Comments by Ellison:

This is a very interesting and well written contribution to the literature on bioenergy and water use. However, I do have several concerns that are generally not well addressed in this paper and frequently also in this literature in general.

Reply:

Thank you for the helpful comments and suggestions, addressed below and in the revised manuscript.

Comment 1)

From my perspective, the analysis of water use should ultimately be significantly more complex than the analysis conducted herein. The approach in this article is essentially a linear type approach: the more biomass material is grown; the more water is used. However, as indicated in publications that focus on the concept of precipitation recycling, this is not a straightforward (linear) proposition. I suggest the authors consider the following referenced literature (van Noordwijk and Ellison 2019; Ellison et al. 2019) in order to begin thinking about alternative strategies for measuring the water impact of biomass production.

From this perspective, the principal impact of growing biomass material is on the atmospheric moisture regime and its potential downwind impact. 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 will presumably lead to the opposite downwind effect on water availability. The local impact of these processes, however, is likely to be the reverse.

In this sense, the issue of geospatial location, mentioned in lines 185-190, is tremendously important. And it is very useful to have a clear sense both of where bioenergy resources are produced, as well as where they could be produced, in particular due to their potential impact on large scale hydrologic cycles and processes.

I realize that most or all of the reviewed studies that provide the foundation for this paper have not considered such atmospheric dynamics. But I think it preferable to note that this is a real disadvantage of most of the current studies analyzing bioenergy resource production and water availability.

I am not sure what the best answer to this problem really is. I am not necessarily expecting the authors to completely revise their approach. But I think some reflection on the relative value and importance of water as atmospheric moisture vs river runoff is called for, but entirely neglected in this type of work.

Reply:

Thank you for this thoughtful suggestion. Indeed, these feedbacks are not considered in any of the studies that we reviewed (nor in any typical study projecting changes in global water resources); therefore, as our review is based on existing studies, we cannot provide an analysis of atmospheric moisture and river runoff from bioenergy irrigation. However, in the revised manuscript, we reflect on this issue based on your literature suggestions in section 3.2 “Study differences in parameters choices and other assumptions” (lines 206-216). Ultimately, expanding the discussion by this point further strengthens our plea for more detailed analyses and accessible data.

Comment 2)

As someone who works a lot with forests, I was surprised to hear the bioenergy discussion so strictly focused on cropland products (rapeseed, oil palms, sugarcane, maize, Miscanthus and switchgrass). From my perspective, much of the focus is instead on forest residues as the principal bioenergy resource. Moreover, since forest residues will otherwise become an emission if left to decay on land, their impact on emissions is generally more or less equivalent (as a bioenergy resource or as land source emission). Thus, I was wondering what share the cropland type resources make up relative to other bioenergy resources, in particular forest residues? If forestry and harvest will

happen anyway, then the forest residue impact on water is presumably marginal. Is this considered in any way in any of the analyses? Likewise, in the Nordic countries these days, waste is also increasingly used as a bioenergy resource and has led to falling prices for biomass-based material.

Reply:

In our literature corpus we could only identify the usage of forest residues or similar as biomass feedstock in the studies of Beringer et al. (2011), Heck et al., 2018, and Stenzel et al., 2019. Beringer et al. (2011) mention "residues from agriculture and forestry, municipal solid waste and animal manures" on the order of ~100 EJ/yr in 2050 but do not include them in their analysis, while Heck et al. (2018) and Stenzel et al. (2019) include the initial timber harvest from the land use conversion of forests. Additionally Fajardy et al. (2018) include wheat straw residues as biomass feedstock. We expanded this paragraph (lines 243-247).

Comment 3)

It would be meaningful to be clearer about the water boundaries within which additional biomass material might be produced. By this I mean that it would be helpful to have clear statements in the text of the total amounts of available, usable water, out of which crops and biomass resources are grown. This would make it easier to interpret the numbers on total water use.

Reply:

We have added numbers for contemporary green and blue water demand on cropland and global runoff in section 3.4 "Bioenergy plantation water abstractions in light of water use in other sectors" (lines 291-294).

Comment 4)

I find the language in the text a little confusing when it addresses blue and greenwater. From my experience, water is essentially always blue until it has either been turned into a gas and thereby made green (evapotranspiration from forests, croplands and other vegetation), or has been polluted through industrial processes (grey water).The text occasionally seems to confuse this language. Thus, for example, speaking of rainfall as green water is unusual, since the blue/green terminology is usually applied to how rainfall is partitioned between the atmosphere and river runoff.

Reply:

Generally we refer to green or blue water depending on the source of water, either direct rainfall (ending up as soil moisture and/or evapotranspiration), or freshwater withdrawn for irrigation from rivers, reservoirs or groundwater. We thus follow the definition used e.g. in Fader et al. (2011) – which is now made more explicit in the Introduction (lines 45-47) and, if needed, anywhere else in the text where "green water" is mentioned.

Comment 5)

The land use competition issue and the availability of land for crops and bioenergy resource production is key and could be more fully addressed. How much additional land is available for this bioenergy production? And what does this mean for wateruse? If bioenergy resource production is additive (and does not displace croplands), the impact of course is much greater.

Reply:

The considered studies assume implementation of biomass plantations on different areas with various prior usage. While we had pointed out in the first manuscript version that these assumptions are certainly crucial, we now have added more information on how much total land is "potentially available" in these different categories (lines 222-226).

Comment 6)
It is somewhat unclear in the paper whether the production of biomass material should be added to the impact of cropland water use, or replaces this? This could perhaps be made somewhat clearer in the text.
Reply:
Generally the studies we analyze disentangle crop irrigation and bioenergy irrigation (however usually only report the latter).

We now explicitly mention in the Abstract (line 8) and Conclusions (lines 378-379) that the bioenergy water demand would come on top of (or compete with) the water demand for crop production, industry and domestic water use.

References:
Fader, M.; Gerten, D.; Thammer, M.; Heinke, J.; Lotze-Campen, H.; Lucht, W. & Cramer, W. Internal and external green-blue agricultural water footprints of nations, and related water and land savings through trade, *Hydrology and Earth System Sciences,* **2011***, 15*, 1641-1660

Comments by Hejazi:

The paper provides a synthesis of previous studies that focus on global scenarios that estimate bioenergy production in the future and their associated water footprints. The topic is definitely timely and highlights the importance of tracking bioenergy water demands in global hydrologic models in the future.
Reply:
We thank you for your helpful comments and suggestions.
Please find in the following our point-by-point response:

I have the following moderate comments:
1) The authors call out the distinction between withdrawal and consumption, then decide to call them either water requirements or water demand. To me this is very confusing. Combining both would mix up between two very different quantities, which makes some of the comparisons across studies unfair. I would suggest that authors keep that distinction throughout the analysis and show the results for each variable separately, the same way they have dealt with blue water and green water separately
Reply:
We apologize for any confusion. While we did not mix the different quantities in the previous manuscript, we now differentiate more clearly between (lines 81-83), and provide different figures for, withdrawal and consumption as Figures 2 and A2. Additionally we always refer to "water withdrawal" and/or "water consumption", and in case this is not possible use the phrase "water abstractions".

2) Some of the assumptions made by the authors to tease out some of the variables shown in Figure 3 might lead to errors in the interpretation of previous assessments(also section 2.2). Given that there are only 16 studies and many by the same research group, have the authors attempted to reach out to these teams to see if they can offer the necessary data from these studies?
3) A better approach might have been a model inter-comparison exercise with a set of harmonized scenarios and some sensitivity analysis around some key parameters would have been a much more effective approach to address the outlined questions. Obviously, I am not expecting the authors to restructure their approach and take on such an endeavor, but I think highlight the need for such an effort might be an othertake away message from this study.
Reply to 2) and 3):
We acknowledge that receiving and analyzing all these data would shed some more light on details of the individual studies. The range of results among models would be partially decreased by a systematic study intercomparison, but likely remain large due to considerable differences in the structure of models, underlying assumptions, and others.
While the scope of our review is to synthesize documented knowledge, we absolutely agree that a model intercomparison with standardized input datasets and assumptions would be required as a next step and added this to the Abstract (lines 17-18) and Conclusions (lines 388-389).

4) How does the study handle multiple studies using the same model/approach?For example, the GCAM study is relatively old, and I have seen recent studies where the biomass irrigation requirements are much smaller than their 2014study, since water demand is constrained by water availability in some more recent studies.
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2018WR023452
https://gmd.copernicus.org/articles/12/677/2019/#&gid=1&pid=1
Reply:
In our analysis, we only report the model names, not analyzing if more recent studies with the same, or updated versions, of particular models produced different results (which also could stem from other sources of uncertainty such as assumptions about available water or land). In the revised manuscript, we incorporate this line of thought into the Conclusions (386-389).

