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Trade-offs between land and water requirements for large-scale bioenergy production

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Abstract

Bioenergy is expected to play an important role in the future energy mix as it can substitute fossil fuels and contribute to climate change mitigation. However, large-scale bioenergy cultivation may put substantial pressure on land and water resources. While irrigated bioenergy production can reduce the pressure on land due to higher yields, associated irrigation water requirements may lead to degradation of freshwater ecosystems and to conflicts with other potential users. In this article, we investigate the trade-offs between land and water requirements of large-scale bioenergy production. To this end, we adopt an exogenous demand trajectory for bioenergy from dedicated energy crops, targeted at limiting greenhouse gas emissions in the energy sector to 1100 Gt carbon dioxide equivalent until 2095. We then use the spatially explicit global land- and water-use allocation model MAgPIE to project the implications of this bioenergy target for global land and water resources. We find that producing 300 EJ yr^{-1} of bioenergy in 2095 from dedicated bioenergy crops is likely to double agricultural water withdrawals if no explicit water protection policies are implemented. Since current human water withdrawals are dominated by agriculture and already lead to ecosystem degradation and biodiversity loss, such a doubling will pose a severe threat to freshwater ecosystems. If irrigated bioenergy production is prohibited to prevent negative impacts of bioenergy cultivation on water resources, bioenergy land requirements for meeting a 300 EJ yr^{-1} bioenergy target increase substantially (+ 41%) – mainly at the expense of pasture areas and tropical forests. Thus, avoiding negative environmental impacts of large-scale bioenergy production will require policies that balance associated water and land requirements.

Keywords: bioenergy, land, land-use model, projection, sustainability, water, water-land nexus

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Introduction

A recent model intercomparison study projects bioenergy deployment between 70 and 230 Exajoules (EJ) per year in 2100 for scenarios without climate policy, with bioenergy primarily used to produce liquid fuels for the transport sector (Rose *et al.*, 2014). With climate policies aiming at ambitious mitigation targets, bioenergy demand in 2100 is projected to reach 200–320 EJ yr^{-1} (Rose *et al.*, 2014) since bioenergy in combination with carbon capture and storage can remove carbon dioxide from the atmosphere (Azar *et al.*, 2006).

This bioenergy demand is in the same order of magnitude as the gross energy value of all harvested biomass in the year 2000 of around 300 EJ (Haberl *et al.*, 2007). Therefore, concerns about negative environmental and societal implications of large-scale bioenergy production are discussed. It is expected that bioenergy production may require up to 550 Mha of additional cropland (Popp *et al.*, 2014), corresponding to around 35% of current total cropland (FAO, 2013). Such substantial land requirements may have negative impacts on greenhouse gas emissions (Searchinger *et al.*, 2008; Popp *et al.*, 2011a, 2012), food prices (Lotze-Campen *et al.*, 2014) and biodiversity (Smith *et al.*, 2013).

Land requirements for bioenergy production are highly dependent on the achievable yield. Cultivation of dedicated bioenergy crops is very water intensive (Berndes, 2002; Gerbens-Leenes *et al.*, 2009), so water limitations are a key constraint for achievable bioenergy yields in rainfed production systems. Reducing the water deficit by applying additional irrigation water plays a crucial role in achieving high yields (Smith *et al.*,

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2012). Beringer *et al.* (2011) estimate that irrigation has the potential to increase bioenergy yields by more than 100% compared to rainfed production systems in large parts of India, Africa, Latin America, North America, and Australia. Irrigation may therefore be an option to reduce the pressure of bioenergy production on land resources.

Additional irrigation water requirements can however fundamentally change the global water cycle and put additional pressure on water resources. Potential water requirements of large-scale irrigated bioenergy production may be in the same order of magnitude as current total agricultural water withdrawals (Berndes, 2002; Beringer *et al.*, 2011) or even up to twice as high (Chaturvedi *et al.*, 2013). This is critical as many regions already face water scarcity (Falkenmark & Molden, 2008; Arnell *et al.*, 2011) and freshwater ecosystems are degraded by human activity (Poff & Zimmerman, 2010; Grafton *et al.*, 2012). We may thus face a fundamental trade-off between global land and water requirements for bioenergy production. A quantitative assessment of this trade-off is however lacking to date.

We investigate the land- and water-use implications of bioenergy production under two different scenarios using the spatially explicit land- and water-use allocation model MAgPIE (Model of Agricultural Production and its Impacts on the Environment) (Lotze-Campen *et al.*, 2008; Popp *et al.*, 2010). In the first scenario, no restrictions on irrigated bioenergy production are imposed. The share and spatial allocation of irrigated bioenergy production is determined endogenously based on economic optimization. The second scenario includes a policy that prohibits irrigated bioenergy cultivation. This setup allows us to quantify the implications of water-saving bioenergy production strategies for global land-use dynamics and natural land ecosystems.

Materials and methods

MAgPIE model

General description. Model of Agricultural Production and its Impacts on the Environment is a spatially explicit, global land- and water-use allocation model and simulates land-use dynamics in 10-year time steps until 2095 using recursive dynamic optimization (Lotze-Campen *et al.*, 2008; Popp *et al.*, 2010). The objective function of MAgPIE is the fulfilment of food, feed and material demand at minimum costs under socio-economic and biophysical constraints. Demand trajectories are based on exogenous future population and income projections (see Section Scenarios). Major cost types in MAgPIE are: factor requirement costs (capital, labour and chemicals, e.g., fertilizer), land conversion costs, transportation costs to the closest market and investment costs for technological change. Socio-economic constraints like demand, factor requirement costs and investment costs are defined at the regional level (10 world regions) (Figure S1). Biophysical constraints such as crop yields, carbon density, and water availability – derived from the global hydrology and vegetation model LPJmL (Bondeau *et al.*, 2007; Rost *et al.*, 2008; Müller & Robertson, 2014) – as well as land availability (Krause *et al.*, 2013), are introduced at the grid cell level (0.5 degree longitude/latitude; 59 199 grid cells). Due to computational constraints, all model inputs at 0.5 degree resolution are aggregated to 1000 simulation units for the optimization process based on a k-means clustering algorithm (Dietrich *et al.*, 2013). The clustering algorithm combines grid cells to simulation units based on the similarity of biophysical conditions.

MAgPIE features land-use competition based on cost-effectiveness at simulation unit level among the land-use related activities crop, livestock, and bioenergy production. Available land types are cropland, pasture, forest, other land (including nonforest natural vegetation, abandoned agricultural land and desert) and settlements. Cropland (rainfed and irrigated), pasture, forest, and other land are endogenously determined, while settlement areas are assumed to be constant over time. The forestry sector, in contrast to the crop and livestock sectors, is currently not implemented dynamically in MAgPIE. Therefore, timberland needed for wood production – consisting of forest plantations and modified natural forest – is excluded from the optimization (about 30% of the initial global forest area of 4235 Mha). In addition, other parts of forestland, mainly undisturbed natural forest, are within protected forest areas, which cover about 12.5% of the initial global forest area (FAO, 2010). Altogether, about 86% of the world's land surface is freely available in the optimization of the initial time-step.

