the largest contribution to global production of the particular crop. When two or more references were available, we took the average HI. Appendix A gives an overview of HIs. The crop residue weight fraction is derived from the HI and expressed as *crop residue weight fraction* = *1* − *HI* (see Appendix C). The by-product weight fraction is defined as the ratio of the by-product mass over the mass of all products. For example, the primary product of sugar cane is sugar, by-products are bagasse and molasses. The bagasse weight fraction is the ratio of the bagasse mass to the sum of the sugar, bagasse and molasses mass. Appendix B gives the weight fractions of sugar cane and sugar beet.

Step 2 calculates the value fractions. The value fraction $fv\,[p]$ of an output product p (monetary unit/monetary unit) is defined as the ratio of the product market value to the aggregated market value of all output products (Hoekstra et al., 2011):

$$fv\,[p] = \frac{wf[p]*price[p]}{\sum_{p=1}^{z} wf[p]*price[p]} \tag{1}$$

in which $wf[p]$ refers to the weight fraction of product p obtained from the input. For example, for a crop yield this is the ratio of the crop yield to the total biomass yield (i.e. HI). $price[p]$ refers to the price of product p (monetary unit/mass). We took prices of crop yields and residue fractions from the country with the largest global production. Appendix D gives an overview of prices. For sugar cane bagasse and sugar beet pulp, the value fraction, fv, is calculated for sugar, molasses and bagasse or pulp.

Step 3 calculates the WF of crop residues (m^3/t). For the ten crops, we took the global average green, blue and grey WF (WF_{crop1}) from Mekonnen and Hoekstra (2011), who allocated WFs fully to the crop yields (ignoring the by-products). Appendix A gives the WF of the ten crops, two wood types and of miscanthus. To assess the WF of the crop residue ($WF_{residue}$) and the new WF of the crop yield (WF_{crop2}), we first calculate the WF per unit of total biomass yield ($WF_{total\ biomass\ yield}$) from the WF per unit of crop yield (WF_{crop1}) based on the harvest index (HI):

$$WF_{total\ biomass\ yield} = WF_{crop1}*HI \tag{2}$$

Next, $WF_{total\ biomass\ yield}$ is allocated over the crop yield and the residue fraction. The WF of the crop yield (WF_{crop2}) is calculated as:

