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Discussions

Global scenarios of irrigation water use for bioenergy production: a systematic review

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Abstract. Many scenarios of future climate evolution and its anthropogenic drivers include considerable amounts of bioenergy as fuel source, negative emission technology, or for final energy production. The associated freshwater requirements for irrigation of dedicated biomass plantations might be substantial and therefore potentially increase water limitation and stress in affected regions; however, assumptions and quantities of water use provided in the literature vary strongly. This paper reviews existing global assessments of freshwater requirements for such bioenergy production and puts these estimates into the context of scenarios for other water use sectors. We scanned the available literature and (out of 430 initial hits) found 16 publications (partly including several scenarios) with reported values on global water demand for irrigation of biomass plantations, suggesting a range of 125–11,350 $\mathrm{km^3\,yr^{-1}}$ water use (consumption), compared to about $1,100$–11,600 $\mathrm{km^3\,yr^{-1}}$ for other (agricultural, industrial, and domestic) water withdrawals. To provide an understanding of the origins of this large range, we present the diverse underlying assumptions, discuss major study differences, and make the freshwater amounts involved comparable by estimating the original biomass harvests from reported final energy or negative emissions. We conclude that due to the potentially high water demands and the trade-offs that might go along with them, bioenergy should be an integral part of global assessments of freshwater demand and use. For interpreting and comparing reported estimates of possible future bioenergy water demands, full disclosure of parameters and assumptions is crucial. A minimum set should include annual blue water consumption and withdrawal, bioenergy crop species, rainfed as well as irrigated bioenergy plantation locations (including total area), and total bioenergy harvest amounts.

1 Introduction

Projections of future energy demand and its partitioning increasingly assume replacement of carbon-intense fossil energy carriers with biomass, which could provide carbon-neutral energy or fuels (Nakićenović et al., 1998; Rose et al., 2014; Bauer et al., 2018). However, in order to limit mean global warming to 2 °C or even 1.5 °C (UNFCCC, 2015), technologies providing additional negative emissions (NEs) are potentially needed to compensate for residual and past emissions (Rockström et al.,

Table 1. List of abbreviations

BECCS	bioenergy with carbon capture and storage
BP	bioenergy plantation
CCS	carbon capture and storage
c_{eff}	carbon conversion efficiency
DGVM	dynamic global vegetation model
EFR	environmental flow requirement
ESM	earth system model
IAM	integrated assessment model
NE	negative emission
NET	negative emission technology
PyCCS	pyrogenic carbon capture and storage
SSP	shared socioeconomic pathway

2017; Minx et al., 2018; Rogelj et al., 2018). One such NE technology (NET) is bioenergy with carbon capture and storage (BECCS). Bioenergy utilizes plants' photosynthetic capacity to make available energy from sunlight in biomass, whereby CO_2 is extracted from the atmosphere but at the same time water is consumed from the soils. Due to the large amount of potentially needed NEs in the second half of the century (e.g. $3.3\,\mathrm{GtC\,yr^{-1}}$, Smith et al. 2016; 2–$5\,\mathrm{GtC\,yr^{-1}}$, Rogelj et al. 2015), the feedstock will probably have to be grown on large managed plantations and include substantial irrigation. Suggested energy carriers are either energy-rich plant organs (e.g. rapeseed, oil palms, sugarcane) to be directly converted to biofuels (first-generation bioenergy) or pure biomass from fast-growing plants such as maize, *Miscanthus*, switchgrass, willows or *Eucalyptus* (Yuan et al., 2008; Soccol et al., 2016), i.e. second-generation bioenergy. These diverse plants have different growth rates, preferred climatic zones, and also – depending on the location where they are projected to be grown – different freshwater demands.

While burning of fossil energy carriers leads to (net positive) emissions of greenhouse gases, use of bioenergy is net neutral apart from land-use and process-chain emissions (e.g. from transport or conversion) (Al-Ansari et al., 2017). Thus, use of bioenergy can offset other carbon-intensive means of energy generation, such as coal, gas, or oil (Gough et al., 2018; Fajardy and Mac Dowell, 2017). To provide respective NEs, bioenergy use needs to be complemented by means of carbon storage. Proposed methods include pyrogenic carbon capture and storage (PyCCS - Werner et al. 2018; Schmidt et al. 2019), BECCS (Azar et al. 2006; Lenton 2010), or other long-term storage preventing a release of the captured carbon back to the atmosphere. For a comprehensive analysis of carbon capture technologies, see for example Markewitz et al. (2012).

In assessments of water use for bioenergy plantations (BPs), it is important to consider that they can be either purely rainfed or (partially) irrigated. Plantations of the former type would be completely dependent on "green" precipitation water stored in soils (Wang et al., 2017), while the latter additionally include more or less pronounced use of "blue" water from

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lakes, rivers, reservoirs and aquifers (Hoekstra et al., 2009) – in this review, we focus on the latter since the required high biomass productivity promotes irrigation to reduce trade-offs with e.g. food production. Li et al. (2018) report at least 15% (and potentially much more due to most studies not reporting this parameter) of field experiments with lignocellulosic bioenergy crops to be irrigated, suggesting that also productive use might use irrigation to maximize yields.

Ranges for the green water demand of bioenergy range from below 50 to over 3,000 $\mathrm{km}^3\,\mathrm{GtC}^{-1}$ of biomass harvest (King et al., 2013; Séférian et al., 2018; Smith and Torn, 2013; Smith et al., 2016; Varis, 2007). Additionally the process chain from biomass to NEs requires water as well, but has rarely been quantified (e.g. in Smith et al. 2016). This might be because large-scale CCS is not yet in place and the process of conversion to energy and subsequent long-term storage is usually not modeled in detail by the existing models (one exception is Fajardy et al. 2018, who also include polluted ("gray") water from the biomass processing chain).

The blue water requirements can be expressed as water withdrawals (gross extraction from rivers, lakes, reservoirs; sometimes also referred to as water use) or as water consumption (eventual evapotranspiration, excluding return flows to the rivers and water bodies that may occur after withdrawal). As an umbrella term, if we can not be more specific, we use "water demand" or "water requirements" throughout the manuscript. The potentially large quantities of blue water use assumed for BP irrigation, which may occur in competition with other water uses and may increase water stress in relatively water-scarce regions where BPs are considered, motivates a comprehensive understanding and quantification of their intrinsic water demands (Hejazi et al., 2015; Wada et al., 2014). So far there have been review studies on the potentials of BECCS and other NE technologies by e.g. Creutzig et al. (2015), Smith et al. (2016) and Fuss et al. (2018), which however do not provide a comprehensive overview of the associated freshwater requirements (besides their precursory mentioning). The BECCS demand, and thereby presumably the respective water demand, is projected to be especially high in ambitious climate scenarios limiting global warming to 2 °C or below in 2100.

Thus, the subject of the present paper is to fill this knowledge gap and systematically review the current literature on projected freshwater requirements in global NE or energy scenarios relying on BECCS/bioenergy. It is guided by the following questions:

1. What is the global freshwater demand for irrigation of bioenergy plantations in the future as projected in available global-scale studies?
2. How does this amount compare to other sectors?
3. What are the key modelling parameters and assumptions of global bioenergy studies that affect the inherent water demand projections?
4. Is there a dependence between the simulated freshwater requirements and the total global biomass production across studies?