Crop yields depend not only on biophysical conditions but also on management practices that differ across world regions and can change over time (Dietrich *et al.*, 2012). Therefore, biophysical yield potentials from LPJmL are calibrated to FAO yields (FAO, 2013) in 1995 before they enter MAgPIE. Regional land-use intensities that reflect the status of agricultural management in 1995 are derived from historical data (Dietrich *et al.*, 2012). MAgPIE can endogenously decide to invest into technological change (TC) on a regional level in order to increase land-use intensities, thereby increasing agricultural yields (Dietrich *et al.*, 2014). The ratio of TC investments to yield improvements (investment-yield ratio) is determined from historical data on agricultural Research and Development spending (Pardey *et al.*, 2006), agricultural infrastructure investments (Narayanan & Walmsley, 2008), and yields (FAO, 2013). The investment-yield ratio increases with the land-use intensity (Dietrich *et al.*, 2014), reflecting the fact that low land-use intensities can be improved by closing yield gaps while yield increases in intensive systems require higher investments to push the technology frontier.

The cost minimization problem is solved through endogenous variation in spatial rainfed and irrigated production patterns (subject to regional trade constraints; Schmitz *et al.*, 2012), land conversion (all at simulation unit level) and technological change (at regional level) (Lotze-Campen *et al.*, 2010).

Bioenergy. Present day modern bioenergy for electricity and liquid fuel generation relies mainly on conventional food crops such as maize and sugarcane (first generation bioenergy) (Gerbens-Leenes *et al.*, 2009). To avoid competition with food production, techniques are being developed to convert the lignocellulosic components of plant biomass to biofuels (Schmer *et al.*, 2008; Gerbens-Leenes *et al.*, 2009). This will allow the use of dedicated grassy and woody bioenergy crops (second generation bioenergy) and is expected to increase the energy yield per unit of crop significantly (Gerbens-Leenes *et al.*, 2009).

In MAgPIE, bioenergy feedstock consists of dedicated herbaceous and woody lignocellulosic bioenergy crops. Bioenergy demand enters the model as an exogenous trajectory at the global level (see Section Scenarios). Spatial allocation of bioenergy production is an endogenous model decision resulting from the cost minimizing objective function, which takes into account land and water availability as well as bioenergy yields, production costs, and competing demand for food and material.

In MAgPIE, bioenergy crops can be grown in rainfed and irrigated production systems. Rainfed and irrigated bioenergy yields at simulation unit level for the initialization of MAgPIE are derived from LPJmL (Beringer *et al.*, 2011). While LPJmL simulations supply data on potential yields, i.e., yields achievable under the best currently available management options, MAgPIE aims at representing actual yields, i.e., yields realizable under actual current management that differs regionally. Therefore, LPJmL bioenergy yields are calibrated on regional level based on FAO yield data (FAO, 2013) and the ratio of regional land-use intensities to the European intensity. This is done because LPJmL potential bioenergy yields are consistent with observations from well-managed test sites in Europe and the United States (Beringer *et al.*, 2011) and management intensities in other world regions are generally lower (Dietrich *et al.*, 2012). Low calibration factors for Sub-Saharan Africa (0.28) and Latin America (0.38) reflect large yield gaps with respect to best management practices (Table S1).

Highest rainfed herbaceous bioenergy yields occur in the South-Eastern US, China, Pacific Asia and Latin America (Figure S2, Table S1). Irrigation renders regions attractive for bioenergy production, where rainfed yields are strongly water limited (Beringer *et al.*, 2011): India, Northern Africa, Southern US and Australia. Within MAgPIE, endogenous investments into yield increasing technological change (see General description) affect all crops equally, including bioenergy crops.

Water and irrigation

In MAgPIE, available water at simulation unit level for domestic, industrial, and agricultural use comprises renewable blue water resources only, i.e., precipitation that enters rivers, lakes, and aquifers (Rost *et al.*, 2008). Input data for available water is obtained from LPJmL (details in the Supplementary Online Material). We assume that all renewable freshwater is available for human use, i.e., no water is reserved for environmental purposes. Domestic and industrial water demand enters the model as an exogenous scenario (Figure S3) based on WaterGAP simulations (Alcamo *et al.*, 2003; Flörke *et al.*, 2013). We assume that domestic and industrial water demand is fulfilled first, effectively limiting water availability for agricultural use (similar to Elliott *et al.*, 2013). Within these limits of available water, agricultural water demand for irrigated food, feed, and bioenergy production as well as livestock feeding is determined endogenously based on cost-effectiveness. Spatially explicit per hectare irrigation water requirements for the 16 food crops and two bioenergy crops represented in MAgPIE are obtained from LPJmL (see Supplementary Online Material), while livestock water requirements are based on FAO data (FAOSTAT, 2005). Rainfed crop production relies on green water resources only, i.e., precipitation infiltrated into the soil, and does therefore not affect agricultural irrigation water demand.

Irrigated crop production is not only constrained by water availability but also requires irrigation infrastructure for water distribution and application. The initial pattern of area equipped for irrigation is taken from the AQUASTAT database (Siebert *et al.*, 2006). During the optimization process, the model can endogenously deploy additional irrigation infrastructure (see Supplementary Online Material). Irrigation costs comprise investment costs for the deployment of additional irrigation infrastructure as well as annual costs for operation and maintenance of irrigation systems (see Supplementary Online Material). Yield increases through technological change enhance land as well as irrigation water productivity (see Section Scenarios).

Scenarios

Food, livestock, and material demand (Figure S4) is calculated using the methodology described in Bodirsky *et al.* (under review, 2012), as well as SSP 2 population and GDP projections (IIASA, 2013). SSP2 population and GDP projections belong to a 'Middle of the Road' scenario from the Shared Socio-economic Pathways (SSP) scenario family (O'Neill *et al.*, 2013) that is being developed as the successor of the widely used Special Report on Emissions (SRES) scenarios from the Intergovernmental Panel on Climate Change (IPCC) (Intergovernmental Panel on Climate Change, 2000) for use in climate change research.

Global primary bioenergy demand is obtained from Popp *et al.* (2011b), a study with a coupled version of MAgPIE and the global energy-economy-climate model REMIND (Leimbach *et al.*, 2010). Within this modelling framework, primary bioenergy from dedicated bioenergy crops is used for electricity production via BioCHP (biomass combined heat and power; conversion efficiency 43%) and BIGCC (biomass integrated coal gasification combined cycle; conversion efficiency 31–42%), and liquid fuel production (conversion efficiency 40%). Bioenergy demand is calculated under climate policies that limit greenhouse gas emissions in the energy sector to 1100Gt CO2 equivalent up to 2095 and accounts for 25% of total primary energy in 2095 (Popp *et al.*, 2011b). Other renewables (wind, solar, hydropower) also contribute 25% to global primary energy. Demand for primary bioenergy from dedicated bioenergy crops starts at 7 EJ yr^{-1} in 2015, strongly increases in mid-century and reaches a level of ~ 300 EJ yr^{-1} in 2095 (Table 1).