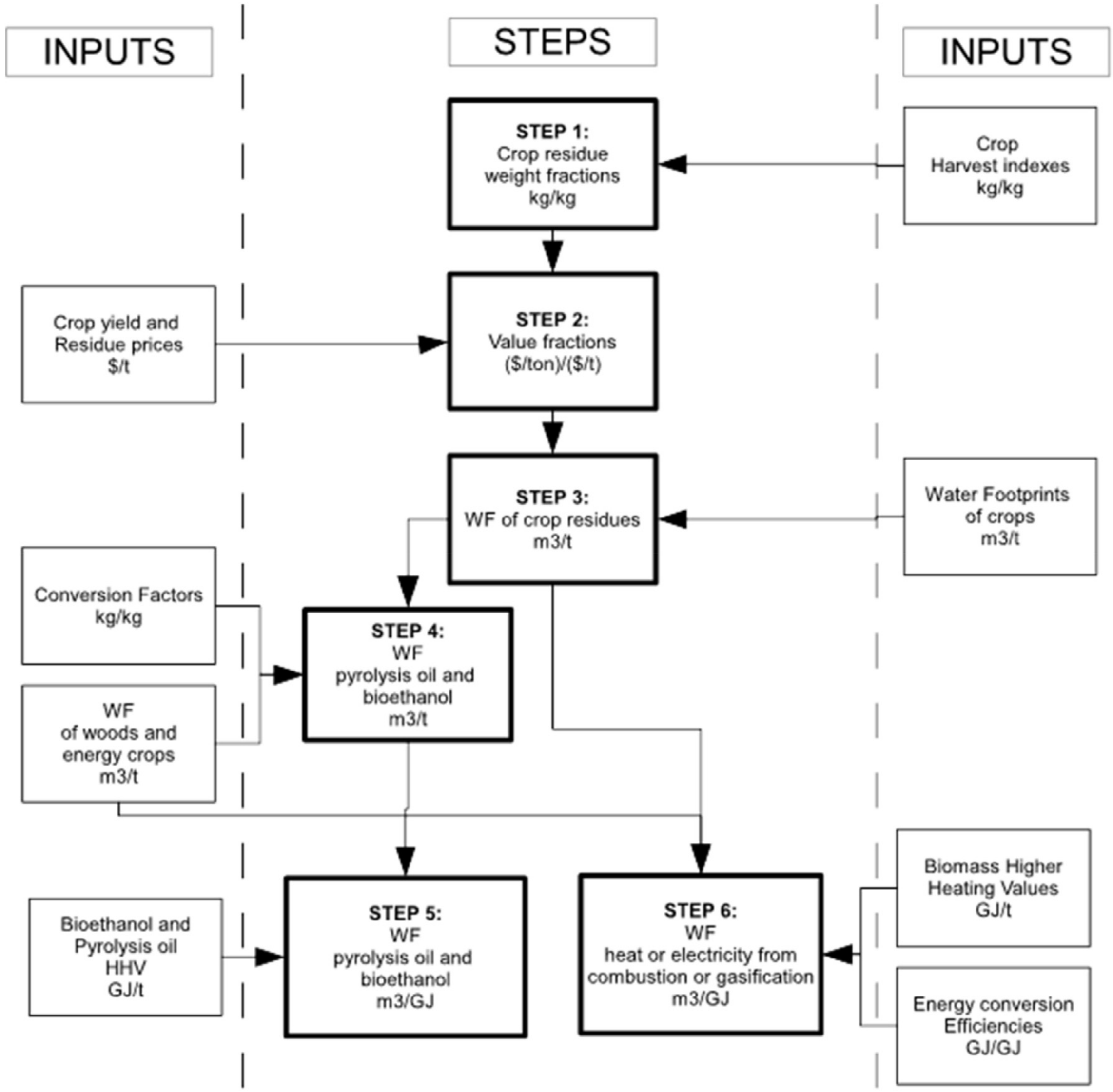

Fig. 1. Six steps for the calculation of the WF of second-generation bioenergy.

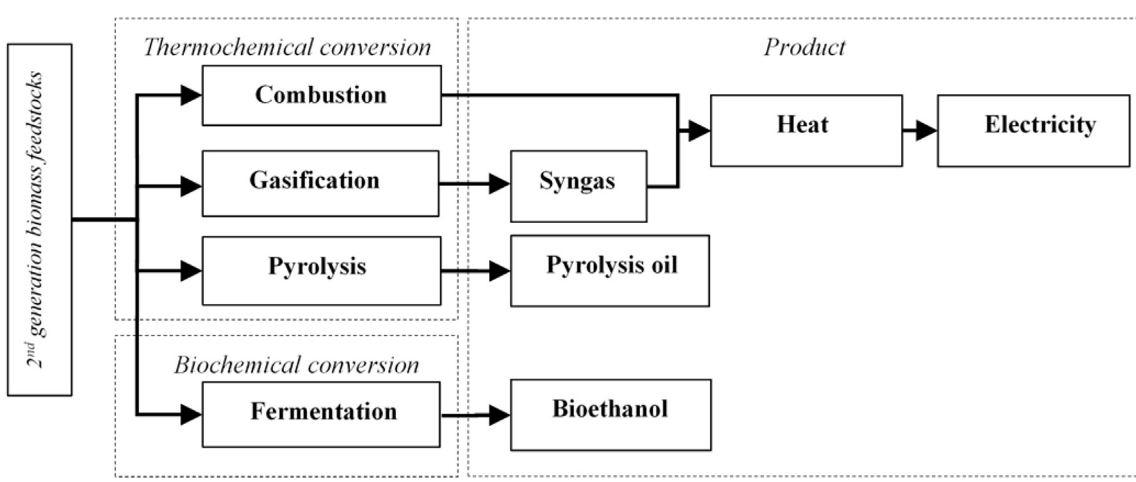

Fig. 2. Thermochemical and biochemical biomass feedstock conversion pathways and the resulting products syngas, pyrolysis oil, bioethanol, heat and electricity.

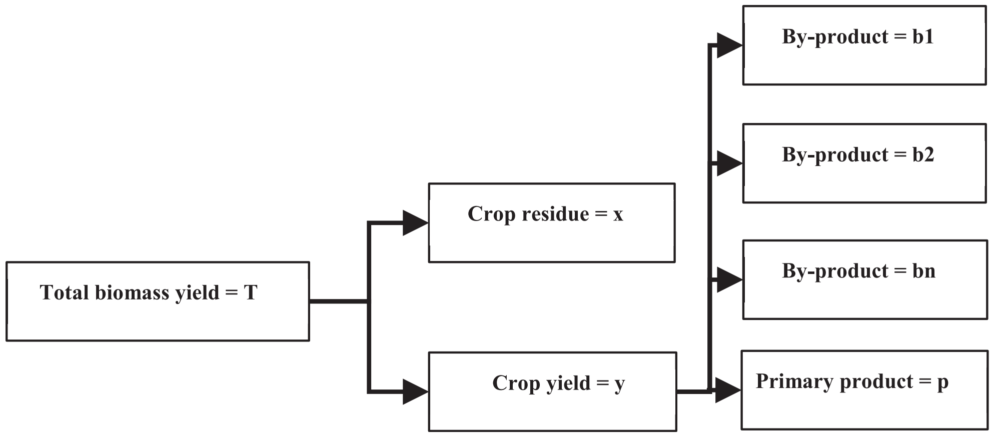

Fig. 3. Separation of the total biomass yields into a crop residue and a crop yield fraction. The crop yield is the feedstock for the different byproducts.

$$WF_{crop2} = \frac{WF_{total\ biomass\ yield}}{HI} * f\nu \quad (3)$$

where fv is the value fraction of the crop yield. The WF of the crop residues ($WF_{residue}$) is calculated as:

$$WF_{residue} = \frac{WF_{total\ biomass\ yield}}{wf[residue]} * f\nu \quad (4)$$

where $wf[residue]$ is the residue mass fraction and fv is the value fraction of the crop residue. The WF of sugar cane bagasse and sugar beet pulp is calculated in a similar way, based on product fractions and the relative values of bagasse and pulp to the sugar. We assumed that the process WF is negligible. The WF of pine, eucalyptus and miscanthus does not need allocation. For pine and eucalyptus, we derived data from Van Oel and Hoekstra (2012) (m^3 water/m^3 mass). We converted the WF per unit of volume to WF per unit of mass (m^3/ton) using the pine density of 500 kg/m^3 and eucalyptus density of 496 kg/m^3 from Brown (1997). Data on the WF of miscanthus were taken from Gerbens-Leenes et al. (2009b).

