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LETTER

Freshwater requirements of large-scale bioenergy plantations for limiting global warming to 1.5 °C

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Abstract

Limiting mean global warming to well below 2 °C will probably require substantial negative emissions (NEs) within the 21st century. To achieve these, bioenergy plantations with subsequent carbon capture and storage (BECCS) may have to be implemented at a large scale. Irrigation of these plantations might be necessary to increase the yield, which is likely to put further pressure on already stressed freshwater systems. Conversely, the potential of bioenergy plantations (BPs) dedicated to achieving NEs through CO_2 assimilation may be limited in regions with low freshwater availability. This paper provides a first-order quantification of the biophysical potentials of BECCS as a negative emission technology contribution to reaching the 1.5 °C warming target, as constrained by associated water availabilities and requirements. Using a global biosphere model, we analyze the availability of freshwater for irrigation of BPs designed to meet the projected NEs to fulfill the 1.5 °C target, spatially explicitly on areas not reserved for ecosystem conservation or agriculture. We take account of the simultaneous water demands for agriculture, industries, and households and also account for environmental flow requirements (EFRs) needed to safeguard aquatic ecosystems. Furthermore, we assess to what extent different forms of improved water management on the suggested BPs and on cropland may help to reduce the freshwater abstractions. Results indicate that global water withdrawals for irrigation of BPs range between ~400 and ~3000 $km^3 yr^{-1}$, depending on the scenario and the conversion efficiency of the carbon capture and storage process. Consideration of EFRs reduces the NE potential significantly, but can partly be compensated for by improved on-field water management.

Introduction

With the Paris Agreement (UNFCCC 2015), the international community has agreed to aim for a global mean temperature (GMT) (see table 3 for a full list of abbreviations) increase of *well below 2 °C* compared to preindustrial levels, and *pursue efforts to limit it to 1.5* °C. Since the remaining carbon emissions budget for such ambitious climate goals is very small (Fuss *et al* 2014), the use of negative emission technologies (NETs) seems almost inevitable (Rockström *et al* 2017, Minx *et al* 2018, Rogelj *et al* 2018). The necessity for NET deployment might even increase, should efforts of decarbonization be less pronounced or come into action later than envisioned today.

The NET most widely used in projections for the 21st century is bioenergy plantations (BPs) with subsequent carbon capture and storage (BECCS) (Fuss *et al* 2014, Schleussner *et al* 2016). BECCS utilizes fast growing plant species to convert atmospheric CO_2 to biomass, which is regularly harvested and burned for energy generation or fermented to produce bio-fuels. The CO_2 from the exhaust or by-product of fermentation is captured, compressed, stored permanently (e.g. in geologic reservoirs), and thus removed from the natural carbon cycle (Lenton 2010, Caldeira *et al* 2013). BECCS could potentially provide large amounts of negative emissions (NEs), but in turn competes with agriculture and other uses such as ecosystem conservation for land requirements. Different (portfolios of) NETs (Minasny *et al* 2017, Werner *et al* 2018) or alternative mitigation pathways (van Vuuren *et al* 2018) are receiving more and more attention, but bioenergy utilization will likely be significant during the 21st century (Masson-Delmotte *et al* 2018), since it is relatively cheap, compared to direct-air-capture and more land-effective than afforestation (Smith *et al* 2016). Therefore, our study provides additional value in support of making deployment decisions based not only on economic, but also eco-hydrologic reasoning.

The cultivation of plants to generate biomass at the level needed to satisfy high NE demands requires extensive plantation areas (Boysen *et al* 2017), and even more so, if realized under rainfed conditions (Beringer *et al* 2011). Because of the land scarcity, future BPs are likely to be irrigated to a significant amount in order to expand into more marginal terrain. In view of already existing water stress in many regions (Wada *et al* 2011, Schewe *et al* 2014), the quantification of freshwater demands for large-scale BECCS is critical but remains largely unknown—especially under the assumption not to constrain existing demands from agriculture, industry, and domestic users. Furthermore, there is a need to more systematically explore the NE constraints imposed by freshwater limitations (including the trade-off with flow requirements to sustain freshwater ecosystems), and to what extent such limitations could be alleviated by optimal water management on agricultural and BP areas.

Previous studies have provided first assessments of freshwater demands corresponding to large-scale BECCS deployment required to constrain GMT rise. Berndes (2002) projected 2281 $km^3 yr^{-1}$ of additional withdrawals for biomass-based energy production of 304 EJ yr^{-1} in 2100 (mainly from first generation BPs), while more recent estimates from Smith *et al* (2016) suggest 720 $km^3 yr^{-1}$ of additional water use to achieve NEs of 3.3 Gt C yr^{-1} in 2100. A further model study by Bonsch *et al* (2016) arrived at an additional water demand of 3,362–5860 $km^3 yr^{-1}$ for generating 300 EJ yr^{-1} in 2100. The large range of these estimates results from different assumptions on productivity increases, the associated BP area demand, and irrigation water productivity levels. Accounting for diverse spatially explicit nature protection areas, Beringer *et al* (2011) estimate a bioenergy water demand in the range of 1481–3880 $km^3 yr^{-1}$ to generate 130–270 EJ. More recently, Yamagata *et al* (2018) suggested 1910 $km^3 yr^{-1}$ of consumptive water demand for bioenergy crops to achieve NEs of 3.3 Gt C yr^{-1}, while Séférian *et al* (2018) estimate the water demand for producing 220–270 EJ in 2100 to be only 178 $km^3 yr^{-1}$, which is probably a result of strong restriction of irrigation and model limitations. Jans *et al* (2018) project a demand of 1,500–5000 $km^3 yr^{-1}$ to generate 200–1000 EJ, while also securing environmental flow requirements (EFRs) with the prospect of maintaining freshwater ecosystems in a good state.

The large span in projected water demands as a result of the diverse methodologies applied motivates a more systematic and internally consistent approach. The present study comprehensively quantifies how much freshwater for irrigation of BPs will potentially be needed to constrain GMT rise to 1.5 °C above pre-industrial levels by the end of the century. It advances previous studies through process-based and spatio-temporally explicit simulations of water use and water consumption of BPs (in addition to other sectors), considering a range of irrigation intensities (including a rainfed option), water management improvements, EFR protection goals, a range of carbon conversion efficiencies (percentage of carbon from harvest of BPs that is permanently removed from the carbon cycle), and their combinations (table 1). The water requirements under each of these setups are evaluated for yearly carbon sequestration demands simulated to follow a prescribed trajectory based on NE trajectories for a 1.5 °C climate from Rogelj *et al* (2015) (see SI figure S1 available online at stacks.iop.org/ERL/14/084001/mmedia), representative of the upper end of the set of exclusive 1.5 °C scenarios (those that are not within the ranges of *likely* or *medium* 2 °C scenarios). The respective NE demands ramp up from 0.54 Gt C in 2030 to 5.45 Gt C in 2100. The scenarios analyzed in Rogelj *et al* (2015) already take into account a wide range of technologies to reduce emissions, including an increasing global carbon price which is assumed to lead to a lowering of total energy demand, increasing energy efficiency, carbon capture and storage in remaining fossil fuel energy generation plants, greater use of bioenergy in primary energy generation, electrification of the transport sector, and fossil fuel replacement (especially in the transport sector) by biofuels (Bauer *et al* 2018). By applying the NE demand curve, we implicitly incorporate these underlying model assumptions of the socio-economic scenarios consistent with 1.5 °C. The focus of our analysis is on the sequestration of carbon via BECCS that could serve to achieve the prescribed NE targets, above and beyond the effects of these other transformations, and specifically on the associated water requirements. We do not however consider the economic aspects of implementation of such strategies, which are beyond the scope of the current analysis.

The total sequestration demand corresponding to this target is 255 Gt C over 2030–2100. To account for the possibility of partial or failed mitigation (Werner *et al* 2018), and, thus, a higher NE demand for compensating remaining emissions, a more ambitious total sequestration demand of 355 Gt C is also

Table 1. Parameterization of BP simulations and respective water management assumptions (RF, IRR, EFR, WM). Each water management scenario is simulated for five different BP parameterizations (basic, TechUp, IrrExp, TechUp$_{355}$, IrrExp$_{355}$). The latter two refer to a higher sequestration target of 355 Gt C. irr$_{frac}$—maximum globally irrigated BP yield share (1.0—all BPs can potentially be irrigated; 0.33—at most a third of the BPs can be irrigated); c_{eff}—fraction of the carbon from the harvested biomass, which can be permanently removed from the carbon cycle (50% or 70%).

