WILEY **BIOENERGY**

ORIGINAL RESEARCH

Biomass production in plantations: Land constraints increase dependency on irrigation water

Yvonne Jans[1,2] iD　|　Göran Berndes[3]　|　Jens Heinke[1]　|　Wolfgang Lucht[1,2]　|　Dieter Gerten[1,2]

[1]Potsdam Institute for Climate Impact Research, Potsdam, Germany

[2]Department of Geography, Humboldt-Universität zu Berlin, Berlin, Germany

[3]Department of Physical Resource Theory, Chalmers University of Technology, Göteborg, Sweden

Correspondence
Yvonne Jans, Potsdam Institute for Climate Impact Research, Telegraphenberg A62, DE-14473 Potsdam, Germany.
Email: jans@pik-potsdam.de

Abstract

Integrated assessment model scenarios project rising deployment of biomass-using energy systems in climate change mitigation scenarios. But there is concern that bioenergy deployment will increase competition for land and water resources and obstruct objectives such as nature protection, the preservation of carbon-rich ecosystems, and food security. To study the relative importance of water and land availability as biophysical constraints to bioenergy deployment at a global scale, we use a process-detailed, spatially explicit biosphere model to simulate rain-fed and irrigated biomass plantation supply along with the corresponding water consumption for different scenarios concerning availability of land and water resources. We find that global plantation supplies are mainly limited by land availability and only secondarily by freshwater availability. As a theoretical upper limit, if all suitable lands on Earth, besides land currently used in agriculture, were available for bioenergy plantations ("Food first" scenario), total plantation supply would be in the range 2,010–2,300 EJ/year depending on water availability and use. Excluding all currently protected areas reduces the supply by 60%. Excluding also areas where conversion to biomass plantations causes carbon emissions that might be considered unacceptably high will reduce the total plantation supply further. For example, excluding all areas where soil and vegetation carbon stocks exceed 150 tC/ha ("Carbon threshold savanna" scenario) reduces the supply to 170–290 EJ/year. With decreasing land availability, the amount of water available for irrigation becomes vitally important. In the least restrictive land availability scenario ("Food first"), up to 77% of global plantation biomass supply is obtained without additional irrigation. This share is reduced to 31% for the most restrictive "Carbon threshold savanna" scenario. The results highlight the critical —and geographically varying—importance of co-managing land and water resources if substantial contributions of bioenergy are to be reached in mitigation portfolios.

KEYWORDS
biodiversity, bioenergy, climate change, global biosphere model, mitigation

1 | INTRODUCTION

Visions on a circular and bio-based economy have been formulated in response to concerns about resource scarcity and impacts associated with unsustainable use of renewable and nonrenewable resources (Geissdoerfer, Savaget, Bocken, & Hultink, 2017; German Bioeconomy Council, 2018; Ghisellini, Cialani, & Ulgiati, 2016; Gregson, Crang, Fuller, & Holmes, 2015; Hetemäki et al., 2017; Hobson, 2016; Hobson & Lynch, 2016; Priefer, Jörissen, & Frör, 2017). Biomass is increasingly used to displace nonrenewable resources (especially fossil fuels) in response to energy and climate policies (Guo, Song, & Buhain, 2015). As biomass resources are of major significance for the economy, business, and industry in many countries, biomass use also increases in response to policies intending to promote innovation and growth in industries toward a more sustainable society. Bioenergy is often assigned an important role in the future energy mix and is proposed to contribute to improved energy security, climate change mitigation, rural development, and other social and economic objectives (Souza, Victoria, Joly, & Verdade, 2015). A review by the Intergovernmental Panel on Climate Change (IPCC) of 164 long-term energy scenarios showed projected bioenergy deployment levels in year 2050 at 80–150 and 118–190 EJ per year for 440–600 and <440 ppm CO_2eq concentration targets, respectively (25th and 75th percentiles) (Edenhofer et al., 2011). IPCC WG3 reported in the Fifth Assessment Report that widespread deployment of bioenergy with CO_2 capture and storage (BECCS) in climate stabilization scenarios indicate that this option can become important if the needed technologies and resources are available (Edenhofer et al., 2014). However, BECCS is yet unproven as a climate change mitigation option and researchers caution that the possibility of achieving negative emissions in the future may become a dangerous distraction from near term emission abatement efforts (Azar, Johansson, & Mattsson, 2013; Fuss et al., 2014).

The possible future size of biomass resources is a subject that divides researchers. Estimates vary widely due to differences in the approaches used to consider important factors, which in themselves are uncertain. Population development (Bodirsky et al., 2015; Lutz, 2013), the evolution of consumer behavior, for example, diet (Wirsenius, Azar, & Berndes, 2010), and economic and technological development (Azar, Lindgren, Larson, & Möllersten, 2006) together determine future biomass demands for food and other biobased products. Supply side factors such as crop yields, water use efficiency, and adaptation to specific growing conditions (Beddington et al., 2012; Müller et al., 2015; Neumann, Verburg, Stehfest, & Müller, 2010) determine how this biomass demand in turn translates into demands for land, water, and other resources. Supply side factors also influence prospects for bioenergy. Studies may in different ways include restrictions on access to land, water, and other resources, which are intended to reflect societal priorities, for example, related to nature protection and scarcity/vulnerability of resources (Beringer, Lucht, & Schaphoff, 2011). For recent overviews focusing on bioenergy resources, see Slade, Bauen, and Gross (2014; Creutzig et al., (2015).

Despite the uncertainties, it can be concluded that organic postconsumer waste, and residues and by-products from the agricultural and forest sectors, can make important contributions. But these biomass sources will not suffice to meet the levels of biomass demand for energy found in many climate stabilization scenarios (Edenhofer et al., 2011, 2014). Dedicated biomass production systems (henceforth designated "biomass plantations") would be needed for meeting part of the biomass demand in such scenarios.

This study provides a comprehensive model-based quantification of global annual biomass supply from biomass plantations (henceforth designated "plantation supply") while explicitly accounting for regional biophysical climatic and hydrological conditions. We pay particular attention to the question how different rates of irrigations, different irrigation efficiencies, and ecological constraints to freshwater use affect the plantation supply. We also include detailed and spatially explicit datasets of potential land access restrictions to assess whether land or water is the predominant limiting factor regionally and globally. Regional climatic and hydrological conditions, and land/water use constraints, have been considered in earlier studies (Beringer et al., 2011; Berndes, 2002; Bonsch et al., 2016; Boysen, Lucht, & Gerten, 2017; Boysen, Lucht, Gerten, & Heck, 2016; Dornburg et al., 2010; Fraiture, Giordano, & Liao, 2008; Gheewala, Berndes, & Jewitt, 2011; Jackson et al., 2005; King et al., 2013; Smith et al., 2016) but, to the best of our knowledge, the interplay between land and water availability has not been addressed at the level of detail captured in this study. Water availability and use is determined at river basin scale to ensure that the interaction between upstream and downstream water availability and use is considered. Economic considerations are not included, and the availability of land and water resources for bioenergy is set exogenously to reflect competing biomass demand and nature/resource protection requirements. As such, our scenarios should be understood as indicative of how different degrees of access to, and management of, land and water resources influence the plantation supply achievable at global and regional level.

2 | MATERIALS AND METHODS

2.1 | Simulating water use and yield potential of bioenergy crop production

Major determinants of plantation supply are (a) the areas and locations of land (i.e., soil and climate conditions)

available for biomass plantations; (b) the availability of (irrigation) water; and (c) the land and water productivity of the biomass production systems. All these features are simulated by the global dynamic vegetation model LPJmL, here operated at a 0.5° spatial resolution and daily time steps. LPJmL simulates the growth dynamics of natural and agricultural vegetation depending on daily meteorological conditions and soil characteristics and was used to assess potential yields of energy crops (Bondeau et al., 2007; Lapola et al., 2010; Sitch et al., 2003). It considers nine plant functional types and 12 crop functional types, respectively, and three bioenergy plantation systems, one grass type and two short-rotation coppice (SRC) tree types (Beringer et al., 2011). The model calculates closed balances of carbon fluxes and pools and water fluxes including river routing and irrigation water use (Jägermeyr et al., 2015; Rost et al., 2008). Photosynthesis is simulated following the Farquhar model approach (Sitch et al., 2003). Carbon and water dynamics are closely linked so that the effects of changing climate and water availability are accounted for (Gerten, Schaphoff, & Lucht, 2007; Gerten, Schaphoff, Haberlandt, Lucht, & Sitch, 2004). Physiological and structural plant traits determine water requirements and consumption. The model's integrated approach of coupling water balance to vegetation allows to divide total water consumption into productive (transpiration) and unproductive (interception loss, soil evaporation) parts. Furthermore, water fluxes are distinguished by the contribution of precipitation (green) and irrigation (blue) water (Jägermeyr et al., 2015, 2016 ; Rost et al., 2008). The suitability of the LPJmL framework for vegetation and water studies has been demonstrated, among others by validating phenology (Bondeau et al., 2007), river discharge (Biemans et al., 2009; Gerten et al., 2004), evapotranspiration (Gerten et al., 2004; Sitch et al., 2003), and energy crop yields (Beringer et al., 2011; Heck, Gerten, Lucht, & Boysen, 2016) (see Schaphoff et al. (2017) for an overall model evaluation). Simulations of dedicated biomass producing plantations differ from those of corresponding natural vegetation by assuming higher productivity and harvest at regular or growth-dependent intervals. Harvest management of woody and herbaceous BFTs represents reported agricultural practices on second-generation biomass plantations. Woody biomass plantations are represented by the characteristics of poplar and willows for temperate regions and Eucalyptus for tropical regions. They are simulated to be harvested every eight years and clear-cut after 40 years. During harvest, 65% of the sapwood and 50% of the heartwood are taken and put into a harvest carbon pool. Herbaceous biomass plantations are represented by the properties of the fast-growing grass types Miscanthus and switchgrass. In contrast to Beringer et al. (2011), these grasses are assumed to allocate carbon on a daily basis and to be harvested as soon as 400 gC/m^2 are reached whereby 85% of the above-ground plant material is taken away (Ashworth, Keyser, Holcomb, & Harper, 2013; Johnson, Clementson, Mathanker, Grift, & Hansen, 2012). Also, bioenergy trees are now parameterized to be more resistant to water stress (through larger rooting depths). Model parameterization results in the best overall match between data and observations. A comparison of the simulated woody and herbaceous plantation productivity with observations from field data verifies that our results capture a realistic magnitude of production (Heck et al., 2016). For this study, the LPJmL model is run for the period 1960–2009, forced with the Climate Research Unit's (CRU) TS 3.1 monthly climatology for temperature, cloudiness, and wet days (Harris, Jones, Osborn, & Lister, 2014), and with the Global Precipitation Climatology Centre's (GPCC) precipitation data (Version 5) (Rudolf, Becker, Schneider, Meyer-Christoffer, & Ziese, 2011). If not indicated otherwise, results are presented as 1960–2009 averages. In order to assess the possible bioenergy crop productivity and to inform possible shifts in plantation areas, we assume for our simulations that all bioenergy crops can theoretically be grown everywhere—that is, we derive the theoretical potential for each location and then apply constraints to the actual potential by assumptions about land and water availability (see different scenarios below). The link between bioenergy crop yields and water consumption is simulated for both ends of scale, that is, for a situation without irrigation (rain-fed plantations) and for additional irrigation up to the extent that energy crops do not experience water stress, respectively. Due to the model's ability to separate water fluxes into green and blue the maximum attainable increase of biomass $\Delta Y_{\max}$ related to the amount of blue water consumption $\Delta WB_{\max}$—that is, through irrigation—can be calculated by.