Step 4 calculates the WF of pyrolysis oil and bioethanol (m^3/t). We allocated the WF of the residue to the pyrolysis oil from the pyrolysis process and to bioethanol from the fermentation process. The WF of an energy carrier, $WF_{energycarrier}$, (m^3/t), is calculated as:

$$WF_{energycarrier} = \frac{WF_{residue}}{f_{ec}} \quad (5)$$

where f_{ec} (mass/mass) is the conversion factor of the energy carrier. Appendix E gives the pyrolysis oil and bioethanol conversion factors. For the calculations, we used the average numbers.

Step 5 converts the WF of an energy carrier per unit of weight (m^3/t) to a WF per unit of energy, $WF_{energycarrier2}$ (m^3/GJ). Biomass has a calorific value, the so termed higher heating value (HHV) (Sheng and Azevedo, 2005), which refers to the total energy that is released through combustion (GJ/kg) (Rosillo-Calle, 2012). The calculation is based on the HHV of pyrolysis oil and bioethanol. The WF of the energy content of the energy carriers is calculated as:

$$WF_{energycarrier2} = \frac{WF_{energycarrier} * 1000}{\text{HHV}} \quad (6)$$

where the factor 1000 is applied to convert MJ to GJ. Appendix F gives the HHVs of bio-oils. For the calculations, we used the average HHVs. The ethanol HHV is 29.7 MJ/kg (Gupta et al., 2015). We derived the HHV of wood from Telmo and Lousada (2011) and WF values from Van Oel and Hoekstra (2012).

Step 6 calculates the WF of heat or electricity from gasification or combustion based on the energy conversion efficiency (the efficiency of converting one energy carrier into another), defined as energy output over energy input (IEA, 2008). When one energy carrier is converted into another, losses occur that determine the amount of energy output and the efficiency. Some indicative energy efficiencies for biomass conversions are: sugar cane combustion (0.611) (Mbohwa, 2006); corn stover gasification (0.85) (Carpenter et al., 2010) and soybean straw combustion (0.73) (Repic et al., 2010). The energy input is the HHV of the biomass used for conversion. The WF of heat or electricity, $WF_{heat\ and\ electricity}$ (m^3/GJ), is calculated as:

$$WF_{heat\ and\ electricity} = \frac{WF_{residue} * 1000}{\text{HHV} * \text{fthermal}} \quad (7)$$

where the factor 1000 converts MJ to GJ and $f_{thermal}$ is the thermal or electrical conversion efficiency of the conversion pathway. We allocated the WF of the residues for gasification, combustion or power generation to the produced heat or electricity. For hardwood combustion, we took data for eucalyptus, a hardwood (Treasure et al., 2012), assuming that the efficiency is equal to eucalyptus combustion efficiency. Appendix G gives all energy efficiencies.

3. Results

Fig. 4 shows the WF of ten crop residues, two wood types and miscanthus (m^3/t). All WFs are dominated by the green WF, while all crops also have a blue and grey WF. The two wood types and miscanthus and sunflower straw have relatively large green WFs. Sugar beet pulp has the smallest total WF. Compared to the WF of crop residues, the WF of miscanthus, an energy crop, has a relatively large WF: 15 times larger than the WF of sugar beet pulp. The total WF of crop residues differs by a factor of 14. The total WFs of eucalyptus and pine are 28 times larger than the total WF of sugar beet pulp. Sunflower straw has the largest value fraction amongst the crop residues, which, in combination with a relatively large total WF before allocation, results in the largest WF of the crop residues. Appendix H gives an overview of all WFs.

Allocating the WF of crop production partly to residues decreases the WF of crops. Table 1 gives the WF of the crop yields (m^3/t) before allocation based on data from Mekonnen and Hoekstra (2011) and after partial allocation of WFs to residues based on the calculations of this study. Soybean, cotton and rice have a high value fraction of the yield compared to the residue. Consequently,

