Global scenarios of irrigation water abstractions 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 providing electricity. The associated freshwater abstractions 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 abstractions 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 irrigation water abstractions for biomass plantations, suggesting water withdrawal in the range of 128.4–$9{,}000\,\mathrm{km^3\,yr^{-1}}$, which would come on top of (or compete with) 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 calculate an inverse water use efficiency (iwue) which facilitates comparison of the required freshwater amounts per produced biomass harvest. 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 abstractions, full disclosure of parameters and assumptions is crucial. A minimum set should include the complete water balances of bioenergy production systems (including partitioning of blue and green water), bioenergy crop species and associated water use efficiencies, rainfed and irrigated bioenergy plantation locations (including total area and meteorological conditions), and total biomass harvest amounts. In the future, a model intercomparison project with standardized parameters and scenarios would be helpful.

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
SSP	shared socioeconomic pathway

1 Introduction

20 Previous assessments of global green and blue water requirements of a potential widespread bioenergy industry show a large variation in the estimates (withdrawals of 128.4–$9{,}000\,\mathrm{km}^3\,\mathrm{yr}^{-1}$ – de Fraiture et al. 2008; Hejazi et al. 2014), while there is still insufficient analysis of the underlying sources of variation and assumptions, that need to be standardized.

Projections of future energy demand and its partitioning increasingly assume replacement of carbon-intense fossil energy carriers with biomass, which could provide carbon-neutral electricity or fuels (Nakićenović et al., 1998; Rose et al., 2014; Bauer

25 et al., 2018). However, in order to limit mean global warming to $2\,^{\circ}\mathrm{C}$ or even $1.5\,^{\circ}\mathrm{C}$ (UNFCCC, 2015), technologies providing additional negative emissions (NEs) are potentially needed to compensate for residual and past emissions (Rockström et al., 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

30 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 is projected to be grown on large managed plantations and include substantial irrigation, demanding for trade-offs between negative emissions and area requirements as well as water consumption to be solved sustainably.

Suggested energy carriers for BECCS 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*, switch-

35 grass, 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 (King et al., 2013).

While burning of fossil energy carriers leads to (net positive) emissions of greenhouse gases, use of biomass is net neutral apart from land-use and process-chain emissions (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).

Bioenergy plantations (BPs) can be either purely rainfed or (partially) irrigated. Plantations of the former type would completely depend on "green" precipitation water stored in soils, while the latter additionally include more or less pronounced use of "blue" water from lakes, rivers, reservoirs and aquifers (Hoekstra et al., 2009; Fader et al., 2011; Wang et al., 2017).

The discussion for or against large scale irrigation on BPs revolves around a set of economic and sustainability trade-offs, requiring a more comprehensive quantification of water use of bioenergy systems. The required high biomass productivity for reaching ambitious climate targets might promote irrigation to reduce land requirement trade-offs with e.g. food production. This however would happen at the expense of freshwater ecosystems (Poff and Zimmerman, 2010) and human societies in terms of increased overall water stress (Schewe et al., 2014), or lead to unwanted modification of terrestrial water cycling (Vervoort et al., 2009). Additional investment in irrigation systems would be required (Hogan et al., 2007), which however might become economically feasible due to an increased value of biomass through carbon pricing (Bauer et al., 2018). 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.

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.

Review studies on the potentials of BECCS and other NE technologies (e.g. Creutzig et al. (2015), Smith et al. (2016) and Fuss et al. (2018)), did so far not provide a comprehensive overview of the associated freshwater abstractions (besides their precursory mentioning).

The suggested large quantities of blue water withdrawals/consumptions assumed for BP irrigation in the literature, which may occur in competition with other water uses and may increase water stress in relatively water-scarce regions where BPs are considered, motivate a comprehensive understanding and quantification of their intrinsic water requirements (Hejazi et al., 2015; Wada et al., 2014). Thus, the subject of the present paper is to fill this knowledge gap and systematically review the current literature on projected freshwater abstractions in global NE or energy scenarios relying on BECCS/bioenergy. Additionally, we illustrate how such global scale syntheses could be standardized in data requirements/formats, analytical framework, scopes of inference, supporting assumptions, and reconciliation across spatio-temporal scales.

The analysis is guided by the following questions:

1. What are the key modeling parameters and assumptions of global bioenergy studies that affect the inherent water demand projections? (section 3.1 and section 3.2)

2. What are the global freshwater abstractions for irrigation of bioenergy plantations in the future as projected in available global-scale studies? (section 3.3)

3. How do amounts of freshwater abstractions for irrigated biomass plantations compare to other sectors? (section 3.4)

4. Is there a dependence between the simulated freshwater abstractions and the total global biomass production across studies? (section 3.5)

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 up-scaled or compared with the global studies due to a lack of site specific data for plantation locations in global studies. We separate quantities of blue water application on BPs into withdrawals (gross extraction from rivers, lakes, reservoirs) or consumption (eventual evapotranspiration, excluding return flows to the rivers and water bodies that may occur after withdrawal). Existing studies are then compared regarding a) the total global water volume to deal with it as a component of hydrological cycle, and b) the global mean water use efficiency per biomass produced (iwue – water abstractions per biomass produced, see Equation 1) inferred from the studies as a component of field-scale water 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 and excluded studies which focus on algae or electrofuels:

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("BECCS" OR "bioenergy production" OR "bioenergy cultivation" 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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Table 2. List of publications with published key bioenergy parameters analyzed in this review. See supplementary dataset (Stenzel et al., 2020) for additional parameters and all scenarios per study.