5) The paper is generally well written, although on occasions, the text becomes some-what redundant (e.g., omit the paragraph (lines 76-80) or move to later section) and some of the descriptions could benefit from summarizing the results in tabular form(especially in the case of section 3.2 on study differences). I would also suggest that the discussion section is structured in a way to be more aligned with the four science questions that were articulated at the end of the intro section. For instance, it is not clear which section addresses the 3rd question.

Reply:

We appreciate the suggestions and have added labels for section 3.2, where we discuss differences in parameters between the studies. Additionally the main study differences are now displayed in a new overview table (see next comment). We rearranged the research questions and added the respective section numbers.

6) Figures 1 and 2 don't really add much value, so I would suggest that you move these to the supplementary section. I was going to suggest that you move figure S1 to come as the first figure in the paper and before you show figure 3, but I would suggest that you include a table instead similar to Table A1 (without the title of the paper column), and with the addition of the details shown in figure S1.

Reply:

We replaced Figure 1 and 2 with an overview table of the analyzed literature and key parameters based on former Table A1 and enriched it with some more study parameters.

Comments by Anonymous:

The manuscript titled ''Global scenarios of irrigation water use for bioenergy production: a systematic review" summarizes recent literature on global water requirements for irrigation of bioenergy production (BP). Using a systematic review approach, the authors have searched, identified, extracted and analysed recent studies that report estimates of global water water demand for irrigation of BP. They found that water use for BP is wide ranging and that this water use is of same order of magnitude as water use for other sectors of the global economy (agriculture, industries, households). They examined the cause of variation in estimates of global water use across studies and highligthed the minimum set of parameters and assumptions that should be included in future studies to allow consistency in estimates and straightforward comparision of estimates of global water use across studies. Overall the manuscript itself is interesting and the topic is timely giving the relatively few studies on global water use of bioenergy with carbon carpture and sequestration (BECCS) as well as on global water use of negative emission technologies (NETs). However, they are issues that need to be addressed before the manuscript can become a valuable contribution to the current literature. The manuscript also requires a thourough english grammar check/edit to improve the readability. I have corrected few sentences but there are many more to check and correct.

Reply:

We thank the referee for his/her time and the detailed comments, as well as the assessment that the manuscript is interesting and timely. In the following we provide a point-by-point response to the comments. We also checked English language throughout the paper.

General comments

In general I think the methodology section to be improved. It is not clear clear to this reviewer how grey papers/reports were obtained and what were the inclusion and exclusion criteria used to include/exclue a study in/from the analysis. For example, marine biomass also consumes water (like terrestrial crops), and some of these biomass types may be cultivated in farm pond. I am puzzle why marine biomass feedstock was exluded from the review? Are they excluded because they consume less water? or because there is not algae/marine biomass based BECCs? Could author state in the methodology their inclusion and exclusion criteria? Could authours also provide rational for including review studies in their analysis. Often review studies are excluded from systematic review or meta-analysis studies. How was the grey lietrature obtained? In the methods section, authors state that they manually added the study of Hejazi et al. 2014 which could not be obtain using search querries. I therefore wonder how does grey lierature was obtained? by contacting authors of these articles/reports?

Reply:

The issue of increased freshwater stress for humanity through additional irrigation for biomass plantations in the future is essentially a terrestrial one. While there are some studies on producing large amounts of biomass also in marine environments, they do not provide amounts of blue (i.e. fresh) water consumed, which is why they were not selected. We also excluded grey literature, because they are not peer-reviewed.

In order to facilitate understanding of our literature selection, we have added labels for section 3.2 discussing the parameter differences. Additionally we replaced the former Figures 1 and 2 with an overview table summarizing the main parameters of each study.

The section 3.1 (overview) could be improve significantly by for example making a graph showing the global distribution of the studies reviewed (how many studies originates from EU?USA?Japan/China? etc), How many focus on BECCs and how many deal with NETs? How many consider the whole supply chain (from biomass production to conversion to energy with carbon storage) and how many treat only a segment/Stage of the supply chain (e.g. biomass production only, biomass conversion only, carbon capture and storage only etc). How many include green, blue and grey water?green+blue?Blue+grey?green+grey? how many consider only green/only Blue or only grey water? How many studies use numerical simulations models? how many use other types of models?

Reply:
We do not think that a geographical overview of research groups would be helpful (especially since we only consider global-scale studies) but we worked on making more transparent the further selection criteria that you mentioned, and use results from those studies in the Discussion as far as they are appropriate in our context.
As for better summarizing the aspects included in the studies we surveyed, in section 3.2, we decided to not present every variable as “12 out of 16 studies use numerical models”. For detailed information the readers are referred to the newly created overview table 2 and the supplementary data (which contains all extracted information).

Authors state in the conclussion section that there is a lack of clear relationship between water requirment and total BP. After reading this manuscript I wonder if this lack of clear relationship between water requirment and total bienergy production is not due to the fact that the donwstream process of biomass conversion are also included in the analysis. Could authors check if there will be a relationship betwen water requirements and total BP, when downstrem processes/stages are excluded (i.e;limiting the analysis to energy crops production only).
Reply:
Stating that “there is no clear relationship between water requirements and total bioenergy production” we meant to say that it is not simply a linear relationship. The variance however is largely determined by the various methodologies and parameters of the underlying studies, which we now further highlight in section 3.5 (lines 339-341).

Specific comments:
Line 127: Some of the studies include in the analysis were out of the scope of this review, but the authors still maintain them in their analysis. Why not simply use these studies to substantiate the discussion section? It would important to clearly state in the methodology section what were the inclusion and the exclusion criteria.
Reply:
Our focus is on blue water abstractions (now separately analyzed for withdrawals and consumption), therefore green water studies were excluded from the main analysis. However, we now report in more detail the associated green water requirements in section 3.1 (lines 155-161) and Figure A3.

Line 140: I think this statement is not complete. Please complete this statement by adding ‘’Berndes (2002) combines bioenergy demand secnario and projection based on measured evapotranspiration fluxes to compute global blue/green water demand for BP‘’
Line 146: Please consider rephrasing, it is not clear as it is now. Perhaps ‘’supply driven studies” rather than ‘’potential studies’
Reply:
We adopted the suggestions by the reviewer.

I found that some of the sentences/description in section3.2 actually fit in section 3.1. Please consider moving these sentences/description into section 3.1. It would be nice if section 3.2 is resctricted to the explanation of the cause of variation in the estimates of water use in the reviewed studies (difference in model used, difference in model structure, difference in model parameters, inputs data, difference in assumptions used). Which of the model is actually better suited for analysis of water use of a given stage/process of the BECCs/NETs supply chains?which model is better suited for assessment of water use of carbon capture and sequestration only?Do integrated assessment models (IAM) capture well the water use process than other model?Please discuss also here the strenghts and weaknesses of the model used(A table would be better).
Reply:
We have moved the paragraphs in which we state which models/approaches are best suited for what kind of analysis to section 3.1 (lines 137-146).

Line 167-169. Why mentioning this model here (ESMmodels) if they were not used in the reviewed studies?
Reply:
Seferian et al. (2018) use an ESM, we thus removed the text in brackets, even though the respective study is not part of our main analysis we believe that this information is still worth mentioning here.

Line 155, please insert ‘by’ between ‘demand’ and ‘comparing’ in this line, so as to read‘’...water demand by comparing rainfed and irrigated BPs.…”
Reply: done

Line 177, please consider rewriting this statement, it does not read well as is now
Reply:
We thank the reviewer for noticing this and have rewritten the statement (lines 147-149).

Line 211. Rephrase to state that ‘Among the reviewed studies, only two consider 1G bioenergy plants as feedstocks’ or ‘Only two of the reviewed studies consider 1G bioenergy crops’
Line 214 Please rephrase to state that ‘some studies assume change in biomass productivity over the 21stcentury”
Reply:
We adopted the above suggestions by the reviewer.

Line 215 Please rephrase to state that ‘This increase in productivity might, however be difficult to reach in the case of 2G crops because the whole aboveground biomass is used for bioenergy’. I also think that the argument here that productivity is difficult to increase in the case of 2Genergy crops because the whole plant is used is weak. There are several studies showing increase in productivity (via genetic improvment) of 2G energy crops
Reply:
We have rephrased the statement and added a sentence on the potential for improved water use efficiencies through breeding programs (lines 248-253).

Line 218: Here and in many other place in this manuscript. It is not clear to me what the authors mean by ‘’demand studies”. Do you actually mean ‘’demand driven” studies or ‘’demand driven case studies”, please consider rewriting because it is not clear.
Reply:
We adopted the suggestion by the reviewer and replaced “potential studies” with “supply driven studies” and “demand studies” with “demand driven studies” throughout the manuscript.

Line 228: I think these are not losses, but the efficiency of the CCS technology adopted. Losses are only 10-15% (say this efficiency range represent that of the CSS solely, and not the supply chain carbon efficiency which can be much lower)
Reply:
We replaced “losses” by “efficiencies” and improved the sentence structure (lines 263-265).