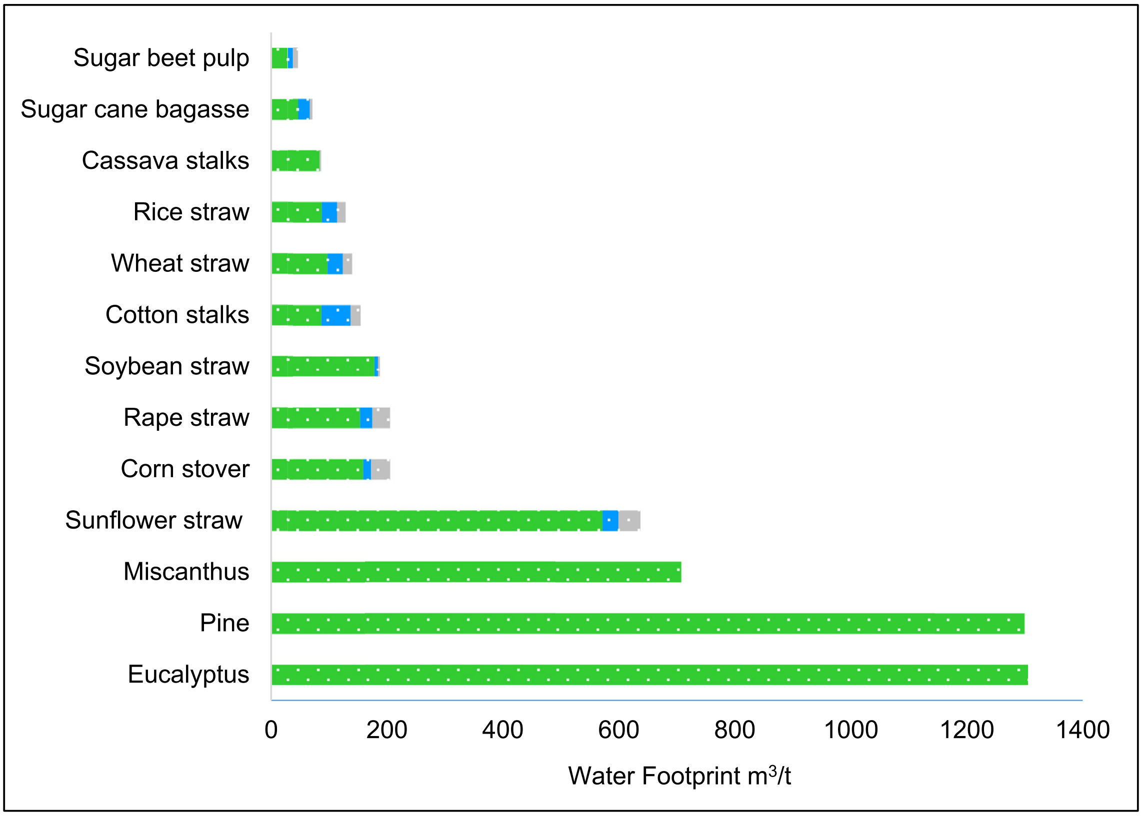

Fig. 4. Green, blue and grey water footprint of 10 crop residues, 2 wood types and miscanthus (m^3/tonne). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Water footprints of crop yields and residues with and without allocation.

Crop	Without allocation to residues	With allocation to residues	
	Water footprint crop yield[a] m^3/t	Water footprint of crop yield[b] m^3/t	Water footprint residue[b] m^3/t
Sugar cane	210	176	72
Corn	1222	961	205
Rice	1673	1523	129
Wheat	1827	1633	140
Sugar beet	132	103	47
Cassava	564	476	87
Soybean	2145	2002	188
Rapeseed	2271	1583	205
Cotton	4029	3796	154
Sunflower	3366	2014	636

[a] Mekonnen and Hoekstra (2011).
[b] This study.

the WF of the crop yield is relatively large. Sunflower, sugar beet and rapeseed have a relatively high residue value fraction and a relatively large WF of the residues.

Fig. 5a shows the WF of pyrolysis oil from crop residues, wood and miscanthus (m^3/t). The ranking order of the WF of crop residues differs from the ranking order of the WF of pyrolysis oil. For example, the ranking order of sugar cane bagasse and sugar beet pulp has changed. Sugar cane bagasse pyrolysis oil has the smallest total WF and sugar beet pulp pyrolysis oil the second smallest WF, despite that sugar beet pulp has the smallest WF of all residues. The reason is the two times larger conversion factor of bagasse to pyrolysis oil compared to pulp to pyrolysis oil. Also, soybean straw pyrolysis oil has a relatively small WF caused by the favourable conversion factor from soybean straw to pyrolysis oil (0.7), the largest among the crops included in here. The pyrolysis oils with the largest total WF are produced from pine and sunflower straw that have moderate conversion factors. Although the WFs of eucalyptus and pine are almost equal, the WF of eucalyptus pyrolysis oil is almost half the WF of pine pyrolysis oil. The conversion factor of eucalyptus to pyrolysis oil is two times larger than the conversion factor of pine to pyrolysis oil.

Fig. 5b shows the WF of bioethanol from ten crop residues, two wood types and miscanthus (m^3/t). We find that, given a certain feedstock, the WF of bioethanol is larger than the WF of pyrolysis oil. Further, the WF of sugar beet pulp bioethanol is relatively small and the WF of pine bioethanol is relatively large. The total WF of sugar beet pulp bioethanol is the smallest of all crops included in here (green WF 117 m^3/t, blue WF 37 m^3/t and grey WF 36 m^3/t).