Table 1 Trajectory of global dedicated primary bioenergy demand (EJ yr^{-1}) from Popp *et al.* (2011b)

	2015	2025	2035	2045	2055	2065	2075	2085	2095
EJ yr^{-1}	7	6	12	38	109	225	301	310	307

We investigate two bioenergy production scenarios (Table 2). In BE, dedicated bioenergy cultivation is unrestricted, i.e., the model can endogenously decide to use rainfed and irrigated production systems for bioenergy crops. BE_RF represents a water protection policy, where only rainfed bioenergy cultivation is allowed. Since the focus of this analysis is on resource requirements of bioenergy production and not on climate change mitigation targets, we assume that no climate change policy (e.g., emission pricing) is implemented in the land-use sector. In our standard model implementation, yield increasing technological change increases both, land productivity (output per hectare – tons ha^{-1}) and irrigation water productivity (output per m^3 of irrigation water – tons m^{-3}). For this setup, we assume that per hectare irrigation water requirements (m^3 ha^{-1}) are constant. Thus, technological change enhances irrigation water productivity (tons m^{-3}) by increasing the yield (tons ha^{-1}). To test the stability of our results, we perform a sensitivity analysis with static irrigation water productivity (static WP). For this setup, we assume that the irrigation water demand per ton output (m^3 ton^{-1}) is constant so that yield increases from technological change increase per hectare irrigation water demand (m^3 ha^{-1}). In our standard model, we assume that bioenergy crops can profit from technological change in the same way as food crops. Krausmann *et al.* (2013) however estimate that almost half of the past yield increases were due to increasing the share of harvested biomass to total plant biomass. This is more difficult to achieve for second generation bioenergy crops since all aboveground biomass can be used for energy production. We therefore conduct a sensitivity analysis where we assume that the effect of yield increases from technological change on second generation bioenergy crops is reduced by 50% compared to conventional crops (low Yields).

Results

Bioenergy production

Irrigation plays a key role for bioenergy provision in the BE scenario (Fig. 1). In 2095, 58% of global bioenergy supply stems from irrigated production. The region with the highest share of irrigated bioenergy production is South Asia with an irrigation share of 95% in 2095. Further regions with high irrigation shares are North America (71% in 2095), Sub-Saharan Africa (73%) and Latin America (50%). These high irrigation shares are driven by large differences between irrigated and rainfed yields (Figure S2). China is the only region, where bioenergy is mostly produced in rainfed systems (90% in 2095). Spatial allocation of bioenergy production (Fig. 2) to different world regions is mainly driven by spatial differences in bioenergy yields and varies between the scenarios. In the BE scenario, Latin America is the dominant production region contributing 160 EJ yr^{-1} in 2095. Further important bioenergy production regions are South Asia (40 EJ yr^{-1} in 2095), North America (35 EJ yr^{-1}), Sub-Saharan Africa (30 EJ yr^{-1}), and China (CPA, 30 EJ yr^{-1}). The remaining five regions do not contribute significantly to global bioenergy production (together 8 EJ yr^{-1} in 2095).

In the BE_RF scenario, irrigation of bioenergy areas is prohibited and consequently all bioenergy feedstock is provided from rainfed agriculture. Bioenergy production in Latin America and North America is similar to the BE scenario (160 EJ yr^{-1} and 30 EJ yr^{-1} in 2095 respectively). In South Asia on the contrary, rainfed bioenergy production is not competitive due to low yields (Figure S2) and no bioenergy is produced in the BE_RF scenario. This necessitates additional bioenergy production in other regions compared to BE. Bioenergy production increases significantly in Africa with an additional 35 EJ yr^{-1} in 2095 compared to BE. In China, bioenergy production increases by 5 EJ yr^{-1} and the remaining five regions provide an additional 3 EJ yr^{-1} in 2095. Even though bioenergy yields are high in Pacific Asia (Table S1), no bioenergy is produced there because forest requirements for wood production and

Table 2 Scenario definitions. In the standard model, yield increases affect land and irrigation water productivity. In the sensitivity runs, irrigation water productivity is static (static WP) and bioenergy crop yield increases are reduced to 50% compared to conventional crops (low Yields). Bioenergy cultivation is unrestricted in BE but limited to rainfed production systems in BE_RF

	MAgPIE model	Productivity increases	Bioenergy cultivation
BE	Standard model	Land and water	Rainfed and irrigated
BE_RF			Rainfed only
BE_staticWP	Static WP	Land only	Rainfed and irrigated
BE_RF_staticWP			Rainfed-only
BE_lowYields	Low Yields	Land and water; 50% penalty on bioenergy crops	Rainfed and irrigated
BE_RF_lowYields			Rainfed-only

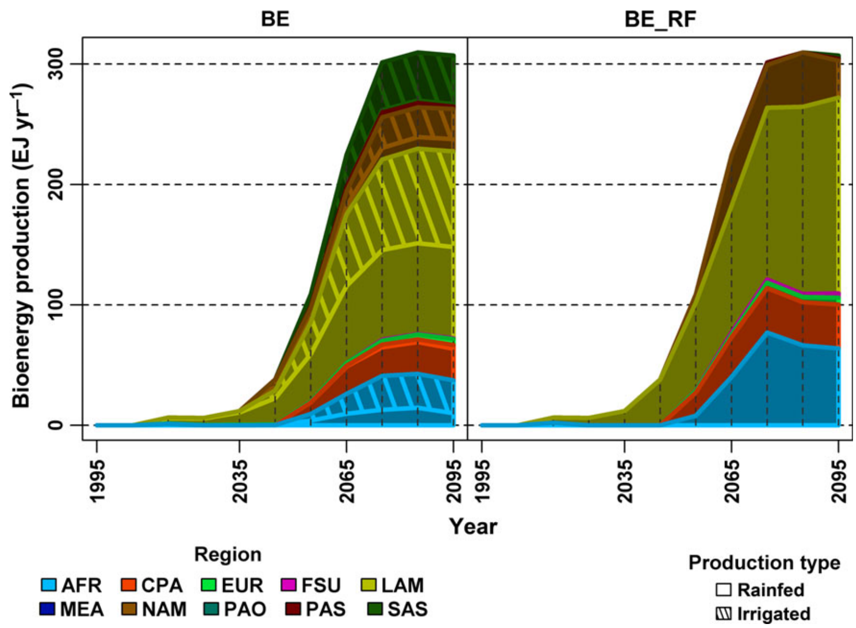

Fig. 1 Regional rainfed and irrigated bioenergy production for BE and BE_RF. AFR = Sub-Saharan Africa, CPA = centrally planned Asia including China, EUR = Europe, FSU = former Soviet Union, LAM = Latin America, MEA = Middle East and North Africa, NAM = North America, PAO = Pacific OECD, PAS = Pacific Asia, SAS = South Asia.