Line 240: This statement in this line does not read well. Do you actually mean ‘’The projections of future freshwater requirements (125-11350 km3/year) for irrigigation of BPs vary substantially across the reviewed studies due to the differences in model structures, the scenarios, as well as the methodologies adopted”. I also think that variation in projection of future water requirements for BPs might be also due to data input and study goal;please add this in the line 240.
Reply:
We changed the sentence based on your suggestion (lines 283-284).

Line 244: please replace ‘’by” with ‘’in” to state that scenario in Hejazi et al. (2014) and food first (FF) in Jans et al. 2018
Reply:

We replaced “by” by “in” here and also elsewhere in the manuscript where we refer to results/scenarios within a certain study.

Line 248. Please repharese to state that ‘’Assuming water use efficiencies of 585 m3/ton for miscanthus Hu et al. Project water requirements of the RCP2.6 to be up to 11350 km3/yr consisten with estimate of Hajazi et al. 2014
Reply:
We rephrased the sentence, but since the approaches are very different, we did not mention that this would be consistent with Hejazi et al. (lines 288-289).

Line 250-254. This sentence is too long and does not read well. Please consider shortening and rephrasing it.
Reply:
We split up and rephrased the sentence (278-282).

Line 254 and also Line 281, not clear to me what authors mean by primary bioenergy. Do you actually mean energy crops?
Reply:
We now explain this at the first occurrence (line 334) and in the Abstract directly refer to electricity.

Line 258:Please replace ‘large span’ by ‘large range’
Line 263 Rephrase to state that ‘’all exisiting croplands in 2005 is assumed to be replaced/converted by/to irrigated plantation for Bps’’
Reply:
We adopted the above suggestions by the reviewer.

Line 273 change in tense from present to past tense, this lead to mix tense within the manuscript. Please consider choosing one tense and stick to it throughout the manuscript. Having the paper edited by a professional native english speaker will significantly improve the readability of this manuscript.
Reply:
We appreciate you noticing this and changed to present tense also in several other places in the manuscript.

Line 320: Does the reported range here correspond to the total water use for the other sector or it just represent the range of each of the sector(agriculture, industrie, households) gathered from different literature source?Please clarify.
Reply:
We clarified that we mean the sum (line 377-378).

Line 325: Authors suggest/recommend that all the scenario parameters be reported in the plucation to enable straightforward interpretation and comparison of results. I wonder if such could be possible given that studies are designed to serve different purposes (e.g. some studies may only focus on a specific stage/segment of the whole BP supply chain such as CCS process). This said, I think it will be good that authors track the parameters and assumptions that contribute most to the global water requirement of BPs, then make recommendation for future studies to include most if not all of these parameters/assumptions to allow consistency and comparison among studies.
Line 326: Here the authors suggest a set of parameter that should be included in future studies to allow consistency and comparison of estimates of different studies. However, this recommendation is not convincing (at least to me), not based on solid evidence from the reviewed studies. Indeed the manuscript lacks a breakdown of contribution of the different paramter/process or stage contributing most to global water use of BPs. What is for example the contribution of plantation locations and crops species to the total water use of BPs? Such breakean will show process/stage having significant influence on estimates of global water use.

Reply:
The parameters were identified when we compiled this work. Deeper analyses and discussion of all of these parameters would have required a much higher level of reporting from the 16 studies (including regional patterns). Such analysis can thus only be done in a systematic comparison study that reports these data in a structured and accessible manner. As this is a review paper, we cannot perform such an analysis even with existing (partly inconsistent, i.e. not directly comparable) data.
Just from the documented results reported in the studies we surveyed, we also cannot rank the parameters according to their importance for these outcomes. For this, sensitivity studies for each model would be required (for example through a model intercomparison study), which (also as an answer to another reviewer) we now mention in Abstract (lines 17-18) and Conclusions (lines 368-370).

Line 338: This (i.e;biodiversity) has not be discussed in the manuscript. I suggest to remove this in the conclusion of this manuscript
Reply:
Biodiversity loss will likely be a result of the large area demand that we found to be projected. Thus we would like to keep it in the manuscript.

Line 345. Please rephrase to state that ‘’integrated assessments that consider all water use sector are highly desirable and are crucial to get a better understanding of the limits and options of the future water use consumption.
Reply:
We adopted the suggestion by the reviewer.

Comments by King:

General comments:
This paper provides a synthesis of 16 global overview studies of potential future blue water use of a widespread bioenergy industry, including some consideration of industrial processing water use, and reference to associated green water use of bioenergy plantations. The review is based on relatively few studies, and the treatment of underlying drivers of geographic variation in water availability, bioenergy water use, and productivity is not very detailed compared to previous studies. Limitations of available data and underlying assumptions are noted, but not explored in depth. The important concept of water use efficiency (unit bioenergy produced per unit water used) forms the basis of some of the underlying calculations, but its use as a unifying central concept that can be integrated across scales to enhance the sustainability of a bioenergy industry is not explored as much as it could be. Although the synthesis of potential blue water demand in the context of other human water needs is very useful, the perspective of the review at times appears to be that of advocating for irrigation of bioenergy plantations without due consideration of economic or environmental sustainability (this is clearly not the intent of the authors, but the writing makes it appear so), and thus needs major revision, especially in the Introduction and Discussion, as noted below in specific comments.
Reply:
We are grateful to Mr. King for providing this very detailed analysis with numerous suggestions and comments for improvement and restructuring, which we considered as much as possible.

We acknowledge the limited treatment of geographic variation in water availability, bioenergy water use, and productivity in our approach and incorporate suggestions to enable this for future studies in the revised manuscript.

As Mr. King notes, it was not our intent to advocate for unsustainable irrigation of bioenergy plantations and we very much appreciate his help to make sure this impression is removed from the manuscript. We rewrote the Introduction and extended the Conclusion with a view on synergistic, sustainable solutions to possibly minimize the water use for biomass plantations – also as an encouragement that future studies should consider such options more properly than in the studies available – and here reviewed – so far.

However, this review is centered around the possibility (supported by the literature), that future biomass plantations might be irrigated. We agree that this should not happen at the costs of ecosystems or water supply for other human needs, though this cannot be excluded. Economic incentives such as a global carbon price (reversely applied also for negative emissions), increasing land demand due to population growth, and the partitioning of the available land between the food-producing agriculture and the biomass industry might influence it.
This review demonstrates that the potentially large amount of withdrawals for bioenergy irrigation should already today be considered when thinking about BECCS deployment.

Specific comments

Abstract
P1 L2: The meaning of the phrase "final energy production" is ambiguous and should be defined.
P1 L9: Remove parentheses and change to "for agricultural, industrial, domestic and other water withdrawals". In general, limit the use of parenthetical phrases embedded in sentences, which there appear to be a lot of.
P1 L14: The concept of bioenergy water use efficiency should be added to the list, as it can be used as a means to match appropriate crop species to regional climates, potentially decreasing blue water demand. It can also be considered a trait targeted in crop improvement programs (e.g. through traditional breeding or genetic modification) with the objective of decreasing crop water use, and thus the need for irrigation.

Reply:
We adopted the above suggestions by Mr King.

Introduction

P2 L26: It is argued that bioenergy feedstocks "will probably have to be grown on large managed plantations and include substantial irrigation". Rather than accept that as a fait accompli, an efficient society would figure out how to sustainably produce bioenergy as part of a broader renewable energy portfolio that is "climatically-competent" and sustainable. If irrigation is used for energy production, it should only be done in areas that have rates of groundwater recharge high enough to offset removals, otherwise you are "borrowing" (some would say stealing) from the future. Solar energy should be produced where there is abundant incident radiation, but otherwise unfavorable for plants or other uses (barren lands, rooftops, etc.). In the same way that wave energy will be produced in coastal areas, wind energy where there is abundant wind resources, hydropower where there is abundant surface water, bioenergy should be produced in regions of the globe where it is climatically "indicated", but without competing with food production. That is why it is so important to develop energy crops that have low water demand, are resilient to environmental stress (like drought), and are as water-efficient as possible. Further, the water balance of all crops grown for bioenergy (and food) should be quantified and considered in the context of the local climate (e.g. precipitation, evapotranspiration, surface/subsurface runoff, and ground-water recharge). In that context, regionally-appropriate crops can be selected, and their water-use efficiency improved through breeding programs or other means.

Reply:
We absolutely agree with your comment and attempt to focus on results from the analyzed studies and mark them as such (e.g. lines 29-32). Additionally we have reworked the Introduction based on your comments below.