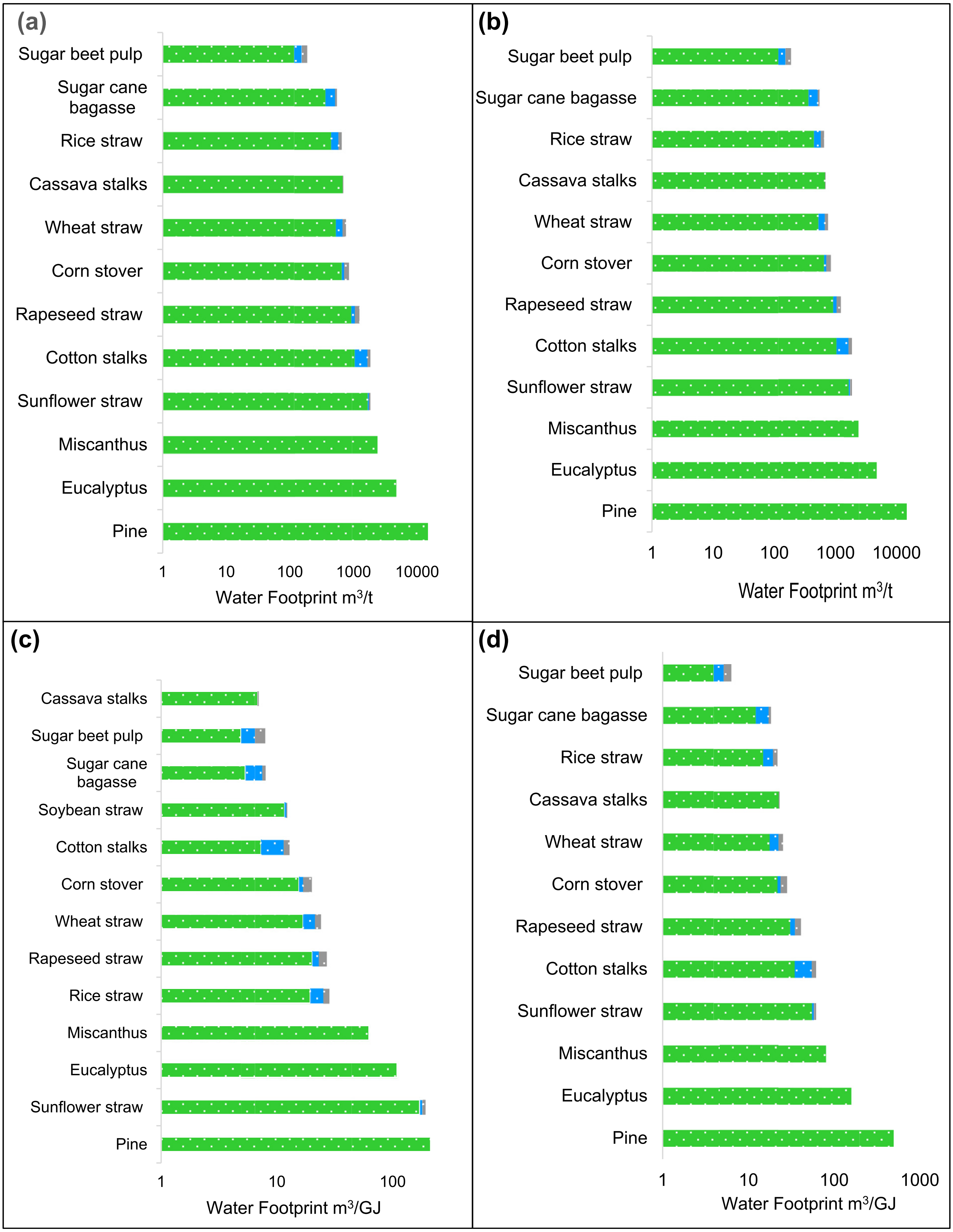

Fig. 5. Green, blue and grey water footprint of pyrolysis oil (a,c) and bio-ethanol(b,d) from 10 crop residues, 2 wood types and miscanthus, in m^3/tonne (a,b) and in m^3/GJ at logarithmic scale (c,d). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The reason is the small WF of the crop residue in combination with the large conversion factor. The total pine bioethanol WF is 14.596 m^3/t, three times larger than the second largest total WF, 4.687 m^3/t for eucalyptus bioethanol. Fig. 5c and d show the WF of pyrolysis oil and bioethanol per unit of energy (m^3/GJ). Sugar cane bagasse, sugar beet pulp and cassava stalks are the feedstock for pyrolysis oil with a relatively small WF per unit of energy, while sunflower straw and pine feedstocks produce pyrolysis oils with a relatively large WF.

For bioethanol, the sugar beet pulp bioethanol WF is relatively small (green 3.94 m^3/GJ, blue 1.25 m^3/GJ and grey 1.2 m^3/GJ), while the pine bioethanol WF is relatively large (green WF 491 m^3/GJ).

Fig. 6 shows the green, blue and grey WF of second-generation bioenergy from crop residues, miscanthus and wood using four different conversion techniques (m^3/GJ): gasification, combustion, electricity from gasification and electricity form combustion.