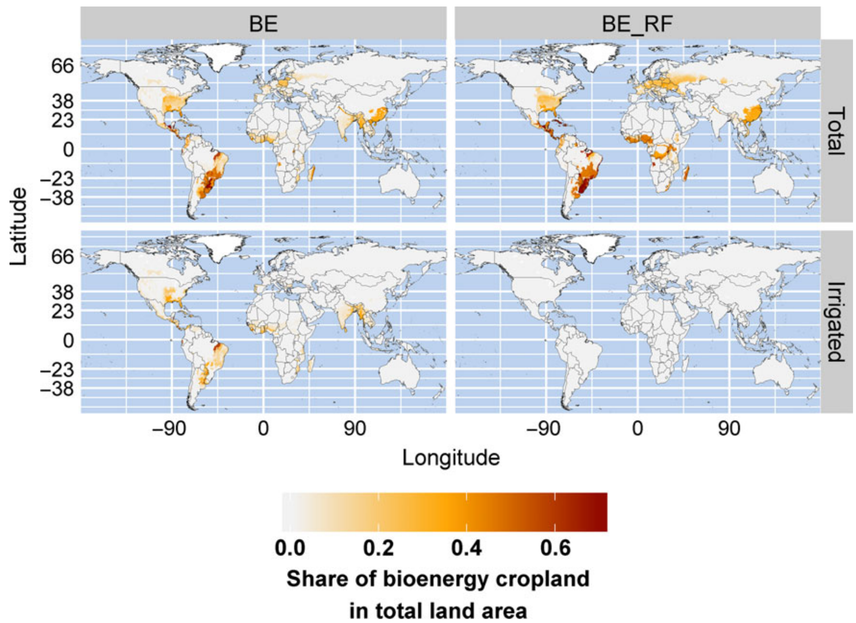

Fig. 2 Spatial allocation of bioenergy cropland for BE (left) and BE_RF (right). Colours indicate the share of bioenergy cropland in total land area. Top row: total bioenergy cropland. Bottom row: irrigated bioenergy cropland.

nature conservation limit land availability (see Section MAgPIE model).

Agricultural water withdrawals

Global agricultural water withdrawals (AWW) for the BE and BE_RF scenarios develop similarly until 2035 (Fig. 3) since almost no bioenergy is produced. Total AWW (energy crops + non-energy commodities) in 1995 are 2926 km^3 and increase to approximately 3250 km^3 in 2035 due to increasing food demand (Figure S4). The development of AWW in our projections in the near future is consistent with the historical trend (Shiklomanov, 2000), but in 1995 our estimate of AWW is around 400 km^3 higher than the one by Shiklomanov. Our initial value is however consistent with historical data around the year 2000 given the uncertainty range from different irrigated area patterns and climate datasets (2200–3800 km^3), (Wisser *et al.*, 2008).

Due to additional water withdrawals for bioenergy crops, the BE scenario exhibits a steep increase in total AWW after 2035, reaching 6400 km^3 in 2075 and levelling off afterwards. Water withdrawals for irrigated food and material crop production and livestock production (nonenergy commodities) in the BE scenario increase moderately until the mid of the century (3250 km^3 in 2055) due to increasing demand for nonenergy commodities. In the second half of the century, the strong increase in bioenergy demand (Figure S4) leads to increased competition for water. Furthermore, demand for nonenergy commodities stagnates while ongoing yield increases from technological change (Fig. 7) continue to increase irrigation water productivity (see section Scenarios). Irrigation water withdrawals for nonenergy commodities therefore decrease slightly in the second half of the century and amount to 3050 km^3 (48% of total withdrawals) in 2095.

Agricultural water withdrawals in the BE_RF scenario in contrast are solely driven by food and material production and increase more slowly until 2055 (3460 km^3). In BE_RF, bioenergy does not compete with other crops

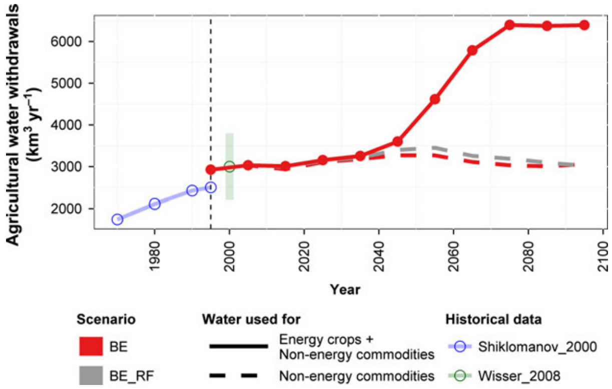

Fig. 3 Global agricultural water withdrawals for BE (rainfed and irrigated bioenergy production allowed) and BE_RF (only rainfed bioenergy production allowed). Total water withdrawals (energy crops + non-energy commodities) appear as a solid line for BE. Dashed lines depict water withdrawals for nonenergy commodities (irrigated food crops, livestock production, and irrigated material crops) only. In BE_RF, water withdrawals for nonenergy commodities equal total agricultural water withdrawals. Historical data from Shiklomanov (2000) and Wisser *et al.* (2008) is displayed for comparison. Wisser *et al.* provide an uncertainty range that is depicted as a shaded area. The vertical dashed line marks the start of the simulation period.

for water, but rainfed bioenergy production can replace irrigated non-energy crops. Therefore, the development of AWW in the second half of the century in BE_RF is similar to water withdrawals for nonbioenergy commodities in BE. The BE_RF scenario requires 53% less irrigation water in 2095 than the BE scenario.

Regional water withdrawals for bioenergy crops in the BE scenario are highest in Latin America, Africa, South Asia, and North America (Fig. 4). AWW for nonenergy commodities in Latin America, Africa, and North America are similar or even higher in BE than in BE_RF indicating that additional water resources are tapped for bioenergy production. In South Asia, bioenergy crops compete directly for water with nonenergy crops indicated by the reduction in AWW for nonenergy commodities in BE compared to BE_RF. This competition for water in South Asia leads to a slight decrease in global AWW for nonenergy commodities in BE compared to BE_RF (Fig. 3).

Land-use change

By the end of the century, bioenergy production will require substantial amounts of land (Fig. 5). In the BE scenario, dedicated bioenergy cropland reaches 490 Mha in 2095. Prohibiting irrigated bioenergy production increases this value by 200 Mha or 41% in the BE_RF scenario. Additional pressure from increasing food demand (Figure S4) drives expansion of cropland for food, feed, and material production (nonenergy cropland) that amounts to 200 Mha (BE) and 180 Mha (BE_RF) until 2095. Increasing bioenergy and nonenergy cropland requirements are fulfilled at the expense of natural forests and pasture. In the BE scenario, global forest and pasture areas decrease by 420 and 470 Mha respectively until 2095. Other land increases by 70 Mha until 2095 due to abandonment of agricultural land. Intensification in the livestock sector leads to reduced demand for animal feedstock from pasture and a reduction in pasture area. Since not all abandoned pasture area is suitable for cropping activities, this process is the main driver for the abandonment of agricultural land. Between 2075 and 2095, bioenergy demand and demand for nonenergy commodities stagnates (Figure S4) while continued technological improvements continue to increase agricultural yields (Fig. 7). Therefore, reductions in bioenergy cropland and nonenergy cropland further contribute to the increase in other land during this period.