Scenario	RF Rainfed	IRR Unconstrained withdrawals	EFR Respect environmental Flow requirements	WM Water management
Irrigation of BPs	No	Yes	Yes	Yes
Environmental flow protection	No	No	Yes	Yes
Water management	No	No	No	Yes

Parameter set	Basic	TechUp	IrrExp	TechUp$_{355}$	IrrExp$_{355}$
Maximum BP irrigation fraction (irr$_{frac}$)	0.33	0.33	**1.0**	0.33	1.0
Carbon conversion efficiency (c_{eff})	50%	**70%**	50%	70%	50%
Carbon sequestration goal (seq)	255 Gt C	255 Gt C	255 Gt C	**355 Gt C**	**355 Gt C**

explored, obtained by linearly upscaling the original yearly demand.

To account for limited land availability, only areas outside of current urban and agricultural land as well as areas of conservation interest are considered for conversion. All simulations are performed with the Dynamic Global Vegetation Model LPJmL, which computes terrestrial water cycling coupled to the carbon balance and vegetation growth of BPs alongside agricultural and natural vegetation, at daily time steps on a global 0.5° grid (Schaphoff *et al* 2018). LPJmL dynamically represents land surface processes such as discharge routing, crop growth, and water use efficiency, as well as yield responses to various stresses in any given grid cell. These features allow to dynamically choose the most productive BP type, based on local soil type, climate, and management options available.

Analysis is driven by the research question whether and under which constellations (degree of irrigation, consideration or neglection of EFRs, on-field water management) the targeted NE demands can be met while minimizing the additional pressure on global freshwater resources.

Methods

Scenarios

We compare the water requirements associated with the two sequestration demands (cumulative 255 Gt C and 355 Gt C between 2030 and 2100, with annual contributions as in figure S1) for four different water use scenarios: rainfed only (RF), unconstrained irrigation withdrawals (IRR), availability-constrained irrigation respecting environmental flow requirements (EFR), and the latter combined with improved crop water management (WM). For each of them, subscenarios are evaluated, considering a basic parameter setting representing low-technology BECCS with only a fraction of the yield being irrigated, and two technologically more ambitious pathways (increased conversion efficiency—TechUp and irrigation expansion—IrrExp) (see table 1). BPs were only considered to be grown on areas outside of urban and agricultural land as well as areas of conservation interest. The remaining areas were consecutively (starting with the highest ratio of net biomass yield per irrigation water per area) converted to BP plantations until the respective sequestration goal was reached (see below). The scenarios were all computed independently of each other.

In scenario RF, only rainfed BPs were allowed to be cultivated; the extent of food cropland (see potential area extent of BPs) and assumptions on irrigation system and extent of irrigated area (Jägermeyr *et al* 2015) were fixed at the state of 2015 in this and all other scenarios, as it is beyond the scope of this study to account for simultaneous changes in food demand and agricultural area. RF also serves as a reference scenario for global water withdrawals for purposes other than BPs (households, industries, livestock (HIL), and irrigated agriculture). As irrigation of BPs is absent, this scenario has the least additional impact on freshwater resources (aside from indirect impacts on streamflow due to a change in evapotranspiration (ET) of BPs, compared to the previous land-use).

In IRR, sprinkler-irrigated herbaceous BPs and drip-irrigated woody BPs (for more information on BP types, see the LPJML mode) can be grown in any suitable grid cell as long as there is enough freshwater available in rivers, lakes, and reservoirs (Jägermeyr *et al* 2017). However, if irrigation would not increase yields by more than 50% (determined in an extra simulation, see below), rainfed BPs are assumed instead in order to irrigate only those BPs, where irrigation increases the yield significantly. Irrigation, as for crops, is applied on a daily basis, when soil moisture falls below a plant-type specific threshold. HIL demand is assumed to be prioritized over irrigation water demand in all scenarios, using data from Flörke *et al* (2013). In case there is not enough water left for meeting the demand of agricultural crops and BPs, the allocation of the available water is distributed according to the ratio of the respective areas. In this scenario, there are no constraints to water withdrawals, thus representing a case with the largest potential withdrawals and the highest NE potential.

In the EFR scenario, the daily amount of available water for irrigation in a grid cell is capped. The EFRs are calculated according to the variable monthly flow estimation method (Pastor *et al* 2014), which classifies months as low-, medium-, and high-flow months and allocates 60%, 45%, and 30% of the flow for ecosystem purposes, respectively. EFRs are determined as 30-yr averages from a simulation based on historical land-use (Jägermeyr *et al* 2017) and the climate of the period 1970–1999. Hence, only water in excess of these reference EFRs is allowed to be used for BP irrigation in the future period. If EFRs are transgressed in a river basin (determined from the outflow cell) solely due to non-BP withdrawals, only rainfed BPs are assumed to be cultivated there.

Finally, scenario WM assumes that in addition to the EFR setup, advanced water management strategies are applied on both food cropland and BPs. They correspond to practices such as mulching, local runoff collection for supplemental irrigation during dry spells, modified irrigation thresholds, and soil management practices (see also the LPJmL model and description in Jägermeyr *et al* (2016)).

For each of the water management scenarios, we consider BP variants with different assumptions on the carbon sequestration demand (seq), carbon conversion efficiency (c_{eff}), and the maximum BP irrigation fraction (irr_{frac}). c_{eff} defines, how much of the carbon from the harvested biomass can be permanently removed from the carbon cycle (50% or 70%). The remaining carbon would eventually be transported back to the atmosphere and thus not permanently removed. A BECCS life-cycle assessment by Smith and Torn (2013) reveals overall conversion efficiencies of 47%, while capture rates of CCS processes typically achieve 85%–90% (Gough and Vaughan 2015). Technological change is likely to improve the efficiencies by reducing losses over time, which motivates our ambitious level of carbon conversion efficiency for the whole BECCS process-chain of 70%. The maximum BP irrigation fraction (irr_{frac}) indicates the maximum level of BP irrigation (1.0—all BPs can potentially be irrigated; 0.33—at most a third of the BPs can be irrigated, roughly representing circumstances where economic or other constraints to irrigation infrastructure apply; 0 for scenario RF).

In the basic parameter set, we consider the NE demands of the regular emission pathway with no mitigation failure ($\mathrm{seq} = 255$ Gt C), a moderate carbon conversion efficiency ($c_{eff} = 50\%$) and a moderate irrigation fraction ($\mathrm{irr}_{frac} = 0.33\%$). In the parameter sets TechUp and IrrExp, the parameters are changed to $c_{eff} = 70\%$ and $\mathrm{irr}_{frac} = 1.0$, respectively. In order to account for increased NE demands caused by failed mitigation actions, we apply the sets TechUp_{355} and IrrExp_{355} which use the same parameters for c_{eff} and irr_{frac} as TechUp and IrrExp, but the sequestration demand is set to 355 Gt C (see table 1).

Potential area extent of BPs

The maximum land area that can be converted to BPs (fraction of 0.5° grid cell) was derived by excluding current cropland (Frieler *et al* 2017, in year 2015 based on HYDE 3.2 by Klein Goldewijk *et al* (2017)), secondary forest areas for industrial roundwood production and urban build-up areas (Hurtt *et al* 2016), intact forest landscapes (Potapov *et al* 2017), wetlands (Lehner and Döll 2004), and areas of conservation interest. Areas of biodiversity concern are derived from a binary dataset developed in this study, considering regions crucial to ecosystem functioning (see figure 1(a), a similar map is also used in Werner *et al* (2018)). Previous approaches usually preserved fractions of grid cells for conservation (Beringer *et al* 2011, Boysen *et al* 2016) rather than excluding entire cells, which can be interpreted as a land sparing approach. Here, a grid cell is excluded from conversion to BPs for reasons of biodiversity protection if it is covered by the World Database on Protected Areas (UNEP-WCMC and IUCN 2015) or if located within Biodiversity Hotspots (Mittermeier *et al* 2011). In addition, we incorporated a catalogue on endemism richness, assuming plants as proxies for all floral and faunal species (Kier *et al* 2009), conserving all areas with an endemism richness above the global average (>21.66 endemic species km^{-2}). Finally, a dataset on threatened species (mean value of amphibians, birds, and mammals) was included (Pimm *et al* 2014), based on which we assume cells to be protected where more than 3% of all species are currently threatened.