Author	Year (public.)	Area [Mha]	Energy [EJ/yr]	NE [GtC/yr]	Year (scen.)	water abstraction [km^3/yr]	water process[§]	c_eff[+] [%]
blue water studies								
Beringer et al.	2011	142-454	52-174	-	2050	1,481-3,880	cons	-
Berndes	2002	-	304	-	2100	2,281	cons	-
Bonsch et al.*	2016	468-740	300	-	2100	3,362-5,860	wd	31-43
Boysen et al.*	2017	441	-	-	2100	125-2,536	cons	50
Fajardy et al.	2018	930	-	3.3	2016	5,700	cons	33
de Fraiture et al.	2008	42.2	-	-	2030	128.4	wd	-
Gerbens-Leenes et al.	2012	-	71	-	2030	466	cons	-
Heck et al.*	2016	1,500	-	-	2005	1,344-1,501	cons	-
Heck et al.*	2018	778-870	151-233	1.2-5.4	2050	1,525	cons	48-90
Hejazi et al.*	2014	596-8,195	40-140	0-10	2095	1,000-9,000	wd	94
Hu et al.*	2020	431	-	3.1	2100	2,260-11,350	cons	36-72
Humpenöder et al.	2018	636	300	-	2100	973-1,211	cons	-
Jans et al.*	2018	400-4,300	200-2350	-	2015	1,300-9,000	cons	-
Mouratiadou et al.	2016	511	400	-	2100	2,700	wd	-
Stenzel et al.*	2019	1,072-1,416	-	4.4-8.9	2100	351-2,946	cons	50-70
Yamagata et al.	2018	250	-	2.9	2095	1,910	cons	33
green water studies								
King et al.	2013	363-493	33-47	-	2050	1,000	cons	-
Séférian et al.	2018	-	220-270	-	2100	178	cons	-
Smith and Torn	2013	218-990	-	1.0	2100	1,600-7,400	cons	47
Smith et al.	2016	100-200	-	3.3	2100	720	cons	100
Varis	2007	-	83.52	-	2050	2,088	cons	-

* parameter ranges span several scenarios

[§] consumption (cons), withdrawals (wd)

[+] carbon conversion efficiency

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 abstractions of large-scale BPs (going from title to abstract to full text). The global bioenergy studies with water consumption values by 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 rainfed biomass plantations (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") together with the main parameters are listed in Table 2. Noticeably, the majority of publications is very recent – only two of them were published before 2010.

2.2 Calculating an inverse water use efficiency (iwue)

Comparison of the literature values of water abstractions for BECCS is not straightforward because of the different assumptions studies made on important model parameters and setups, as described in section 3.2. Nevertheless, besides presenting the absolute global estimates of freshwater withdrawal or consumption, we attempt to make the results of these studies directly comparable: The degree of assumed bioenergy deployment varies strongly among studies, we thus relate the given freshwater abstractions to the absolute amount of biomass assumed to be grown. With this we quantify the estimated water abstractions per harvested biomass. King et al. (2013) compute a similar "bioenergy water use efficiency at the farm gate" for several lignocellulosic bioenergy species based on the yield of (bio)energy per hectare per water volume evapotranspired. We extend this concept of local level water use efficiency to larger spatio-temporal scale and apply it as an inverse (global) water use efficiency (iwue):

$$iwue \left[\frac{\text{km}^3}{\text{GtC}} \right] = \frac{water \ \left[\text{km}^3 \right]}{biomass \ harvest \ [\text{GtC}]} \tag{1}$$

For the analysis, we separate the scenarios into those that report water withdrawals or consumption 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 backtrack the approximate dry biomass harvests by using the gross calorific value of $18.5 \, \text{MJ} \, \text{kgDM}^{-1}$ (Haberl et al., 2010; Brosse et al., 2012). This is equivalent to $37 \, \text{MJ} \, \text{kgC}^{-1}$ or $37 \, \text{EJ} \, \text{GtC}^{-1}$, with the average carbon content of dry biomass of $0.5 \, \text{kgC} \, \text{kgDM}^{-1}$ (Schlesinger and Bernhardt, 1991, p.120) (Equation 2).

$$biomass \ harvest_{from \ energy} \ [\text{GtC}] = \frac{energy \ [\text{EJ}]}{37 \, \text{EJ} \, \text{GtC}^{-1}} \tag{2}$$

With this we approximate 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 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 document 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 derive the dry biomass harvest by division of the NE amount by c_{eff} (Equation 3). Since transport and other losses are usually

125 contained in c_{eff}, the inferred initial biomass values for NE studies are probably more reliable than those for energy studies.

$$biomass\ harvest_{from\ NE}\ [\text{GtC}] = \frac{NE\ [\text{GtC}]}{c_{eff}} \tag{3}$$

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

130 therefore overestimate the raw bioenergy harvests or conversely underestimate the water abstractions per unit of biomass from dedicated BPs.

3 Results and Discussion

3.1 Overview

We synthesize the results from the 16 publications into 34 scenarios of freshwater abstractions for bioenergy (the full data-set

135 is available as Stenzel et al. 2020). As freshwater abstractions we extract reported estimates of blue water consumption or withdrawals, with a preference on consumption.

Modeling approaches used are very different, with each model focusing on a different part of the BECCS deployment process. While Earth System Models (ESMs) dynamically represent large-scale feedbacks between atmosphere, ocean and biosphere with comparably less process detail regarding human management of the biosphere including BPs, integrated as-

140 sessment models (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 withdrawal. If deriving global estimates of BP freshwater withdrawal or consumption is an aim of a study, more straightforward and compu-

145 tationally inexpensive estimations might suffice. Value chain models might be best suited if the details of the BECCS process chain are of most interest.