P2 L29: King et al. (2013) provide a comprehensive review of green water use of major herbaceous and woody candidate bioenergy species, and should be cited here.
Reply: Done

P2 L39: With looming freshwater shortages already occurring in many parts of the world, is it defensible to suggest irrigation be used to sustain high-productivity bioenergy farming?I understand that quantifying the potential blue water demand of a widespread bioenergy industry in the context of other uses is the premise of the current paper, and therefore warranted, but in this reviewer's opinion that should be considered an absolute last resort, and preferably, society will design bioenergy production systems that are climatically robust and environmentally sustainable, and therefore based mostly on green water. In addition, any discussion of irrigating bioenergy crops should consider the economic aspects. Irrigation is expensive and economically-justified for high-value food crops (sometimes), but it is generally not used in forestry, even for high-value saw timber products, so would it hold up for a low marginal value commodity such as energy? It might require economic incentives such as carbon credits/trading in order for bioenergy irrigation to become economically competitive with other energy sources, for example. The Introduction would be improved by placing the current study in the broader context of environmental and economic sustainability.
P3 L43: This is a good point, and certainly I agree that all bioenergy field experiments should report the water balance of the systems studied, including precipitation, ET, runoff/drainage/groundwater recharge, and irrigation.

Reply:
We enhanced the Introduction and hope that economic as well as sustainability issues of bioenergy irrigation become clearer (lines 48-56).

P3 L52 to L62: The authors appear to be discussing bioenergy water use at two different scales, which if articulated a little more clearly would be useful in advancing the current discussion, and ultimately development of a sustainable bioenergy industry. The first scale

is that of total water use of individual bioenergy production systems at the ecosystem scale (e.g. m3 water per hectare per year), which can be broken into green and blue components, and is affected by crop productivity, management, inter-annual variation in weather, long-term climate change, etc. The second scale is the integration of water use of all the individual bioenergy systems present across the landscape to local, regional, and ultimately global scales (e.g. km3 globally per year) to give the overall blue water requirement in the context of the current review paper. The nomenclature adopted in this paragraph, and therefore concepts expressed throughout paper, relating to "water withdrawals", "water demand", "water consumption", and "water requirements", although explicitly attempting to be clarified by the authors, still confounds the spatio temporal scaling aspect, and thus needs a bit more refinement.
Reply:
We added to the Introduction a sentence on the two different ways we compare water requirements (lines 81-83).

P3 L65 to L70: How do these questions advance the science beyond the previous global syntheses upon which this study is based (e.g. Berndes2002, Beringer et al. 2011, Gerbens-Leenes et al. 2012, etc.)? There are many excellent sources on blue and green water aspects of bioenergy providing the foundation of the current study (Table A1), and their synthesis is certainly an important contribution, but the writing of the Introduction and the wording of these questions do not highlight (very well, in my opinion), what new is being contributed here. I'm sure it is there and I will discover it upon reading the rest of the paper, but so far it seems mostly repetition of previous work.
Reply:
This review synthesizes and compares earlier results and discusses underlying assumptions from available studies on global blue water requirements for large scale bioenergy production, which has not been done before. We hope that our overview will help make the potentially severe impacts more visible and help in interpreting and comparing the values, while we ask for more parameters and assumptions to be published and ultimately suggest an inter-model comparison on this topic.

P3 L72 to L80: So here it is, there have been previous assessments of green and blue water requirements of a potential widespread bioenergy industry, but there is large variation in the estimates and insufficient analysis of underlying sources of variation and assumptions, that need to be standardized. This could be the first statement of the Introduction, followed by an analysis of the relevant literature to substantiate the point.
Reply:
We appreciate your suggestions and have added a new first paragraph at the beginning of the Introduction stating this. Following is the introduction of negative emission technologies and BECCS, as well as the basics of water use on biomass plantations.

Without supporting their argument, it is stated that local or regional studies cannot be straightforwardly up-scaled or compared to global studies.
In the age of rapidly advancing process-based ecosystem-landscape-global modeling, remote sensing and increasingly powerful geospatial analytics, paired with well-tested methodology for ground-based ecosystem studies that can fully close bioenergy cropwater budgets, this statement seems anachronistic.
Reply:
This paragraph was moved to the end of the introduction, and extended to explain that up-scaling (while theoretically possible) would require more data from the studies, which is not available.

It seems then, that the main contribution of the current work could be to illustrate how such global scale syntheses can be standardized in data requirements/formats, analytical framework, scopes of inference,supporting assumptions, and reconciliation across spatio-temporal scales. If this is in fact the intention of the authors, then the Introduction needs a major rewriting to clearly make the case.

Reply:
We appreciate your suggestions to make more explicit one of our aims and adopt them for the reworked Introduction.

Methods
P4 L86: Remove second comma.
P5 Figure 2: This figure is unnecessary. The information is stated in a preceding line of text, and is in the body of Table A1. Suggest replacing Figure 2 with table A1 in the body of the text.
P5 L95: Remove comma.
Reply:
We adopted the above suggestions.

P5 L98: The degree of assumed bioenergy deployed may vary greatly among sources, but can be presented as a range, with accompanying discussion of the reasons for the variation and implications. That is typical for such overview review studies.
Reply:
We compare ranges of bioenergy demand (from reported negative emission demand or energy demand) in the Discussion (section 3.5).

P5 L99:The amount of biomass harvested for bioenergy divided into the water used (ET) to grow it on a unit-area of land is termed "bioenergy water use efficiency" (at the farm gate), and was introduced for a variety of prominent woody and herbaceous candidate crop species by King et al. (2013). The values given in King et al. (2013) are based on measured productivity and site specific meteorological data (calculated PET or measured ET), which could inform this discussion up to L119 of the current study, and at the least should be cited here (at least for aspects that do not include industrial water use). The current study nicely and logically extends the water use efficiency concept to larger spatio temporal scale (km3 GtC-1), illustrating its utility as a scaling factor in addition to my earlier comments on its use to increase environmental resilience and bioenergy production efficiency at the farm gate. (Incidentally, water use efficiency is a central concept in plant physiology used to describe the efficiency of C uptake relative to transpirational water loss at the leaf level (umol CO2 mmol water m-2 leaf areas-1), which was scaled in King et al. (2013) to compare the water efficiency of different bioenergy crops at the ecosystem level, and is used here to scale industrial water use to the global level. Water use efficiency is thus a unifying concept of central relevance, warranting more explicit discussion.
Reply:
We extended this paragraph based on your suggestions (lines 107-111).

Results and Discussion
P6 L127: The term "freshwater abstractions" is ambiguous and undefined. Please define what you mean here.
Reply:
We throughout the manuscript use the term "blue water abstractions" or "freshwater abstractions" when talking about the water requirements for bioenergy, when we cannot be as specific as withdrawals or consumption.

P6 L129 to L137: This paragraph argues that the current study is only based on 16 previous synthesis studies of bluewater use of bioenergy plantations because that is all that is available in the literature. It is recognized that most reports of water use of BPs do not include estimates of ET or green water use. I agree with this perspective, however, I think the paragraph (and paper) would have more impact if it took the point of view of arguing for a more comprehensive quantification of water use of bioenergy systems, rather than seeming to advocate for irrigation. I know it is not the intent to argue for irrigation of BPs, but in justifying the current analysis it gives that impression. It should be an objective of future, and to the extent possible, past bioenergy studies, to be placed in the context of full water balance quantification, partitioning sources into green and blue pathways,and

identifying potential means of increasing water use efficiency and decreasing bluewater demands. In that context, the current discussion can present the potential bluewater use of BPs compared to other human water demand based on current knowledge. Blue and green water use are comparable, we just don't have the needed data to do so, which should be an argument forwarded for here.
Reply:
We agree and have reformulated/restructured the paragraph (lines 155-167).

P7 L139 to L183: This is useful discussion of the modeling frameworks of the various studies comprising the data base for the current study, and the advantages of broad scale modeling (such as ESMs) compared to more detailed, process-based or empirical approaches. As an empiricist, I think there is value to a joint-approach using broad scale assessments in tandem with parameterizations and validations based on finer scale process under-standing.
Reply:
Thank you. We slightly restructured this part and added bold-faced labels to facilitate understanding.

P9 L207: Change "is varying a lot" to "varies widely". - adopted
P9 L215: Great gains have been made in tree productivity for species such as Pinus taeda, Pinus radiata, Eucalyptus spp, etc., in breeding programs targeted at timber production, and there is great potential and need to do this for bioenergy crops, especially for the traits of productivity and water use (efficiency). This should not be discussed as something that is not possible, but rather there is great potential for that has not yet been realized.
Reply:
We adopted the suggestion by Mr King.

P9L222: Awkward sentence structure.
Reply:
We modified the sentence (lines 156-158).

P11 Fig 4: Change "inlets" to "inlays" in legend.
P12 L286: "table" is misspelled.
P13 L293: Change "no more" to "no longer".
P13L294: Change "increase" to "increases".
P13 L303: Delete "of".
Reply:
All corrected.