The global area potentially suitable for BPs according to our configuration sums up to 3286 Mha (figure 1(b)). This would be more than twice the current cropland area. Large portions of this area, however, can not sustain BPs with yields above the minimum yield threshold of 2.5 $\mathrm{t\,C\,ha^{-1}\,yr^{-1}}$ due to climatic conditions, or are associated with too high land-use change (LUC) emissions due to the conversion of natural land to a BP (Houghton *et al* 2012, Harper *et al* 2018). We only consider grid cells if the mean yield for the period from plantation start until 2099 is above the harvest threshold. To calculate the LUC emissions as part of the carbon budget, we compare the size of litter, soil and vegetation carbon pools before and after the conversion to BPs and only consider sites where LUC emissions are at least two times compensated for by the net sequestration amount, excluding areas where plantation of bioenergy would only be marginally useful. To choose the most suitable

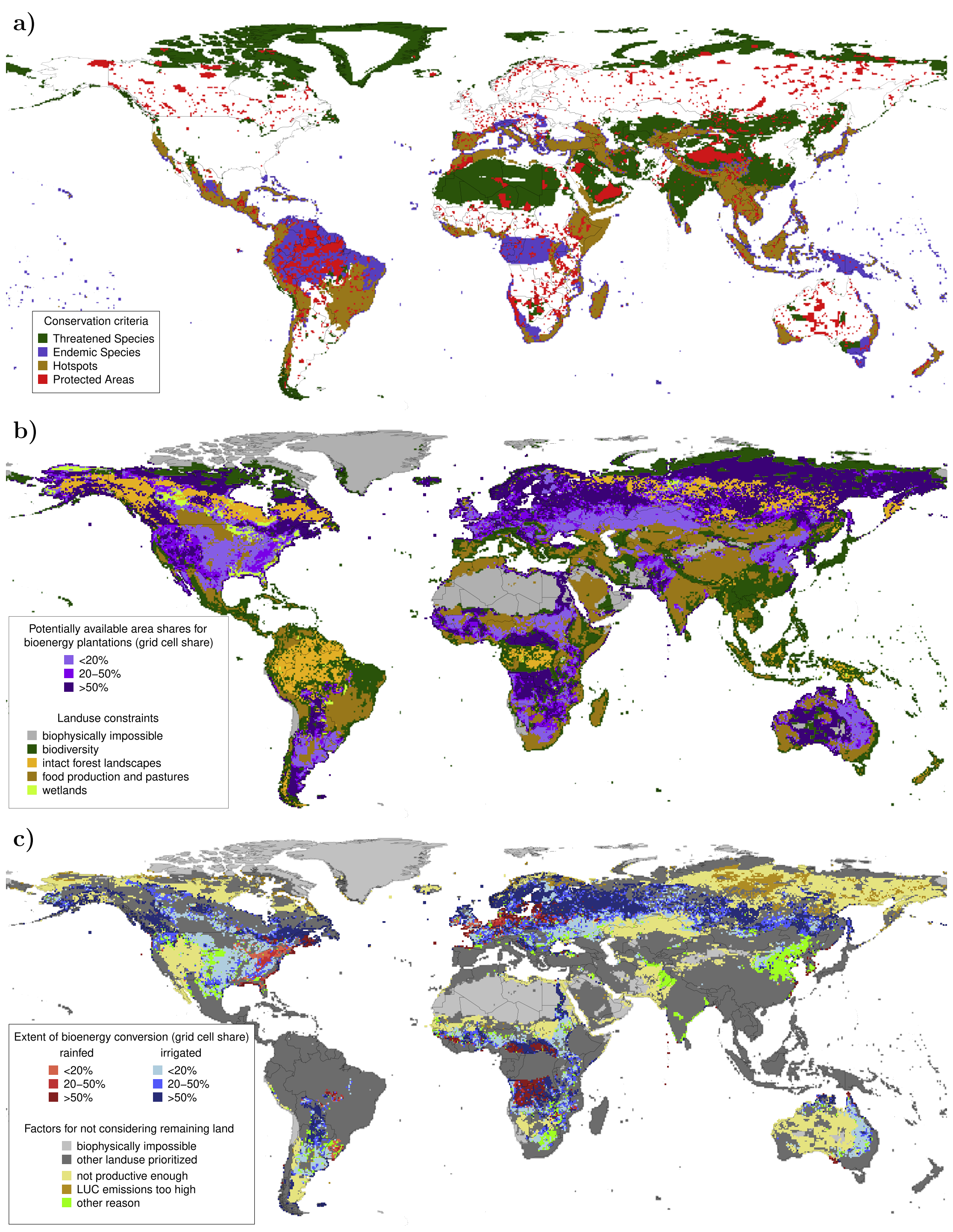

Figure 1. (a) Areas excluded from conversion to BPs due to biodiversity and conservation criteria: Biodiversity hotspots (Mittermeier *et al* 2011), World Database on Protected Areas (UNEP-WCMC and IUCN 2015), endemic species (Kier *et al* 2009), threatened species (Pimm *et al* 2014) (b) potential BP fractional area (%) outside of regions covered by cropland and pastures, or regions protected for reasons of biodiversity (see a and Methods for detailed description). (c) Mean 2090–2099 fractional areas for rainfed (red) and irrigated (blue) BP assumed in scenario WM and parameter set IrrExp; together with factors for not considering BPs in remaining potentially available areas shown in (b).

type of BP for each grid cell (see below for bioenergy functional types in LPJmL), five model runs (assuming plantation on all potential areas with the same type of BP—woody, irrigated woody, herbaceous, irrigated herbaceous, no BP) were performed for scenarios IRR, EFR, and WM. These were used to determine the potential yields and water demands for all grid cell shares available for conversion to BPs in each simulation year. For RF, three such pre-runs (woody, herbaceous, no BP) were sufficient, since irrigation is disallowed.

The net yield (nY) for all four possible BP types (rainfed versus irrigated and woody versus herbaceous) is given by the carbon conversion efficiency (c_{eff}), the yield of the respective bioenergy plant (beY), and the potential timber yield from the initial land-use conversion (tY):

$$nY = c_{eff} \cdot 0.475 \cdot (beY + tY), \quad (1)$$

where c_{eff} defines the percentage of the harvested carbon sequestered and thus extracted from the atmosphere; the factor 0.475 describes the average carbon content of dry biomass from Schlesinger and Bernhardt (2013).

In every grid cell, the net yield is compared with the associated LUC emissions (see figure S2). For most regions, BPs reduce the natural carbon holding capacity and thus have positive LUC emissions. In regions such as eastern Australia, the central/northern United States, or southern Africa, however, managed BPs can have enhancing carbon sequestration effects, besides the yield. For the runs with EFR constraints, the most productive rainfed BP type is chosen if the whole basin or the current cell is already transgressing the EFR requirements. Subsequently, all cells are ranked according to their yield/irrigation water ratio (irrigation water amount is set to 1 if it is a rainfed cell) and from this record, the cells are chosen consecutively (meaning the cell with the highest ratio—least water per yield—is selected first) until the sequestration goal of the respective year is reached. Thereby, overall productivity in each grid cell determines both the type of BP and irrigation, which in turn depend on the soil type, climate conditions, and water availability. This results in unique spatial patterns for each scenario (see figure S3).

LPJmL model

All simulations were conducted with the process-based Dynamic Global Vegetation Model LPJmL (Schaphoff *et al* 2013, 2018), which has recently been evaluated against various data sets from *in situ* measurement sites, satellite observations, and agricultural yield statistics in Schaphoff *et al* (2018). The model considers 67420 land grid cells on a 0.5° × 0.5° global grid. It simulates terrestrial carbon fluxes for establishment, growth, and productivity of natural vegetation (computed dynamically based on climatic conditions), agricultural crops, and pasture (Bondeau *et al* 2007), as well as water fluxes like ET, irrigation, and river routing (Gerten *et al* 2004, Rost *et al* 2008, Biemans *et al* 2011). For 12 crop functional types calibrated to match national yield statistics (Fader *et al* 2010) and a group of other annual and perennial crops, sowing dates are dynamically calculated (Waha *et al* 2012), but here fixed after year 1999.

The model also considers two types of second-generation bioenergy crops. Woody bioenergy crops are parameterized as willows or poplars for temperate regions and *Eucalyptus* for the tropics. Herbaceous bioenergy crops are parameterized as *Miscanthus* or switchgrass. Herbaceous BPs are assumed to be harvested once the above-ground carbon storage reaches $400\ \mathrm{g\ m^{-1}}$, but at least once a year. Bioenergy trees are harvested every eight years, with a maximum plantation life time of 40 years before total clearance and regrowth of saplings. The computed yields have been evaluated against field data by Beringer *et al* (2011) and Heck *et al* (2016).