The natural water availability in bioenergy modeling studies is largely determined by the considered climate input, which in the case of projections for the future also varies among the general circulation models used. In this regard local water abstraction projections might also be analyzed in terms of the projected climate-driven water availability changes in the respective region.

150 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 2, Figure A2, and the supplementary data (Stenzel et al., 2020).

155 All of the found studies also consider rainfed plantations that depend solely on green water stored in the soil (with added irrigation if necessary), however the amount of evapotranspired green water is only reported in a few of them. An overview of

studies reporting global green water abstraction for bioenergy, which 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 evapotranspired water is (King et al., 2013; Varis, 2007) is given in Figure A3. According to these studies, green water consumption of bioenergy ranges from 50 to over 3,000 $km^3\,GtC^{-1}$ of biomass harvest. Since this review focuses on blue water requirements, those estimates are not included in the main analysis.

Focusing on the blue water abstractions, allows us to directly compare them in the light of competition with other human water uses and those of aquatic ecosystems, potentially increasing overall water stress. An objective for future studies should be a more comprehensive quantification of the water requirements of bioenergy systems, partitioning sources into green and blue pathways and identifying potential means of increasing water use efficiency and decreasing blue water abstractions. 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.

3.2 Study differences in parameters choices and other assumptions

Study type. According to our literature review, estimating future global water abstractions 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) to compute the global freshwater consumption on BPs. 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 abstractions for BPs (here referred to as "demand driven studies"), or the aim to find the maximum energy (or NE) potential within given constraints of available land, water restrictions or management ("supply driven 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).

Modeling framework. While Berndes (2002) and Hu et al. (2020) derived their results mainly from meta-analyses of existing literature and approximations of global water consumption 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 withdrawal or consumption for BPs under different scenario constraints. Bonsch et al. (2016) specifically investigated the trade-offs between area and water withdrawals by 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

190 goals were global bioenergy potentials and the associated trade-offs with global water consumption, plantation area demand or planetary boundaries.

The water (and land) implications of an increasing biofuel production in the future were analyzed in de Fraiture et al. (2008) with the water use model WaterSIM and in 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
195 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 IAM) in conjunction with the global hydrological model GWAM to quantify global water scarcity under several future climate change scenarios.
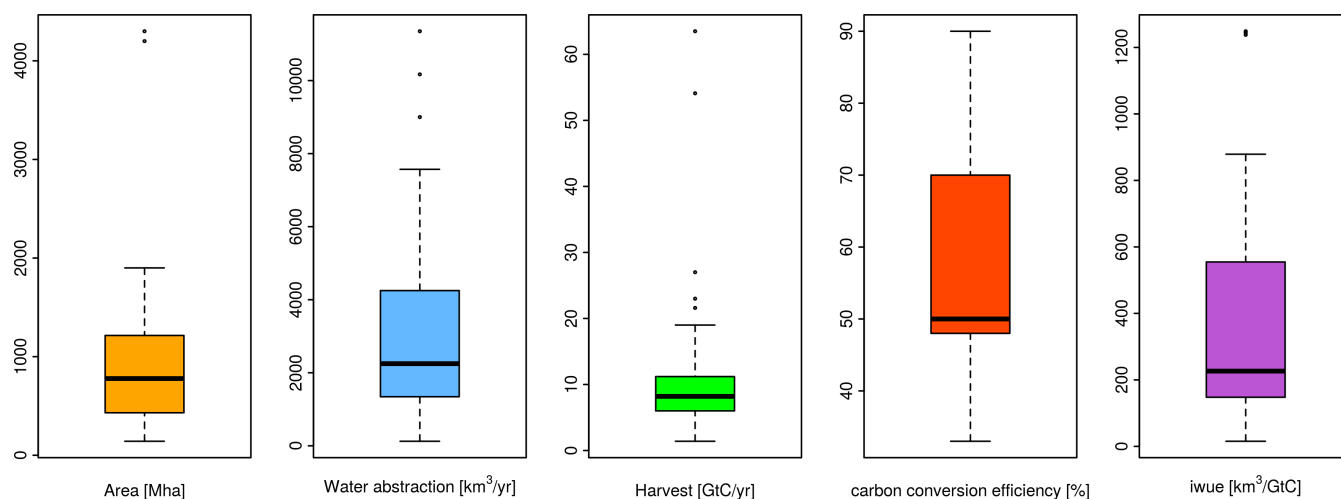
Figure 1. Range of key parameters (global estimates) determining projections of water abstractions for bioenergy in the scenarios examined (see supplementary data Stenzel et al. 2020) presented as boxplots. Note that plantation area and carbon conversion efficiency are not reported in all studies. Inverse water use efficiency per biomass harvest (iwue) is calculated for each scenario, using the means of water abstractions and biomass harvest if ranges are given.

Bioenergy plantation area. The global potential plantation area identified as suitable for BPs differs hugely in size between
200 $42\,\mathrm{Mha}$ 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 1 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 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
205 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 (geospatial) location of additional large-scale irrigation might also be relevant from the perspective of feedbacks with the climate system. Recently it was suggested that the influence

of land cover change and especially irrigation on rainfall (and thus runoff) are larger than expected (Van Noordwijk and Ellison, 2019; Ellison et al., 2019), such that moisture recycling through transpired irrigation water and moisture transport to downwind regions may be affected also by the biomass plantations. Thus, for example, as long as forests are not removed in order to grow the biomass material, the upwind production of additional biomass material could potentially have positive impacts on downwind water availability (if growing more biomass material leads to the production of more atmospheric moisture). However, if less atmospheric moisture is produced (than was previously the case), this would presumably lead to the opposite downwind effect on water availability. The local impact of these processes, however, is likely to be the reverse. New modeling approaches tracking atmospheric moisture pathways (Tuinenburg and Staal, 2020) or direct coupling of land-system and climate models (Pokhrel et al., 2017) might help to better understand these processes.