The general pattern in the BE_RF scenario is similar to the BE scenario. Additional forest losses are 160 Mha and pasture decreases by an additional 140 Mha until 2095 (Fig. 5). On a regional level, additional forest losses in BE_RF compared to BE are highest in Africa (70 Mha in 2095), Latin America (50 Mha) and North America

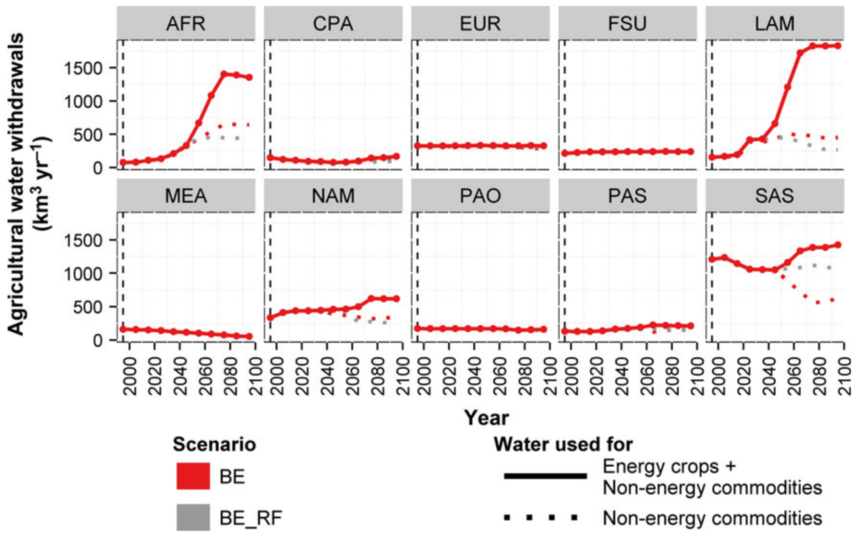

Fig. 4 Regional agricultural water withdrawals for BE and BE_RF. Total water withdrawals (Energy crops + non-energy commodities) appear as a solid line for BE. Dashed lines depict water withdrawals for nonenergy commodities (irrigated food crops, livestock production, and irrigated material crops) only. For BE_RF, irrigation of bioenergy crops is prohibited so that water withdrawals for nonenergy commodities equal total water agricultural withdrawals. The vertical dashed line marks the start of the simulation period.

(40 Mha) (Figure S5). In BE_RF, more land is abandoned between 2075 and 2095 than in BE due to stronger agricultural intensification at the end of the century.

Carbon dioxide emissions from land-use change (Figure S6) in BE_RF amount to 455 Gt CO2 between 1995 and 2095. Compared to emissions in BE of 316 Gt CO2 over the century, they are 44% higher because of increased agricultural land requirements and associated land-use change.

To test our results, we compare regional MAgPIE projections for cropland and pasture with FAO data (FAO, 2013) (Figures S7, S8). Deviations of regional MAgPIE cropland in 1995 from FAO data stay below 12% and deviations in regional pasture area are below 20%. The near term trend in the MAgPIE projections is in general similar to historical trends. The only exception is in the Middle-East and North Africa, where MAgPIE cropland and pasture are lower than FAO data by ~30%. The reason for this behavior is that MAgPIE prefers a more intensive production pathway in the Middle-East than observed in reality. Thus, early investments into technological change increase yields above real world levels and lead to reduced land requirements.

Bioenergy prices

Bioenergy supply prices as calculated by MAgPIE reflect the marginal costs of producing one additional unit of bioenergy given the current bioenergy demand.

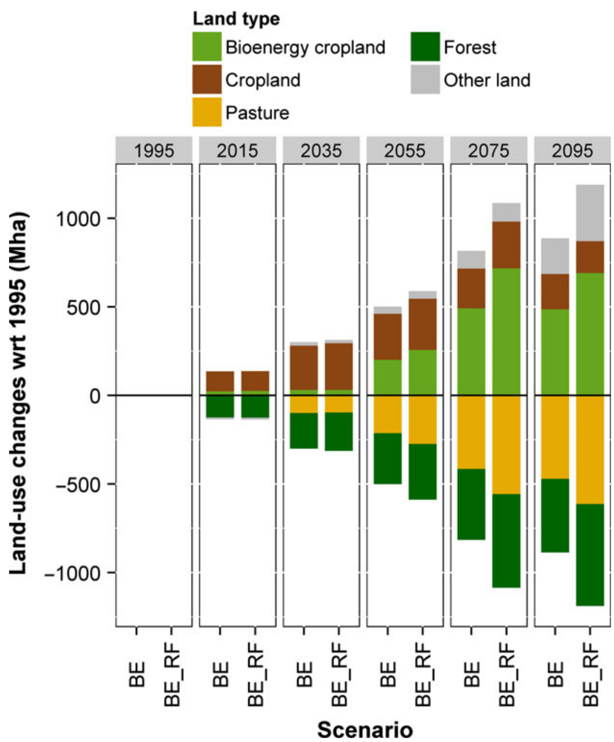

Fig. 5 Global land-use change over the century with respect to 1995 for BE and BE_RF for the land types represented in MAgPIE. Total cropland is split into bioenergy cropland and cropland for food, feed and material production (Cropland). Positive values indicate an increase, negative values a decrease in the corresponding land pool.

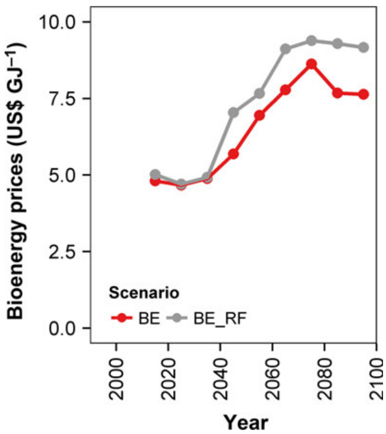

Fig. 6 Bioenergy prices for BE and BE_RF. Prior to 2015, no prices can be calculated since no bioenergy is produced.

In the BE scenario, supply prices for primary energy from dedicated bioenergy crops increase from ~5 US$/GJ in 2015 to 8.6 US$/GJ in 2075 due to increasing bioenergy demand (Fig. 6). Afterwards, bioenergy supply prices slightly decline due to demand stagnation and reach 7.6 US$/GJ in 2095 for a production of ~300 EJ yr^{-1} of bioenergy. In BE_RF, bioenergy supply prices follow a similar trajectory and are always higher than in BE. In 2095 BE_RF exhibits a bioenergy price of 9.2 US $/GJ, around 20% higher than in BE.