$$\frac{\Delta Y_{\max}}{\Delta WB_{\max}} = \frac{Y_{\text{tot}} - Y_{rf}}{W_{GB} - W_G} \qquad (1)$$

where Y_{tot} is the maximum yield achievable if the water demand of energy crops is always fulfilled, Y_{rf} is the yield gained from precipitation only, W_{GB} is the sum of both green and blue water consumption, and W_G the green water consumption only (see de Wit (1958); Tanner and Sinclair (1983) and Kiziloglu, Sahin, Kuslu, and Tunc (2009) on linear relationship between water deficit and yield).

2.2 | Water withdrawals and availability

We analyze the balance of irrigation water supply and demand at the level of river basins. To calculate water availability (blue water potentially available for irrigation) on river basin level, we aggregate simulated runoff at grid cell level. Thus, we only consider the renewable surface

and subsurface water, assuming that no fossil groundwater is available. More precisely, the discharge is first calculated for each grid cell i within a particular catchment area, following the equation.

$$D_{nat_i} = D_{inflow_i} + R_i - AET_i \qquad (2)$$

where D_{nat_i} is the "naturalized" discharge (computed based on patterns of anthropogenic land use and land-cover changes (Fader, Rost, Müller, Bondeau, & Gerten, 2010), but without biomass plantations, human water withdrawals, and reservoir storage), D_{inflow_i} the incoming discharge from upstream grid cells, R_i the local runoff generated in a cell and AET_i the actual evapotranspiration from lakes, rivers, reservoirs, and different type of wetlands.

In a next step, the "naturalized" discharge was reduced by the amount of water currently abstracted and used to fulfill the demand in the agricultural (W_{ag}) and nonagricultural (household, industry, and livestock, HIL) sectors, respectively.

$$D_{avail_i} = max(D_{nat_i} - W_{ag_i} - HIL_i, 0) \qquad (3)$$

HIL is based on recent estimates by Flörke et al. (2013). Finally, we account for environmental flow requirements (EFR) and the limits from seasonal distribution by constraining the maximum availability to 40%–70% of total annual blue water supply (e.g., EFR was set to 30%–60%). Considering different flow regimes and water levels required to maintain the ecological functions (see scenarios described below), we obtain the maximum irrigation water supply of each grid cell, IWS_i.

$$IWS_i = max(D_{avail_i} - D_{nat_i} * EFR, 0) \qquad (4)$$

where EFR represents the flow requirement as fraction (0–1) of a grid cell's naturalized discharge D_{nat_i}. For this study, we assume that freshwater is not freely distributable within river basins but follows the lateral transport along the river network (Döll & Lehner, 2002). Considering upstream–downstream relationships, the calculated IWS in a cell i does not necessarily correspond to maximum amount of water available for irrigation in that cell. As possible upstream water withdrawals reduce available water downstream, the discharge in any of these connected cells must not become negative. Thus, starting from the most upstream cell, the maximum amount of water that can be abstracted in a cell i corresponds to the minimum IWS of i and all its connected downstream cells, respectively.

$$IWS_i = min(IWS_{i,DOWN_i}) \qquad (5)$$

Actual irrigation water withdrawal, IWWD, of a grid cell i is determined as.

$$IWWD_i = \frac{\Delta WB_{max_i} * A_{BP_i}}{EAP} \qquad (6)$$

where A_{BP_i} is the area in i potentially available for biomass plantations in the different land constraint scenarios, and EAP is the application efficiency reflecting the conveyance losses of the irrigation system. In case that $IWWD_i > IWS_i$, additional water can be taken from the neighboring cell with the largest upstream area, otherwise $IWWD_i \leq IWS_i$. Subsequently, we determine the fraction of the potential plantation area of each grid cell (F_{BP_i}) that could be irrigated to get the maximum yield in that cell.

$$F_{BP_i} = min\left(\frac{IWS_i}{IWWD_i}, 1\right) \qquad (7)$$

The additional biomass harvest gained through irrigation (Y_{IR_i}) is calculated as.

$$Y_{IR_i} = \Delta Y_{max_i} * A_{BP_i} * F_{BP_i} \qquad (8)$$

2.3 | Scenarios of land and water availability

We define four different scenarios for irrigation water supply. The scenario of highest water availability (hereinafter "High") is based on the assumptions that (a) the EFR corresponds to 30% of the annual river discharge; and (b) the irrigation system has no conveyance losses. In the "Medium" water availability scenario, the EFR corresponds to 60% of the annual river discharge while conveyance losses remain zero. In the scenario of lowest irrigation water availability (hereinafter "Low"), EFRs are as in "Medium" but the conveyance efficiency of the irrigation system is

TABLE 1 Scenarios of irrigation water availability

Scenario	Definition
High	Renewable water resources reduced by current water usage in agricultural and nonagricultural sectors, 30% reserved for ecosystem functions, highly efficient irrigation system (no conveyance losses, withdrawal equivalent to water consumption)
Medium	Renewable water resources reduced by current water usage in agricultural and nonagricultural sectors, 60% reserved for ecosystem functions, highly efficient irrigation system (no conveyance losses, withdrawal equivalent to water consumption)
Low	As *Medium*, but less efficient irrigation system with conveyance losses of 25% resulting in higher withdrawal
Rain-fed	No additional irrigation, precipitation is the only source of plant available water

assumed to be 75% which results in a higher withdrawal (gross irrigation requirement). Additionally, we employ a scenario "*Rain-fed*" where precipitation, that is, green water, is the only source of all plant available water (see Table 1).

As shown in numerous publications, future land requirements for food production can be both higher and lower than today (Balmford, Green, & Scharlemann, 2005; Foley et al., 2011; Gerbens-Leenes, 2002; Gerbens-Leenes, Nonhebel, & Ivens, 2002; Hobbs, 2007; Kastner, Rivas, Koch, & Nonhebel, 2012; Ray, Mueller, West, & Foley, 2013; Schmitz et al., 2014; Verburg, Eickhout, & Meijl, 2008; Wallace, 2000). As it is outside the scope of this study to directly model land use and land use change (LUC) associated with future food production, we adopt for our *Food first* scenario the simple assumption that land currently under agricultural use will not be available for establishment of biomass plantations. For that purpose, spatially explicit global information on cropland extent is obtained from the MIRCA2000 land use dataset (Portmann, Siebert, & Döll, 2010) following Fader et al. (2010).

Further restrictions on land availability are applied to quantify how approaches to protect natural ecosystems and to keep LUC emissions below certain thresholds (based on the estimated carbon storage in soils and aboveground vegetation) influence the plantation supply.

In the *Food & Nature* scenario, plantations are not allowed on legally protected lands, wetlands, and areas of high biodiversity and/or classified as wilderness. In this scenario, also areas of severely degraded soils are excluded (for detailed description see Beringer et al. (2011)). We acknowledge that this approach does not consider that establishment of biomass plantations can improve conditions for nature and biodiversity. For example, many studies have shown that the integration of new types of biomass production systems into existing agricultural landscapes can have positive impacts by restoring or conserving soils, reducing water pollution, and enhancing landscape diversity (Baum, Bolte, & Weih, 2012; Berndes, Börjesson, Ostwald, & Palm, 2008; Dauber, Jones, & Stout, 2010; Dimitriou et al., 2009; Firbank, 2008; Holland et al., 2015; Manning, Taylor, & Hanley, 2015; Verdade, Piña, & Rosalino, 2015).

Finally, two land use scenarios are defined to represent ambitions to keep LUC emissions below certain threshold levels. The rationale is that low LUC emissions make the so-called carbon payback time (CPT) short. The CPT is the time it takes until bioenergy use has contributed to avoiding as much GHG emissions as was emitted (LUC emissions) when land was converted into biomass plantations associated with the bioenergy system. The CPT depends on the size of LUC emissions and the annual GHG savings arising from the bioenergy use, which in turn depends on

the avoided emissions due to displacement of other energy sources and the supply chain emissions of the bioenergy system (Berndes, Ahlgren, Börjesson, & Cowie, 2013; Fargione, Hill, Tilman, Polasky, & Hawthorne, 2008; Gibbs et al., 2008). Thus, larger LUC emissions do not translate into longer CPT if higher annual GHG savings outweigh the effect of the larger LUC emissions. Also, a bioenergy system associated with shorter CTP may not be preferred if the annual GHG savings are small, as the cumulative GHG savings per unit land then grow slowly: preference depends on whether shorter or longer term mitigation effects are priority.