Fig. 6a shows that the total WF of heat produced by combustion show a large variation, from 5 m^3/GJ (cassava stalks) to 91 m^3/GJ (pine), a difference of a factor of 18. For cotton stalks, with a relatively large energy conversion efficiency, the WF of heat by combustion is the smallest after the WF of cassava stalks and sugar cane bagasse. Fig. 6b shows the WF of heat from gasification (m^3/GJ thermal). When Fig. 6b is compared to 6a, it shows that for eucalyptus, pine, miscanthus, corn stover and wheat straw, the WF of heat from gasification is smaller than the WF of heat from combustion (m^3/GJ thermal). Eucalyptus, pine, miscanthus, corn stover and wheat straw have higher energy conversion efficiencies for gasification compared to combustion and consequently a smaller WF for heat from gasification. The energy conversion efficiencies of electricity are smaller than of combustion. Fig. 6c shows the WF of electricity by combustion (m^3/GJ electrical). When Fig. 6a and c are compared, it shows that the WF of electricity by combustion is larger than the WF of heat by combustion. There are large differences between the WF of electricity by combustion from crop residues and the WF of electricity by combustion from miscanthus, pine and eucalyptus. Fig. 6c shows that sugar cane bagasse has the smallest total WF and eucalyptus the largest. Miscanthus has an over two times larger total WF of electricity by combustion than corn stover, which is the crop residue with the largest WF of electricity by combustion. Fig. 6d shows the WF of electricity by gasification (m^3/GJ electrical) for four crop residues and for miscanthus. Sugar cane bagasse has the smallest WF, miscanthus electricity from gasification the largest. As a result of the higher energy conversion efficiencies of electricity by gasification compared to electricity by combustion, the WF of electricity by gasification is smaller than the WF of electricity by combustion. Nevertheless, the WF of electricity by gasification is larger than the WF of heat by gasification.

Fig. 7 shows the WF of pyrolysis oil, bioethanol, heat from combustion or gasification and electricity after combustion or biomass gasification per feedstock for ten crop residues, two wood types and one energy crop (m^3/GJ). Some feedstocks have more products than others. Our calculations for products from different feedstocks were based on conversion efficiencies or conversion factors we found in literature. Therefore, some WF values are missing, like for soybean straw bioethanol and sugar beet pulp combustion.

In general, the WF of second-generation bioenergy from crop residue feedstocks is relatively small, while the WF of miscanthus, sunflower straw, pine and eucalyptus are relatively large.

4. Discussion

Energy production can be measured as gross or net production. Gross energy production refers to the total output of energy, without deduction of energy inputs along the production chain. Net energy production deducts all the energy inputs, including energy inputs in agriculture. In the production chain of bio-ethanol, for example, energy inputs include the energy used for the production of fertilizers and pesticides, for irrigation, and for electricity and transport (Pimentel, 2003). This study has calculated water footprints per unit of gross energy produced. Energy use in the production chain was excluded. The energy balance changes when energy inputs in the chain are taken into account. For example, for sugarcane ethanol, the energy return on energy investment (EROI) is 0.8–10 (Murphy and Hall, 2010). Consequently, with an EROI of 5 as an example, the WF per unit of net energy produced is (EROI/(EROI-1) = 5/(5 − 1) =) 1.25 times larger than the WF per unit of gross energy produced.

Freshwater is not only needed in agriculture, but also in the production chain when feedstock is converted to bio-energy. However, the quantities needed are relatively small, so that overall WF is dominated by the WF in agriculture. For example, cooling water is needed for electricity production. Water may be used for machinery cleaning as well. For example, the process water of a sugar cane mill with an annexed distillery for ethanol is 0.021 m^3 per kg of processed cane (De Carvalho Macedo, 2005). This study assumed that 7.6 kg of sugar cane bagasse is needed to produce 1 kg of bioethanol. The WF of bagasse bioethanol is 546 m^3/kg, while the process water is only 0.16 m^3/kg. This amount of water is so small that it does not influence the blue WF. Also other processes, like the production of pulp or sugar from sugar beet, consume zero or a small amount of process water (Gerbens-Leenes and Hoekstra, 2012).

Miscanthus does not directly compete with food, but it has the largest WF of all biomass feedstocks studied here except wood. In this way, it indirectly competes with food. The results indicate that miscanthus is not a favourable crop for energy purposes from a water perspective, because crop residues have a smaller WF. Additionally, food crops produce food while miscanthus does not.

The results of this study indicate that two of the globally most produced crops, sugar cane and cassava, have crop residues with a relatively small WF. Moreover, these crops are predominantly produced in developing countries, indicating that developing countries have greater potential to produce sustainable bioenergy than developed countries.

The method used in this study can be applied for WF calculations of any crop residue, for example for residues applied for animal feed, but also for by-products in the energy conversion processes studied here. This study did not consider by-products from the processes that generate bioethanol, pyrolysis oil, combustion heat, gasification heat or electricity, while various energy conversion technologies actually generate useful by-products. For example, apart from heat, gasification also generates syngas or pyrolysis oil. Combustion and pyrolysis produce biochars. For example, when corn stover is pyrolysed, 17% of the pyrolysis products are biochars (Mullen et al., 2010). In this way, the WF of the main product is overestimated.

Residue and yield prices determine the value fraction, which determines the allocation of the WF over the residue and the yield. This study calculated the WF based on prices for one particular year and country and assumed that these prices apply globally. However, prices vary among countries and in time causing WF variation. For example, the corn stover price used for this study was 0.038 $/kg (USA - 2003) but the price went up to 0.075 $/kg in 2012 (Edwards, 2015). As a result, the green WF of corn stover almost doubled from 0.16 m^3/kg to 0.26 m^3/kg, while the green WF of corn (corn ear) dropped from 0.75 m^3/kg to 0.63 m^3/kg.