The resulting literature corpus consists of 16 publications containing a total of 34 scenarios. In principle one could also include local or regional studies, but their numbers cannot be straightforwardly compared with the global studies (i.e. a different

```
("BECCS" OR "bioenergy production" OR "bioenergy
cultivation" OR "bioenergy crop*" OR "biomass
production" OR "biomass plantation*")
AND (( "water" AND ("use" OR "demand" OR
"consumption" OR "withdrawal")) OR "irrigation")
AND ("global")
NOT ("algae" OR "algal" OR "electrofuels")
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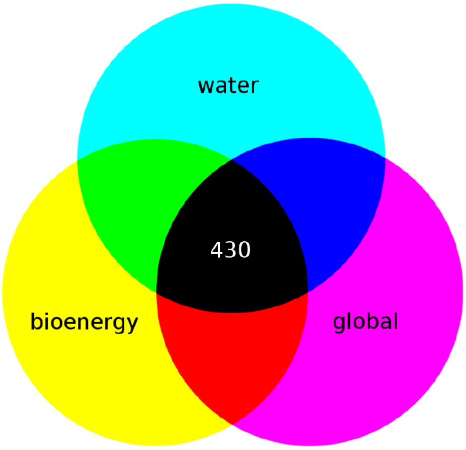

Figure 1. Search query used for the WebOfScience and SCOPUS databases. We found 430 publications, from which 15 had quantified values for the global freshwater demand of BPs.

reference region) and also cannot be simply up-scaled. Furthermore, it would be difficult to compare the BECCS water use with water uses of other sectors in the affected regions, as the latter are often not reported in those studies.

We reveal a large range of existing estimates and put these in context with ranges of future projections of water use and consumption for other sectors (agriculture, industries, households), which according to our best knowledge has not been demonstrated so far. This analysis will also include an attempt of systematizing the existing studies, as they often have distinct assumptions about indirect factors influencing the water use, such as the targeted bioenergy production and the underlying land use patterns and management.

2 Methods

2.1 Literature search query

We scanned the WebOfScience, as well as the SCOPUS database on February 05, 2020 with a query covering all global BECCS and bioenergy studies that mention use, consumption, withdrawal, or demand of water in their abstract, keywords, or title (Figure 1) and excluded studies which focus on algae or electrofuels.

From the resulting 430 studies, we removed all those, which did not deal with BPs or BECCS at all, had only a regional scope, or only gave qualitative estimates of the freshwater demand of large-scale BPs (going from title to abstract to full text). The global bioenergy studies with water demand values King et al. (2013); Smith et al. (2016); Smith and Torn (2013); Varis (2007); Séférian et al. (2018) were included as supplementary "green water studies" in our corpus, because they did not consider irrigation, but only transpired green water (and CCS process water in the case of Séférian et al. 2018). We manually added the study by Hejazi et al. (2014) which did not show up in the systematic query described above. The resulting total of

16 "blue water" publications (+ 5 "green water") are listed in Table A1. Noticeably, the majority of publications is very recent – only two of them were published before 2010 (Figure 2).

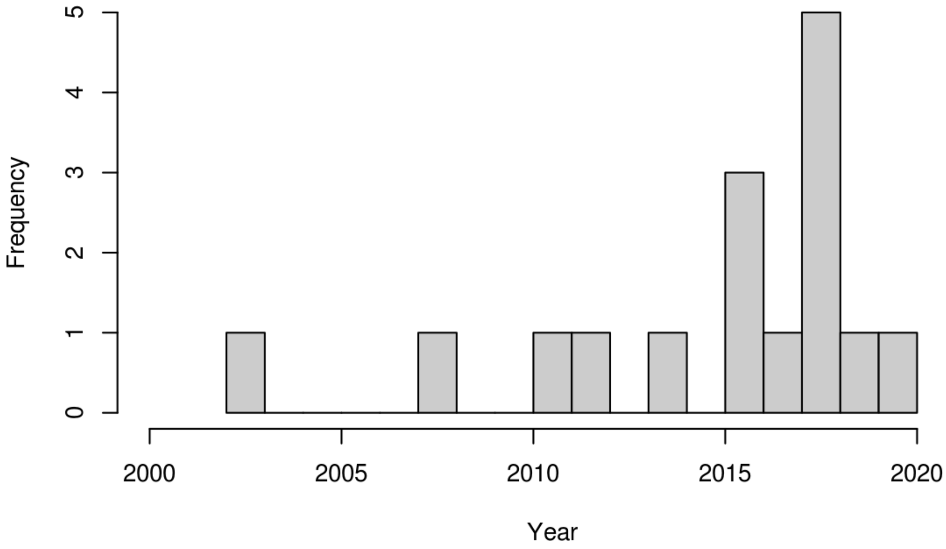

Figure 2. Frequency of found global-scale studies on the freshwater demand of bioenergy plantations, with publication dates from years 2002 to 2020.

2.2 Comparing BECCS water demand estimates

95 Comparison of the literature values of water demand for BECCS is not straightforward, because of the different assumptions studies made on important model parameters and setups, as described in the section Study differences. Nevertheless, besides presenting the absolute global estimates of freshwater use and consumption, we attempt to make the results of these studies directly comparable: The degree of assumed bioenergy deployment varies strongly among studies, which is why we relate the given freshwater demand to the absolute amount of biomass assumed to be grown. With this we quantify the estimated water demand per harvested biomass. For the analysis, we separated the scenarios into those that report water demand per energy unit supplied from bioenergy ("energy studies") and those that report NEs along with estimates of related withdrawals or consumption ("NE studies"). From the energy studies, we could backtrack the approximate dry biomass harvests by using the gross calorific value of $18.5\,\mathrm{MJ\,kgDM^{-1}}$ (Haberl et al., 2010; Brosse et al., 2012). This is equivalent to $37\,\mathrm{MJ\,kgC^{-1}}$ or $37\,\mathrm{EJ\,GtC^{-1}}$, with the average carbon content of dry biomass of $0.5\,\mathrm{kgC\,kgDM^{-1}}$ (Schlesinger and Bernhardt, 1991, p.120) (Equation 1).

$$initial\ biomass\ harvest_{from\ energy}\ [\mathrm{GtC}] = \frac{energy\ [\mathrm{EJ}]}{37\,\mathrm{EJ\,GtC^{-1}}} \tag{1}$$

With this we approximated the initial biomass harvest from the reported bioenergy supply, however neglecting losses during processing, if they were considered. Note that using one value for carbon content of biomass is an oversimplification, naturally

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the value depends on the bioenergy crop type (Ma et al., 2018). Therefore, for ideal comparability not only the feedstock type, but also the harvest shares would need to be reported. For NE studies that documented an assumed carbon conversion efficiency (c_{eff} – the fraction of carbon from biomass harvest that is eventually sequestered and removed from the carbon cycle), we derived the dry biomass harvest by division of the NE amount by c_{eff} (Equation 2). Since transport and other losses are usually contained in c_{eff}, the inferred initial biomass values for NE studies are probably more reliable than those for energy studies.

$$initial\ biomass\ harvest_{from\ NE}\ [\mathrm{GtC}] = \frac{NE\ [\mathrm{GtC}]}{c_{eff}} \tag{2}$$