Acknowledging that the level of LUC emissions is an insufficient indicator if the purpose is to evaluate the climate change mitigation value of plantations, we assume that lands are not available for plantations if total carbon stock values are above 150 t C/ha (shrubland/savanna) and 270 t C/ha (forests). Adopting data from Gibbs et al. (2008), these threshold values correspond to a CPT of 10 and 50 years, respectively, if the land is planted with oil palm to produce biodiesel. Table 2 provides a qualitative description of the land use scenarios analyzed here. A quantitative description of the scenarios of water and land availability showing the individual spatial patterns is given in Figures 1 and 2, respectively. We present estimates of achievable supply under the different scenarios at global

TABLE 2 Land use scenarios used to evaluate potential biomass from plantations

Land use scenario	Abbreviation	Definition
Food first	FF	Land resource reduced by current cropland and pastures (extent of around the year 2000)
Food & Nature	FN	As in "*Food first*," but additionally reduced by protected areas[a], wetlands[b], areas of high biodiversity/wilderness[c], and areas of severely degraded soils[d]
Carbon threshold "Forest"	CTF	As in "*Food & Nature*," but additionally reduced by areas where soil and vegetation carbon stock exceeds 270 t C ha
Carbon threshold "Savanna"	CTS	As in "*Food & Nature*," but additionally reduced by areas where soil and vegetation carbon stock exceeds 150 t C ha

[a]Brooks (2006); Rodrigues et al. (2004); Naidoo et al. (2008).
[b]Lehner and Döll (2004).
[c]Mittermeier et al. (2003); Bryant et al. (1997); Sanderson (2002); Myers, Mittermeier, Mittermeier, Fonseca, and Kent (2000); Stattersfield, Crosby, Long, and Wege (1998); Davis, Heywood, and Hamilton (1994); Olson and Dinerstein (2002).
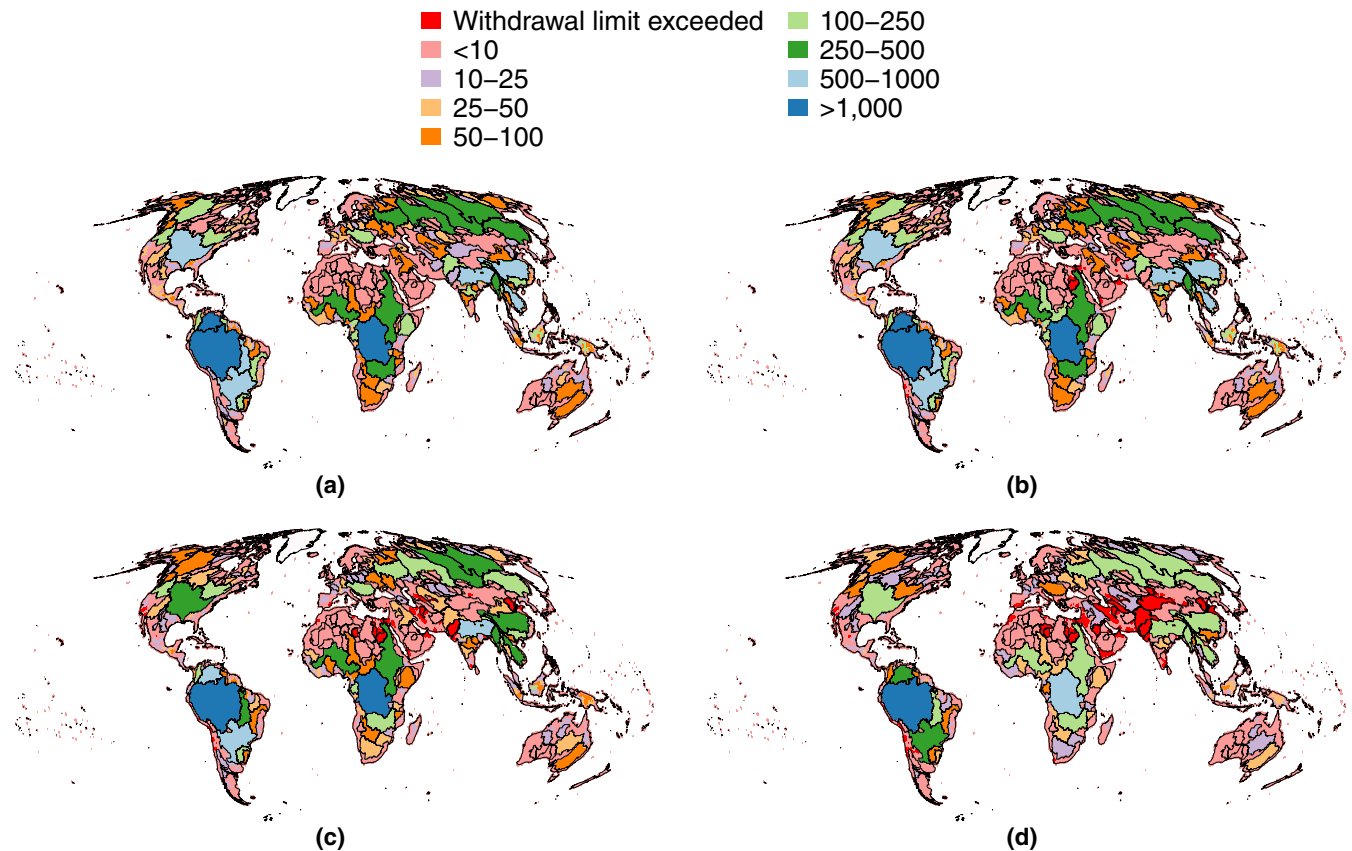[d]Oldeman, Hakkeling, Sombroek, and Batjes (1991).

—WILEY | 633

FIGURE 1 Scenarios of available irrigation water (km^3/year) if renewable available water resources are (a) not restricted, (b) reduced by current water use for agricultural and nonagricultural sectors, respectively, (c) additionally reduced by 30% for environmental flow requirements, (d) additionally reduced by 60% for environmental flow requirements. LPJmL simulations averaged over years 1960–2009

level, for world regions, at basin level, and at grid cell level, respectively.

For reasons of brevity, we focus on herbaceous energy crops. In general, productivity of perennial bioenergy crops species, both C3 trees and C4 grasses, is limited predominantly by water availability (Clifton-Brown & Lewandowski, 2000; Clifton-Brown, Lewandowski, Bangerth, & Jones, 2002). Mainly caused by their higher maintenance respiration, woody bioenergy crops are less productive compared to bioenergy grass (Heaton, Long, Voigt, Jones, & Clifton-Brown, 2004; Ragauskas et al., 2006). However, for comparison, all simulation results for both grass and tree bioenergy crops are presented in Tables S1–S4.

3 | RESULTS

3.1 | Global level

Figure 3a demonstrates a large spectrum of plantation supply depending on the chosen combination of land and water availability (Tables 1, 2). The plantation supply in the FF case (2,350 EJ/year) corresponds to a bioenergy plantation area roughly threefold the current global agriculture area (Figure 3c) and a global water use six times

higher than currently (Figure 3b). Doubling the ecological flow requirements in this scenario from 30% to 60% of renewable freshwater resources reduces the global supply from irrigated biomass plantations by about a quarter and the total supply (irrigated + rain-fed) by 215 EJ. If 25% of water withdrawn for irrigation of bioenergy plantations is lost during conveyance, the supply from irrigated biomass plantations is reduced by another 13% (total supply, 4%) (Supporting information Tables S1,). The effect of constraining the availability of water resources depends on land availability, for example, a doubling of the ecological flow requirements to 60% of renewable freshwater resources reduces the supply from irrigated biomass plantations significantly more (37%) in the CTS scenario compared to FF. This is because the land constraint applied in the CTS scenario primarily excludes plantation areas with a significant production potential under rain-fed conditions. The further reduction caused by assuming 25% conveyance losses is, however, roughly the same as in the FF scenario (12%). Land availability also influences the relative contribution of rain-fed versus irrigated systems. In the FF and CTS cases, 67% and 16% of the biomass is grown under rain-fed conditions, respectively (water use scenario "High").
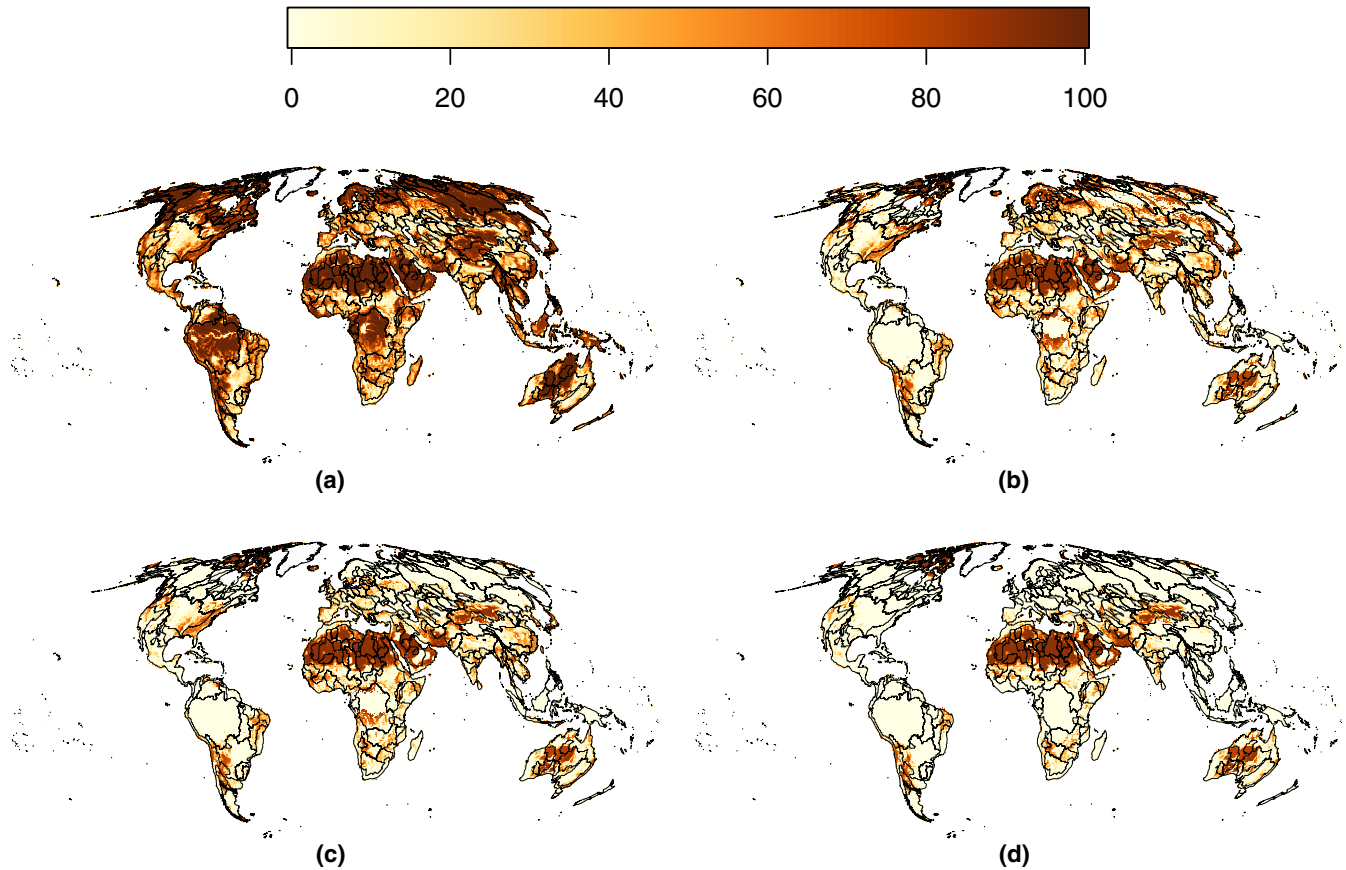
FIGURE 2 Available land as percentage of grid cell for land use scenarios (a) "Food first," (b) "Food & Nature," (c) "Carbon threshold Forest," (d) "Carbon threshold savanna," as described in Table 2

3.2 | Regional level

The regional contribution to the global plantation supply is shown for each land and water use scenario in Figure 4 (see also for abbreviations of the world regions). Comparing all land use scenarios under rain-fed conditions reflects how these plantation supplies depend on land accessibility and natural environmental conditions. In the FF scenario, the world regions LAM (36%), AFR (21%), and PAS (12%) contribute most to the global plantation supply. An additional exclusion of protected areas (FN) reduces the contribution of LAM to 13%, as large nature reserves such as the Central Amazon Conservation Complex, the Iguazu National Park, and the Cerrado Protected Areas are located in this region. Introducing a carbon threshold as in the CTF scenario reduces the contribution of FSU and PAS by 57% and 67%, respectively, as areas with considerable soil and vegetation carbon stocks (but currently not protected) are widespread in these regions. Constraining land availability further in the CTS scenario once again causes a shift of regional shares. In this most restrictive land availability scenario, more than half of the total plantation supply comes from LAM (24%) and AFR (27%). The contribution of PAO and SAS roughly doubles to 14% and 13%,

respectively, while it decreases to <1% for FSU and PAS. The contribution of the MEA region is negligible in all scenarios.

