Global advanced bioenergy potential under environmental protection policies and societal transformation measures

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Abstract
Bioenergy plays an important role in low greenhouse gas stabilization scenarios. Among various possible sources of bioenergy, dedicated bio-crops could contribute to most of the potential. However, large scale bio-crop deployment raises sustainability concerns. Policies to alleviate the pressure of bio-crops on the terrestrial environment can affect bioenergy potential and production costs. Here, we estimated the maximum bioenergy potential under environmental protection policies (biodiversity and soil protection) and societal transformation measures from demand and supply side (demand-side policy includes sustainable diet; supply-side policy includes advanced technology and trade openness for food) by using an integrated assessment modelling framework, which consists of a general equilibrium model (Asian-Pacific Integrated Model/Computable General Equilibrium) and a spatial land use allocation model (Asian-Pacific Integrated Model/Platform for Land-Use and Environmental Model). We found that the global advanced bioenergy potential under no policy was 245 EJ/year and that 192 EJ/year could be produced under US$5/GJ. These figures were 149 EJ/year and 110 EJ/year, respectively, under a full environmental policy. Biodiversity protection has a greater impact than soil protection due to its larger coverage and stronger implementation. Societal transformation measures effectively increase them to 186 EJ/year and 143 EJ/year, respectively, even under full environmental policies. These results imply that the large-scale bioenergy deployment possibly needed for the climate target to limit the global mean temperature increase well below 2°C compared to the preindustrial level might face a trade-off with environmental protection targets and that possible mitigation pathways in harmony with other environmental issues need to be explored.

KEYWORDS
biodiversity protection, bioenergy potential, demand- and supply-side policy, integrated assessment, societal transformation, soil protection
Global energy demand keeps increasing with economic development and population growth. Although demand is growing more slowly than in the past, it is still projected to increase by 30% from the current level by 2040, and the increase will be accompanied by energy-related CO₂ emissions if the increase takes place without mitigation efforts (IEA, 2017). Even though it may induce extra emission due to transport, fuel conversion processes, soil carbon losses, and indirect land use change (Haberl et al., 2012; Kraxner et al., 2013; Searchinger et al., 2009), replacing fossil fuels with bioenergy has widely been recognized as a mitigation option for climate stabilization targets (Klein, Luderer, et al., 2014). In particular, it will be more effective when combined with carbon capture and storage; therefore significantly reducing the costs for climate stabilization (Klein, Luderer, et al., 2014; Kriegler, Edenhofer, Reuster, Luderer, & Klein, 2013). The ratio of bioenergy to global primary consumption is expected to increase to 10%–50% by 2,100 under the radiative forcing targets of 3.7 and 2.8 W/m² (Rose et al., 2014). It is also projected that bioenergy demand exceeds 100 EJ/year in 2050 and 200–300 EJ/year in 2,100 are required for a stringent stabilization of greenhouse gas concentrations, with radiative forcing targets between 2.6 W/m² and 4.5 W/m² by 2,100 (Popp et al., 2017; Rose et al., 2014). A variety of studies have also reported the global technical potential for bioenergy supply in 2050, with estimates ranging from several dozens EJ/year (Campbell, Lobell, Genova, & Field, 2008; Haberl et al., 2011) to an upper limit of 270 EJ/year (Beringer, Lucht, & Schaphoff, 2011). The discrepancies arise from multiple aspects, such as coverage of bioenergy types, constraints considered, and differences in socioeconomic scenarios. Several studies also investigated bioenergy potential under environmental constraints, such as van Vuuren et al. (2009), Beringer et al. (2010; Edrisi & Abhilash, 2016; Nijsen et al., 2011; Saha & Eckelman, 2018). In addition, the land use change, expansion of cultivated land area, and increased fertilizer use that accompany bio-crops will also impose huge threats to biodiversity (Immerzeel et al., 2014).

Studies have investigated how much bioenergy will be required under various climate policies and the potential impacts on food markets. For example, bioenergy amounts of about 100–200 EJ/year in 2050 and 200–300 EJ/year in 2,100 are required for a stringent stabilization of greenhouse gas concentrations, with radiative forcing targets between 2.6 W/m² and 4.5 W/m² by 2,100 (Popp et al., 2017; Rose et al., 2014). A variety of studies have also reported the global technical potential for bioenergy supply in 2050, with estimates ranging from several dozens EJ/year (Campbell, Lobell, Genova, & Field, 2008; Haberl et al., 2011) to an upper limit of 270 EJ/year (Beringer, Lucht, & Schaphoff, 2011). The discrepancies arise from multiple aspects, such as coverage of bioenergy types, constraints considered, and differences in socioeconomic scenarios. Several studies also investigated bioenergy potential under environmental constraints, such as van Vuuren et al. (2009), Beringer et al. (2010; Edrisi & Abhilash, 2016; Nijsen et al., 2011; Saha & Eckelman, 2018). In addition, the land use change, expansion of cultivated land area, and increased fertilizer use that accompany bio-crops will also impose huge threats to biodiversity (Immerzeel et al., 2014).