Some studies assume also the use of residues from agriculture and forestry (Beringer et al., 2011; Fajardy et al., 2018), timber harvest from land-use conversion (Heck et al., 2018; Stenzel et al., 2019), municipal solid waste, or animal manures (Beringer et al., 2011) as bioenergy feedstock. Respective amounts, however, are only reported in Beringer et al. (2011)). We may therefore overestimate the raw bioenergy harvests or conversely underestimate the water demand per unit of biomass from dedicated BPs.

3 Results and Discussion

3.1 Overview

We synthesized the results from the 16 publications into 34 scenarios (with similar parameters) of freshwater demand for bioenergy (the full data-set is available as Stenzel et al. 2020). As freshwater requirement we extracted reported estimates of blue water consumption or withdrawals, with a preference on consumption.

There are further studies on global (evapo-)transpiration for designated bioenergy production, who however either do not consider irrigated BPs (Séférian et al., 2018; Smith and Torn, 2013; Smith et al., 2016), or do not specify, where the source of the transpired water is (King et al., 2013; Varis, 2007). Since this review focuses on freshwater abstractions for bioenergy and not on "green" water, they were not included in the main analysis.

We focus on blue water requirements, since they are directly competing with other human water demands and those of aquatic ecosystems, potentially increasing overall water stress. It is unfortunate that there are not more publications fitting our scope, but we believe this does not make our review any less valuable. The right time to provide this review is now, since decisions for large-scale bioenergy implementation are about to be made rather sooner than later. All of the found studies also consider rainfed plantations that depend solely on green water stored in the soil (with top-up irrigation if necessary), however the amount of evapotranspired green water is only reported in a few of them. An overview of studies reporting green water requirements of bioenergy found in our literature query is given in Figure A2. We emphasize that due to the missing component of green water evapotranspiration in scenarios of irrigated BPs, scenarios focusing on either blue or green water demands are not really comparable.

3.2 Study differences in parameters choices and other assumptions

According to our literature review, estimating future global water demands of BPs is being approached with a variety of models and methodologies. Berndes (2002) use projections based on measured evapotranspiration fluxes from field studies (e.g. Berndes and Borjesson 2001), combined with bioenergy demand scenarios (e.g. Nakićenović et al. 1998, p.72–75). Hu et al. (2020) use a similar approach by inversely calculating biomass harvest demands for RCP2.6 (Vuuren et al., 2011) for three scenarios of carbon conversion factors, combined with literature values of water use efficiencies for two C4 grasses. Most studies rely on numerical simulation models, based on an energy (or NE) trajectory controlling the location, productivity and eventually water demand of BPs (here referred to as “demand studies”), or the aim to find the maximum energy (or NE) potential within given constraints of available land, water restrictions or management (“potential studies”). Examples for the former category of studies are de Fraiture et al. (2008); Mouratiadou et al. (2016); Humpenöder et al. (2018); Stenzel et al. (2019) and for the latter category Beringer et al. (2011); Jans et al. (2018); Fajardy et al. (2018).

While Berndes (2002) and Hu et al. (2020) derived their results mainly from meta-analyses of existing literature and approximations of global water demands by extrapolating current water use efficiencies for future energy demand scenarios, others are based on simulations from quite sophisticated global process models of different type. Bonsch et al. (2016), Mouratiadou et al. (2016), and Humpenöder et al. (2018) used the MAgPIE agroeconomic model determining the water use of BPs under different scenario constraints. Bonsch et al. (2016) specifically investigated the trade-offs between area and water demand, comparing rainfed and irrigated BPs, while Humpenöder et al. (2018) analyzed environmental and socioeconomic indicators in bioenergy scenarios. The majority of studies considered here (Beringer et al., 2011; Heck et al., 2016; Boysen et al., 2017; Heck et al., 2018; Jans et al., 2018; Stenzel et al., 2019) were based on a single dynamic global vegetation model (DGVM), LPJmL, yet using different model setups and imposing varied constraints to water availability and use (biophysical potentials from LPJmL were also used as input to MAgPIE-based studies). Main study goals were global bioenergy potentials and the associated trade-offs with global water use, plantation area demand or planetary boundaries.

The water (and land) implications of an increasing biofuel production in the future were analyzed by de Fraiture et al. (2008) with the water use model WaterSIM and Gerbens-Leenes et al. (2012) with the agricultural decision support tool CROPWAT. Yamagata et al. (2018) assessed the impact of large-scale BECCS deployment on land use, water resources, and ecosystem services using the global hydrological model H08 together with the terrestrial ecosystem model VISIT. Fajardy et al. (2018) base their analysis of the whole BECCS supply chain on the MONET value chain model, while Hejazi et al. (2014) employ a combination of GCAM (an integrated assessment model – IAM) in conjunction with the global hydrological model GWAM to quantify global water scarcity under several future climate change scenarios.