Figure 4 shows the regional contribution to the global irrigated plantation supply and reveals distinct regional patterns of dependence on irrigation water availability. The relative contribution of AFR to global plantation supply is consistently larger when irrigation is available. In the other dominating region, LAM, it is smaller in the FF and CTS scenario while it is roughly the same as under rain-fed conditions in the two other scenarios. In AFR in the FF scenario, the relative contribution decreases as irrigation water availability decreases, stays relatively constant in the FN and CTF scenarios, while it increases with decreasing irrigation water availability in the CTS scenario. The same pattern of increasing relative contribution under decreasing water availability is seen for LAM in the FF scenario. One interpretation of this pattern is that—in the absence of land availability restrictions—AFR has relatively large areas where irrigation can boost yield levels substantially, while the irrigated production in LAM is less sensitive to constraints on irrigation water availability. When only unprotected "low-carbon" land is available, it is instead the irrigated plantation supply in AFR that is less sensitive to
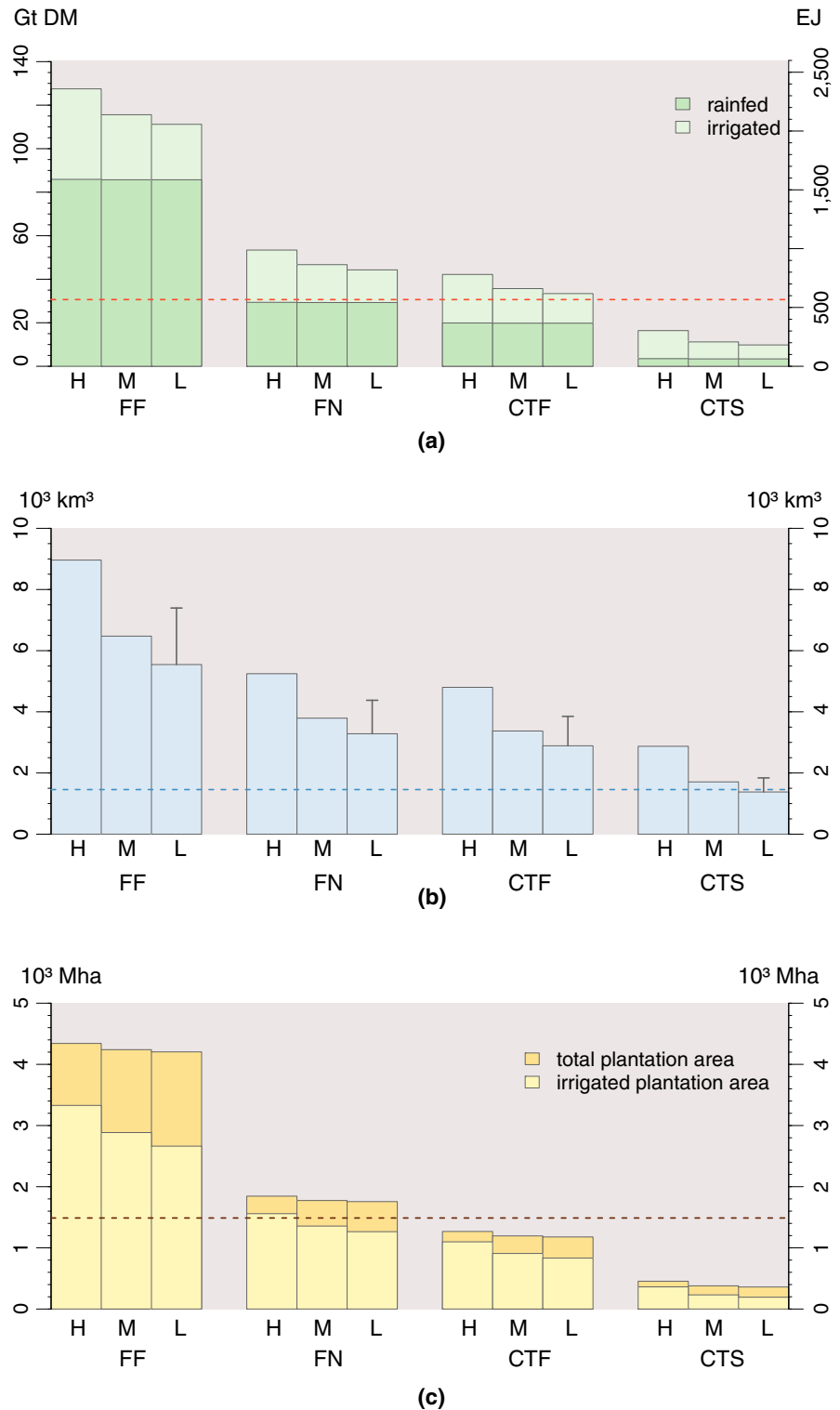
FIGURE 3 (a) Biomass supply (left: Gt DM per year, right: EJ per year) in the different scenarios and associated (b) global water consumption (10^3 km^3) and (c) plantation area (10^3 Mha). Land use scenarios and their abbreviation according to Table 2. The dashed orange line in (a) refers to today's total global primary energy supply according to IEA (2010). Whiskers in (b) indicate withdrawal in case of 25% conveyance losses. The dashed blue line marks current water consumption for agricultural (1,257 km^3 per year, averaged for the time period 2004–2009, according to Jägermeyr et al. (2015)) and nonagricultural (201 km^3 in year 2000) sectors, respectively. The dashed brown line in (c) marks the cropland extent around the year 2000

constraints on irrigation water supply. As a third regional example, results for the CPA region suggest that land availability is limiting the plantation supply in FF, FN, and CTF. However, in the CTS scenario, water availability constrains the plantation supply. In this scenario, land available for biomass plantations is located in basins where the withdrawal limit is either exceeded or available renewable water resources are very low (<10 km^3) (compare Figures 1, 2).

3.3 | Basin level

The analysis of simulation results at basin level elucidates trade-offs between land and water availability. This is exemplarily illustrated for the FN scenario, showing the plantation supply for the different water availability scenarios (Figure 5). Biomass supply is in some basins limited by land rather than water availability, that is, it is close to
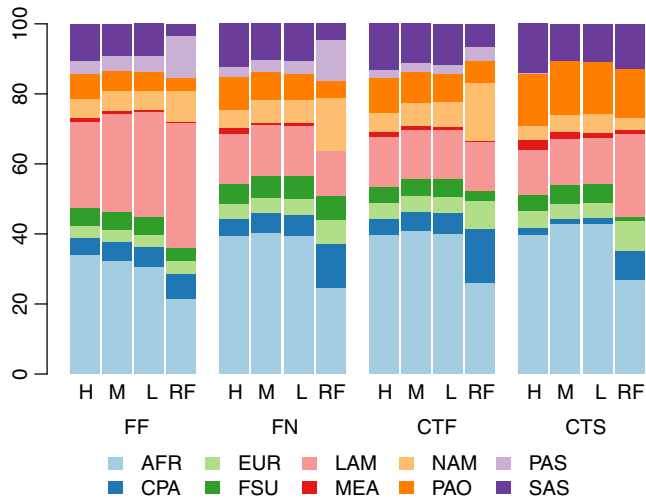
FIGURE 4 Relative contribution (%) of world regions to total biomass production in plantations under rain-fed and irrigated conditions. **RF** refers to rain-fed condition, whereas **H**, **M**, and **L** correspond to water availability scenarios "High," "Medium," and "Low," respectively. World regions are defined as Sub-Saharan Africa (**AFR**), Centrally planned Asia including China (**CPA**), Europe including Turkey (**EUR**), States of the former Soviet Union (**FSU**), Latin America (**LAM**), Middle East/North Africa (**MEA**), North America (**NAM**), Pacific OECD including Japan, Australia, New Zealand (**PAO**), Pacific (or Southeast) Asia (**PAS**), and South Asia including India (**SAS**)

the nonwater limited maximum and not all water resources potentially available for irrigation are used. Examples include basins in large parts of LAM and NAM, EUR, and the southern part of CPA. In contrast, bioenergy supply in most basins in AFR, MEA, SAS, and PAO is constrained by water scarcity. Seven basins were selected to illustrate how the plantation supply changes dependent on availability of irrigation water, and their results are presented in Table 3. In all these basins, simulated maximum plantation supply under irrigation is much larger than the supply under rain-fed conditions. Particularly within the catchment areas of the Syr-Darya and the Colorado, a noticeable plantation supply can only be achieved with substantial irrigation. In the least restrictive scenario concerning water availability for irrigation (High), the Colorado and Sambesi basins could support plantation supplies corresponding to the simulated nonwater limited maximum without exhausting the water resources available for irrigation of biomass plantations. In the five other basins, in contrast, available water resources would become exhausted at plantation supply levels roughly corresponding to 40%–60% of the simulated maximum. In the more restrictive Medium and Low scenarios, available irrigation water resources are exhausted in all considered basins before maximum simulated plantation supplies are reached: for example, plantation supplies in the Colorado and Sambesi basins reach 75% and 55%,

respectively, of the theoretical maximum. Plantation supplies in the other basins reach maximally one-third (Medium) and one-fourth (Low) of the water-unlimited potential, respectively.