The reported land types, which are projected to be converted to BPs, 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 BP 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). Current cropland extent amounts to $1,564\,\text{Mha}$ (Klein Goldewijk et al., 2016). The potentially (theoretically) available land for biomass plantations today in each of the remaining categories would be: 385–$472\,\text{Mha}$ for marginal land (Campbell et al., 2008), $6,899\,\text{Mha}$ for natural vegetation (Boysen et al., 2017), $3,286\,\text{Mha}$ for natural vegetation excluding protected or vulnerable land (Stenzel et al., 2019), and $441\,\text{Mha}$ for the BP area in RCP2.6-SSP2 in 2100 (Boysen et al., 2017).

Irrigation parameters. 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 in 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 varies widely. 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.

Biomass feedstock. 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 reviewed studies, only two consider first-generation bioenergy plants as feedstock like rapeseed, oil-palm, or sugar

cane (de Fraiture et al., 2008; Gerbens-Leenes et al., 2012). Residues from agriculture or forestry, estimated to contribute up to $100\,\mathrm{EJ\,yr^{-1}}$ in 2050 (IEA, 2009; Haberl et al., 2010), are discussed by Beringer et al. (2011) but not included in their analysis. Stenzel et al. (2019) and Heck et al. (2018) include the one-time timber harvest from the land use conversion of forests to biomass plantations. Fajardy et al. (2018) include wheat straw residues as biomass feedstock. Major impacts on water can probably only be expected by designated large scale plantations.

Some studies assume yield productivity changes in the bioenergy harvest over the 21st century based on previous productivity increases observed in crop harvests (Bonsch et al., 2016; Mouratiadou et al., 2016; Humpenöder et al., 2018). There however is also the argument that this increase of productivity might be more difficult to reach than for food crops, since the whole above-ground biomass is used for bioenergy production, instead of only a small ratio as in the case of food crops (Krausmann et al., 2013). Breeding programs might also yield significant potential for improved water use efficiencies in bioenergy crops.

Timing of bioenergy implementation. For demand driven studies crucial (but mostly exogenous) parameters are the starting year and trajectory for the BECCS demand, e.g. whether deployment is assumed to start in 2015 (Humpenöder et al., 2018) or in 2030 (Stenzel et al., 2019). Trajectories of the energy (or NE) demand (Boysen et al., 2017; Hejazi et al., 2014; Berndes, 2002) which require higher yearly biomass yield demands at the end of the century will likely also lead to higher yearly irrigation requirements. The yearly water abstractions given in the studies are not always indicative of average irrigation water abstractions per year, since demand studies mostly report end of study period values (e.g. mean 2090-2099) where irrigated areas are at their maximum.

Carbon conversion efficiency. 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 ranges only describe the CCS efficiency, disregarding the supply chain carbon efficiency, which can be much lower. 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 1).

Other constraints. 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 abstractions. 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 in 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 abstractions (e.g. considered in Fajardy et al. 2018).

3.3 Projections of global irrigation water abstractions for bioenergy plantations

From the 16 studies we synthesized 34 scenarios, for which we collected the projected freshwater abstractions and associated data (see supplementary data Stenzel et al. 2020). We collected: type of study, modeling framework, bioenergy feedstock, land-type converted to biocrop plantation, 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).

The projections of potential future freshwater consumption for irrigation of BPs (125–$11,350\,\mathrm{km^3\,yr^{-1}}$) vary substantially due to differences in model structure, scenarios, study goals, and data input. Extreme cases are the FFICT-B2 scenario in Hejazi et al. (2014) and the Food First (FF) scenario in Jans et al. (2018), who simulate BP cultivation on $4,000$–$8,000\,\mathrm{Mha}$ with associated water withdrawals 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. Assuming water use efficiencies of $585\,\mathrm{m^3\,t^{-1}}$ for *Miscanthus*, Hu et al. (2020) project the water consumption on RCP2.6 consistent BP areas ($431\,\mathrm{Mha}$) to be up to $11,350\,\mathrm{km^3\,yr^{-1}}$.

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

The contemporary global green and blue water consumption on cropland is $5,000$–$10,000\,\mathrm{km^3\,yr^{-1}}$ and 800–$1,500\,\mathrm{km^3\,yr^{-1}}$, respectively (Hoff et al., 2010; Jägermeyr et al., 2015; Rosa et al., 2018). Runoff, feeding these appropriation globally sums up to approximately $40,000\,\mathrm{km^3\,yr^{-1}}$ (Sperna Weiland et al., 2010; Gerten et al., 2013), of which however only 30-40% is geographically and temporally accessible to humans (Postel et al., 1996).