Hence, the modeling approaches used are very different, with each model focusing on a different part of the BECCS deployment process. While Earth System Models (ESMs – no example here) dynamically represent large-scale feedbacks between atmosphere, ocean and biosphere with comparably less process detail regarding human management of the biosphere including BPs, IAMs focus on future developments of e.g. land and water use based on biophysical and economic boundary conditions – explicitly accounting for decisions on BP locations and resource use. In contrast, climate or land use patterns are typically prescribed to crop/vegetation and hydrological models, which in turn usually operate at higher spatio-temporal resolution and provide more process-based interactions especially regarding the simulation of water availability and requirements. If deriving global estimates of BP freshwater use or consumption is an aim of a study, more straightforward and computationally inexpensive estimations might suffice. Value chain models might be best suited if the details of the BECCS process chain are of most interest. Studies which model future bioenergy, usually consider climate projections as input to their simulations, which significantly determines the water availability, since climate change impacts local rainfall patterns as well as potential evapotranspiration.

There could be potential bias of the dataset due to one model providing data for the majority (LPJmL; 9 out of 16 including studies based on the MAgPIE model that uses some input from LPJmL) of the studies, however these studies also differ in terms of land type and area used for bioenergy cultivation, irrigation management, or structural parameters (carbon conversion efficiency/bioenergy demand trajectory) as can be seen in the spread in Figure 4 and the supplementary data (Stenzel et al., 2020).

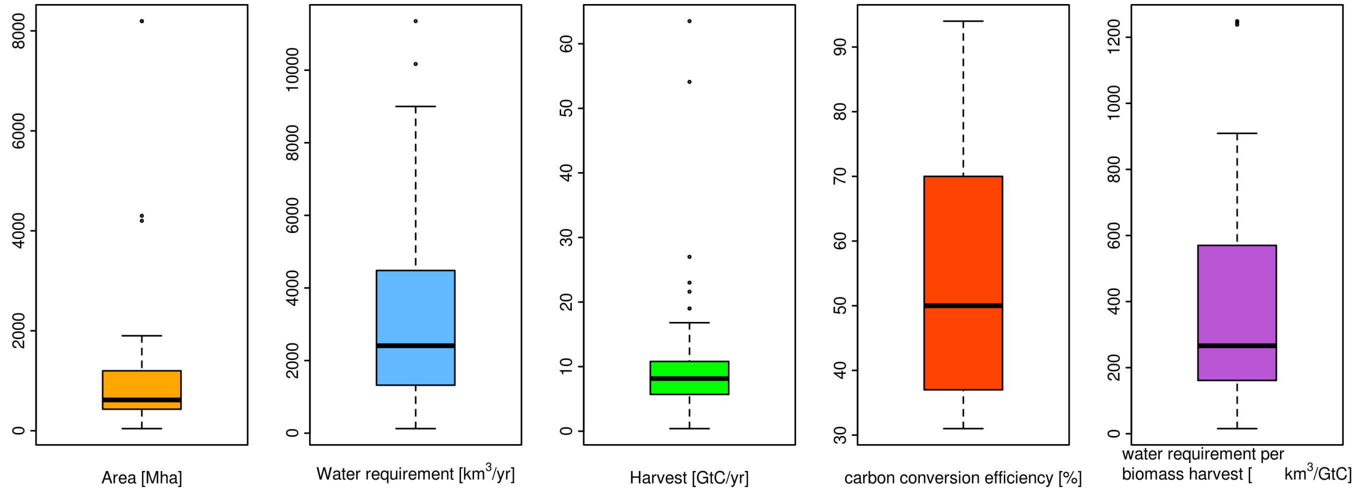

Figure 3. Range of key parameters (global estimates) determining projections of water requirements for bioenergy in the scenarios examined (see supplementary data Stenzel et al. 2020) presented as boxplots. Note that plantation area and carbon conversion efficiency are not reported in all studies. Water requirements per biomass harvest are calculated for each scenario, using the means of water demand and biomass harvest if ranges are given.

The global potential plantation area identified as suitable for BPs differs hugely in size between $42\,\mathrm{Mha}$ in de Fraiture et al. (2008) (only biofuels) and $8{,}195\,\mathrm{Mha}$ in Hejazi et al. (2014) with the median area being $616\,\mathrm{Mha}$ (see Figure 3 and Figure A1). Reported maps show locations scattered around the globe (Stenzel et al., 2019), with clusters in Central Europe, North and South America and North-East China in Beringer et al. (2011) or South America and Central Africa in Bonsch et al. (2016). Note, however, that BP area size and especially locations together with the location specific water use maps are not reported in every study, but would be crucial to compare and interpret the projected magnitudes of global freshwater consumption as determined by the water availability and requirements in the respective locations (King et al., 2013). Studies without explicit bioenergy locations thus need to be interpreted with caution. The reported land types, which are projected to be converted to bioenergy plantations, show a large variety covering marginal land (e.g. Smith et al. 2016), natural vegetation (e.g. Jans et al. 2018), partially excluding protected or vulnerable lands (e.g. Beringer et al. 2011). Some studies create new overall land-use patterns based on spatial and temporal optimization of costs (e.g. Humpenöder et al. 2018) or environmental impacts (e.g. Heck et al. 2018), others use existing exogenous projections for designated bioenergy plantation area (e.g. from RCP2.6-based studies in Boysen et al. 2017). Conversion of cropland to bioenergy plantations is generally avoided (except in Yamagata et al. 2018 and Heck et al. 2016).

Within the studies that explicitly model irrigation of BPs, there is also strong variation in the parameterization of the irrigation systems. Some studies allow potential irrigation, i.e. assuming unlimited availability of (non-)renewable surface and groundwater and neglecting feedbacks resulting from water demands higher than available resources (Hejazi et al., 2014). Conversely, irrigation is in some studies simulated to be constrained by surface water availability (Beringer et al., 2011; Heck et al., 2016), or even further constrained by additionally accounting for so-called "environmental flow requirements" (EFRs) to be withheld for protection of riverine ecosystems (Jans et al., 2018; Humpenöder et al., 2018; Stenzel et al., 2019). Additionally, the water losses due to different efficiencies of irrigation systems can in theory vary between <30% for surface irrigation and >70% for drip irrigation (productive share of the withdrawals) (Jägermeyr et al., 2015). Irrigation efficiencies for BPs are typically assumed to be rather on the upper end of this range (e.g. 66% in Humpenöder et al. 2018). Also the fraction of plantations that are allowed to be irrigated is varying a lot. In their "IrrExp" scenarios, Stenzel et al. (2019) e.g. allow for irrigation on all plantations which would benefit from this irrigation, only constrained by the availability of surface water and EFRs, while their "TechUp" and "Basic" scenarios are limited to 30% of irrigated areas, those with high water productivities preferred.