3.4 | Grid cell level

The detailed simulated spatial distribution of biomass plantations can be discerned from Figure 6. Total plantation production within an individual grid cell (Figure 6c) is determined by biomass productivity (Figure 6b) and the share of the grid cell available for biomass plantations (Figure 6a). As shown in Figure 6b, the biomass productivity is relatively high in many regions and the application of irrigation brings about substantial productivity increases over large areas. However, as shown in Figure 6a, low area availability restricts the total plantation supply in several highly productive regions, notably Europe, the Mid-south of the United States, Central America, and the Australian East coast. Large irrigated plantation production occurs in the Mid-south, Southeast, and East coast regions of the United States, in eastern Brazil and northern Argentina, around the Congo basin, and in India. Considerable plantation production is also simulated, for example, in Southern China, Southeast Asia, and the Northwest of Australia (Figure 6c).

4 | DISCUSSION

We show that availability of land and water, and (irrigation) management of water resources, strongly influence the biomass supply from plantations in individual regions and globally, with water limitations becoming the more relevant, the stricter the assumed constraints on land availability for plantations. This basically confirms conclusions in other studies (Beringer et al., 2011; Creutzig et al., 2015; Offermann et al., 2011) that future possible levels of biomass supply cannot be specified to a narrow range due to inherent uncertainties concerning critical factors, including criteria of exclusion to protect both land and water—which we here distinguish more systematically with respect to their relative effects.

Somerville and Youngs (2014) argued that "…estimating the practical limits to how much bioenergy could be produced in the future has been an academic sport in recent years, but is not a useful activity." Slade et al. (2014) reviewed more than 120 estimates of the future contribution of biomass to global energy supply. They noted that the range of estimates is driven more by the choice of alternative assumptions than methodological differences and concluded that studies provide limited insight into the level of deployment that might be achievable in practice, as many open questions will only be resolved as
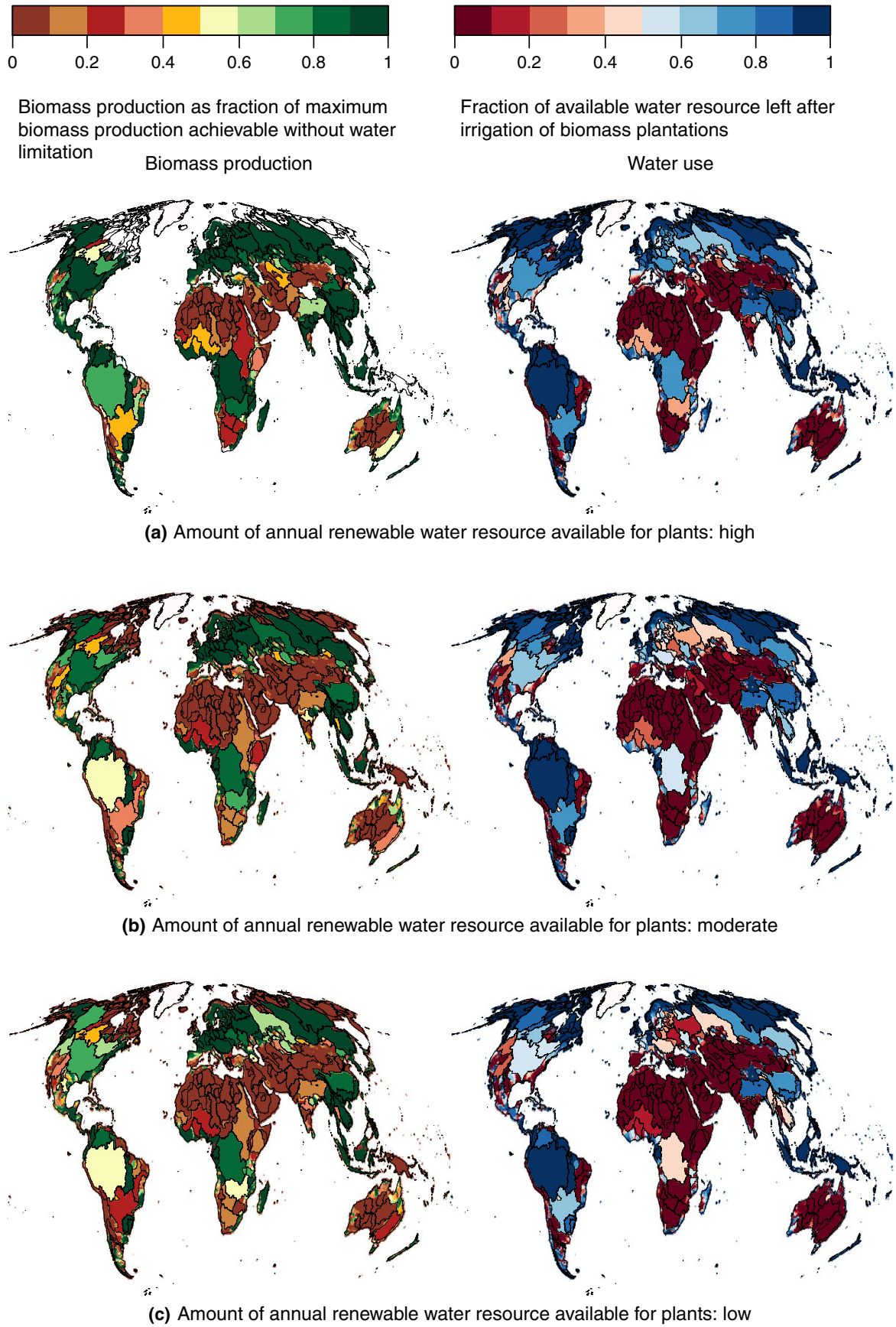
Biomass production as fraction of maximum biomass production achievable without water limitation

Fraction of available water resource left after irrigation of biomass plantations

Biomass production

Water use

(a) Amount of annual renewable water resource available for plants: high

(b) Amount of annual renewable water resource available for plants: moderate

(c) Amount of annual renewable water resource available for plants: low

FIGURE 5 Limitation of bioenergy crop plantations due to available renewable water resources at basin level under the "*Food & Nature*" scenario

TABLE 3 Utilization of maximum biomass production for selected river basins and under different scenarios of water availability

Water availability	Basin	Sao Francisco	Parnaiba	Colorado	Niger	Sambesi	Syr-Darya	Murray
	Outlet coordinates (with reference to the 0.5° × 0.5° high-resolution grid of the LPJmL model)	10.25°S 36.25°W	2.75°S 41.75°W	31.75°N 114.75°W	4.25°N 6.25°E	18.75°S 36.25°E	45.25°N 60.25°E	35.75°S 139.25°E
	Rain-fed biomass production (Mt DM)	235	173	1	372	335	1	75
	Maximum of irrigated biomass production (Mt DM)	722	419	75	2,382	886	332	498
High	Fraction of maximum production	0.62	0.41	1	0.59	1	0.63	0.62
	Fraction of available water exhausted	1	1	0.69	1	0.74	1	1
Medium	Fraction of maximum production	0.37	0.24	0.76	0.36	0.77	0.24	0.33
	Fraction of available water exhausted	1	1	1	1	1	1	1
Low	Fraction of maximum production	0.28	0.18	0.56	0.28	0.58	0.18	0.25
	Fraction of available water exhausted	1	1	1	1	1	1	1

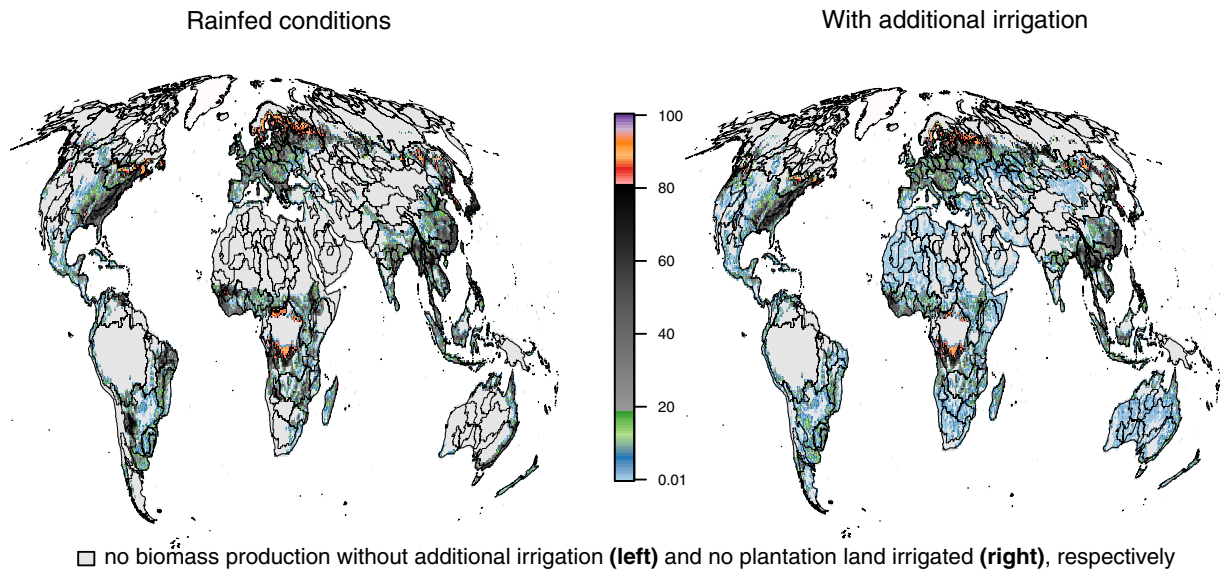*Note.* All results are based on the "Food & Nature" land use scenario.

incremental attempts are made to increase the contribution of biomass in global energy supply. To the extent that high or low estimates of biomass supply are used as a basis for advocacy in the bioenergy debate, we agree with Somerville and Youngs (2014) as well as the recommendation by Slade et al. (2014) on a learning-by-doing approach to identify merits and pitfalls of biomass deployment and improve understanding of the prospects for higher levels of biomass use.