To contextualize the above-discussed estimations of irrigation water abstractions for bioenergy, earlier projections of future water use for the three main other sectors are 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 table 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 is 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 the assumption on future irrigated area, which differ widely, as in the 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 longer 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 increases 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.
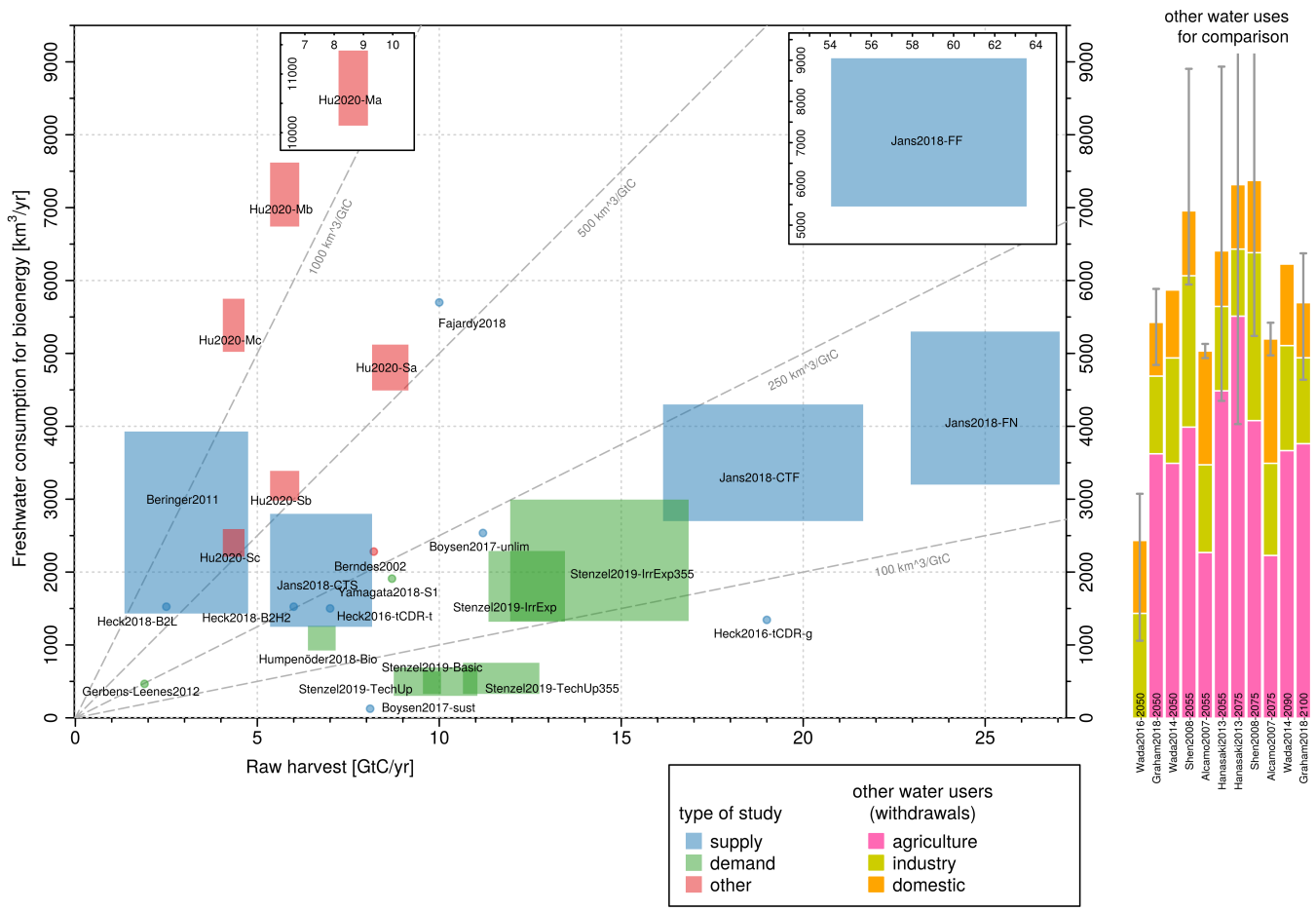
Figure 2. Overview of scenarios of reported values of global blue water consumption required for bioenergy production through biomass plantations (inlays show scenarios outside the plotting region). Scenarios are characterized by freshwater consumption for bioenergy plotted against raw harvest (inferred from reported biomass based energy or negative emissions). They can provide ranges in water withdrawals or raw harvest (illustrated by boxes), or contain single values (depicted by circles). The type of study is marked by the color. Results for studies which report blue water withdrawals can be found in Figure A2, studies of green water consumption in Figure A3.

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}.

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 km^3 yr^{-1} and 328–474 km^3 yr^{-1}, respectively. Future industrial and municipal water withdrawal is projected using empirical approaches. For instance, Alcamo et al. (2003) and Alcamo et al. (2007) develop 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 and the late 21st century are estimated to range between 433–3,313 km^3 yr^{-1} and between 246–3,772 km^3 yr^{-1}, respectively. These ranges primarily reflect differences in efficiency improvement settings. As for domestic water, ranges are 628–1,563 km^3 yr^{-1} and 573–1,726 km^3 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) km^3 yr^{-1}, respectively.

Figure 2 and Figure A2 indicate that 19 out of 34 estimations for global additional irrigation water withdrawal for bioenergy exceed 2,000 km^3 yr^{-1}, 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 km^3 yr^{-1}), SSP2 (6,369 km^3 yr^{-1}), and SSP3 (8,827 km^3 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 and 4,265 million people. Although the water usage is different, it implies that 2,000 km^3 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.

The future price of biomass, as well as the value of freshwater likely depends on political decisions (Klein et al., 2014) or market forces also in other sectors (Dinar and Mody, 2004). Integrated assessments of the combined effects in a globally monetized biomass and food market with potential limitations of irrigation water withdrawals (Hogeboom et al., 2020) or associated high costs (De Fraiture and Perry, 2002), especially under conditions of continued climatic change, poses interesting avenues for further research.