The majority of scenarios consider C4 grasses like *Miscanthus* or switchgrass (29/34), temperate (18/34), and tropical tree species (17/34) as bioenergy feedstock (e.g. Boysen et al. 2017; Yamagata et al. 2018; Heck et al. 2018). Among the studies are only two which consider first-generation bioenergy plants as feedstock like rapeseed, oil-palm, or sugar cane (de Fraiture et al., 2008; Gerbens-Leenes et al., 2012).

Some models assume productivity changes in the bioenergy harvest over the 21st century based on previous productivity increases observed in crop harvests. These however might be more difficult to reach, since for second-generation bioenergy crops all aboveground biomass can be used for energy production, instead of only a small ratio as in the case of food crops (Krausmann et al., 2013).

For demand studies crucial (but mostly exogenous) parameters are the starting year and trajectory for the BECCS demand, e.g. whether deployment is assumed to start e.g. in 2015 (Humpenöder et al., 2018) or in 2030 (Stenzel et al., 2019). There is quite some variety in trajectories of the energy (or NE) demand (Boysen et al., 2017; Hejazi et al., 2014; Berndes, 2002), which could potentially also change the freshwater demand of these scenarios for the 21st century significantly, since higher yearly biomass yield demands which might arise from later deployment start might make more irrigation necessary at the end of the century. The yearly water demand values given in the studies are not always indicative of an average irrigation water demand per year, since demand studies mostly report end of study period values (e.g. mean 2090-2099) where irrigated areas are at their maximum.

An important parameter in the BECCS process chain (and indirectly influencing the water demand of BPs) is the carbon conversion efficiency (c_{eff}), which we define as the overall fraction of harvested biomass carbon that can be sequestered and thus removed from the carbon cycle. Gough and Vaughan (2015) report the capture rates of the CCS processes to be 85–90%, but these are only the losses in the last step of the process chain. Smith and Torn (2013) give an overall conversion efficiency of 47% for typical BECCS process chains. For our literature corpus, c_{eff} (if reported at all) ranges from 31–33% (Bonsch et al., 2016; Fajardy et al., 2018; Yamagata et al., 2018) to 94% (Hejazi et al., 2014) (Figure 3).

As already briefly discussed in the context of irrigation parameters, the studies from our literature corpus consider some other constraints to large-scale BECCS implementation, which are likely to also influence their freshwater demands. Limiting human intervention with the environment, specifically by respecting planetary boundaries (Rockström et al. 2009; Steffen et al. 2015) might limit the BECCS potential significantly as shown by Heck et al. (2018). Similarly, Bonsch et al. (2016) identify a trade-off between irrigation water and plantation area demand, which corresponds to trade-offs with planetary boundaries for freshwater use, biosphere integrity and land-system change. Additionally economic constraints such as the accessibility of BPs, their distance to cities where most energy is needed, and the availability of large geologic storage capacity close to the locations of energy consumption are to be mentioned as further determinants of bioenergy water demand and use (e.g. considered in Fajardy et al. 2018).

3.3 Projections of global irrigation water demand for bioenergy plantations

According to the model-structural differences, scenarios and methodologies described in Study differences, projections of potential future freshwater requirements for irrigation of BPs greatly vary between 125 and 11,350 $\mathrm{km^3\,yr^{-1}}$. Extreme cases are the FFICT-B2 scenario by Hejazi et al. (2014) and the Food First (FF) scenario by Jans et al. (2018), who simulate BP cultivation on 4,000–8,000 Mha with associated water demands of 5,500–9,000 $\mathrm{km^3\,yr^{-1}}$. These scenarios include extremely high amounts of irrigated BPs (Hejazi et al., 2014) or are maximum potential scenarios (largely unconstrained in terms of available area) (Jans et al., 2018), at least in the latter case not meant to be implemented as such. With water use efficiencies of 585 $\mathrm{m^3\,t^{-1}}$ for *Miscanthus*, Hu et al. (2020) project the water requirements also on RCP2.6 consistent areas (431 Mha) to be up to 11,350 $\mathrm{km^3\,yr^{-1}}$.

We also collected associated data on type of study, modeling framework, bioenergy feedstock, land-type converted to biocrops, whether global maps for bioenergy locations are included, whether withdrawal or consumption is reported, type of water (blue/green/gray), simulation year for which data is extracted, c_{eff}, plantation area, provided bioenergy and/or NEs (depending on study type) together with the associated freshwater requirements, for 34 scenarios in total from the 16 studies we found (see supplementary data Stenzel et al. 2020). Reported primary bioenergy ranges from 40 to 2,350 $\mathrm{EJ\,yr^{-1}}$, while NEs range from 1.2 to 10 $\mathrm{GtC\,yr^{-1}}$. After converting primary bioenergy and NEs to initial biomass harvests (see Comparing BECCS water demand estimates), we find the projections of global freshwater demand per harvested biomass to be in the range of 15 to 2,761 $\mathrm{km^3\,GtC^{-1}}$ (15–1,250 $\mathrm{km^3\,GtC^{-1}}$, if the mean scenario values are used – Figure 3). This large span shows that