P13 L307 to L317: This discussion of potentially increasing human water withdrawals by 50 % to irrigate BPs in the face of (increasing) significant human water stressed populations highlights my earlier point of economics and the role of bioenergy in a broader renewable energy portfolio. As the demand for water in other sectors increases, its price will rise, making it less likely to be used to produce a low marginal value commodity like energy. Rather, market forces will direct water use towards food production or other, while energy is produced more cheaply elsewhere. If climate change decreases productivity potential of the land significantly, as predicted (e.g. Beringer et al. 2011), this becomes all the more dire. Partitioning source-studies into "demand", "withdrawal", and other studies in this context (e.g. Fig. 4) was very useful, resulting in widely varying trajectories, that perhaps could be explored a bit more in the discussion in terms of drawing inferences regarding future water availability and use in bioenergy plantations.
Reply:
Thank you, we have added a paragraph on these interesting effects as well (330-334).

Conclusions
P13 L322: I did not feel a wide range of parameters were discovered and explored in the current paper, rather just the primary ones mentioned here.

Reply:
We rephrased this paragraph (lines 367-370).

P14 L325: Insert “future human water use” or similar descriptor before “publications”.
Reply: Done.

P14 L326: As I said earlier, I would also suggest for field studies of including: meteorological conditions of study sites and water availability around the globe or relevant areas, water use and productivity of the bioenergy crops investigated, and the complete water balance of bioenergy production systems, including partitioning of blue and green water sources. To the extent possible, blue water demand should be decreased as much as possible by careful selection of climatically favorable areas, selection of water efficient species/genotypes, and improvement of water use efficiency through breeding programs and development of “smart” irrigation technologies. These topics are beyond the scope of the current paper, but the reader could be pointed in the right direction with a few key citations.
Reply:
We completed the useful parameter set here like in the Abstract and adopted your further suggestions.

P14 L335 to L347: Here the impact of widespread bioenergy farming on biodiversity, economic feasibility, other land uses, etc., are finally considered, which seems too little-too late in the paper. I would discuss these broader aspects upfront in the Introduction, acknowledging their importance but justifying why they are not the subject of the current paper, then you can focus on estimating the potential future bioenergy blue water demand scenarios based on current knowledge, identifying are as that limit understanding that should be the focus of future research.
Reply:
We would prefer to keep this paragraph here as it is one conclusion from the large area demand that we observe to be projected.

P14 L340: I would add the qualifier “assuming it is economically justifiable” or similar after “irrigation”.
Reply:
We adopted the suggestion by Mr King.

Global scenarios of irrigation water ~~use~~ 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 ~~final energy production~~providing electricity. The associated freshwater ~~requirements~~ 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 ~~requirements~~ 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 ~~water demand for irrigation of~~ irrigation water abstractions for biomass plantations, suggesting ~~a range of 125–11,350 km^3 yr^{-1} water use (consumption), compared to about 1,100–11,600 km^3 yr^{-1} for other (~~water withdrawal in the range of 128.4–9,000 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 ~~make the freshwater amounts involved comparable by estimating the original biomass harvests from reported final energy or negative emissions~~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 ~~demands~~abstractions, full disclosure of parameters and assumptions is crucial. A minimum set should include ~~annual blue water consumption and withdrawal~~the complete water balances of bioenergy production systems (including partitioning of blue and green water), bioenergy crop species ~~, rainfed as well as~~ and associated water use efficiencies, rainfed and irrigated bioenergy plantation locations (including total area and meteorological conditions), and total ~~bioenergy~~ 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
PyCCS pyrogenic carbon capture and storageSSP	shared socioeconomic pathway

1 Introduction

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 $km^3 yr^{-1}$ – 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 energy electricity 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., 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 $GtC\,yr^{-1}$, Smith et al. 2016; 2–5 $GtC\,yr^{-1}$2–5 $GtC\,yr^{-1}$, Rogelj et al. 2015), the feedstock will probably have 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*, 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 (King et al., 2013).

While burning of fossil energy carriers leads to (net positive) emissions of greenhouse gases, use of ~~bioenergy~~ biomass 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~~ 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~~ completely depend 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 lakes, rivers, reservoirs and aquifers ~~(Hoekstra et al., 2009) – in this review, we focus on the latter since the~~ (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 ~~promotes~~ 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~~, 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 $\mathrm{km^3\,GtC^{-1}}$ 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~~ . 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~~ 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 ~~use~~ 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, ~~motivates~~ motivate 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.~~

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 ~~requirements~~ abstractions in global NE or energy scenarios relying on BECCS/bioenergy. ~~It~~ 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 ~~is the global freshwater demand~~ 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 ~~does this amount~~ do amounts of freshwater abstractions for irrigated biomass plantations compare to other sectors? (section 3.4)

4. ~~What are the key modelling parameters and assumptions of global bioenergy studies that affect the inherent water demand projections?~~ Is there a dependence between the simulated freshwater ~~requirements~~ 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 ~~(i.e. a different 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~~ 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 ~~underlying land use patterns and~~ 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~~.~~:

```
("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")
```

Table 2. ~~Search query used for the WebOfScience and SCOPUS databases. We found 430~~ List of publications ~~, from which 15 had quantified values~~ with published key bioenergy parameters analyzed in this review. See supplementary dataset (Stenzel et al., 2020) for ~~the global freshwater demand of BPs~~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 ~~demand~~ abstractions of large-scale BPs (going from title to abstract to full text). The global bioenergy studies with water ~~demand values~~ 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 ~~transpired green water~~ 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 ().~~

~~Frequency of found global-scale studies on the freshwater demand of bioenergy plantations, with publication dates from years 2002 to 2020.~~ 2010.

2.2 ~~Comparing BECCS~~ Calculating an inverse water ~~demand estimates~~use efficiency (iwue)

Comparison of the literature values of water ~~demand~~ abstractions for BECCS is not straightforward ~~,~~ because of the different assumptions studies made on important model parameters and setups, as described in ~~the section~~ section 3.2. Nevertheless, besides presenting the absolute global estimates of freshwater ~~use and~~ withdrawal or 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~~ we thus relate the given freshwater ~~demand~~ abstractions to the absolute amount of biomass assumed to be grown. With this we quantify the estimated water ~~demand~~ 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):

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

For the analysis, we ~~separated~~ separate the scenarios into those that report water ~~demand~~ 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 ~~could~~ backtrack the approximate dry biomass harvests by using the gross calorific value of $18.5\,\mathrm{MJ\,kgDM^{-1}}$ ~~(?Brosse et al., 2012)~~(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 2).

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

With this we ~~approximated~~ 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 ~~documented~~ 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 ~~derived~~ derive the dry biomass harvest by division of the NE amount by c_{eff} (Equation 3). 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.

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

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

3 Results and Discussion

3.1 Overview

We ~~synthesized~~ synthesize the results from the 16 publications into 34 scenarios ~~(with similar parameters) of freshwater demand~~ of freshwater abstractions for bioenergy (the full data-set is available as Stenzel et al. 2020). As freshwater ~~requirement we extracted~~ abstractions we extract 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.~~ 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 assessment 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 computationally 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.

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).

~~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~~ added 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 bioenergyfound in our literature query~~ 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. ~~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.~~ 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 ~~demands~~ 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 ~~demand of~~ 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 ("~~potential~~ 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 ~~demands~~ 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 ~~use of~~ withdrawal or consumption for BPs under different scenario constraints. Bonsch et al. (2016) specifically investigated the trade-offs between area and water ~~demand,~~ 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 goals were global bioenergy potentials and the associated trade-offs with global water ~~use~~consumption, plantation area demand or planetary boundaries.

The water (and land) implications of an increasing biofuel production in the future were analyzed ~~by~~ 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 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 and the supplementary data (Stenzel et al., 2020).