3.5 Inverse water use efficiency relating freshwater abstractions and harvest

Reported primary bioenergy (energy content of the biomass harvest to be converted to electricity) ranges from 40 to 2,350 EJ yr^{-1}, while NEs range from 1.2 to 10 GtC yr^{-1}. After converting primary bioenergy and NEs to initial biomass harvests (see section 2.2), we find the projections of global freshwater abstractions per harvested biomass (iwue) to be in the range of 15–2,761 km^3 GtC^{-1} (15–1,250 km^3 GtC^{-1}, if the mean scenario values are used – Figure 1). This large range shows that freshwater withdrawals or consumptions do not linearly depend on the amount of cultivated biomass – it is rather the large variety in other parameters (which cannot be made comparable) that primarily discriminates the scenarios (Figure 2 and Figure A2). 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 iwue values below 100 km^3 GtC^{-1} (15, 50, 49, 46 and 71 km^3 GtC^{-1}). In the theoretical

scenario tCDR-g in Heck et al. (2016), no additional BP locations are determined but all existing croplands 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 iwue. In the "sust-scenario" considered in 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 iwue below $100\,\mathrm{km^3\,GtC^{-1}}$. The highest projected iwue values 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) (1,102–1,402, 315–2,761, 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 consumption, so that the scenario is probably rather following a trend of $1,000\,\mathrm{km^3\,GtC^{-1}}$.

However we are still surprised to find that supply driven studies do not consistently suggest higher harvest than demand driven studies. This could mean that even demand driven studies are operating at the limits of the Earth system, and supply driven 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 abstractions for the bioenergy feedstock considered in this review) require additional water for processing. It should be noted that the additional water abstractions for the biofuel refinement process (on top of the on-field water abstractions) are 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).

4   Conclusions

We discover a large range of parameters and scenario criteria (Table 2 and more detailed in the supplementary dataset Stenzel et al. 2020) that are crucial for estimating the irrigation water abstractions for BPs. We are not able to quantify the contribution of each parameter, however strong dependencies are expected for the targeted primary bioenergy or negative emissions amounts, the assumed carbon conversion efficiency, and the assumed plantation area.

A number of parameters were however not documented in the publications. Thus we recommend that all scenario parameters be reported in future publications on irrigation of BPs, enabling more straightforward interpretation and comparison of results. A minimum set of reported parameters, ideally spatially detailed, should in our view include the complete water balances of BPs (including partitioning of blue and green water), water use efficiencies of the respective plant types, rainfed and irrigated BP locations (including total area and climatic conditions), and total biomass harvest amounts.

We find the global water withdrawals for irrigation of biomass plantations assumed in the available literature to be in the range of 128.4–$9,000\,\mathrm{km^3\,yr^{-1}}$ (consumption: 125–$11,350\,\mathrm{km^3\,yr^{-1}}$), compared to about 1.100–$11,600\,\mathrm{km^3\,yr^{-1}}$ for the sum of other (agricultural, industrial, and domestic) water withdrawals and thus at similar magnitude. It needs to noted that the water abstractions for bioenergy production would come on top of (or compete with) that for the other uses.

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Surprisingly, there is no clear relationship (e.g. linear) between water abstractions and total bioenergy production. However, by comparing the freshwater abstractions per harvested biomass, we find that most of the scenarios fall between 100–$1,000\,\mathrm{km^3\,GtC^{-1}}$. The full range of 15–$1,250\,\mathrm{km^3\,GtC^{-1}}$ 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 $3.3\,\mathrm{GtC\,yr^{-1}}$ as projected to be necessary by Smith et al. 2016.

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The studies analyzed in this manuscript span a time of almost 20 years, such that there might be significant changes even among different versions of the same model (e.g. GCAM in Hejazi et al. 2014 vs. in Graham et al. 2018, as discussed in Calvin et al. 2019), suggesting the need for a concerted model intercomparison for projections of bioenergy water demands under controlled assumptions and with the latest model versions.

390 These additional water abstractions 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 abstractions, 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 assuming it is economically justifiable. Some scenarios also explicitly protect vulnerable natural areas. These considerations promote the use of marginal or degraded lands for BPs.