This study used global WF data and average values of HHV, HI, energy conversion efficiencies and conversion factors. All these values vary within certain ranges and differ among regions, crop varieties, seasons and countries. Consequently, countries with high crop yields may have smaller WFs and countries with low crops yields the opposite.

5. Conclusion

From a freshwater perspective, it is efficient to apply crop

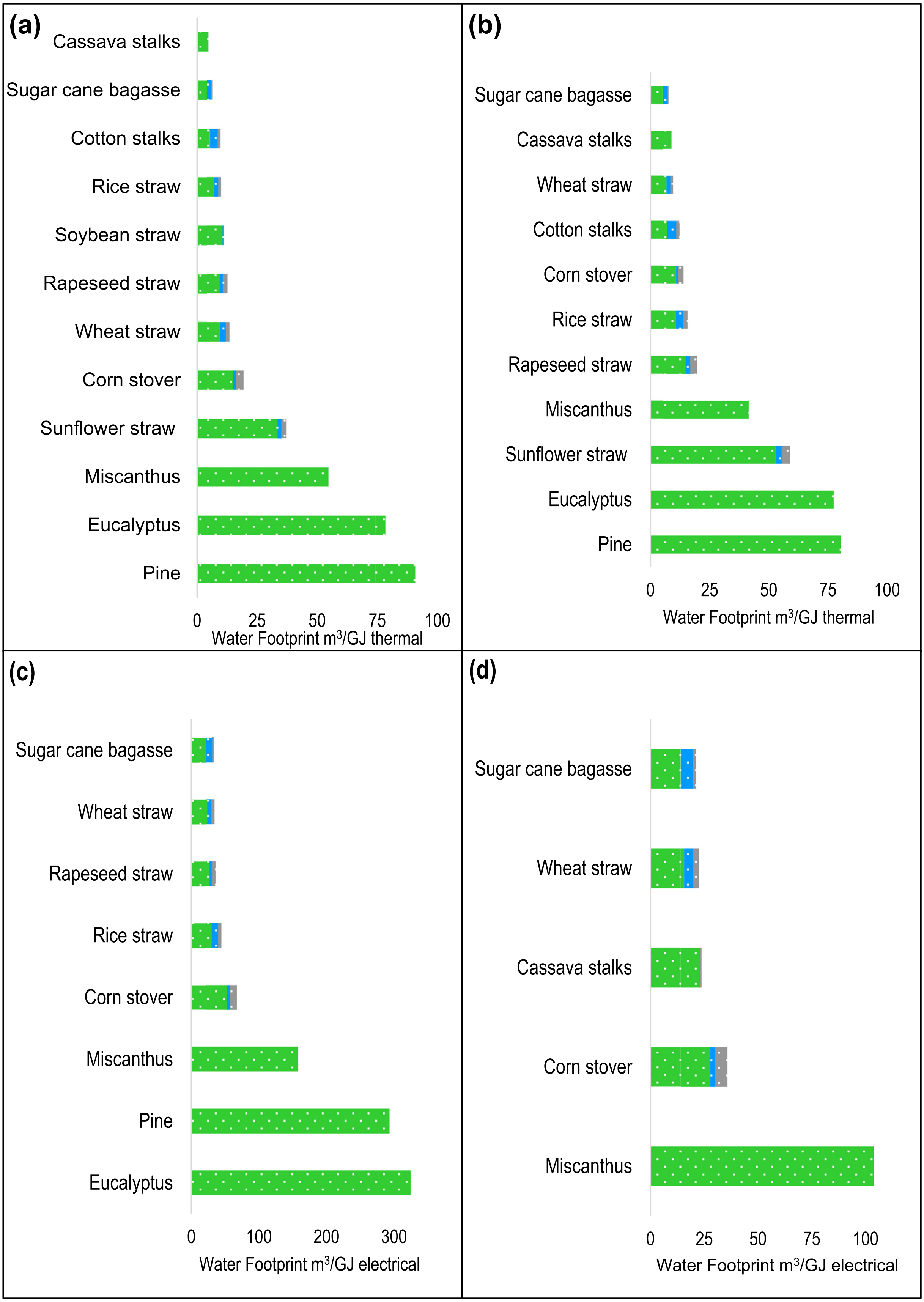

Fig. 6. Green, blue and grey water footprints of second-generation bioenergy from crop residues, miscanthus and wood using four different conversion techniques (m^3/GJ): (a) combustion, (b) gasification, (c) electricity generation after combustion and (d) electricity generation after gasification. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