The results presented in this study may in this regard inform the planning of further studies to address aspects of biomass mobilization in basins or multi-basin regions identified as potentially important locations for large-scale biomass production. Such studies can complement scenario studies of the kind summarized by the IPCC (Edenhofer et al., 2011) by providing more comprehensive regional-level information about current and prospective availability and use of land and water resources, as well as other factors that influence conditions for deployment.
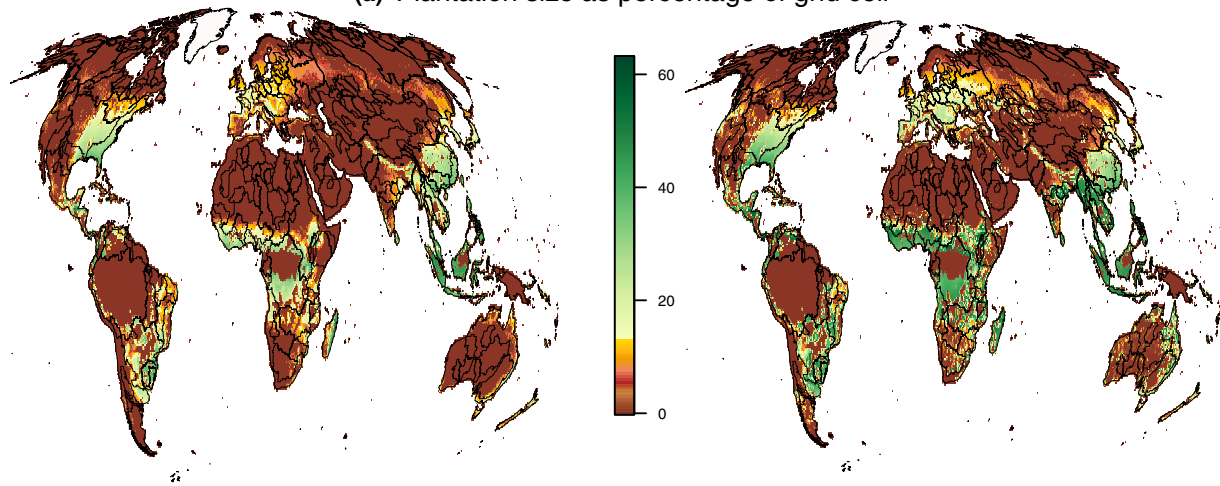
To limit global warming to 2 °C (1.5 °C), integrated assessment studies project a BECCS contribution of 0.5 to 2.7 GtC/ year (0.6 to 4.1 GtC/ year) from dedicated bioenergy crops to negative emission requirements in 2050 (Fuss et al., 2014; Rogelj et al., 2015). The simulation results reported here do not provide a basis for ruling out bioenergy deployment at levels found in those studies. The higher end in the ranges for bioenergy use in these scenarios is within the range for plantation supply in the most restrictive land use scenario CTS. But the results cannot either be used as a basis for concluding that the scenarios are feasible, as prospects for bioenergy depends on many factors that have not been considered in this study, for example, challenges related to high plantation expansion rates including the build-up of irrigation systems and

governance to avoid or mitigate negative effects and maintain public support for bioenergy. According to Turner, Field, Lobell, Sanchez, and Mach (2018), the rate of land use conversion in climate change mitigation scenarios with a likely chance of limiting global warming to 2°C in 2100 proceeds at a median rate of 8.8 Mha/year from 2020 to 2050. In total, the authors estimate 272 Mha of new energy cropland to be enrolled over the next three decades. These results are comparable to our assessments, where in the most restrictive CTS scenario a plantation area of 289 Mha is needed to yield 3 Gt DM/year (that is ~1.5 Gt C/year) of highly productive bioenergy crops. If evaluated consequently in terms of environmental impacts such as those considered in the concept of "planetary boundaries," there is little maneuvering space left for biomass plantations (Boysen et al., 2017; Heck, Gerten, Lucht, & Popp, 2018). Rising atmospheric CO_2 content as well as associated climate change effects may affect biomass supply estimates provided here (Deryng et al., 2016; Haberl et al., 2011), yet such impacts need to be examined in the future studies.

Some results of this study, especially regarding the simple assumptions about freshwater availability for irrigation of plantations, are subject to uncertainties. For example, our parameter choice regarding EFRs is based on the hydrologic consideration that water withdrawal in excess of specific percentages of natural mean annual flow represents a risk to riverine ecosystems' integrity. To account for different levels of protection, we specified scenarios representing a range of flow volumes (and irrigation efficiencies) but do not differentiate across regions. In a refined assessment, different EFR estimation methods could be used to assign different EFR volumes depending on month, location, and flow regime. This issue has been addressed in other studies based on a version of LPJmL (developed in

Rainfed conditions

With additional irrigation

☐ no biomass production without additional irrigation **(left)** and no plantation land irrigated **(right)**, respectively

(a) Plantation size as percentage of grid cell

(b) Productivity per grid cell [t DM ha^{-1}]

(c) Biomass production per grid cell [Mt DM]

FIGURE 6 Plantation of bioenergy crops under the land use scenario "*Food & Nature*" and the water availability scenario "*Low*"

parallel to the one employed here) that incorporate dynamic representations of EFRs and also system irrigation efficiencies (Jägermeyr, Pastor, Biemans, & Gerten, 2017), yet solely focusing on agricultural water demand—including bioenergy water demand in an integrated assessment with a more sophisticated modeling approach is a research desiderate for future applications. Meanwhile, a more detailed assessment of uncertainties of supply estimates, with a focus on the choice of freshwater allocation rules within river basins, is subject of a follow-up study (Y. Jans et al., in preparation).

The strong influence of irrigation water availability on the simulated level of plantation supply needs to be considered in the context of evolving water scarcities, which are expected to be influenced by both demand-side and supply-side factors where climate change is an important but uncertain factor (Gosling & Arnell, 2016; Haddeland et al., 2014; Mekonnen & Hoekstra, 2016; Schewe et al., 2014). Climate-driven freshwater limitations could in some regions necessitate reversion of large cropland areas from irrigated to rain-fed management, while freshwater abundance in other regions may help ameliorate resulting production losses, if required infrastructure investments take place (Elliott et al., 2014; Jägermeyr et al., 2016, 2017). The freshwater use associated with the irrigated plantation supplies reported in this study (Figure 3) is very significant in comparison with current freshwater withdrawals (Oki & Kanae, 2006) and consumptive use (Shiklomanov & Rodda, 2004), as well as global freshwater withdrawal limits considered to be associated with physical water scarcity (Defraiture, Molden, Amarasinghe, & Makin, 2001; Vorosmarty, Green, Salisbury, & Lammers, 2000) and planetary boundaries (Rockström et al.., 2009; Steffen et al., 2015). It is, however, not straightforward to translate such observations into firm conclusions about the feasibility of certain levels of biomass supply, as water-related consequences of biomass deployment depend on location, context, and rationales behind the deployment. The cultivation of drought tolerant plants, such as feedstock for bioenergy and other bio-based products, may offer an alternative use of lands where emerging freshwater scarcity causes challenges for irrigated production of more vulnerable crops. Conversely, a possible future need for increased food production in regions with relative water abundancy should be considered if biomass production for bioenergy and other bio-based products is contemplated as an option for making productive use of land in areas where food production is currently not viable due to more competitive production elsewhere. The integration of new forms of biomass production into agricultural landscapes can provide several products from the same land area, enhance resource use efficiency, and help mitigate some of the impacts associated with current land use (Berndes & Fritsche, 2016).

ORCID

Yvonne Jans iD http://orcid.org/0000-0003-4298-6026

REFERENCES

Ashworth, A. J., Keyser, P. D., Holcomb, E. D., & Harper, C. A. (2013). Yield and stand persistence of switchgrass as affected by cutting height and variety. *Forage and Grazinglands*, *11*(1). https://doi.org/10.1094/FG-2013-0043-RS

Azar, C., Johansson, D. J. A., & Mattsson, N. (2013). Meeting global temperature targets—the role of bioenergy with carbon capture and storage. *Environmental Research Letters*, *8*(3), 034004.

Azar, C., Lindgren, K., Larson, E., & Möllersten, K. (2006). Carbon capture and storage from fossil fuels and biomass – costs and potential role in stabilizing the atmosphere. *Climatic Change*, *74* (1–3), 47–79.

Balmford, A., Green, R. E., & Scharlemann, J. P. W. (2005). Sparing land for nature: Exploring the potential impact of changes in agricultural yield on the area needed for crop production. *Global Change Biology*, *11*(10), 1594–1605.

Baum, S., Bolte, A., & Weih, M. (2012). Short rotation coppice (SRC) Plantations provide additional habitats for vascular plant species in agricultural mosaic landscapes. *BioEnergy Research*, *5*, 573–583.

Beddington, J. R., Asaduzzaman, M., Clark, M. E., Bremauntz, A. F., Guillou, M. D., Howlett, D. J. B., … Wakhungu, J. (2012). What next for agriculture after durban? *Science*, *335*(6066), 289–290. https://doi.org/10.1126/science.1217941

Beringer, T., Lucht, W., & Schaphoff, S. (2011). Bioenergy production potential of global biomass plantations under environmental and agricultural constraints. *GCB Bioenergy*, *3*(4), 299–312.

Berndes, G. (2002). Bioenergy and water—the implications of large-scale bioenergy production for water use and supply. *Global Environmental Change*, *12*(4), 253–271.

Berndes, G., Ahlgren, S., Börjesson, P., & Cowie, A. (2013). Bioenergy and land use change—state of the art. *Wires Energy Environment*, *2013*(2), 282–303. https://doi.org/10.1002/wene.41.

Berndes, G., Börjesson, P., Ostwald, M., & Palm, M. (2008). Multifunctional biomass production systems —an introduction with presentation of specific applications in India and Sweden. *Biofuels, Bioproducts and Biorefining*, *2*, 16–25.

Berndes, G., & Fritsche, U. (2016). May we have some more land use change, please? *Biofuels, Bioproducts and Biorefining*, *10*(3), 195–197. https://doi.org/10.1002/bbb.1656

Biemans, H., Hutjes, R. W. A., Kabat, P., Strengers, B. J., Gerten, D., & Rost, S. (2009). Effects of precipitation uncertainty on discharge calculations for main river basins. *Journal of Hydrometeorology*, *10*(4), 1011–1025.

Bodirsky, B. L., Rolinski, S., Biewald, A., Weindl, I., Popp, A., & Lotze-Campen, H. (2015). Global food demand scenarios for the 21st century. *PLoS ONE*, *10*(11), e0139201.

Bondeau, A., Smith, P. C., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W., … Smith, B. (2007). Modelling the role of agriculture for the 20th century global terrestrial carbon balance. *Global Change Biology*, *13*(3), 679–706.

Bonsch, M., Humpenöder, F., Popp, A., Bodirsky, B., Dietrich, J. P., Rolinski, S., … Gerten, D. (2016). Trade-offs between land and water requirements for large-scale bioenergy production. *GCB Bioenergy*, *8*(1), 11–24.

Boysen, L. R., Lucht, W., & Gerten, D. (2017). Trade-offs for food production, nature conservation and climate limit the terrestrial carbon dioxide removal potential. *Global Change Biology*, *23*(10), 4303–4317.