400 This review provides a first comprehensive overview of the current literature on global projections of the freshwater abstractions 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. Integrated assessments that consider all water use sectors (incl. bioenergy, along with potential trade-offs based on detailed understanding of local limitations) are highly desirable and are crucial to get a better understanding of the
405 limits and options of future water 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.
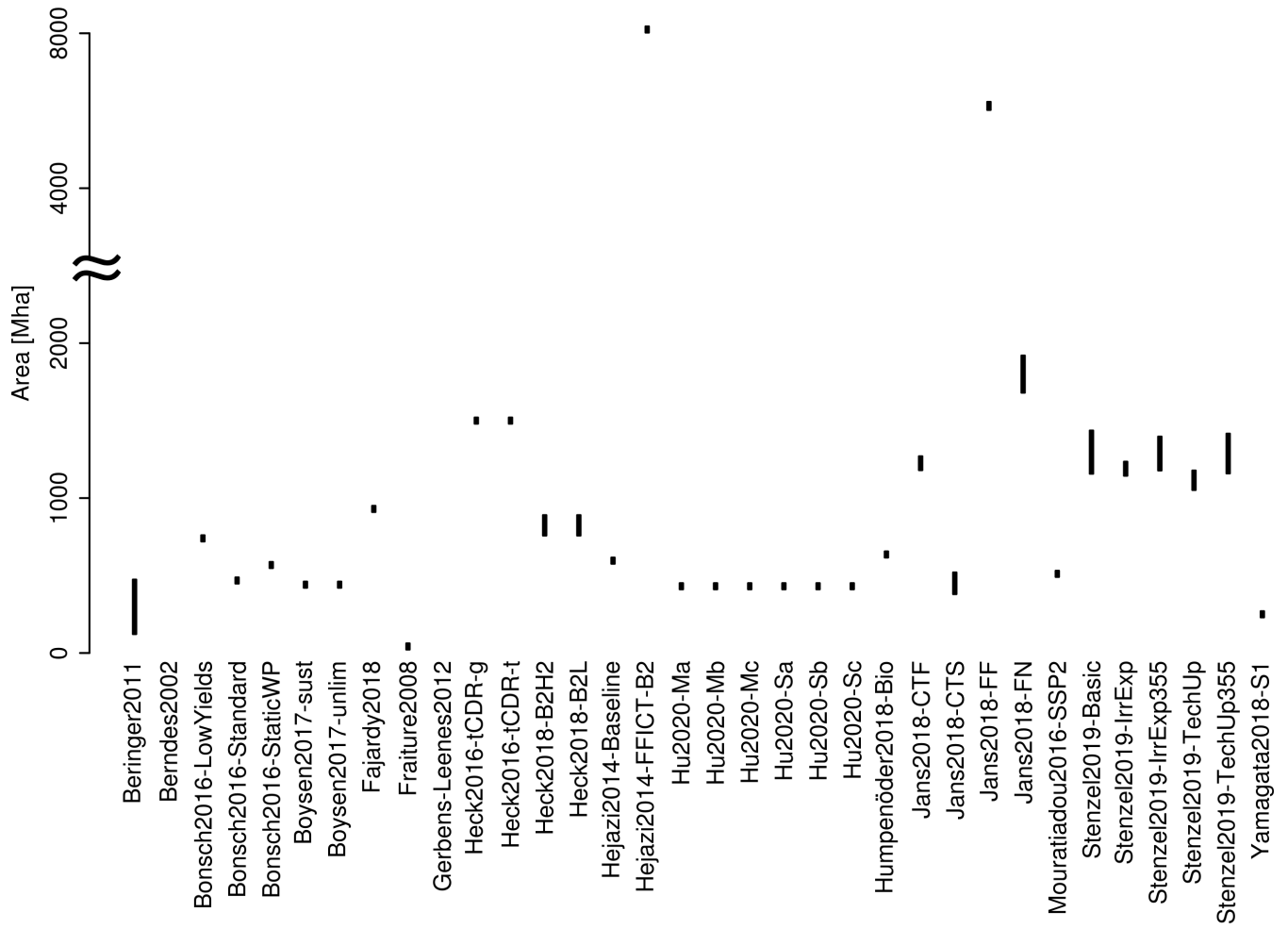
Figure A1. Overview of reported total global area of bioenergy plantations.
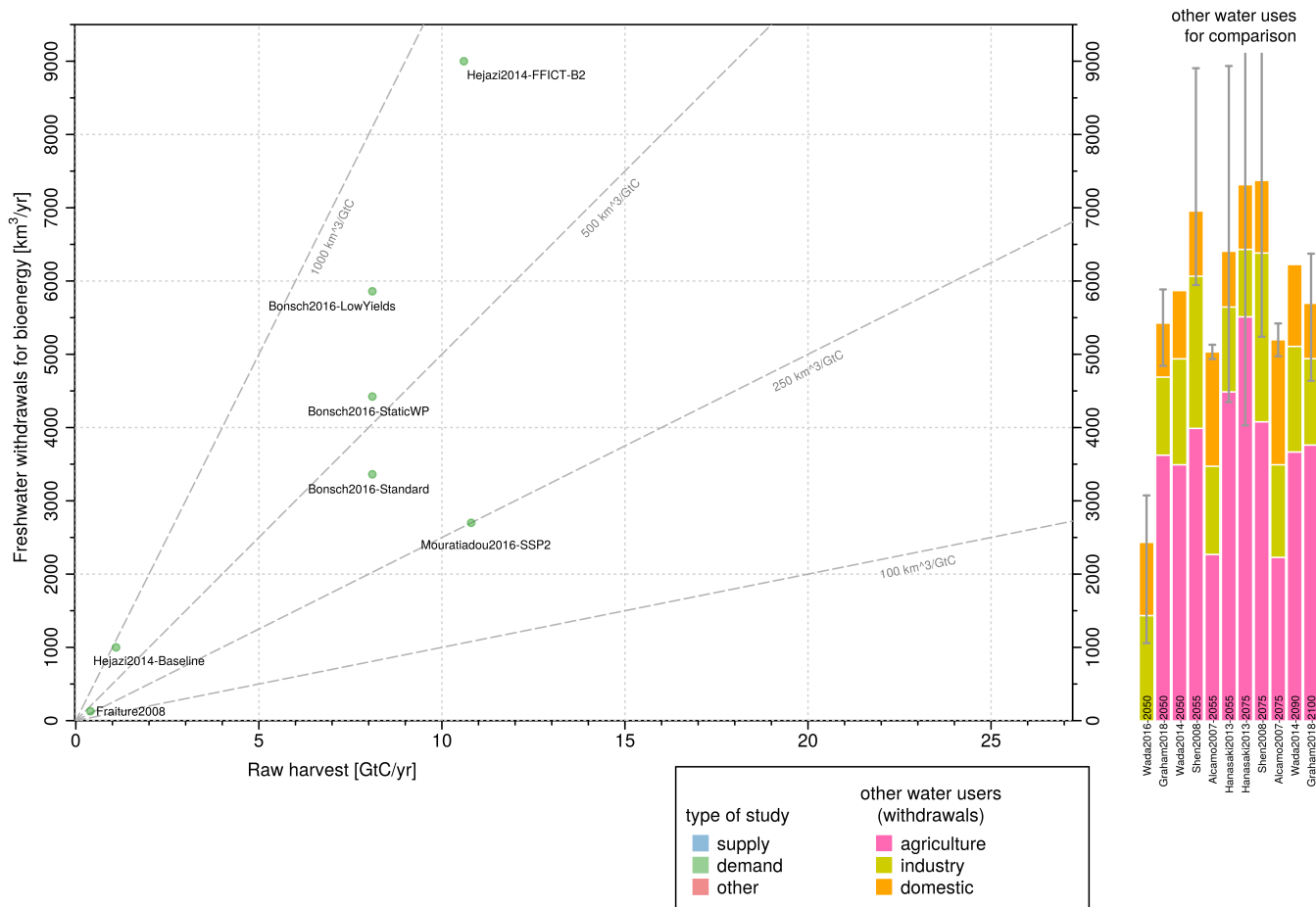
Figure A2. Analogous to Figure 2 but for scenarios of reported values of global blue water withdrawals required for bioenergy production through biomass plantations. Scenarios are characterized by water withdrawals for bioenergy plotted against raw harvest (inferred from reported biomass based energy or negative emissions). They can provide ranges in water withdrawals or raw harvest (illustrated by boxes), or contain single values (depicted by circles). The type of study is marked by the color.