However, a large deployment of dedicated bio-crops can pose risks to the environment. Major concerns include water stress, deforestation, land quality deterioration, and biodiversity loss (Bonsch et al., 2016; Immerzeel, Verweij, Hilst, & Faaij, 2014; Popp, Lakner, Harangi-Rákos, & Fári, 2014; Wise et al., 2009). Therefore, balancing the trade-offs among various sustainable development targets is important when considering the use of bioenergy. In modelling studies, environmental concerns have been projected to increase when bioenergy demand exceeds 100 EJ/year in 2050 (Creutzig et al., 2015; Schleussner et al., 2016). Schueler, Weddige, Beringer, Gamba, and Lamers (2013) and Searle and Malins (2015) also found that sustainable bioenergy from dedicated crops is not likely to be much higher than 100 EJ/year. Currently, around 1–6 Gha of land was degraded globally (Gibbs & Salmon, 2015) and the well-being of 3.2 billion people was undermined by land degradation (IPBES, 2018). Continuing intensive farming practices on degraded land may worsen its biophysical condition, which could pose additional long-term risks to the ecosystem and food security (van Vuuren, Vliet, & Stehfest, 2009). Biophysical studies suggest that converting the land use from annual to perennial cropping is beneficial for restoring degraded soil (Fernando, Costa, Barbosa, Monti, & Rettenmaier, 2018; Paustian et al., 2016). In particular, using degraded land sustainably for bioenergy crops could help improve soil quality (Immerzeel et al., 2014; Nijsen, Smeets, Stehfest, & Vuuren, 2011) and avoid competition with food crops, even though the yield will be lower. Several studies have assessed the bioenergy production potential of those degraded lands (Dornburg et al., 2010; Edrisi & Abhilash, 2016; Nijsen et al., 2011; Saha & Eckelman, 2018). In addition, the land use change, expansion of cultivated land area, and increased fertilizer use that accompany bio-crops will also impose huge threats to biodiversity (Immerzeel et al., 2014).

This research adds to earlier work by simulating environmental protection policies (soil and biodiversity) in varying degrees and combinations to achieve other land-based SDGs (especially Goal 15). In addition, the environmental
protection scenarios were designed based on newly compiled datasets recording spatial information on soil quality and biodiversity protection priority. Therefore, the scenarios more closely mimic potential policy implementation in the future. Finally, this study goes beyond the scope of most existing studies on bioenergy potential by exploring societal transformation measures both from demand and supply side (demand-side policy includes sustainable diet; supply-side policy includes advanced technology and trade openness for food) to ensure bioenergy supply under strict environmental protection targets.

2 | MATERIALS AND METHODS

2.1 | Model

The study framework is illustrated in Figure 1. First, regional land demand for crops, afforestation, grass, and forest was derived by the Asian-Pacific Integrated Model/Computable General Equilibrium (AIM/CGE) for each scenario. The land demand for each region was then fed into the Asian-Pacific Integrated Model/Platform for Land-Use and Environmental Model (AIM/PLUM) for spatial disaggregation to 0.5-degree grid cells. Bio-crops were then allocated on the remaining land using the accessibility factors for different land categories: 0.5 was used for both forestland and grassland (van Vuuren et al., 2009).

AIM/CGE is a recursive dynamic general equilibrium model containing 17 regions globally and 42 industrial classifications including 10 agricultural sectors (Fujimori, Masui, & Yuzuru, 2012). It has been widely adopted for various studies on climate change (e.g., Fujimori, Abe, et al., 2017; Fujimori, Hasegawa, et al., 2018; Fujimori, Kainuma, Masui, Hasegawa, & Dai, 2014; Hasegawa et al., 2014; Hasegawa, Fujimori, Shin, et al., 2015; Hasegawa, Fujimori, Takahashi, & Masui, 2015; Hasegawa, Fujimori, Takahashi, Yokohata, & Masui, 2016; Hasegawa et al., 2018; Hasegawa et al., 2016). Production sectors in AIM/CGE are characterized by profit maximization under multi-nested constant elasticity substitution (CES) functions. Household expenditures are modeled by a linear expenditure system function. The income elasticity of the food demand for each region and commodity was derived from the per-capita food consumption and gross domestic product data reported in Alexandratos and Bruinsma (2012). The elasticity of livestock products was derived from a function based on the meat calorie intake and income, which was estimated from time-series cross-country data. The parameters were updated recursively to achieve the assumed income elasticity. The Armington assumption was imposed for substitution between domestic and imported commodities with the current account assumed to be balanced. The CES function was used for the aggregation of the domestic and imported commodities. The disaggregation between the exports and domestic supply was described by a constant elasticity transformation function. The supply, demand, trade, and investment functions respond to changes in the prices of production factors, commodities, technologies, and preference parameters on the basis of the assumed population, GDP, and consumer preferences. For the land use, AIM/CGE uses a land-nesting strategy, where the land is categorized into one of three ecological zones and the land market operates in each zone. The regional total land is disaggregated into each land use type (e.g., grassland, forest, afforestation, pasture, and crops) via a multi-nominal logit function where differences in substitutability across land categories are reflected in the land rent. The function assumes that land owners in each region and agroecological zone decide on land sharing between land use types with the land rent depending on the production of each land type (Fujimori, Hasegawa, Masui, & Takahashi, 2014).