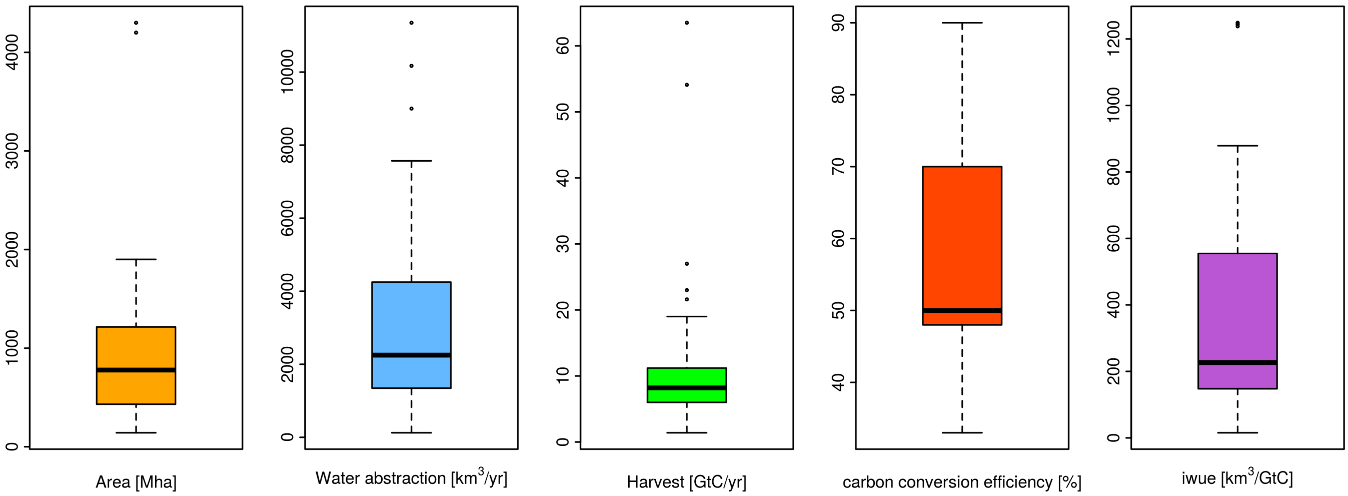

Figure 1. Range of key parameters (global estimates) determining projections of water requirements abstractions for bioenergy in the scenarios examined (see supplementary data Stenzel et al. 2020) presented as boxplots. Note that plantation area and carbon conversion efficiency are not reported in all studies. Water requirements Inverse water use efficiency per biomass harvest are (iwue) is calculated for each scenario, using the means of water demand 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 42 Mha in de Fraiture et al. (2008) (only biofuels) and 8,195 Mha in Hejazi et al. (2014) with the median area being 616 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 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 (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 ~~bioenergy plantations~~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 ~~bioenergy plantation~~ 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 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 Mha for marginal land (Campbell et al., 2008), 6,899 Mha for natural vegetation (Boysen et al., 2017), 3,286 Mha for natural vegetation excluding protected or vulnerable land (Stenzel et al., 2019), and 441 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 ~~) (Jägermeyr et al., 2015)~~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 ~~is varying a lot~~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 ~~studies are only two which~~ 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 models assume~~ Some studies assume yield productivity changes in the bioenergy harvest over the 21st century based on previous productivity increases observed in crop harvests ~~. These however~~ (Bonsch et al., 2016; Mouratiadou et al., 2016; Humpenöder e There however is also the argument that this increase of productivity might be more difficult to reach ~~, since for second-generation bioenergy cropsall aboveground biomass can be used for energy~~ 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.

~~For demand~~ **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 ~~e.g.~~ in 2015 (Humpenöder et al., 2018) or in 2030 (Stenzel et al., 2019). ~~There is quite some variety in trajectories~~ 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~~ which require higher yearly biomass yield demands ~~which might arise from later deployment start might make more irrigation necessary~~ at the end of the century will likely also lead to higher yearly irrigation requirements. The yearly water ~~demand values~~ abstractions given in the studies are not always indicative of ~~an~~ average irrigation water ~~demand~~ 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 ~~are only the losses in the last step of the process chain~~ 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 ~~demands~~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 ~~by~~ 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 ~~demand and use~~ abstractions (e.g. considered in Fajardy et al. 2018).

3.3 Projections of global irrigation water ~~demand~~ abstractions for bioenergy plantations

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}.

According to the model-structural differences, scenariosand methodologies described in , 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 wit associated water demands of 5 From the 16 studies we synthesized 34 scenarios, 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 collectedassociated data on 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 biocropsbiocrop 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)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), 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 –) . This large span shows that 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 (). 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 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 $\mathrm{km}^3\,\mathrm{GtC}^{-1}$). Here we denote, that the very high value (2,771 $\mathrm{km}^3\,\mathrm{GtC}^{-1}$) 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 $\mathrm{km}^3\,\mathrm{GtC}^{-1}$. .

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 °CThe projections of potential future freshwater consumption for irrigation of BPs (125–11,350 $\mathrm{km}^3\,\mathrm{yr}^{-1}$) 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 Mha with associated water withdrawals of 5,500–9,000 $\mathrm{km}^3\,\mathrm{yr}^{-1}$. 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 $\mathrm{m}^3\,\mathrm{t}^{-1}$ for *Miscanthus*, Hu et al. (2020) project the water consumption on RCP2.6 consistent BP areas (431 Mha) to be up to 11,350 $\mathrm{km}^3\,\mathrm{yr}^{-1}$.

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

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 $\mathrm{km}^3\,\mathrm{yr}^{-1}$ and 800–1,500 $\mathrm{km}^3\,\mathrm{yr}^{-1}$, respectively (Hoff et al., 2010; Jägermeyr et al., 2015; Rosa et al., 2018). Runoff, feeding these appropriation globally sums up to approximately 40,000 $\mathrm{km}^3\,\mathrm{yr}^{-1}$ (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 requirements abstractions 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; W 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., 20 compiled for comparison (see supplementary tabel table file). Agriculture is globally the largest water using sector among

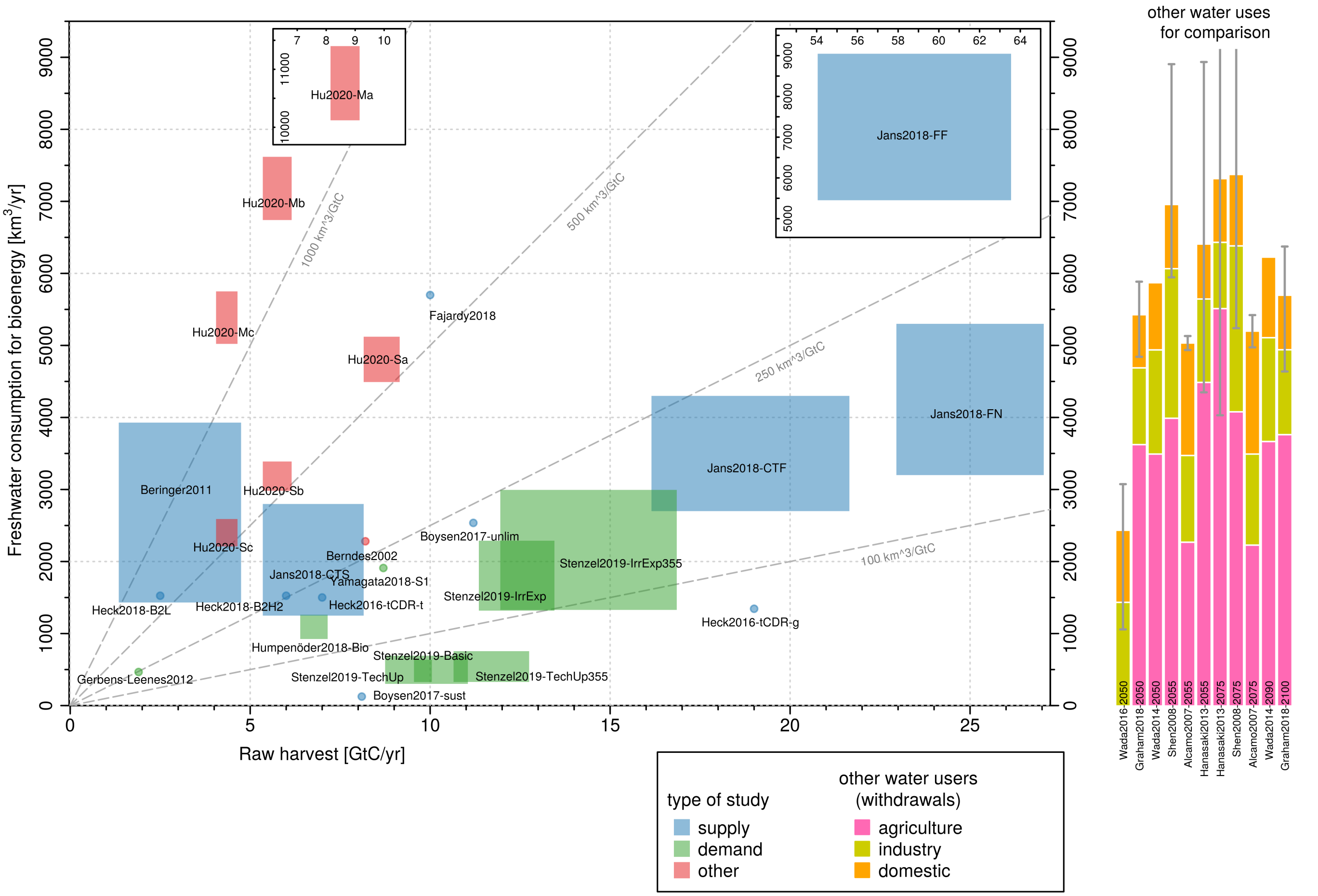

Figure 2. Overview of scenarios of reported values of global blue water consumption required for bioenergy production through biomass plantations (inlays show scenarios outside the plotting region). Scenarios are characterized by freshwater consumption for bioenergy plotted against raw harvest (inferred 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}.

the three, with a global total irrigated area reported to be 306 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 km^3 yr^{-1}~~2,402–3,214 km^3 yr^{-1}. Future agricultural water withdrawal ~~has been~~ 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 km^3 yr^{-1} and 2,211–8,434 km^3 yr^{-1}~~2,256–6,037 km^3 yr^{-1} and 2,211–8,434 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 ~~more~~ 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 ~~increase~~ increases at a rate of 0.6 % 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 km^3 yr^{-1} and 328–474 km^3 yr^{-1}, respectively. Future industrial and municipal water withdrawal ~~has been~~ is projected using empirical approaches. For instance, Alcamo et al. (2003) and Alcamo et al. (2007) ~~developed~~ 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 ~~of~~ and the late 21st century are estimated to range between ~~433 and 3,313 km^3 yr^{-1} and between 246 and 3,772 km^3 yr^{-1}~~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}~~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.