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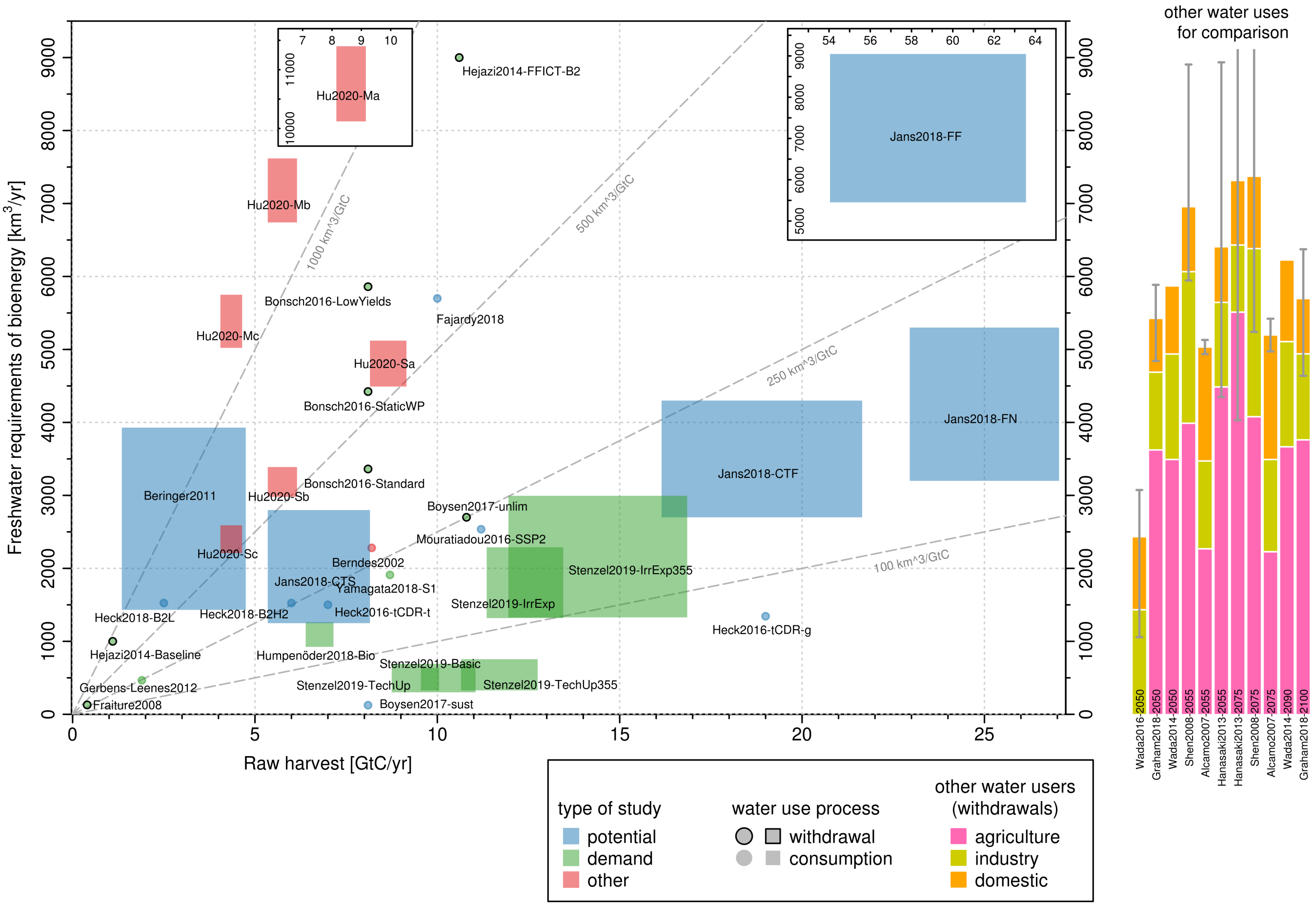

Figure 4. Overview of scenarios of reported values of global blue water volumes (withdrawal or consumption as marked) required for bioenergy production through biomass plantations (inlets show scenarios outside the plotting region). Scenarios are characterized by water demand for bioenergy plotted against raw harvest (inferred from reported biomass based energy or negative emissions). They can provide ranges in water demand or raw harvest (illustrated by boxes), or contain single values (depicted by circles). The type of study is marked by the color and if withdrawal is given instead of consumption it is shown by a black border.

For contextualization, projections for other water uses (withdrawals) are shown to the right, together with their uncertainty ranges. Names of the bioenergy scenarios are constructed as {author}{publication year}-{scenario name}, those of "other water use" scenarios as {author}{publication year}-{simulation year}.

there is no simple dependence of the freshwater demand on the amount of cultivated biomass – it is rather the large variety in other study parameters (which cannot be made comparable) that primarily discriminates the scenarios (Figure 4). Scenarios "sust" from Boysen et al. (2017), "Basic", "TechUp", and "TechUp355" from Stenzel et al. (2019) and "tCDR-g" from Heck et al. (2016) demonstrate values below $100\,\mathrm{km^3\,GtC^{-1}}$ (15, 50, 49, 46 and $71\,\mathrm{km^3\,GtC^{-1}}$). In the theoretical scenario tCDR-g in Heck et al. (2016), no additional BP locations are determined but simply all cropland area existent in year 2005 is assumed to be replaced with BPs and assumed to be irrigated very efficiently, which results in high harvests and thus low water/harvest ratios. In the "sust-scenario" considered by Boysen et al. (2017), only 40 out of a total $441\,\mathrm{Mha}$ BP area are considered to be irrigated, but the authors do not provide values to discriminate the respective harvests. In their "TechUp-WM" scenario, Stenzel et al. (2019) assume a high c_{eff} of 70% together with EFR restrictions on freshwater withdrawals, which keeps water demands below $100\,\mathrm{km^3\,GtC^{-1}}$. The highest projected values for water demand per harvested biomass stem from the M*-scenarios from Hu et al. (2020), Beringer et al. (2011), the "Baseline" and "FFICT-B2" scenario from Hejazi et al. (2014) and the "Low-Yields" scenario from Bonsch et al. (2016) (1102–1402, 315–2761, 909, 849 and $723\,\mathrm{km^3\,GtC^{-1}}$). Here we denote, that the very high value ($2{,}771\,\mathrm{km^3\,GtC^{-1}}$) for Beringer et al. (2011) might be an artefact of how we handle data value ranges, since the scenario producing the lowest energy yields, is most likely not the one with the highest water demand, so that the scenario is probably rather following a trend of $1{,}000\,\mathrm{km^3\,GtC^{-1}}$.

However we were still surprised to find that potential studies do not consistently suggest higher harvest than demand studies. This could mean that even demand studies are operating at the limits of the Earth system, and potential studies, especially when considering sustainability constraints, cannot provide more negative emissions than are already demanded for ambitious climate targets like $1.5\,^{\circ}\mathrm{C}$.

Only few global studies consider biofuels (e.g. Gerbens-Leenes et al. 2012; de Fraiture et al. 2008) which (aside from the irrigation water demand of the bioenergy feedstock considered in this review) require additional water for processing. It should be noted that this additional water demand for the biofuel refinement process (on top of the on-field water demand) is considered in many regional life cycle assessment studies and assumed to be about 4 units of water per unit of ethanol according to Fike et al. (2007) and Keeney and Muller (2006). General assessments including both primary bioenergy and biofuels would need to consider different conversion efficiencies for the different biomass pathways (as in Bonsch et al. 2016, or Heck et al. 2018).

3.4 Bioenergy plantation water use in light of water use in other sectors

To contextualize the above-discussed estimations of irrigation water requirements for bioenergy, earlier projections of future water use for the three main other sectors were collected (Alcamo et al., 2007; Shen et al., 2008; Hanasaki et al., 2013b, a; Wada and Bierkens, 2014; Wada et al., 2016; Graham et al., 2018) and compiled for comparison (see supplementary tabel file). Agriculture is globally the largest water using sector among the three, with a global total irrigated area reported to be $306\,\mathrm{Mha}$ in 2000 (Siebert et al., 2015). Estimates of present (between 2000 and 2010) agricultural water withdrawal are in the range $2{,}402$–$3{,}214\,\mathrm{km^3\,yr^{-1}}$. Future agricultural water withdrawal has been projected by grid-based numerical hydrological or crop growth models. For the mid (around 2050) and the late 21st century (between 2075 and 2090), estimates range between $2{,}256$–$6{,}037\,\mathrm{km^3\,yr^{-1}}$ and $2{,}211$–$8{,}434\,\mathrm{km^3\,yr^{-1}}$, respectively. These wide ranges in estimations are primarily attributed to