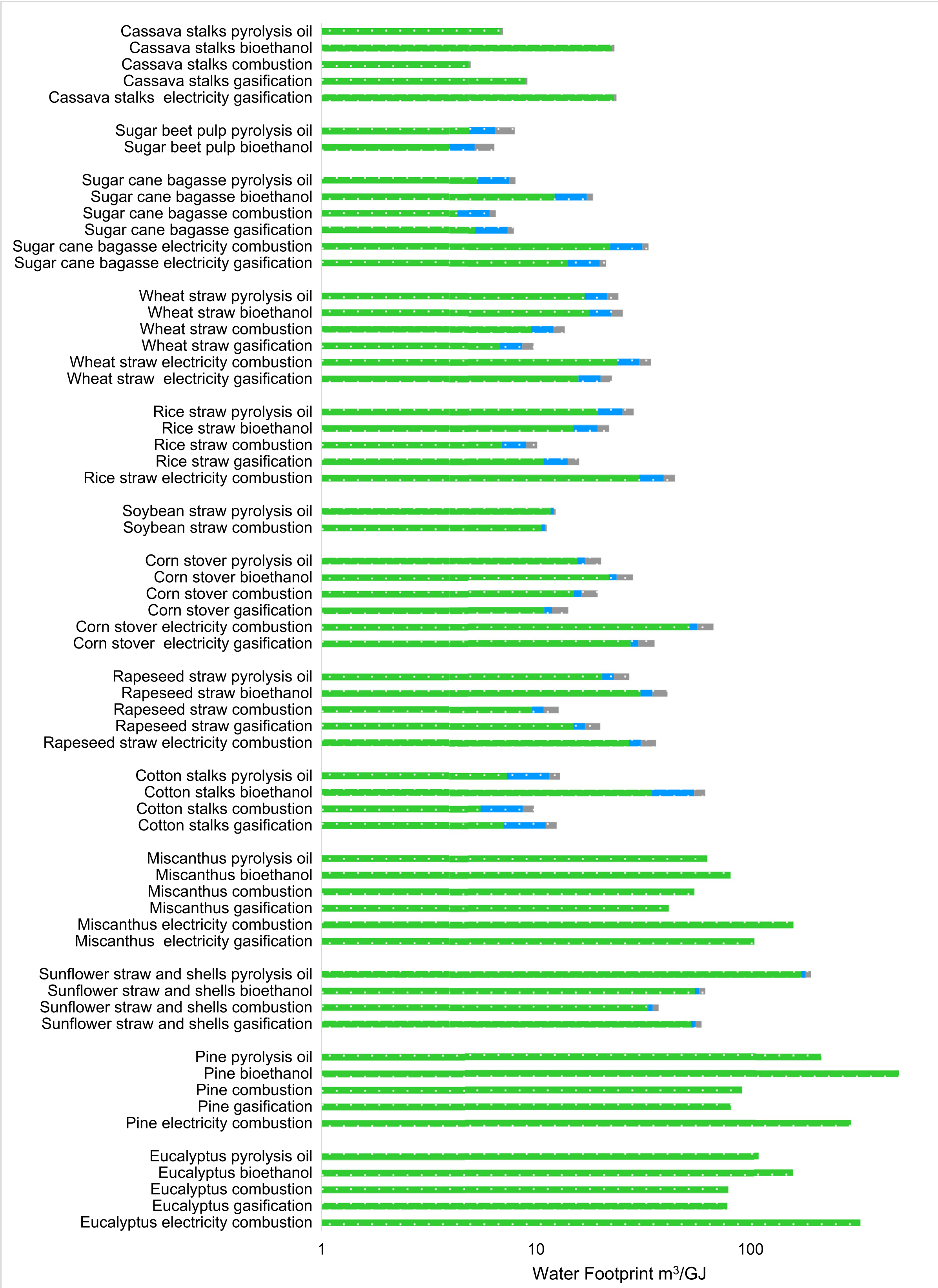

Fig. 7. Green, blue and grey water footprint of pyrolysis oil, bioethanol, heat and electricity from 10 crop residues, 2 types of wood and miscanthus. Logarithmic scale. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

residues to produce second-generation bioenergy. The water footprint (WF) of crop residues is favourable when compared to miscanthus, eucalyptus or pine. Available conversion techniques to convert the biomass to heat and electricity or to energy carriers (ethanol and pyrolysis oil) have different efficiencies, resulting in a different WF per unit of energy generated. The total WF of residue feedstocks from cassava, sugar beet, sugar cane, wheat, rice, soybean, corn, rapeseed and cotton ranges between 5 and 67 m^3/GJ. Pine and eucalyptus have the largest WF, between 77 and 491 m^3/GJ. The WF of heat from combustion (5–91 m^3/GJ) or from gasification (8–80 m^3/GJ) is similar. The WF range for pyrolysis oil (7–213 m^3/GJ) is comparable to the range for bioethanol from fermentation (6–491 m^3/GJ), but given a certain feedstock, the WF of pyrolysis oil is smaller than the WF of bioethanol from fermentation. It is more efficient to generate electricity by gasification than by combustion. The WF of electricity by gasification lies between 21 and 104 m^3/GJ; the WF of electricity by combustion ranges from 33 to 324 m^3/GJ.

This study provides the first detailed analysis of the WF of second-generation bioenergy, comparing different types of biomass feedstock and alternative conversion techniques. The study gives an overview of the state-of-the-art efficiencies and conversion factors of techniques to produce second-generation bioenergy from residue feedstocks. Given the potential of bioenergy from crop residues, the study contributes useful information to choose wisely amongst different alternative forms of second-generation bioenergy. A drawback of first-generation bioenergy is that it competes with food, while second-generation bioenergy from crop residues does not. Crop residues form a potentially sustainable feedstock for bioenergy, in this way decreasing carbon dioxide emissions without increasing the use of natural resources like freshwater.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2017.02.032.

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