~~indicates~~ Figure 2 and Figure A2 indicate that 19 out of ~~35 estimations exceed 2,000 km^3 yr^{-1} of~~ 34 estimations for global additional irrigation water withdrawal for bioenergy ~~globally~~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 ~~persons~~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.

We find the global water demand for irrigation of biomass plantations assumed by the available literature

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 $\mathrm{EJ\,yr^{-1}}$, while NEs range from 1.2 to 10 $\mathrm{GtC\,yr^{-1}}$. After converting primary bioenergy and NEs to initial biomass harvests (see section 2.2), we find the projections of global freshwater abstractions per harvested biomass (iwue) to be in the range of 125–11,350 $\mathrm{km^3\,yr^{-1}}$ water use (consumption)15–2,761 $\mathrm{km^3\,GtC^{-1}}$ (15–1,250 $\mathrm{km^3\,GtC^{-1}}$, 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", compared to about "TechUp", and "TechUp355" from Stenzel et al. (2019) and "tCDR-g" from Heck et al. (2016) demonstrate iwue 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 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 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) (1,100–11,600 $\mathrm{km^3\,yr^{-1}}$ for other (agricultural, industrial, and domestic) water withdrawals and thus at similar magnitude102–1,402, 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 °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 demand of BPs, including abstractions for BPs. We are not able to quantify the contribution of each parameter, however strong dependencies are expected for the targeted primary energy bioenergy 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

A number of parameters were however not documented in the publications. Thus we recommend that all scenario parameters be reported in publicationsfuture 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 eyes include annual blue water consumption and withdrawal, bioenergy crop speciesview 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 bioenergy plantation BP locations (including total area and climatic conditions), and total bioenergy 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 $km^3\,yr^{-1}$ (consumption: 125–11,350 $km^3\,yr^{-1}$), compared to about 1.100–11,600 $km^3\,yr^{-1}$ 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.

Surprisingly, there is no clear relationship between water requirements (e.g. linear) between water abstractions and total bioenergy production. However, by comparing the freshwater demand abstractions per harvested biomass, we find that most of the scenarios fall between 100–1,000 $km^3\,GtC^{-1}$100–1,000 $km^3\,GtC^{-1}$. The full range of 15–1,250 $km^3\,GtC^{-1}$ 15–1,250 $km^3\,GtC^{-1}$ fo biomass harvest implies that, given a carbon conversion efficiency of 50%, we might need 99–8,250 km^3 99–8,250 km^3 to reach NEs of 3.3 $GtC\,yr^{-1}$. as projected to be necessary by Smith et al. 2016.

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.

These additional water ~~requirements~~ 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 ~~demand~~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.

This review provides a first comprehensive overview of the current literature on global projections of the freshwater ~~demand~~ 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. ~~Integrative studies considering~~ 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 ~~a requirement~~ are crucial to get a better ~~, integrated~~ understanding of the limits and options of future ~~overall water use and~~ 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.

Appendix A: Supplementary Information

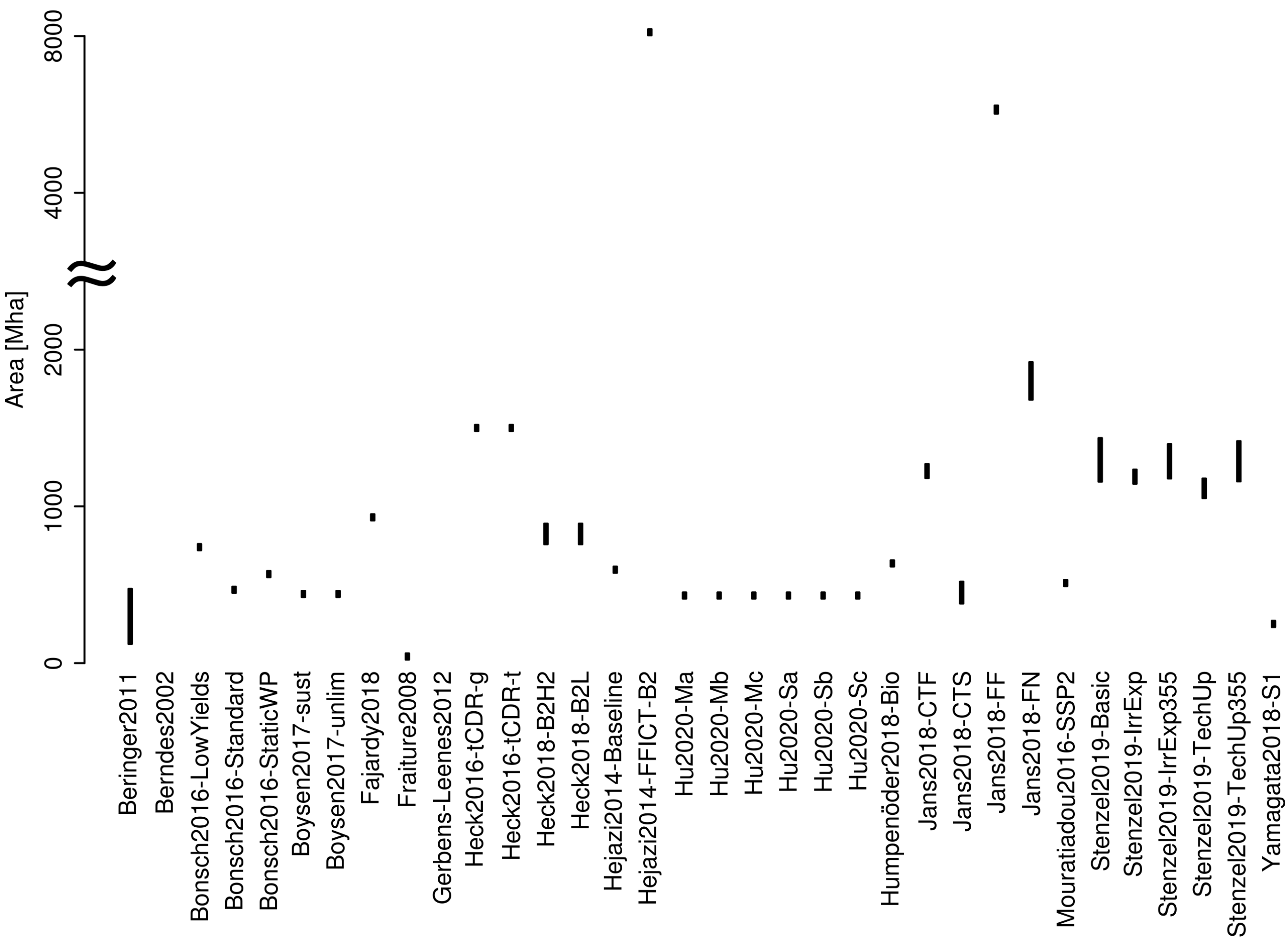

Figure A1. Overview of reported total global area of bioenergy plantations.

List of publications, providing scenarios for this review. **Author Year Title** blue water studiesBeringer et al. 2011Bioenergy production potential of global biomass plantations under environmentaland agricultural constraintsBerndes 2002The feasibility of large-scale lignocellulose-based bioenergy productionBonsch et al. 2016Trade-offs between land and water requirements for large-scale bioenergy productionBoysen et al. 2017The limits to global-warming mitigation by terrestrial carbon removalFajardy et al. 2018 the BECCS resource nexus: delivering sustainable negative emissionsde Fraiture et al. 2008Biofuels and implications for agricultural water use: blue impacts of green energyGerbens-Leenes et al. 2012Biofuel scenarios in a water perspective: The global blue and green water footprint ofroad transport in 2030Heck et al. 2016Is extensive terrestrial carbon dioxide removal a 'green' form of geoengineering?A global modelling studyHeck et al. 2018Biomass-based negative emissions difficult to reconcile with planetary boundariesHejazi et al. 2014Integrated assessment of global water scarcity over the 21st centuryunder multiple