Yield growth due to technological change

Yield growth for agricultural crops followed a linear trend in the past (Hafner, 2003; Fischer & Edmeades, 2010). The calculation of average annual growth rates would thus be misleading since it would suggest exponential growth. We therefore report yield growth due to technological change by calculating a global yield index (1995 = 100) (Fig. 7). Investments into yield increasing agricultural research and development are an endogenous model decision on regional level. Until 2075, increasing demand for agricultural products (Figure S4) leads to an approximately linear increase in global yield levels by ~12 points per decade. Afterwards, the yield trajectory flattens out, especially for BE, because demand stagnates and there is no further incentive for the model to invest into technological change. Regional yield increases (Table 3) are highest in the Middle East, Africa, Latin America, and South Asia. Initial land-use intensities in these regions are low and yield improvements can be achieved by closing yield gaps at low costs. In Europe and North America in contrast, initial land-use intensities are high. Further yield increases therefore require pushing the technology frontier, are expensive, and therefore less attractive. Historical data from Dietrich *et al.* (2012) shows global yield increases due to technological change by ~14 points per decade after 1960. Fischer & Edmeades (2010) find that yields for the important food crops maize, rice and wheat increased at about 8 to 16 points per decade between 1988 and 2007. Historical corn yield levels in the United States increased at ~14 points per decade between 1960 and present (Egli, 2008). Thus, our productivity pathway is compatible with historical data at the global scale. It is however unclear, whether historical yield trends can be maintained after current yield gaps have been closed (Cassman, 1999). In our projections, bioenergy yields stay within the yield potential achievable under current best management as simulated by LPJmL for most regions (Figure S9, left). In Latin America however, MAgPIE bioenergy yields at the end of the century exceed LPJmL potential yields by 12%.

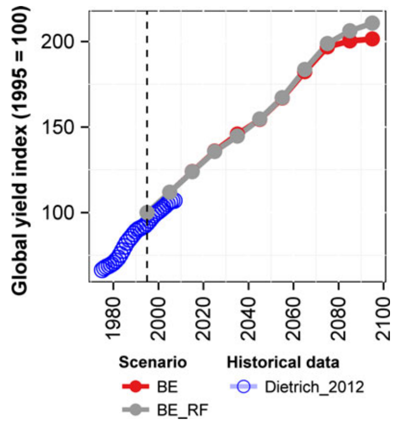

Fig. 7 Global yield index (1995 = 100) for BE and BE_RF. Changes reflect yield increases due to technological change on regional level. The global average is calculated using crop area as a weight. Historical data from Dietrich *et al.* (2012) are displayed for comparison. The vertical dashed line marks the start of the simulation period.

Sensitivity analysis

In the standard implementation, yield gains from technological innovation increase land and irrigation water productivity simultaneously (see Section Scenarios). If technological change only increases land productivity and leaves irrigation water productivity unchanged (static WP), water withdrawals for BE and BE_RF are significantly higher than in the standard model (Table 4). The relative difference in AWW between BE and BE_RF in 2095 is however comparable for the standard model (110%) and the static WP model (100%).

Since water is less productive in static WP at the end of the century, less bioenergy area can be irrigated in the BE scenario for static WP. Therefore, static WP requires more total bioenergy area in the BE scenario than the standard model and forest losses until the end

Table 3 Regional yield index in 2095 for BE and BE_RF (1995 = 100). The global average is calculated using crop area as a weight

	WORLD	AFR	CPA	EUR	FSU	LAM	MEA	NAM	PAO	PAS	SAS
BE	201	317	167	110	109	267	409	146	113	150	239
BE_RF	211	331	167	110	108	295	409	152	111	148	219

Table 4 Results of the sensitivity analysis. The first row contains results for the standard model for the scenarios BE and BE_RF. The second row depicts results for a model version with no improvements in irrigation water productivity (static WP). The third row contains results for a model version where bioenergy crop yields increase at half the rate of conventional crops (low Yields). Per cent numbers indicate the difference between the sensitivity results and the corresponding standard model results

Model run	Agricultural water withdrawals 2095 (in $km^3\ yr^{-1}$)		Total bioenergy area in 2095 (in million ha)		Irrigated bioenergy area in 2095 (in million ha)		Forest lost between 1995 and 2095 (in million ha)	
Standard model								
BE	6393		486		228		416	
BE_RF	3031		689		0		576	
Static WP								
BE_staticWP	8879	+38%	568	+16%	142	–38%	516	+24%
BE_RF_staticWP	4456	+47%	683	−1%	0	+0%	560	−3%
Low Yields								
BE_lowYields	8306	+30%	740	+52%	350	+53%	556	+33%
BE_RF_lowYields	2446	−20%	1002	+45%	0	+0%	690	+20%

of the century are higher. Bioenergy area in the BE_RF scenario is not affected by different irrigation water productivity assumptions.

If yield increases from technological change are only half as efficient for bioenergy crops as for traditional crops (low Yields), bioenergy land requirements increase substantially and reach up to 1002 Mha for BE_RF. With lower yields, irrigation becomes even more attractive and AWW in BE increase by 30% compared to the standard model. In BE_RF, AWW are reduced because rainfed bioenergy cropland replaces irrigated food cropland. Bioenergy yields are lower in the low Yields model than in the standard model and stay within yield potentials as simulated by LPJmL (Figure S9, right).

To test the sensitivity of our results with respect to bioenergy demand, we conduct a sensitivity analysis where we reduce bioenergy demand in 15% steps from the original demand of 307 EJ yr^{-1} in 2095 (Figure S10). While for both scenarios, bioenergy area decreases with decreasing demand, bioenergy area in BE_RF is higher than in BE over the range of demand scenarios considered. For a demand reduction of 30%, BE_RF requires the same amount of bioenergy area as BE with the full demand of 307 EJ yr^{-1}.

Discussion

Several studies have highlighted that large-scale irrigated bioenergy production may require significant amounts of water and fundamentally alter the state of global freshwater resources (Berndes, 2002; Beringer *et al.*, 2011; Chaturvedi *et al.*, 2013). The present study investigates the trade-offs between water and land resources for producing ~300 EJ of bioenergy per year in 2095 from dedicated energy crops using a spatially explicit global land and water-use allocation model. We compare a scenario where irrigation water use for bioenergy production is allowed within the limits of available water (BE) to a rainfed-only bioenergy production scenario that aims at minimizing the impacts of bioenergy production on water resources (BE_RF). This experimental setup allows us to determine the water-use implications of large-scale bioenergy production as well as the land-use implications of water-saving bioenergy production strategies.