Boysen, L. R., Lucht, W., Gerten, D., & Heck, V. (2016). Impacts devalue the potential of large-scale terrestrial CO_2 removal through biomass plantations. *Environmental Research Letters*, *11*(9), 095010.

Boysen, L. R., Lucht, W., Gerten, D., Heck, V., Lenton, T. M., & Schellnhuber, H. J. (2017). The limits to global-warming mitigation by terrestrial carbon removal. *Earth's Future*, *5*(5), 463–474.

Brooks, T. M. (2006). Global biodiversity conservation priorities. *Science*, *313*(5783), 58–61.

Bryant, D., Nielsen, D., Tangley, L., Sizer, N., Miranda, M., Brown, P., … Miller, K. (1997). *The last frontier forests: Ecosystems and economies on the edge. What is the status of the worlds remaining large natural forest ecosystems?* Technical report. Washington, DC: World Resources Institute.

Clifton-Brown, J., & Lewandowski, I. (2000). Water use efficiency and biomass partitioning of three different Miscanthus genotypes with limited and unlimited water supply. *Annals of Botany*. https://doi.org/10.1006/anbo.2000.1183

Clifton-Brown, J. C., Lewandowski, I., Bangerth, F., & Jones, M. B. (2002). Comparative responses to water stress in stay-green, rapid- and slow senescing genotypes of the biomass crop, Miscanthus. *New Phytologist*, *154*(2), 335–345.

Creutzig, F., Ravindranath, N. H., Berndes, G., Bolwig, S., Bright, R., Cherubini, F., … Masera, O. (2015). Bioenergy and climate change mitigation: An assessment. *GCB Bioenergy*, *7*(5), 916–944.

Dauber, J., Jones, M. B., & Stout, J. C. (2010). The impact of biomass crop cultivation on temperate biodiversity. *GCB Bioenergy*, *2*(6), 289–309.

Davis, S. D., Heywood, V. H., and Hamilton, A. C. (1994). *Centres of plant diversity: A guide and strategy for their conservation*. Technical report. Cambridge, UK: IUCN Publications Unit.

de Wit, C. T. (1958). *Transpiration and crop yields*. Agric. Res. Rep. 64(6), Wageningen, The Netherlands: Pudoc.

Defraiture, C., Molden, D., Amarasinghe, U., & Makin, I. (2001). PODIUM: Projecting water supply and demand for food production in 2025. *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere*, *26*(11–12), 869–876.

Deryng, D., Elliott, J., Folberth, C., Müller, C., Pugh, T. A., Boote, K. J., … Rosenzweig, C. (2016). Regional disparities in the beneficial effects of rising co 2 concentrations on crop water productivity. *Nature Climate Change*, *6*(8), 786.

Dimitriou, I., Baum, C., Baum, S., Busch, G., Schulz, U., Köhn, J., … Bolte, A. (2009). The impact of Short Rotation Coppice (SRC) cultivation on the environment. *Landbauforschung vTI Agriculture and Forestry Research*, *3*(59), 159–162.

Döll, P., & Lehner, B. (2002). Validation of a new global 30-min drainage direction map. *Journal of Hydrology*, *258*(1–4), 214–231.

Dornburg, V., van Vuuren, D., van de Ven, G., Langeveld, H., Meeusen, M., Banse, M., … Faaij, A. (2010). Bioenergy revisited: Key factors in global potentials of bioenergy. *Energy & Environmental Science*, *3*(3), 258.

Edenhofer, O., Pichs Madruga, R., Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S., … von Stechow, C. (Eds.) (2011). *Renewable energy sources and climate change mitigation: Special Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press.

Edenhofer, O., Sokona, Y., Farahani, E., Kadner S., Seyboth, K., Adler, A., … Minx, J., (Eds.) (2014). *Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press.

Elliott, J., Deryng, D., Müller, C., Frieler, K., Konzmann, M., Gerten, D., … Wisser, D. (2014). Constraints and potentials of future irrigation water availability on agricultural production under climate change. *Proceedings of the National Academy of Sciences*, *111*(9), 3239–3244.

Fader, M., Rost, S., Müller, C., Bondeau, A., & Gerten, D. (2010). Virtual water content of temperate cereals and maize: Present and potential future patterns. *Journal of Hydrology*, *384*(3–4), 218–231.

Fargione, J., Hill, J., Tilman, D., Polasky, S., & Hawthorne, P. (2008). Land clearing and the biofuel carbon debt. *Science*, *319*(5867), 1235–1238.

Firbank, L. (2008). Assessing the ecological impacts of bioenergy projects. *BioEnergy Research*, *1*(1), 12–19.

Flörke, M., Kynast, E., Bärlund, I., Eisner, S., Wimmer, F., & Alcamo, J. (2013). Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: A global simulation study. *Global Environmental Change*, *23*(1), 144–156.

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., … Zaks, D. P. M. (2011). Solutions for a cultivated planet. *Nature*, *478*(7369), 337–342.

Fraiture, C. D., Giordano, M., & Liao, Y. (2008). Biofuels and implications for agricultural water use: Blue impacts of green energy. *Water Policy*, *10*(S1), 67.

Fuss, S., Canadell, J. G., Peters, G. P., Tavoni, M., Andrew, R. M., Ciais, P., … Yamagata, Y. (2014). Betting on negative emissions. *NatureClimate Change*, *4*(10), 850–853.

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The Circular Economy – A new sustainability paradigm? *Journal of Cleaner Production*, *143*(Supplement, C):757–768. https://doi.org/10.1016/j.jclepro.2016.12.048

Gerbens-Leenes, P. (2002). Consumption patterns and their effects on land required for food. *Ecological Economics*, *42*(1–2), 185–199.

Gerbens-Leenes, P. W., Nonhebel, S., & Ivens, W. (2002). A method to determine land requirements relating to food consumption patterns. *Agriculture, Ecosystems & Environment*, *90*(1), 47–58.

German Bioeconomy Council. (2018). *Bioeconomy policy (part III): Update report of national strategies around the world*. http://biooekonomierat.de/fileadmin/Publikationen/berichte/

GBS_2018_Bioeconomy-Strategies-around-the_World_Part-III.pdfaccessed May 7, 2018.

Gerten, D., Schaphoff, S., Haberlandt, U., Lucht, W., & Sitch, S. (2004). Terrestrial vegetation and water balance—hydrological evaluation of a dynamic global vegetation model. *Journal of Hydrology*, *286*(1–4), 249–270.

Gerten, D., Schaphoff, S., & Lucht, W. (2007). Potential future changes in water limitations of the terrestrial biosphere. *Climatic Change*, *80*(3–4), 277–299.

Gheewala, S. H., Berndes, G., & Jewitt, G. (2011). The bioenergy and water nexus. *Biofuels, Bioproducts and Biorefining*, *5*(4), 353–360.

Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*, *114*, 11–32.

Gibbs, H. K., Johnston, M., Foley, J. A., Holloway, T., Monfreda, C., Ramankutty, N., & Zaks, D. (2008). Carbon payback times for crop-based biofuel expansion in the tropics: The effects of changing yield and technology. *Environmental Research Letters*, *3*(3), 034001.

Gosling, S. N., & Arnell, N. W. (2016). A global assessment of the impact of climate change on water scarcity. *Climatic Change*, *134*(3), 371–385.

Gregson, N., Crang, M., Fuller, S., & Holmes, H. (2015). Interrogating the circular economy: The moral economy of resource recovery in the EU. *Economy and Society*, *44*(2), 218–243.

Guo, M., Song, W., & Buhain, J. (2015). Bioenergy and biofuels: History, status, and perspective. *Renewable and Sustainable Energy Reviews*, *42*, 712–725.

Haberl, H., Erb, K.-H., Krausmann, F., Bondeau, A., Lauk, C., Müller, C., … Steinberger, J. K. (2011). Global bioenergy potentials from agricultural land in 2050: Sensitivity to climate change, diets and yields. *Biomass and Bioenergy*, *35*(12), 4753–4769.

Haddeland, I., Heinke, J., Biemans, H., Eisner, S., Flörke, M., Hanasaki, N., … Wisser, D. (2014). Global water resources affected by human interventions and climate change. *Proceedings of the National Academy of Sciences*, *111*(9), 3251–3256.

Harris, I., Jones, P. D., Osborn, T. J., & Lister, D. H. (2014). Updated high-resolution grids of monthly climatic observations–the CRU TS3. 10 Dataset. *International Journal of Climatology*, *34*(3), 623–642.

Heaton, E. A., Long, S. P., Voigt, T. B., Jones, M. B., & Clifton-Brown, J. (2004). Miscanthus for renewable energy generation: European Union experience and projections for Illinois. *Mitigation and Adaptation Strategies for Global Change*, *9*(4), 433–451.

Heck, V., Gerten, D., Lucht, W., & Boysen, L. R. (2016). Is extensive terrestrial carbon dioxide removal a green'form of geoengineering? A global modelling study. *Global and Planetary Change*, *137*, 123–130.

Heck, V., Gerten, D., Lucht, W., & Popp, A. (2018). Biomass-based negative emissions difficult to reconcile with planetary boundaries. *Nature Climate Change*, *8*(4), 345.

Hetemäki, L., Hanewinkel, M., Muys, B., Ollikainen, M., Palahi, M., & Trasobares, A. (2017). *Leading the way to a European circular bioeconomy strategy. From Science to Policy 5*. European Forest Institute.

Hobbs, P. R. (2007). Conservation agriculture: What is it and why is it important for future sustainable food production? *The Journal of Agricultural Science*, *145*(2), 127.

Hobson, K. (2016). Closing the loop or squaring the circle? Locating generative spaces for the circular economy. *Progress in Human Geography*, *40*(1), 88–104.

Hobson, K., & Lynch, N. (2016). Diversifying and de-growing the circular economy: Radical social transformation in a resource-scarce world. *Futures*, *82*(Supplement, C): 15–25.

Holland, R. A., Eigenbrod, F., Muggeridge, A., Brown, G., Clarke, D., & Taylor, G. (2015). A synthesis of the ecosystem services impact of second generation bioenergy crop production. *Renewable and Sustainable Energy Reviews*, *46*, 30–40.

IEA. (2010). *World energy outlook 2010*. Technical report. Paris: International Energy Agency.

Jackson, R. B., Jobbágy, E. G., Avissar, R., Roy, S. B., Barrett, D. J., Cook, C. W., … Murray, B. C. (2005). Trading water for carbon with biological carbon sequestration. *Science*, *310*(5756), 1944–1947.