Dependent on the scenario, managed areas can be rainfed or irrigated, which determines the source of water to fulfill the demand of the plants to be either only precipitation water or precipitation and additional water from local storage or main discharge of the respective grid cell and neighboring cells. The irrigation module accounts for three irrigation techniques: surface, sprinkler, and drip (Jägermeyr *et al* 2015), with different supply efficiencies. Water use for household, industry, and livestock (HIL) (Flörke *et al* 2013) is prescribed. Additionally, water management strategies such as mulching, water harvesting, and conservation tillage are represented for cropland and, newly in this study, for BPs as well, following (Jägermeyr *et al* 2016) by adapting the parameters (reduced soil evaporation of 50%, local storage capacity of 200 mm, collected on 50% of the managed areas, irrigation if soil moisture <40% of field capacity, and optimized soil infiltration) for BPs.

We forced the LPJmL model with monthly climate data (1901–2100) from the PanClim dataset (Heinke *et al* 2013) consistent with a 1.5 °C trajectory in 2100 with a slight temperature overshoot; with soil texture data (Nachtergaele *et al* 2009), and with land-use patterns (prescribed agriculture from Frieler *et al* (2017), based on HYDE 3.2 by Klein Goldewijk *et al* (2017), and BPs as per scenario). Since the target variables in this study (freshwater withdrawals, BP area, carbon sequestration) are much more sensitive to the individual parameter setups than to the actual climate input (forcing LPJmL with output from other climate models changed global BP water consumption by ±4%; data not shown), we force the model with only one climate model (MPI-ECHAM5). Simulations are performed with an initial spinup of 5010 years of potential natural vegetation (recycling the first 30 years of climate input) to bring global carbon pools to an equilibrium, followed by 316 years of transient spinup using historic land-use patterns from 1700 to 2015. The food crop land-use pattern from 2015 is kept constant for the remainder of the 21st century. BP plantations are assumed to not be implemented before 2030.

The total annual water withdrawals in every grid cell are computed as the sum of applied irrigation water as well as drainage and evaporative conveyance losses and withdrawals for HIL. Water consumption is computed as the sum of applied irrigation water, evaporative conveyance losses, and HIL consumption minus return flows from applied irrigation water. Attribution of consumption and withdrawal to BPs is obtained through computing the cell-wise difference between withdrawals in the run with BPs and the reference simulation without.

Table 2. Global model results for simulations included in figure 2.

Basic	Unit	RF	IRR	EFR	WM
Sequestration	Gt C	225	263	229	246
Net sequestration (*Seq − LUC*)	Gt C	170	217	181	195
Total BECCS yield	Gt C	450	525	458	491
Rainfed BP yield	Gt C	403	337	284	308
Total BP area	Mha	1036	1416	1177	1247
Only woody BP area	Mha	725	1047	881	927
Total withdrawals	$km^3 yr^{-1}$	3011	3653	2739	2619
BP withdrawals	$km^3 yr^{-1}$	0	701	400	387
Total blue water consumption	$km^3 yr^{-1}$	1160	1782	1237	1144
BP blue water consumption	$km^3 yr^{-1}$	0	642	361	351
IrrExp	Unit	RF	IRR	EFR	WM
Sequestration	Gt C	225	275	258	278
Net sequestration (*Seq − LUC*)	Gt C	170	262	226	243
Total BECCS yield	Gt C	450	550	517	556
Rainfed BP yield	Gt C	403	58	121	118
Total BP area	Mha	1036	1195	1164	1215
Only woody BP area	Mha	725	1001	909	927
Total withdrawals	$km^3 yr^{-1}$	3011	5280	3749	3895
BP withdrawals	$km^3 yr^{-1}$	0	2388	1474	1742
Total blue water consumption	$km^3 yr^{-1}$	1160	3358	2216	2313
BP blue water consumption	$km^3 yr^{-1}$	0	2239	1368	1553
TechUp	Unit	RF	IRR	EFR	WM
Sequestration	Gt C	318	326	320	326
Net sequestration (*Seq − LUC*)	Gt C	252	272	261	268
Total BECCS yield	Gt C	455	466	457	466
Rainfed BP yield	Gt C	388	282	270	275
Total BP area	Mha	946	1158	1072	1097
Only woody BP area	Mha	570	821	738	779
Total withdrawals	$km^3 yr^{-1}$	3011	3612	2755	2654
BP withdrawals	$km^3 yr^{-1}$	0	638	417	416
Total blue water consumption	$km^3 yr^{-1}$	1160	1735	1258	1173
BP blue water consumption	$km^3 yr^{-1}$	0	587	383	378
IrrExp$_{355}$	Unit	RF	IRR	EFR	WM
Sequestration	Gt C	224	330	268	294
Net sequestration (*Seq − LUC*)	Gt C	170	321	235	259
Total BECCS yield	Gt C	447	659	535	587
Rainfed BP yield	Gt C	414	63	127	127
Total BP area	Mha	1069	1377	1198	1262
Only woody BP area	Mha	750	1105	920	937
Total withdrawals	$km^3 yr^{-1}$	3010	5998	3768	3903
BP withdrawals	$km^3 yr^{-1}$	0	3167	1493	1744
Total blue water consumption	$km^3 yr^{-1}$	1160	4041	2227	2324
BP blue water consumption	$km^3 yr^{-1}$	0	2946	1379	1561

Table 2. (Continued.)

TechUp$_{355}$	Unit	RF	IRR	EFR	WM
Sequestration	Gt C	344	396	349	370
Net sequestration (*Seq − LUC*)	Gt C	277	337	289	309
Total BECCS yield	Gt C	492	566	498	529
Rainfed BP yield	Gt C	436	357	309	326
Total BP area	Mha	1055	1396	1179	1237
Only woody BP area	Mha	629	906	772	823
Total withdrawals	$km^3 yr^{-1}$	3011	3731	2756	2707
BP withdrawals	$km^3 yr^{-1}$	0	775	415	473
Total blue water consumption	$km^3 yr^{-1}$	1160	1847	1254	1213
BP blue water consumption	$km^3 yr^{-1}$	0	706	378	419

Results

The projected total global freshwater withdrawals (2090–2099) exhibit a large range between 2619 and 5998 $km^3 yr^{-1}$, with a BP contribution of 387–3167 $km^3 yr^{-1}$ (see table 2 for tabled simulation data). The baseline scenario without BPs reaches ~3000 $km^3 yr^{-1}$ for the same period. Adding BP with unrestrained withdrawals (IrrExp—IRR) almost doubles the total withdrawals compared to purely rainfed BPs. By respecting EFRs and applying improved water management (EFR and WM), the total global water withdrawals can be kept below 4000 (3000) $km^3 yr^{-1}$ in IrrExp (TechUp). Note that despite non-negligible withdrawals for BPs in the order of 400 $km^3 yr^{-1}$ in scenario WM of basic and TechUp setups, the total withdrawals may even fall below those of the respective RF scenario (3011 $km^3 yr^{-1}$), because EFRs are taken into account also for withdrawals of agricultural irrigation and because water is assumed to be more effectively managed also on cropland. Total global (food) crop yields are not substantially changing for RF and IRR compared to a reference run without BP. They are reduced by 3.5% in EFR, while in WM the water and soil management results in 8.4% higher crop yields than in RF.

We observe that most of the scenarios do not reach the target sequestration, meaning that from a certain year on, no more additional BP area is available that fulfills the respective scenario requirements. The dedicated freshwater withdrawals for irrigation of BPs needed to provide 255 Gt C of NEs range from 416 $km^3 yr^{-1}$ (TechUp—WM) to 2388 $km^3 yr^{-1}$ (IrrExp—IRR).