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the assumption on future irrigated area, which differ widely, as in case of BP projections. The lower ends assume that irrigated area hardly increases in the future, based on the view that land for new irrigation projects is no more available (e.g. Alcamo et al. 2007 and the low-end scenario of Hanasaki et al. 2013a). The high-end projection assumes that irrigated area increase at a rate of $0.6\,\%\,\mathrm{yr}^{-1}$ (i.e. the high-end scenario of Hanasaki et al. 2013a). Another case assumes that agricultural water grows in proportion to the total population as observed in the latter half of the 20th century (Shen et al., 2008). Other assumptions with respect to changes in irrigation efficiency, crop intensity and climate change further widen the range of estimates.

Industry and municipality are the second and third largest water using sectors. The estimates of present industrial and domestic water withdrawal are in a range of 691–894 $\mathrm{km}^3\,\mathrm{yr}^{-1}$ and 328–474 $\mathrm{km}^3\,\mathrm{yr}^{-1}$, respectively. Future industrial and municipal water withdrawal has been projected using empirical approaches. For instance, Alcamo et al. (2003) and Alcamo et al. (2007) developed nation-wide regression models to model water withdrawal in response to key drivers (e.g. population, income, electricity production, efficiency improvements) used in an exponential form to express the empirical facts that per activity water use continuously drops by time. Future industrial water in the middle of and the late 21st century are estimated to range between 433 and 3,313 $\mathrm{km}^3\,\mathrm{yr}^{-1}$ and between 246 and 3,772 $\mathrm{km}^3\,\mathrm{yr}^{-1}$, respectively. These ranges primarily reflect differences in efficiency improvement settings. As for domestic water, ranges are 628–1,563 $\mathrm{km}^3\,\mathrm{yr}^{-1}$ and 573–1,726 $\mathrm{km}^3\,\mathrm{yr}^{-1}$, respectively, for the two future time periods.

The median (first and third quartile) of total water withdrawal for the present, the mid- and the late 21st century is 3,770 (3,724–3,824), 5,806 (5,311–6,378), and 6,076 (5,063–6,984) $\mathrm{km}^3\,\mathrm{yr}^{-1}$, respectively.

Figure 4 indicates that 19 out of 35 estimations exceed 2,000 $\mathrm{km}^3\,\mathrm{yr}^{-1}$ of additional irrigation water withdrawal for bioenergy globally, which corresponds to half of present water withdrawals. This additional volume is roughly equivalent to the differences in total water withdrawal between SSP1 (4,295 $\mathrm{km}^3\,\mathrm{yr}^{-1}$), SSP2 (6,369 $\mathrm{km}^3\,\mathrm{yr}^{-1}$), and SSP3 (8,827 $\mathrm{km}^3\,\mathrm{yr}^{-1}$) in 2050 (Hanasaki et al., 2013a) – (SSP: shared socioeconomic pathway). A significant increase in water withdrawal for biomass production is likely to intensify water stress in respective regions, if not carefully planned in view of other water uses. The estimated global total water stressed population for SSP1, SSP2, and SSP3 are 2,853, 3,642, 4,265 million persons. Although the water usage is different, it implies that 2,000 $\mathrm{km}^3\,\mathrm{yr}^{-1}$ of additional irrigation may increase the water-stressed population by 600–800 million people (Hanasaki et al., 2013a) – however, integrative studies that account for all major water users including bioenergy in a consistent framework, at global scale yet spatially explicit, are basically lacking.

4 Conclusions

We find the global water demand for irrigation of biomass plantations assumed by the available literature to be in the range of 125–11,350 $\mathrm{km}^3\,\mathrm{yr}^{-1}$ water use (consumption), compared to about 1,100–11,600 $\mathrm{km}^3\,\mathrm{yr}^{-1}$ for other (agricultural, industrial, and domestic) water withdrawals and thus at similar magnitude.

We discover a large range of parameters and scenario criteria that are crucial for estimating the irrigation water demand of BPs, including the targeted primary energy or negative emissions amounts, the assumed carbon conversion efficiency, and the assumed plantation area. There were however also many parameters that we could not find in the publications. Thus we recommend that all scenario parameters be reported in publications, enabling more straightforward interpretation and comparison of results. A minimum set of reported parameters should in our eyes include annual blue water consumption and withdrawal, bioenergy crop species, rainfed and irrigated bioenergy plantation locations (including total area), and total bioenergy harvest amounts.

Surprisingly, there is no clear relationship between water requirements and total bioenergy production. However, by comparing the freshwater demand per harvested biomass, we find that most of the scenarios fall between 100–$1{,}000\,\mathrm{km}^3\,\mathrm{GtC}^{-1}$. The full range of 15–$1{,}250\,\mathrm{km}^3\,\mathrm{GtC}^{-1}$ for biomass harvest implies that, given a carbon conversion efficiency of 50%, we might need 99–$8{,}250\,\mathrm{km}^3$ to reach NEs of $3.3\,\mathrm{GtC\,yr}^{-1}$. These additional water requirements for bioenergy, which are at the same magnitude of water demand projections for conventional usage seem to paint a picture of a future where water scarcity can become a global and perpetual issue.

It would have been desirable to also include regional studies into our analysis, but this would have required more information than is usually provided, to for example analyze local yield and/or water productivity, and data on other water use sectors.