Jägermeyr, J., Gerten, D., Heinke, J., Schaphoff, S., Kummu, M., & Lucht, W. (2015). Water savings potentials of irrigation systems: Global simulation of processes and linkages. *Hydrology and Earth System Sciences*, *19*(7), 3073–3091.

Jägermeyr, J., Gerten, D., Schaphoff, S., Heinke, J., Lucht, W., & Rockström, J. (2016). Integrated crop water management might sustainably halve the global food gap. *Environmental Research Letters*, *11*(2), 025002.

Jägermeyr, J., Pastor, A., Biemans, H., & Gerten, D. (2017). Reconciling irrigated food production with environmental flows for sustainable development goals implementation. *NatureCommunications*, *8*, 15900.

Johnson, P. C., Clementson, C. L., Mathanker, S. K., Grift, T. E., & Hansen, A. C. (2012). Cutting energy characteristics of Miscanthus x giganteus stems with varying oblique angle and cutting speed. *Biosystems Engineering*, *112*(1), 42–48.

Kastner, T., Rivas, M. J. I., Koch, W., & Nonhebel, S. (2012). Global changes in diets and the consequences for land requirements for food. *Proceedings of the National Academy of Sciences*, *109*(18), 6868–6872.

King, J. S., Ceulemans, R., Albaugh, J. M., Dillen, S. Y., Domec, J.-C., Fichot, R., … Zenone, T. (2013). The challenge of lignocellulosic bioenergy in a water-limited world. *BioScience*, *63*(2), 102–117.

Kiziloglu, F. M., Sahin, U., Kuslu, Y., & Tunc, T. (2009). Determining water–yield relationship, water use efficiency, crop and pan coefficients for silage maize in a semiarid region. *Irrigation Science*, *27*(2), 129–137.

Lapola, D. M., Schaldach, R., Alcamo, J., Bondeau, A., Koch, J., Koelking, C., & Priess, J. A. (2010). Indirect land-use changes can overcome carbon savings from biofuels in Brazil. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(8), 3388–3393.

Lehner, B., & Döll, P. (2004). Development and validation of a global database of lakes, reservoirs and wetlands. *Journal of Hydrology*, *296*(1), 1–22.

Lutz, W. (2013). *The future population of the world: What can we assume today*. London, UK: Routledge.

Manning, P., Taylor, G., & Hanley, M. E. (2015). Bioenergy, food production and biodiversity – an unlikely alliance? *GCB Bioenergy*, *7*(4), 570–576. https://doi.org/10.1111/gcbb.12173

Mekonnen, M. M., & Hoekstra, A. Y. (2016). Four billion people facing severe water scarcity. *Science Advances*, *2*(2), e1500323.

Mittermeier, R. A., Mittermeier, C. G., Brooks, T. M., Pilgrim, J. D., Konstant, W. R., da Fonseca, G. A. B., & Kormos, C. (2003).

Wilderness and biodiversity conservation. *Proceedings of the National Academy of Sciences of the United States of America*, *100*(18), 10309–10313.

Müller, C., Elliott, J., Chryssanthacopoulos, J., Deryng, D., Folberth, C., Pugh, T. A. M., & Schmid, E. (2015). Implications of climate mitigation for future agricultural production. *Environmental Research Letters*, *10*(12), 125004.

Myers, N., Mittermeier, R. A., Mittermeier, C. G., da Fonseca, G. A., & Kent, J. (2000). Biodiversity hotspots for conservation priorities. *Nature*, *403*(6772), 853–858.

Naidoo, R., Balmford, A., Costanza, R., Fisher, B., Green, R. E., Lehner, B., … Ricketts, T. H. (2008). Global mapping of ecosystem services and conservation priorities. *Proceedings of the National Academy of Sciences*, *105*(28), 9495–9500.

Neumann, K., Verburg, P. H., Stehfest, E., & Müller, C. (2010). The yield gap of global grain production: A spatial analysis. *Agricultural Systems*, *103*(5), 316–326.

Offermann, R., Seidenberger, T., Thrän, D., Kaltschmitt, M., Zinoviev, S., & Miertus, S. (2011). Assessment of global bioenergy potentials. *Mitigation and Adaptation Strategies for Global Change*, *16*(1), 103–115.

Oki, T., & Kanae, S. (2006). Global hydrological cycles and world water resources. *Science*, *313*(5790), 1068–1072.

Oldeman, L. R., Hakkeling, R. T. A., Sombroek, W. G., & Batjes, N. H. (1991). *Global Assessment of Human-induced Soil Degradation (GLASOD)*. Technical report. Wageningen, The Netherlands: International Soil Reference and Information Centre.

Olson, D. M., & Dinerstein, E. (2002). The Global 200: Priority ecoregions for global conservation. *Annals of the Missouri Botanical Garden*, *89*, 199–224.

Portmann, F., Siebert, S., & Döll, P. (2010). MIRCA2000–global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modeling. *Global Biogeochemical Cycles*, *24*(1).

Priefer, C., Jörissen, J., & Frör, O. (2017). Pathways to Shape Bioeconomy. *Resources*, *6*, 1–23.

Ragauskas, A. J., Williams, C. K., Davison, B. H., Britovsek, G., Cairney, J., Eckert, C. A., … Tschaplinski, T. (2006). The path forward for biofuels and biomaterials. *Science*, *311*(5760), 484–489.

Ray, D. K., Mueller, N. D., West, P. C., & Foley, J. A. (2013). Yield trends are insufficient to double global crop production by 2050. *PloS One*, *8*(6), e66428.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin III, F. S., Lambin, E., … Foley, J. (2009). Planetary Boundaries: Exploring the Safe Operating Space for Humanity. *Ecology and Society*, *14*(2).

Rodrigues, A. S., Akcakaya, H. R., Andelman, S. J., Bakarr, M. I., Boitani, L., Brooks, T. M., … Gaston, K. J. (2004). Global gap analysis: Priority regions for expanding the global protected-area network. *AIBS Bulletin*, *54*(12), 1092–1100.

Rogelj, J., Luderer, G., Pietzcker, R. C., Kriegler, E., Schaeffer, M., Krey, V., & Riahi, K. (2015). Energy system transformations for limiting end-of-century warming to below 1.5 c. *NatureClimate Change*, *5*(6), 519.

Rost, S., Gerten, D., Bondeau, A., Lucht, W., Rohwer, J., & Schaphoff, S. (2008). Agricultural green and blue water consumption and its influence on the global water system. *Water Resources Research*, *44*(9), 1–17.

Rudolf, B., Becker, A., Schneider, U., Meyer-Christoffer, A., & Ziese, M. (2011). New GPCC full data reanalysis version 5 provides high-quality gridded monthly precipitation data. *Gewex News*, *21*(2), 4–5.

Sanderson, E. W. (2002). The human footprint and the last of the wild. *BioScience*, *14*(10), 1614.

Schaphoff, S., Forkel, M., Müller, C., Knauer, J., von Bloh, W., Gerten, D., … Waha, K. (2017). LPJmL4 - a dynamic global vegetation model with managed land: Part II – Model evaluation. *Geoscientific Model Development Discussions*, *2017*, 1–41.

Schewe, J., Heinke, J., Gerten, D., Haddeland, I., Arnell, N. W., Clark, D. B., … Kabat, P. (2014). Multimodel assessment of water scarcity under climate change. *Proceedings of the National Academy of Sciences*, *111*(9), 3245–3250.

Schmitz, C., van Meijl, H., Kyle, P., Nelson, G. C., Fujimori, S., Gurgel, A., … Popp, A. (2014). Land-use change trajectories up to 2050: Insights from a global agro-economic model comparison. *Agricultural Economics*, *45*(1), 69–84.

Shiklomanov, I. A. and Rodda, J. C. (2004). *World water resources at the beginning of the twenty-first century*. Cambridge, UK: Cambridge University Press. 00529 Google-Books-ID: 9PYGN-S3yF5gC.

Sitch, S., Smith, B., Prentice, I. C., Arneth, A., Bondeau, A., Cramer, W., … Venevsky, S. (2003). Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. *Global Change Biology*, *9*(2), 161–185.

Slade, R., Bauen, A., & Gross, R. (2014). Global bioenergy resources. *Nature Climate Change*, *4*(2), 99–105.

Smith, P., Davis, S. J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., … Kriegler, E. (2016). Biophysical and economic limits to negative CO_2 emissions. *Nature Climate Change*, *6*(1), 42–50.

Somerville, C., & Youngs, H. (2014). How big is the bioenergy piece of the energy pie? Who cares—it's pie!. *Biotechnology and Bioengineering*, *111*(9), 1717–1718. https://doi.org/10.1002/bit.25312

Souza, G. M., Victoria, R. L., Joly, C. A., & Verdade, L. M. (2015). *Bioenergy & sustainability: Bridging the gaps*, Vol. 72. Sao Paulo, Brazil: SCOPE.

Stattersfield, A. J., Crosby, M. J., Long, A. J., & Wege, D. C. (1998). *Endemic bird areas of the world: Priorities for biodiversity conservation*. Cambridge, UK: Birdlife International.

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., … Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science*, *347*(6223), 1259855.

Tanner, C. B. and Sinclair, T. R. (1983). Efficient water use in crop production: research or re-search? In H. M. Taylor, W. R. Jordan, and T. Sinclair (Eds.) *Limitations to efficient water use in crop production*, (pp. 1–27). ASA, CSSA, and SSSA.

Turner, P. A., Field, C. B., Lobell, D. B., Sanchez, D. L., & Mach, K. J. (2018). Unprecedented rates of land-use transformation in modelled climate change mitigation pathways. *Nature Sustainability*, *1*(5), 240–245.

Verburg, P. H., Eickhout, B., & van Meijl, H. (2008). A multi-scale, multi-model approach for analyzing the future dynamics of European land use. *The Annals of Regional Science*, *42*(1), 57–77.

Verdade, L. M., Piña, C. I., & Rosalino, L. M. (2015). Biofuels and biodiversity: Challenges and opportunities. *Environmental Development*, *15*, 64–78.

Vorosmarty, C. J., Green, P., Salisbury, J., & Lammers, R. B. (2000). Global water resources: Vulnerability from climate change and population growth. *Science*, *289*(5477), 284–288.

Wallace, J. (2000). Increasing agricultural water use efficiency to meet future food production. *Agriculture, Ecosystems & Environment*, *82*(1–3), 105–119.

Wirsenius, S., Azar, C., & Berndes, G. (2010). How much land is needed for global food production under scenarios of dietary changes and livestock productivity increases in 2030? *Agricultural Systems*, *103*(9), 621–638. https://doi.org/10.1016/j.agsy.2010.07.005

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.