In the basic scenarios RF, IRR, EFR, and WM (figure 2, bottom center), total NEs from BPs are not fulfilling the sequestration target of 255 Gt C. The RF scenario reaches 170 GtC (with no additional water use on top of the global non-BP water use of currently 3011 $km^3 yr^{-1}$). Irrigation of BPs (unconstrained by EFRs) with 701 $km^3 yr^{-1}$ (2090–2099 mean)

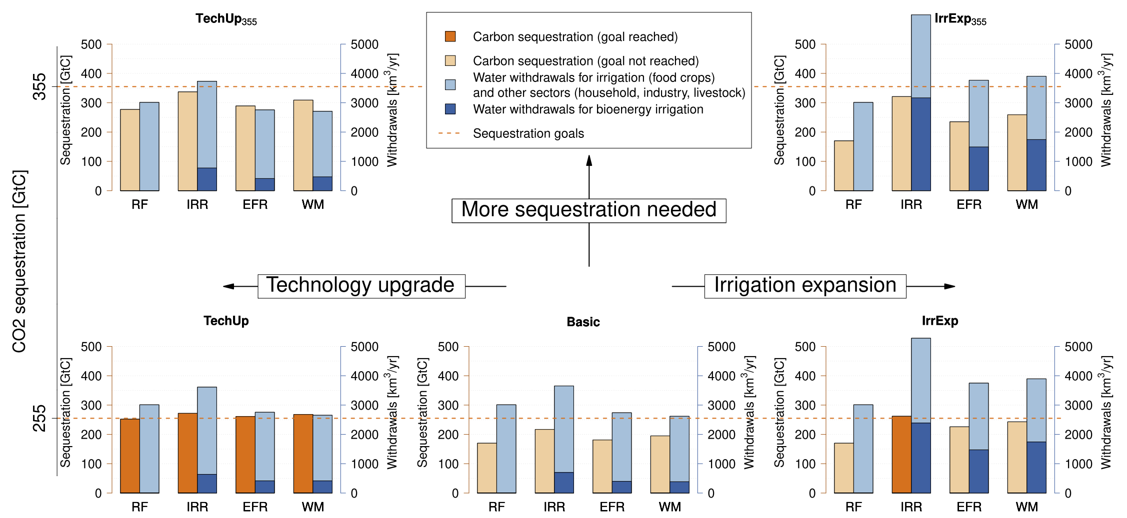

Figure 2. Total global carbon sequestration (2030–2100) and yearly freshwater withdrawals (mean 2090–2099) including withdrawals for agriculture and HIL for the four scenarios in five different parameter setups. Basic, $c_{eff} = 50\%$ and $\mathrm{irr}_{frac} = 0.33$; IrrExp, same but $\mathrm{irr}_{frac} = 1.0$; TechUp, same as basic but $c_{eff} = 70\%$. The upper panel ('more sequestration') refers to an increased sequestration target of 355 Gt C instead of 255 Gt C. RF—rainfed, IRR—unconstrained withdrawals, EFR—respective environmental flow requirements, WM—water management (see also table 1).

increases this value to 217 GtC (IRR). With stringent environmental flow protection (EFR) the water demand is reduced to 400 km^3 yr^{-1}, whereby a total sequestration of only 181 GtC is achievable. Additional water management (WM) strategies slightly increase the sequestration to 195 GtC while staying below the irrigation water demand of EFR (387 km^3 yr^{-1}).

To possibly increase the carbon sequestration, we considered either irrigation expansion or technology upgrades. An increase of irr_{frac} from 0.33 to 1.0 (figure 2, bottom right) enables scenario IRR to reach the sequestration goal and WM to almost reach it (243 GtC). These gains, however, come at the cost of strongly increased water withdrawals for the BPs. IRR more than triples the demand for BP irrigation to 2388 km^3 yr^{-1}, while in the WM scenario, more than four times more irrigation water is used (1742 km^3 yr^{-1}) compared to basic. In the EFR scenario, less water compared to WM is used (1474 km^3 yr^{-1}), however, for a lower sequestration amount. In the TechUp setup (figure 2, bottom left), in which c_{eff} is increased from 50% to 70%, the additional carbon that can be sequestered from the raw yields is enough to fulfill the sequestration target of 255 Gt C in all four scenarios (RF, IRR, EFR, WM). As a beneficial effect, the associated freshwater withdrawals for BP irrigation are comparable to those of the basic setup (IRR, 638 km^3 yr^{-1}; EFR, 417 km^3 yr^{-1}; WM, 416 km^3 yr^{-1}).

Table 3. List of abbreviations.

BECCS	Bioenergy with carbon capture and storage
BP	Bioenergy plantation
c_{eff}	Carbon conversion efficiency
EFR	Environmental flow requirement
ET	Evapotranspiration
GMT	Global mean temperature
HIL	Household, industry and livestock
irr_{frac}	Irrigation fraction
LPJmL	Lund-Potsdam-Jena managed land—a dynamic global vegetation model
LUC	Land-use change
NE	Negative emission
NET	Negative emission technology
seq	Carbon sequestration
VMF	Variable monthly flow method (EFR allocation method)

The higher sequestration demand of 355 Gt C, which could become necessary due to delayed or failed mitigation, was analyzed in the TechUp$_{355}$ (top left) and IrrExp$_{355}$ setups (top right). None of the scenarios, however, can deliver sequestrations that high. The IRR scenarios come the closest, although they neglect the EFRs (337 GtC / 775 km^3 yr^{-1} for TechUp$_{355}$ and 321 GtC / 3167 km^3 yr^{-1} for IrrExp$_{355}$).

For scenarios that reach the sequestration goal (figure 3) with restricted irrigation use (TechUP—RF, IRR, EFR, and WM) the majority of irrigated BPs is situated in higher latitudes, namely Canada, Scandinavia, and Russia (due to the preference for cells with a low water/productivity ratio), while areas of highest productivity (figure S3) and highest LUC emissions (figure S2) are in the tropics. The biophysical limitations allow the productive growth of herbaceous bioenergy plants only in latitudes between −40° and 50°. Due to their plant physiology, woody bioenergy plants have significantly lower yield productivities, but are able to grow in subpolar regions. The optimization scheme also simulates plantation of bioenergy trees in