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}.
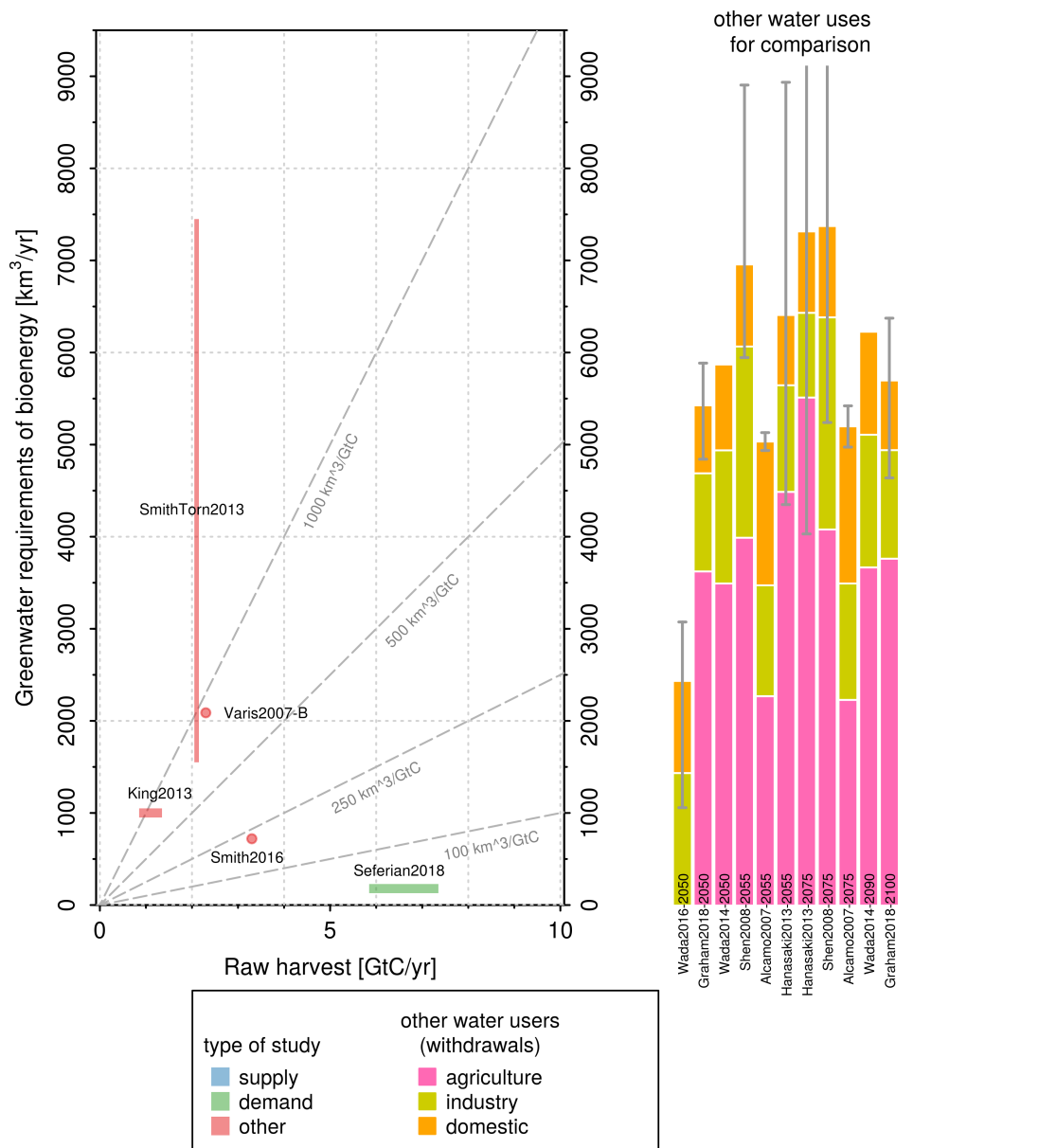
Figure A3. Analogous to Figure 2, but for scenarios of reported global green water consumption volumes required for bioenergy production through biomass plantations. Scenarios are characterized by water consumption for bioenergy plotted against raw harvest (inferred from reported biomass based energy or negative emissions). They can provide ranges in water consumption 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}.

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

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