Implications of bioenergy production for water resources

Our results suggest that irrigation will play a key role in providing bioenergy feedstock if no policy restrictions are imposed. In contrast to comparable studies (Berndes, 2002; Chaturvedi *et al.*, 2013), the decision between rainfed and irrigated bioenergy production is treated here as an endogenous process. Thus, the large irrigated fraction in total bioenergy production (58%) in the BE scenario reflects comparative advantages, especially significant yield improvements through irrigation in important bioenergy production regions such as India, Latin America, North America, and Africa. This is in line with results by Beringer *et al.* (2011) who found that natural water limitations reduce bioenergy yields in large parts of these regions by up to 100% of the yield achievable without water limitations.

In this study, irrigation water requirements associated with the production of 300 EJ/yr of second generation bioenergy crops reach 3350 km^3 if no policy restrictions on irrigated bioenergy production are imposed. This number is comparable to current global agricultural water withdrawals (Shiklomanov, 2000; Wisser *et al.*, 2008) and is consistent with previous studies on bioenergy water withdrawals. Beringer *et al.* (2011) estimates irrigation water requirements of large-scale bioenergy production of 1500–3900 km^3. Chaturvedi *et al.* (2013) explore the water-use implications of several climate change mitigation scenarios. They project water withdrawals for bioenergy production between 670 and 5200 km^3 depending on the bioenergy deployment (<100–850 EJ yr^{-1}). Given the substantial associated water withdrawals, the question whether irrigated bioenergy production will impair freshwater ecosystems needs to be addressed. Experience from past and present human influence on water resources suggests that even current levels of human water withdrawals pose a major threat to aquatic ecosystems. It has been estimated that freshwater vertebrate populations have declined by 54% globally and that 32% of the world's amphibian species are threatened with extinction due to human interference (Dudgeon *et al.*, 2006). Hoekstra *et al.* (2012) have estimated that human water use exceeds the sustainably allowed level at least 1 month per year in 223 of 405 large river basins globally. A recent special issue has highlighted that direct human influence will pose the biggest threat to freshwater ecosystems in the coming decades (Vörösmarty *et al.*, 2013). Since agriculture contributes around 70% to current human water withdrawals (Rost *et al.*, 2008), these studies suggest that the projected doubling of agricultural water withdrawals due to large-scale bioenergy production will have substantial adverse impacts on freshwater ecosystems. Especially projected irrigated bioenergy production in South Asia (40 EJ yr^{-1}), a region facing severe water scarcity and overexploitation of groundwater resources (de Fraiture *et al.*, 2008; Biewald *et al.*, 2014) is worrisome in this context.

Implications of a water-saving bioenergy production strategy

Can ambitious bioenergy targets be reached without threatening global water resources? In our experimental setup, it is possible to produce 300 EJ yr^{-1} of bioenergy – an amount comparable to current total human appropriation of primary biomass production (Haberl *et al.*, 2007) – without tapping additional blue water resources for irrigation. There are, however, caveats associated with such a rainfed-only bioenergy production scenario.

Land requirements for producing ~300 EJ yr^{-1} of bioenergy increase significantly if irrigated bioenergy production is prohibited since rainfed bioenergy yields are lower than irrigated yields. In our simulations, an additional 200 Mha of bioenergy cropland will be required if irrigated bioenergy production is prohibited. This corresponds to the extent of current total cropland in the United States and Australia together (~210 Mha) (FAO, 2013). A recent model intercomparison exercise projects land requirements for the production of 150–250 EJ yr^{-1} of bioenergy feedstock with three integrated assessment models (Popp *et al.*, 2014; Rose *et al.*, 2014). The projected bioenergy cropland from this study is 450 to 550 Mha, comparable to our bioenergy cropland projections for producing 300 EJ yr^{-1} of 490 Mha (BE) to 690 Mha (BE_RF).

Prohibiting irrigated bioenergy production leads to an increase in bioenergy supply prices. In a market economy, such price increases would lead to a decreased demand for bioenergy and could reduce the additional land requirements in a rainfed-only bioenergy production scenario. The feedback of increased bioenergy prices on bioenergy demand depends crucially on the willingness-to-pay for bioenergy in the energy system. Rose *et al.* (2014) suggest that bioenergy is an economically attractive energy carrier, especially in combination with carbon capture and storage under climate change mitigation scenarios. Klein *et al.* (2014) find a high willingness-to-pay for bioenergy in case of stringent climate targets. Our sensitivity analysis demonstrates that bioenergy demand would need to decrease by 30% in BE_RF compared to BE to avoid bioenergy area expansion compared to BE.

Additional land requirements for bioenergy production in the rainfed-only case are partly fulfilled at the expense of pasture areas. While bioenergy expansion into pasture areas can lead to the loss of important ecosystems featuring high biodiversity (Alkemade *et al.*, 2013) and carbon storage potential (Conant *et al.*, 2001), the impact on natural forests is even more worrisome. Our results suggest that a rainfed-only bioenergy scenario would lead to substantially increased losses of natural forests (580 Mha) compared to the unrestricted bioenergy scenario (420 Mha), especially in tropical regions where additional forest losses in BE_RF compared to BE amount to 120 Mha by 2095. Tropical rainforests are high priority conservation targets since they are major biodiversity hotspots (Barlow *et al.*, 2007) and provide a number of important ecosystem services such as carbon sequestration and water flow regulation

(Onaindia *et al.*, 2013). It is thus likely that protecting freshwater ecosystems from degradation due to bioenergy production will accelerate the loss of important land ecosystems if no strict land-use change regulations are implemented.

Aside from the trade-off between water and land resources for bioenergy production, economic considerations may form an obstacle to the implementation of water-saving bioenergy production policies. With rising energy prices, bioenergy production may become an important source of income for farmers (Walsh *et al.*, 2003), and can play a key role for economic development in developing countries (Demirbas & Demirbas, 2007). We find that restricting irrigation changes the comparative advantages between regions and leads to reallocation of production and associated economic benefits.

Assumptions and limitations

This study investigates implications of different bioenergy production strategies on land and water resources in a cost optimization framework with a fixed bioenergy target of ~300 EJ yr^{-1} in 2095. While this setup allows us to investigate the cost optimal resource allocation as well as bioenergy supply prices for a fixed bioenergy demand under different production scenarios, we are not able to quantify price-induced changes in bioenergy demand between the scenarios. Thus, this study provides insights into the implications of substituting water resources with land resources for large-scale bioenergy production, but does not claim to provide a comprehensive picture of future bioenergy related resource requirements under different scenarios.

The influence of bioenergy production on water resources is not restricted to irrigation water requirements. First, water is also needed during the conversion of biomass into final energy (e.g., electricity, fuel, heat, Singh *et al.*, 2011). Processing requirements are however small compared to water requirements during feedstock production (Berndes, 2002; Gerbens-Leenes *et al.*, 2009; Gheewala *et al.*, 2011) and have therefore been neglected in this analysis. Second, bioenergy plantations will to some extent alter the balance between runoff and evapotranspiration, thereby changing available blue water in rivers, lakes and aquifers (Berndes, 2002). The magnitude of this effect is however highly uncertain (Haddeland *et al.*, 2011) and depends on the location and the type of vegetation that is replaced by bioenergy crops (Berndes, 2002). Quantifying the overall effect of bioenergy on water availability would therefore require a full coupling to a global vegetation and hydrology model such as LPJmL, which is beyond the scope of this analysis. Third, we focus on water quantity and do not investigate bioenergy implications for water quality.