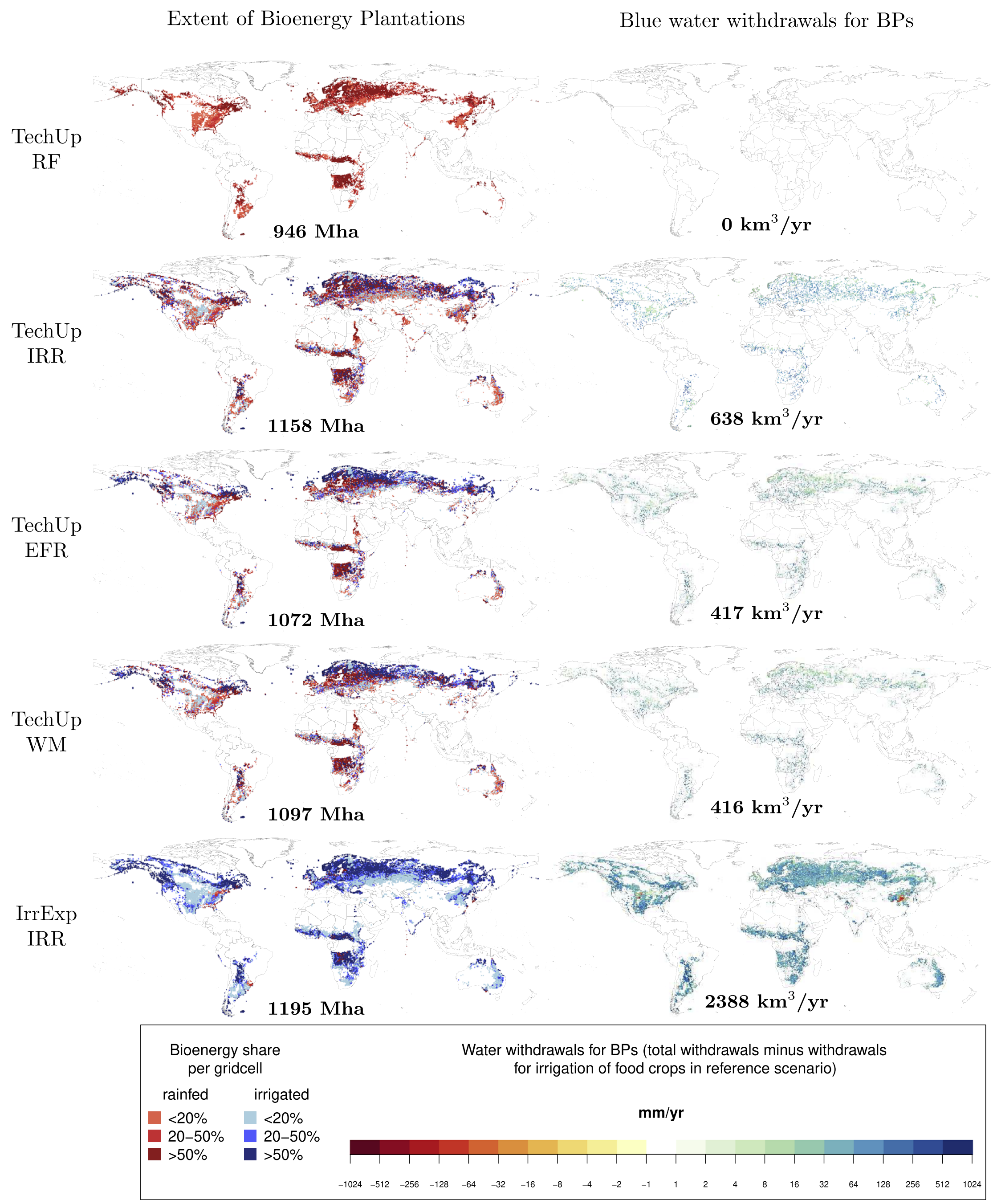

Figure 3. Mean 2090–2099 fractional areas for rainfed (red) and irrigated (blue) BPs—left panel—, and water withdrawals for irrigation of BPs (computed as difference of total withdrawals minus withdrawals from food-crops-only reference run)—right panel—displayed for all scenarios that fulfill the sequestration target of 255 Gt C. Attributed blue water withdrawals can be negative, if the respective scenario withdraws less water than the reference run. This can happen for cells, where addition of BPs changes local ET-fluxes, or new upstream irrigation reduces discharges below EFRs.

the tropics, which are either chosen for their greater net carbon sequestration or their lesser need for irrigation.

Discussion

This study was designed to estimate the biophysical potential and water requirements for BECCS if being applied as the primary NET for fulfilling the 1.5 °C target. This approach to model BECCS is based on explicit modeling of BPs (and the associated emissions from land-use change in the process of plantation allocation) together with an assumed carbon conversion efficiency. We thereby adopt an Earth System perspective based on the planet's biophysical capacity and especially the trade-offs associated with freshwater availability and management, rather than explicitly addressing economic feasibility. We have not considered the logistics and economics of transport of solid biofuels, nor the costs of CCS (e.g. Tauro *et al* (2018), Strefler *et al* (2018)) as these were beyond the scope of our research. We acknowledge that these issues will be important for the feasibility of strategies for BECCS, not least because the areas identified having the greatest potential for BPs are far from areas of greatest energy demand. However, if these constraints were considered additionally in a more comprehensive study, NE potentials may not necessarily be lower but the BP area would most likely be simulated to shift to other regions (see Bonsch *et al* 2016).

The key finding is that NE demands necessary to limit global warming to 1.5 °C cannot be met by BECCS alone due to freshwater limitations (and under the land available for conversion assumed here), except under the most ambitious assumptions about conversion efficiency or water use. The only scenario not relying on a high carbon conversion efficiency of 70% is a scenario without respecting EFRs, which thus would come at the cost of riverine ecosystems and overall environmental sustainability. Safeguarding EFRs in turn, would largely limit the irrigation-sustained NE potential. These results add new evidence to the discussion that pathways towards higher water use efficiencies and carbon conversion efficiencies need to be prioritized to meet targeted NEs. The projected additional freshwater withdrawals for achieving the 1.5 °C target using BECCS as the primary NET (figure 2) are substantial (up to 2400 $\mathrm{km}^3\,\mathrm{yr}^{-1}$—mean 2090–2099) and could thus reach the order of current global water withdrawals. Correspondingly, the total water consumption across all sectors would rise to above 3300 $\mathrm{km}^3\,\mathrm{yr}^{-1}$ (figure S4), thereby possibly transgressing the 'planetary boundary' for freshwater use (currently set at a total human consumption of 2800 or 4000 $\mathrm{km}^3\,\mathrm{yr}^{-1}$, respectively; Gerten *et al* 2013, Steffen *et al* 2015), with associated detrimental effects for the Earth system. In comparison with previous water consumption estimates for BPs, as for instance in Beringer *et al* (2011) (1481–3880 $\mathrm{km}^3\,\mathrm{yr}^{-1}$), Bonsch *et al* (2016) (3000–6000 $\mathrm{km}^3\,\mathrm{yr}^{-1}$), or Jans *et al* (2018) (1500–5000 $\mathrm{km}^3\,\mathrm{yr}^{-1}$), our global estimates exhibit a similar to larger span while being somewhat more conservative in absolute terms (351–2946 $\mathrm{km}^3\,\mathrm{yr}^{-1}$) due to the large range of scenarios considered and other divergent assumptions such as on the potential locations for BPs in particular. Our study thus does not constrain the previous range but provides a systematic exploration of underlying causes (water use limitations, environmental constraints, management options).

Thus, it is important to note for our study as well that the global amount of freshwater requirements strongly depends on the underlying assumptions about conversion efficiency, water management, and EFR protection. Most freshwater is simulated to be consumed in the IrrExp scenario, whereas the the basic and TechUp scenarios involve significantly lower water consumption. Naturally, among the water use scenarios of each parameter setup, IRR always leads to highest water consumption, while EFR and WM show lower values due to their strict water allocation scheme (EFR) and the constrained water use (WM), respectively.

Our results indicate that a targeted NE amount of 255 Gt C (between 2030 and 2100) could be produced under rainfed conditions only if high conversion efficiencies would apply ($c_{eff} \geqslant 70\%$). Even under this condition, though, rainfed BPs would not provide enough biomass for possible higher NE demands up to the here considered 355 Gt C, which may become necessary if climate change mitigation efforts fail or slow down. The basic setup cannot provide enough NE to fulfill the sequestration demand of even the lower target (255 Gt C), suggesting that either irrigation expansion or highly efficient BECCS systems exceeding 50% carbon conversion efficiency will be needed (or a combination of both). It appears unlikely to implement such high efficiencies at the global level within the next decades due to multiple obstacles such as a lack of socio-political acceptance, policy incentives, and technological readiness (Fuss *et al* 2014, Reiner 2016, Fridahl and Lehtveer 2018, Gough *et al* 2018, Vaughan *et al* 2018).

In view of these technical and institutional challenges, productivity improvements supported by irrigation expansion come into focus for near-term solutions. It is clear that additional water withdrawals at the level presented here would be associated with severe environmental degradation (at least in scenarios where EFRs are not respected) or increased water stress (Rockström *et al* 2014, Hejazi *et al* 2015). While such obstacles require further systematic study, any sustainable implementation of BECCS requires serious consideration of freshwater issues in the form of rigid environmental protection, water legislation, and water management improvements.

In addition to the water requirements for irrigation, BPs need extensive land areas (for further discussion, see Boysen *et al* (2016), Heck *et al* (2016), Werner *et al* (2018)). In our study, the maximum additional arable area for BPs under rainfed conditions is roughly 1000 Mha. Irrigation makes more grid cells (200–400 Mha) productive enough to cross the minimum yield threshold and compensate for LUC emissions (see figure S2). The yield threshold is the lower limit of what is considered economically feasible today, while both yields and the threshold may change in the future (even though they are already quite optimal parameters) due to e.g. genetic optimization and management. The assumption that BPs would only be planted if LUC emissions are at least twice compensated for by the net sequestration amount is strict, but economically justified. Conversely, irrigation makes BPs in many regions more productive, such that per unit of NEs, less land is needed. This can be understood as a trade-off between water and land, which has been described before (Bonsch *et al* 2016, Jans *et al* 2018).

However, large portions of the identified potentially available areas for BPs in this study are recreational areas or wild remote landscapes which are already in a state of increasing risk for biodiversity loss (Steffen *et al* 2015). Given that the scenarios suggest replacement of, for example, larger fractions of boreal forest in Scandinavia and northern Asia, which is unlikely to occur in reality at such large scale, our estimates appear to be on the conservative side. If those areas would not be released for conversion, larger BP areas, or more intense irrigation, would have to take place elsewhere to achieve a similar amount of NEs, probably involving even stronger pressure on freshwater systems there. Thus, we stress that the here simulated spatial BP patterns are to be interpreted as biophysical maximum potentials derived under strict conservation criteria, distributed and optimized globally according to the water use efficiency. Further analysis could evaluate the wider consequences of ecosystem change (e.g. terrestrial and aquatic biodiversity loss through conversion of natural land to BPs), like Ostberg *et al* (2018) provide for biospheric change under scenarios designed to sustain Paris mitigation efforts. Additionally, competition for water between irrigated agriculture and BPs could be explicitly studied by, for example, exploring scenarios where the irrigation of crops always has the highest priority.