Besides the freshwater demand, potential impacts of BPs mostly stem from the implied land cover and land use conversion. Replacing natural vegetation with bioenergy crops could affect biodiversity, while, if grown on cropland, they would tamper with food security. Overall, most of the analyzed scenarios do not explicitly replace existing cropland by BPs. This in turn means that most studies (at least implicitly) assume investments in additional infrastructure for irrigation. Some scenarios also explicitly protect vulnerable natural areas. These considerations promote the use of marginal or degraded lands for BPs.

This review provides a first comprehensive overview of the current literature on global projections of the freshwater demand for irrigated bioenergy plantations. Furthermore, it is the first study that highlights the potential dependence on irrigation for BECCS to deliver NEs for ambitious climate targets and calls for further investigation and reporting on the underlying (model) assumptions. Integrative studies considering all water use sectors incl. bioenergy (along with potential trade-offs based on detailed understanding of local limitations) are highly desirable and a requirement to get a better, integrated understanding of the limits and options of future overall water use and consumption.

Data availability. The results from the literature analysis are available with temporal access for the review as .xlsx and .csv tables under https://dataservices.gfz-potsdam.de/panmetaworks/review/46e4043dd95b623e0ba8dbc09fb437b7c92d1aa56bf264547e6d37646cb381ae-pik/ and will receive a doi once this manuscript is accepted (Stenzel et al., 2020). Any additional data that support the findings of this study are included within the article.

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Appendix A: Supplementary Information

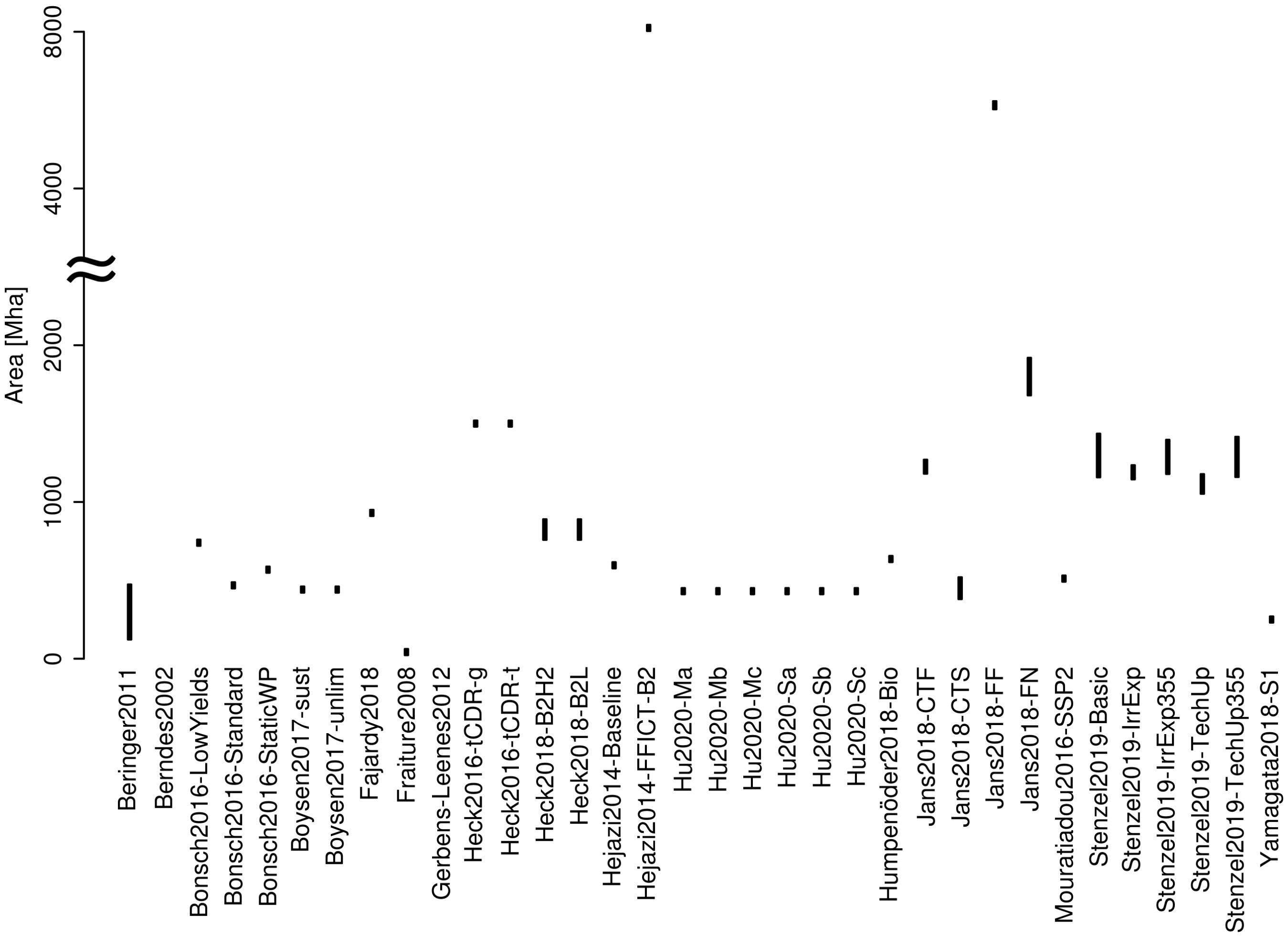

Figure A1. Overview of reported total global area of bioenergy plantations.

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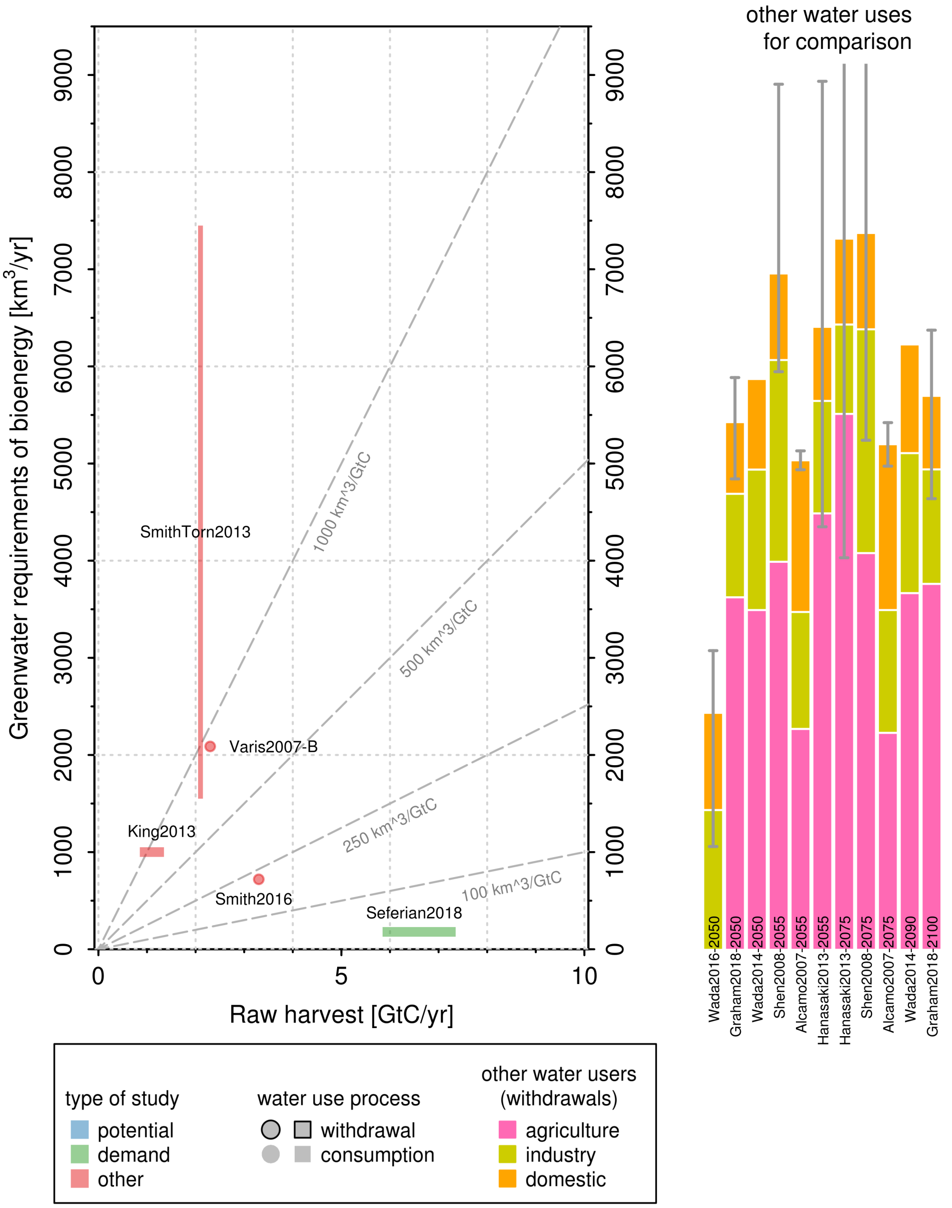

Figure A2. Analogous to Figure 4, but for scenarios of reported global green water consumption volumes required for bioenergy production through biomass plantations. Scenarios are characterized by water demand for bioenergy plotted against raw harvest (inferred from reported biomass based energy or negative emissions). They can provide ranges in water demand or raw harvest (illustrated by boxes), or contain single values (depicted by circles). For contextualization, projections for other water uses (withdrawals) are shown to the right, together with their uncertainty ranges. Names of the bioenergy scenarios are constructed as {author}{publication year}-{scenario name}, those of "other water use" scenarios as {author}{publication year}-{simulation year}.

We want to stress, that these numbers are not directly comparable with those in Figure 4, because scenarios with irrigated bioenergy plantations also include additional (but largely unreported) green water transpiration.

Table A1. List of publications, providing scenarios for this review.

Author	Year	Title
blue water studies		
Beringer et al.	2011	Bioenergy production potential of global biomass plantations under environmental and agricultural constraints
Berndes	2002	The feasibility of large-scale lignocellulose-based bioenergy production
Bonsch et al.	2016	Trade-offs between land and water requirements for large-scale bioenergy production
Boysen et al.	2017	The limits to global-warming mitigation by terrestrial carbon removal
Fajardy et al.	2018	Investigating the BECCS resource nexus: delivering sustainable negative emissions
de Fraiture et al.	2008	Biofuels and implications for agricultural water use: blue impacts of green energy
Gerbens-Leenes et al.	2012	Biofuel scenarios in a water perspective: The global blue and green water footprint of road transport in 2030
Heck et al.	2016	Is extensive terrestrial carbon dioxide removal a 'green' form of geoengineering? A global modelling study
Heck et al.	2018	Biomass-based negative emissions difficult to reconcile with planetary boundaries
Hejazi et al.	2014	Integrated assessment of global water scarcity over the 21st century under multiple climate change mitigation policies
Hu et al.	2020	Can bioenergy carbon capture and storage aggravate global water crisis?
Humpenöder et al.	2018	Large-scale bioenergy production: how to resolve sustainability trade-offs?
Jans et al.	2018	Biomass production in plantations: Land constraints increase dependency on irrigation water
Mouratiadou et al.	2016	The impact of climate change mitigation on water demand for energy and food: An integrated analysis based on the Shared Socioeconomic Pathways
Stenzel et al.	2019	Freshwater requirements of large-scale bioenergy plantations for limiting global warming to 1.5 °C
Yamagata et al.	2018	Estimating water-food-ecosystem trade-offs for the global negative emission scenario (IPCC-RCP2.6)
green water studies		
King et al.	2013	The Challenge of Lignocellulosic Bioenergy in a Water-Limited World
Séférian et al.	2018	Constraints on biomass energy deployment in mitigation pathways: the case of water scarcity
Smith and Torn	2013	Ecological limits to terrestrial biological carbon dioxide removal
Smith et al.	2016	Biophysical and economic limits to negative CO_2 emissions
Varis	2007	Water demands for bioenergy production

Author contributions. FS designed the study, and carried out the literature analysis of bioenergy-freshwater-demands. DG contributed to study design. NH carried out the literature analysis of other water users. FS prepared the manuscript. DG and NH contributed to manuscript preparation.

Competing interests. The authors declare that they have no conflict of interest.

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