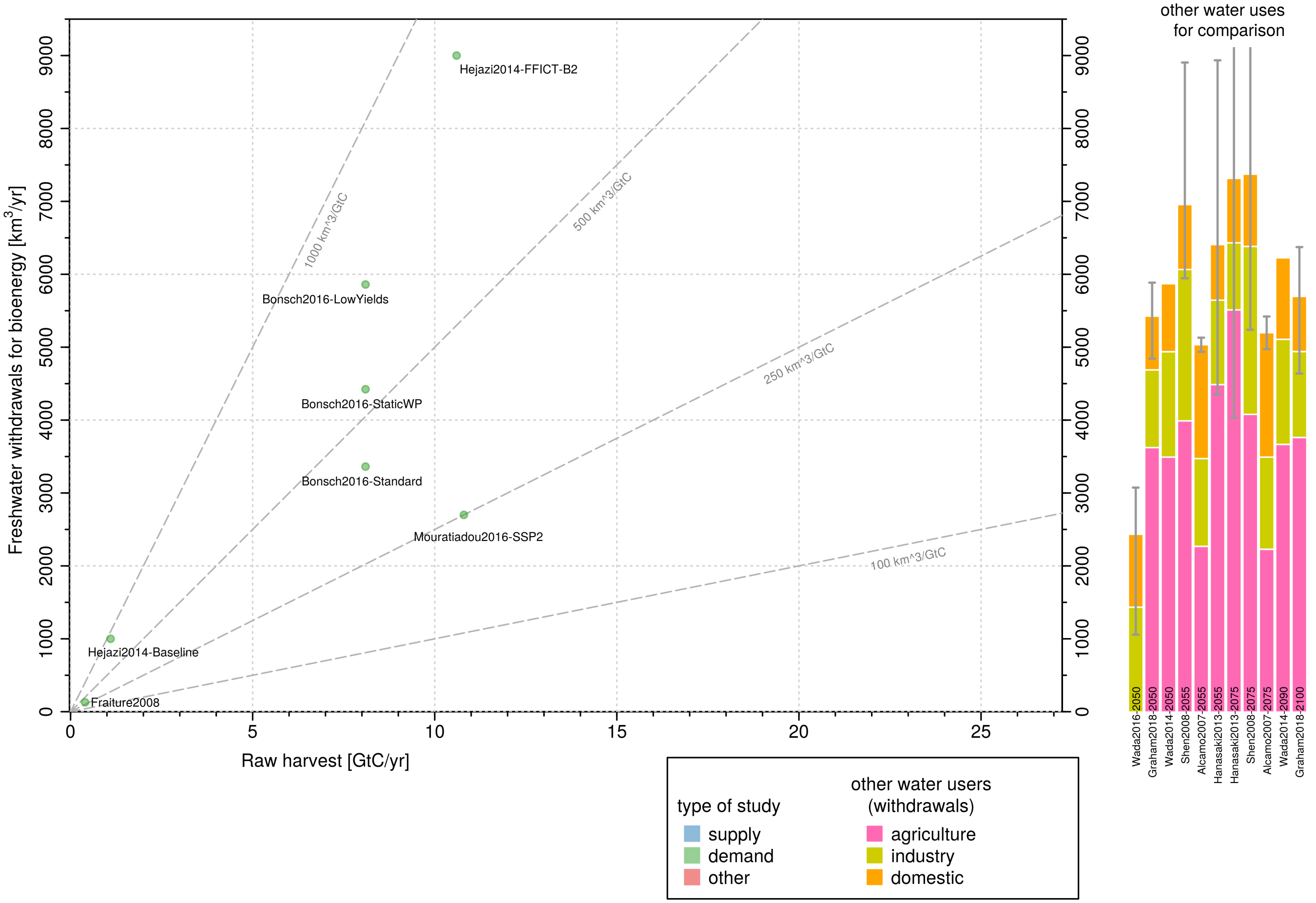

Figure A2. Analogous to Figure 2 but for scenarios of reported values of global blue water withdrawals required for bioenergy production through biomass plantations. Scenarios are characterized by water withdrawals for bioenergy plotted against raw harvest (inferred from reported biomass based energy 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}.

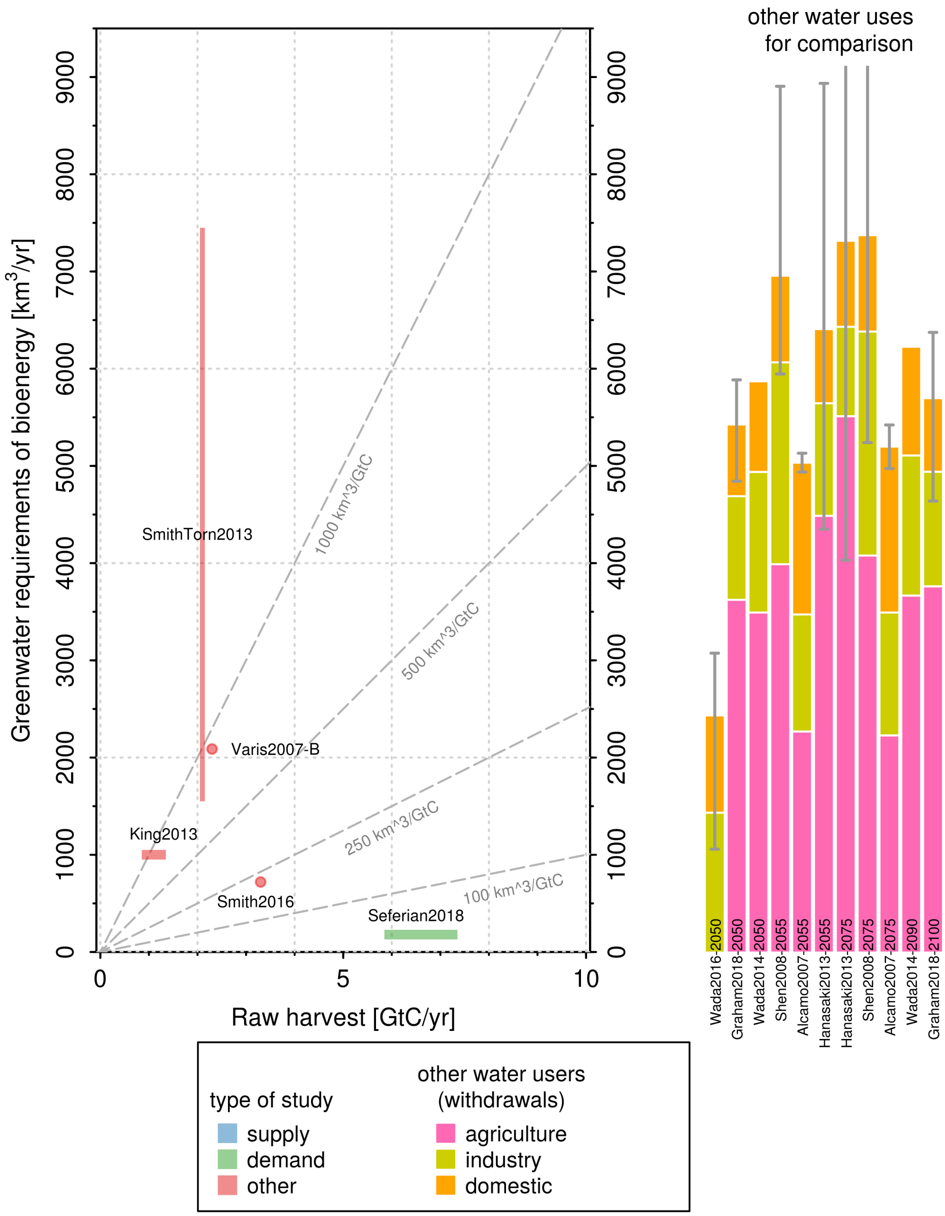

Figure A3. Analogous to Figure 2, but for scenarios of reported global green water consumption volumes required for bioenergy production through biomass plantations. Scenarios are characterized by water ~~demand~~ consumption for bioenergy plotted against raw harvest (inferred from reported biomass based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

climate change mitigation policiesHu et al. 2020Can bioenergy carbon capture and storage aggravate global water crisis?Humpenöder et al. bioenergy production: how to resolve sustainability trade-offs? Jans et al. 2018Biomass production in plantations: Land constraints increase dependency on irrigation waterMouratiadou et al. 2016The impact of climate change mitigation on water demand for energy and food:An integrated analysis based on the Shared Socioeconomic PathwaysStenzel et al. 2019Freshwater requirements of large-scale bioenergy plantations for limiting global warming to 1.5 °CYamagata et al. 2018Estimating water-food-ecosystem trade-offs for the global negative emission scenario (IPCC-RCP2.6)green water studiesKing et al. 2013The Challenge of Lignocellulosic Bioenergy in a Water-Limited WorldSéférian et al. 2018Constraints on biomass energy deployment in mitigation pathways: the case of water scarcitySmith and Torn 2013Ecological limits to terrestrial biological carbon dioxide removalSmith et al. 2016Biophysical and economic limits to negative CO_2 emissions Varis 2007Water demands for bioenergy production

Author contributions. FS designed the study, and carried out the literature analysis of bioenergy-freshwater-abstractions. 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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