In sum, we find that second-generation bioenergy combined with CCS alone can deliver sufficient NEs for ambitious climate targets only under highly optimized conditions and with potentially detrimental side effects on freshwater ecosystems. This first benchmark quantification merits more detailed follow-up studies, especially to analyze synergies and trade-offs with additional NETs operating in different domains, in a complex modeling framework. However, according to initial studies, other NETs would come along with environmental side-effects too, for example, with respect to the area demand of afforestation or the water demand of direct-air-capture (Smith *et al* 2016).

Conclusion

Despite the socio-political and technological barriers to the implementation of BECCS, bioenergy will most likely become more relevant as a substitution for fossil energy with the need to convert large areas to BPs. To increase the yields and thus reduce the pressure on land, these plantations might have to be irrigated to a substantial degree, potentially putting many freshwater systems under severe additional pressure. Therefore, local water policies, such as for safeguarding EFRs, are important tools to sustain the integrity of freshwater ecosystems. We show that there is a trade-off between limiting irrigation on BPs to sustain EFRs and attaining levels of NEs likely required for limiting global warming to 1.5 °C. On-field water and soil management can help reducing this water gap for BPs and for agriculture. Nevertheless, a stringent and fast reduction of CO_2 emissions is inevitable, because higher carbon sequestration demands would have profound impacts on freshwater systems and their ecological functions that are fundamental to life and societies.

Acknowledgments

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Supplementary Information

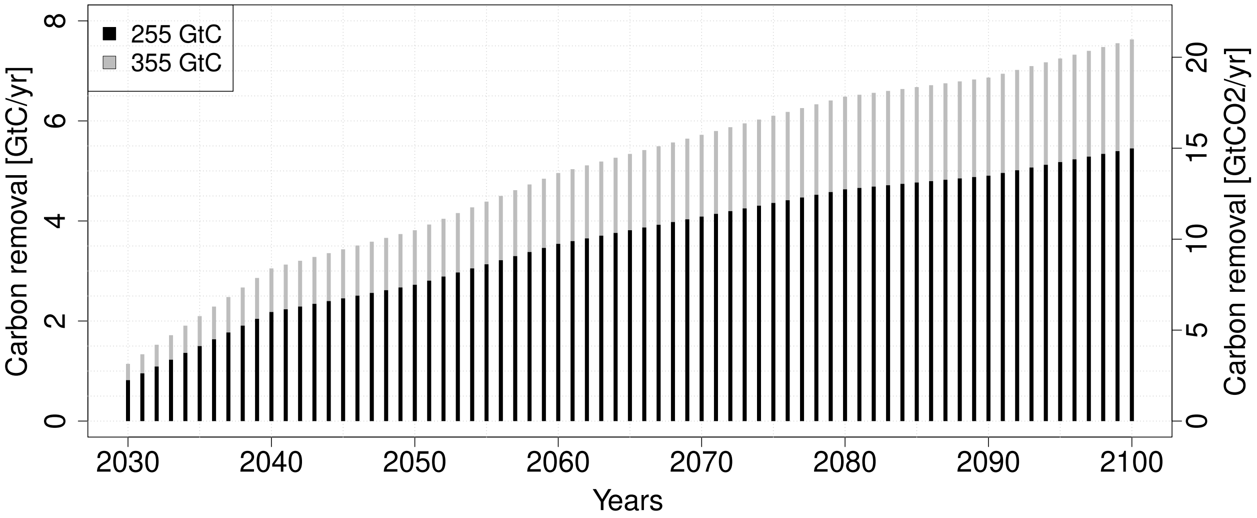


Figure S1: Amount of sequestration needed per year to stay within 1.5 °C warming (255 Gt C – black bars), after Rogelj et al. (2015), and to reach a higher sequestration demand of 355 Gt C (grey bars), obtained by linear up-scaling of the 255 Gt C curve.

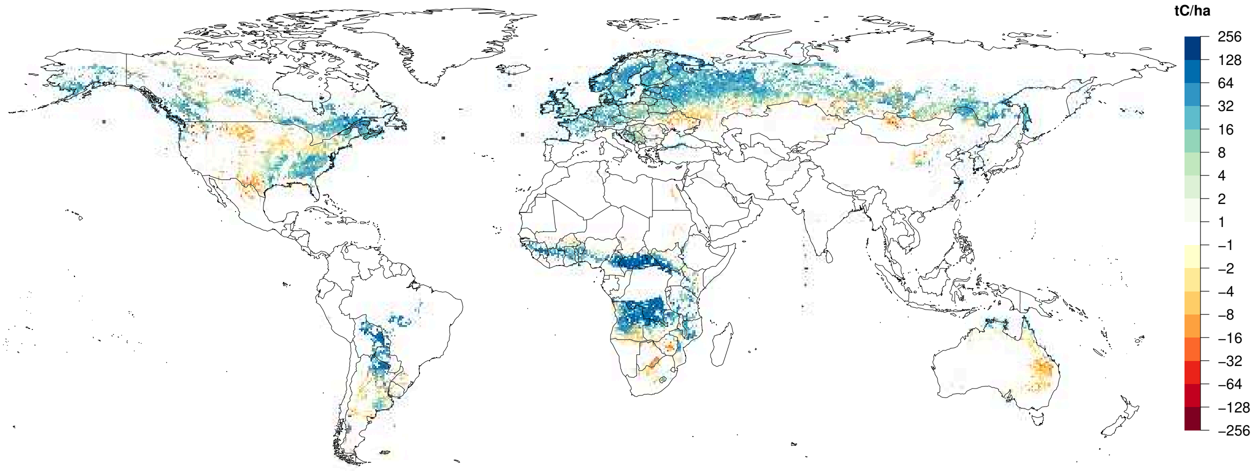
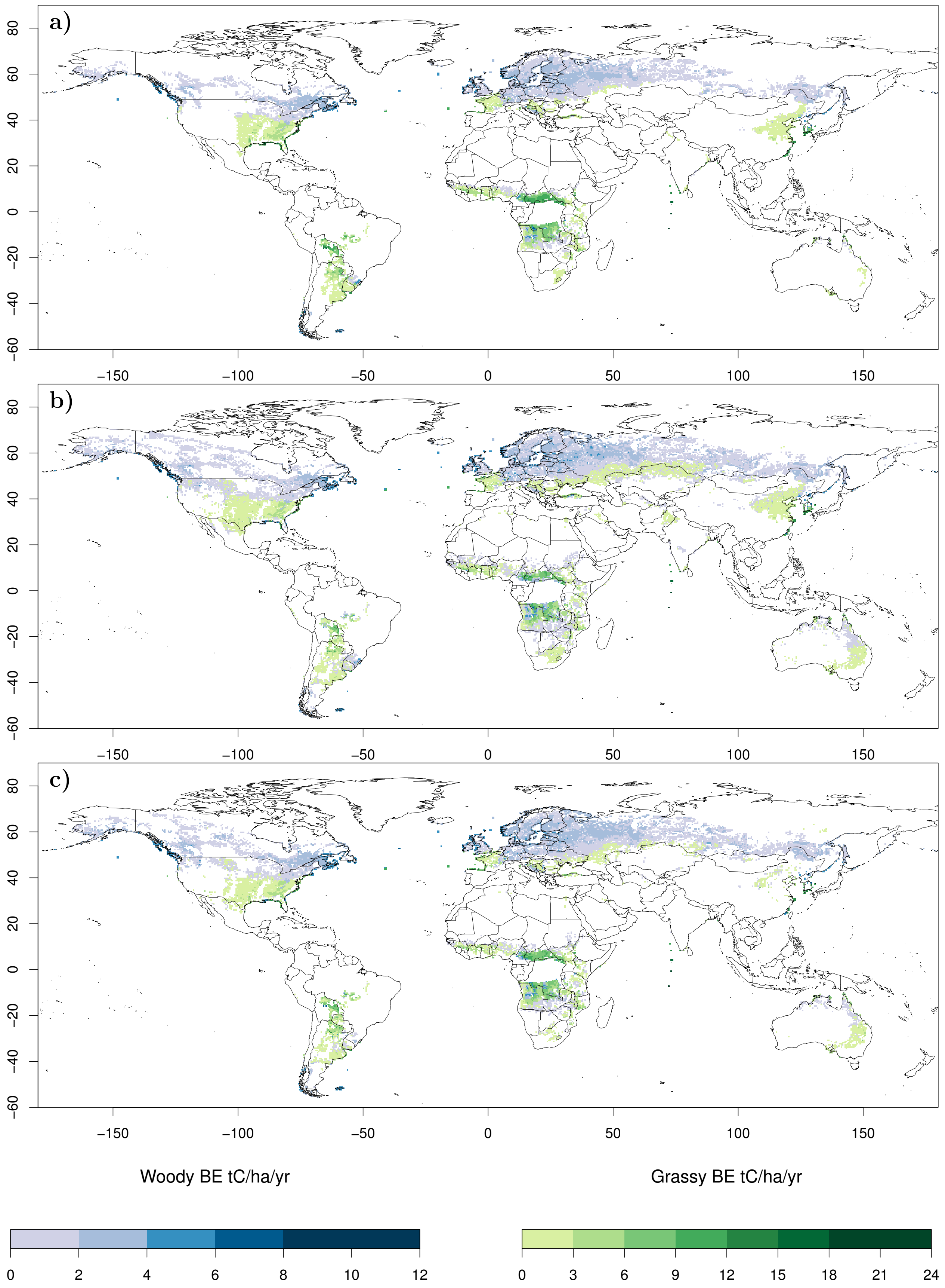