Land requirements for bioenergy production crucially depend on bioenergy yields (Creutzig *et al.*, 2014). Observed bioenergy yields on test sites in Europe range between 120 and 280 GJ ha^{-1} yr^{-1} (Chum *et al.*, 2011). Average European bioenergy yields in 1995 in our model of 115 GJ ha^{-1} yr^{-1} (rainfed) and 220 GJ ha^{-1} yr^{-1} (irrigated) are consistent with these observations. It is however unclear, if the yields that were achieved under test conditions can be realized over large areas (Johnston *et al.*, 2009). Due to investments into agricultural research and development, all agricultural yields – including bioenergy yields – in our projections approximately double until the end of the century on global average. This yield projection is consistent with historical data on yield increases for conventional crops. It is however unclear, whether plant physiological limits will limit future yield increases (Cassman, 1999). Moreover, almost half of the past yield increases can be attributed to harvest index improvements (Krausmann *et al.*, 2013). In the case of lignocellulosic bioenergy crops, all aboveground biomass can be used for energy production, so that increasing the harvest index is hardly possible (Searle & Malins, 2014). On the other hand, breeding of lignocellulosic bioenergy crops has just started, fostering the hope that significant yield improvements are possible (Chum *et al.*, 2011). Several studies argue that natural productivity poses an upper limit to bioenergy yields (Erb *et al.*, 2012; Smith *et al.*, 2012; Haberl *et al.*, 2013). Within our model, bioenergy yields in 2095 stay within the potential yield achievable under current best management as simulated by LPJmL, except for Latin America. In summary, rainfed bioenergy yields within our model of up to 450 GJ ha^{-1} yr^{-1} in 2095 are within the range reported by Haberl *et al.*(2010) (69–600 GJ ha^{-1} yr^{-1} in 2055), but bioenergy yields remain a key uncertainty of our analysis.

Restrictive land-use change policies that mainly aim at conserving natural forests (REDD) are discussed as an option to mitigate climate change (Angelsen *et al.*, 2009). Our scenarios do not contain a REDD policy and therefore allow conversion of forests and other natural vegetation into bioenergy plantations. Under scenarios with a REDD policy, such expansion would be strictly limited and could lead to stronger land productivity increases, reduced land-use implications of bioenergy but potentially higher bioenergy prices.

Aside from land productivity, water productivity is a key determinant of the resource requirements for large-scale bioenergy production (King *et al.*, 2013). In our standard model implementation, agricultural research and development is assumed to increase both, land and irrigation water productivity. This assumption is supported by various studies on crop water productivity (Kijne *et al.*, 2004; Rosegrant *et al.*, 2009; Molden

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et al., 2010) and can be achieved by: minimizing losses in the water distribution system; increasing the ratio of transpiration to evaporation on the field; increasing plant water-use efficiency by breeding and improved management of all inputs. The extent of possible irrigation water productivity improvements is however uncertain, especially in already highly intensified agricultural systems. Our sensitivity analysis shows that agricultural water requirements are significantly higher if no improvements in irrigation water productivity can be realized. The competitiveness of irrigated bioenergy production and the possible doubling of agricultural water withdrawals due to bioenergy production is, however, robust with respect to different assumptions on water productivity.

Policy implications and conclusions

In the context of the presented results, it is important that policies to protect freshwater ecosystems from degradation due to bioenergy production are carefully designed and address the trade-off with land ecosystems and the economic incentives opposing sustainable water use. Certification schemes are one possibility to manage the water implications of bioenergy production (Fehrenbach, 2011). A certificate for rainfed bioenergy production would allow consumers to make an informed choice and could create a market incentive for less water intensive production. Governments could furthermore create direct incentives for rainfed bioenergy production through taxes and subsidies. South Africa has for example already decided to stop the support for bioenergy crops under irrigation (Moraes *et al.*, 2011).

Policies that aim at incentivizing rainfed bioenergy production are useful to protect water resources but neglect the trade-off with land resources and may therefore endanger land ecosystems. Rather than promoting rainfed-only bioenergy production, one could therefore restrict water use for bioenergy production to sustainable levels. Such an approach would require site specific estimates of how much water is required for a functioning ecosystem. Estimates of how much water needs to be reserved for environmental purposes – also called environmental flows – are already available (Smakhtin *et al.*, 2004; Poff *et al.*, 2010), although more research is needed to increase the accuracy of such estimates (Pastor *et al.*, 2013). The implementation of comprehensive water management strategies that take into account the different types of human water use and environmental flow requirements (Pahl-Wostl *et al.*, 2013) would allow irrigation of bioenergy where enough water resources are available. Thus, negative impacts of bioenergy production on water resources could be prevented while irrigation could still contribute to reducing land requirements for bioenergy crops. Ideally, such sustainable water management policies would be accompanied by forest protection policies that can further reduce the negative impacts of bioenergy production on natural land ecosystems (Popp *et al.*, 2011b).

Producing 300 EJ yr^{-1} of bioenergy from dedicated bioenergy crops is a very ambitious scenario (Creutzig *et al.*, 2014). Lower second generation bioenergy production will of course have less implications for land and water resources and may raise less sustainability concerns. Even with a lower contribution from dedicated crops, bioenergy can make an important contribution to the future energy mix since forestry and residues can provide 35–125 EJ yr^{-1} in 2050 already (Creutzig *et al.*, 2014). It is furthermore likely that market forces lead to a decreased bioenergy demand because of higher prices if irrigation of bioenergy crops is prohibited. This process could mitigate the negative impacts of water-saving bioenergy production strategies on land resources. Our results however suggest that a price-induced demand reduction of 30% would be necessary to fully compensate additional land requirements if irrigated bioenergy production is prohibited.

In summary, our results indicate that without dedicated water protection policies, large-scale bioenergy production from dedicated 2^{nd} generation energy crops may lead to severe degradation of freshwater ecosystems. It is therefore crucial that the focus of bioenergy strategies shifts from land-use efficiency (Gheewala *et al.*, 2011) to a broader sustainability perspective including water resources. We find that prohibiting irrigated bioenergy crop production for water resources protection can lead to the loss of important natural land ecosystems, especially tropical forests. Policies that balance water- and land-use implications of large-scale bioenergy production are therefore needed. The concept of environmental flow protection is a promising avenue since it protects freshwater ecosystems while still allowing for irrigated bioenergy production to increase yields and thereby decrease the pressure on land ecosystems. Further research should aim at investigating additional implications of water-saving bioenergy production strategies that were not covered here. Those include feedbacks on bioenergy deployment in the energy system, as well as implications for the water cycle due to changes in evapotranspiration on bioenergy plantations.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Data S1. Additional model description and results.