Figure S2: LPJmL-simulated LUC emissions for scenario WM and Basic parameter set, computed as the difference (2090–2099 average) relative to the reference run without BPs of the sum of the mean carbon content in soil, vegetation and litter pools, shown exemplarily for the TechUp parameter set and scenario WM.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−60
−150
−100
−50
0
50
100
150
Woody BE tC/ha/yr
Grassy BE tC/ha/yr
0
2
4
6
8
10
12
0
3
6
9
12
15
18
21
24

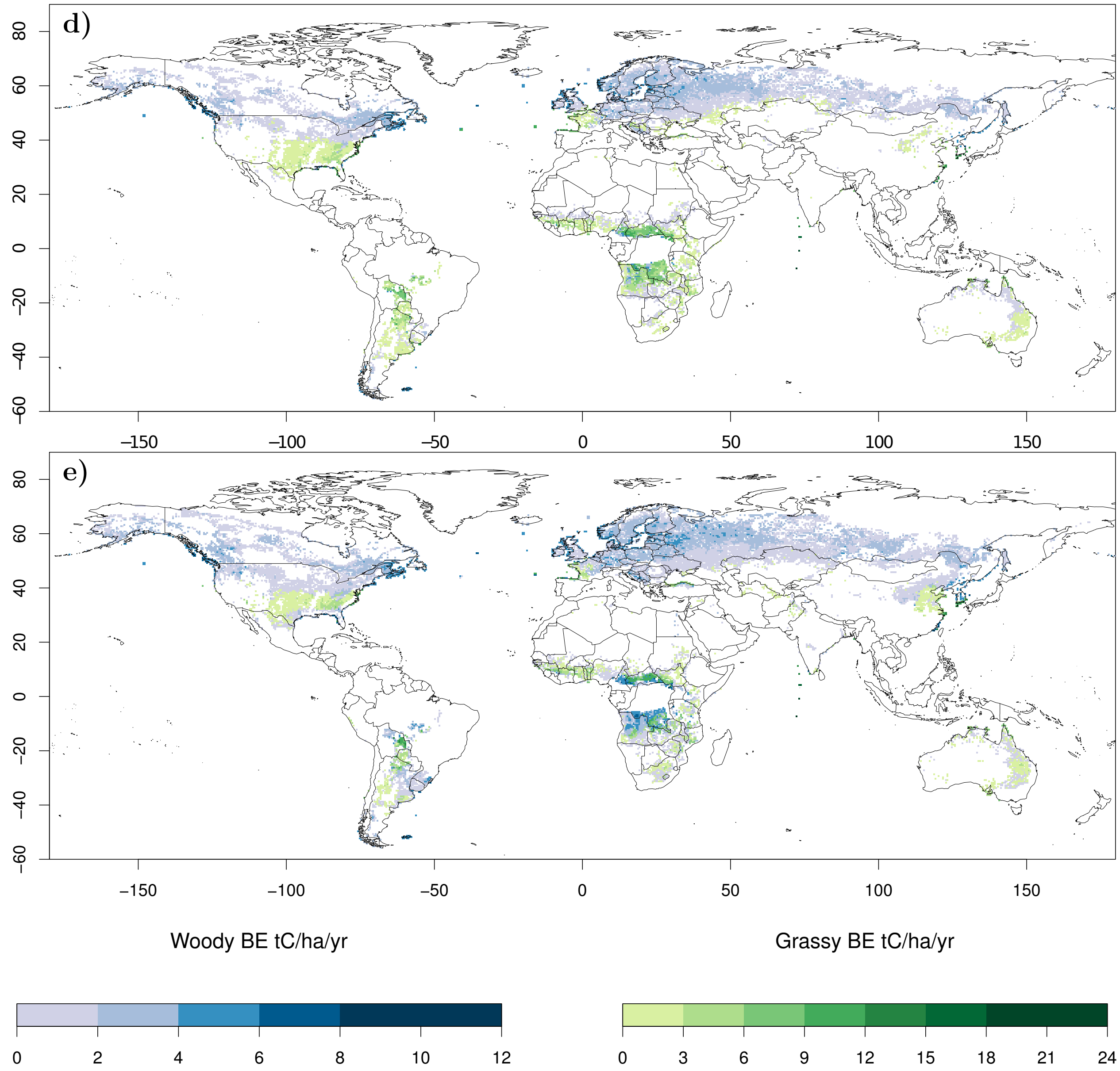

Figure S3: Simulated productivity and spatial distribution of woody and herbaceous BP types in the period 2090–2099, for **a)** TechUp RF, **b)** TechUp IRR, **c)** TechUp EFR, **d)** TechUp WM, **e)** IrrExp IRR.

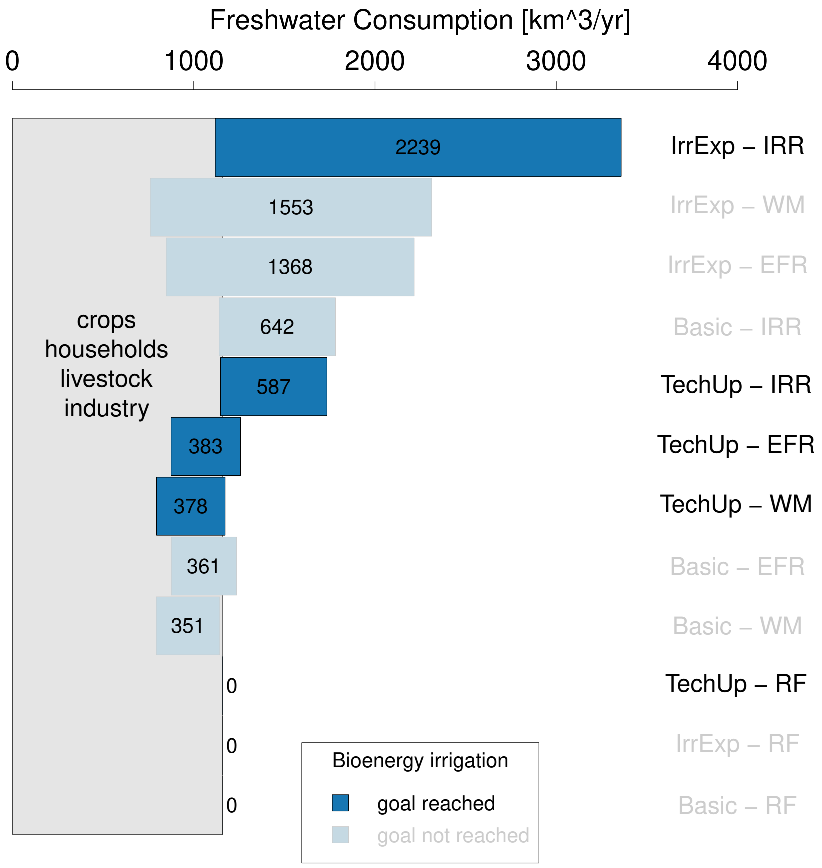

Figure S4: Yearly (mean 2090–2099) freshwater consumption of bioenergy plantations, agriculture, households, industry and livestock for scenarios targeting a carbon sequestration of 255 GtC.