AIM/PLUM is a global land use allocation model designed for the disaggregation of regional land demand outputted by the AIM/CGE model (Hasegawa, Fujimori, Ito, Takahashi, & Masui, 2017). It has a spatial resolution of 0.5 degree and consistent regional divisions with AIM/CGE (see Table S1). Cropland and afforestation are allocated based on profit maximization. Such allocation is operated separately for each region, and land transactions across regions were not considered. The modelling approach enables us to show the net land use changes for each grid cell; however, it is not able
to explicitly imply the transformation pathways. This model has been applied in research related to climate change, such as the macroeconomic impacts of climate change linked with crop yields (Fujimori, Iizumi, et al., 2018).

Various sources of feedstock are available for generating energy, including traditional biomass, agricultural and forestry residues, and dedicated energy crops (Beringer et al., 2011; van Vuuren, Belleverat, Kitous, & Isaac, 2010). Bioenergy converted from dedicated crops is thought to account for most of the potential production (IEA Bioenergy, 2009; Slade, Bauen, & Gross, 2014). Due to the high biomass and energy yield, the second generation (advanced) bioenergy crop, which uses woody and grassy lignocellulosic sources, are expected to become a promising feedstock. In this study, we focused on the production of herbaceous crops (miscanthus and switchgrass).

Production costs in this study are composed of input costs and land transition costs. Input costs, including intermediate inputs and primary factors such as capital and labour, were derived using the AIM/CGE model. Land transition costs include labour costs (labor for land clearance), road construction costs, and emission costs. The land transition cost was calculated based on wages (associated with the GDP) and the payback period of the investment cost for agriculture, road construction, and GHG emissions. The payment period of the investment for GHG emissions is grid specific, while the other components of the land transition cost are the same within each region. Figure S1b shows the regional average production cost over time.

The supply curve was constructed via a spatially explicit cost analysis, using a similar approach as to that in Hoogwijk et al. (2009) and van Vuuren et al. (2009). First, the per unit (GJ) bioenergy production in each 0.5° grid cell was calculated. Then, the supply quantity for a certain price was found by summing over all the production in the grid cells whose production cost was below this price. Finally, a supply curve was constructed by changing the prices and repeating the above step.

### 2.2 | Scenario settings

To evaluate the impact of environmental policies combined with societal transformation measures on bioenergy potential, we designed nine scenarios, with varying environmental protection policies and societal transformation measures as summarized in Table 1. Intuitively, we expect that bioenergy potential will be restricted under stricter environmental policies, but societal transformations could in part compensate for these impacts. Socioeconomic scenario for all the scenarios is based on the ‘middle-of-the-road’ SSP2 storyline, which has intermediate challenges for adaption and mitigation (O’Neill et al., 2017). This SSP assumes that current trends will continue for social, economic, and technological development. No climate change impact and mitigation policies are involved, and the model parameters are based on Fujimori, Abe, et al. (2017).

#### 2.2.1 | Environmental protection policy

We consider two aspects of environmental protection policies in this study: biodiversity and soil protection. For each

| Scenario name | Environmental protection policy | Societal transformation measure |
|---------------|---------------------------------|---------------------------------|
| (a) No policy | WDPA (Ia, Ib, II, III) | × |
| (b) Moderate biodiversity protection | WDPA (all) &KBA | × |
| (c) Enhanced biodiversity protection | WDPA (all) &KBA; biodiversity sensitive area | × |
| (d) Moderate soil protection | Severely degraded land | × |
| (e) Enhanced soil protection | Seriously degraded land | × |
| (f) Full environmental policy | Enhanced biodiversity protection; enhanced soil protection | × |
| (g) Demand-side policy | Full environmental policy | Sustainable diet |
| (h) Supply-side policy | Full environmental policy | Advanced technology; trade openness for food |
| (i) Demand- and supply-side policy | Full environmental policy | Sustainable diet; advanced technology; trade openness for food |

**TABLE 1** Scenario setting
policy, two scenarios with varying levels of protection (moderate and enhanced) were simulated.

Protected areas are major tools for conserving species and ecosystem services, protecting landscapes, sustainably using natural resources, and maintaining cultural values (Dudley, 2008). In moderate biodiversity protection scenario, all the current established protected areas are excluded from food and bioenergy production in the allocation process by AIM/PLUM; in the enhanced case, bioenergy production are further restricted in the biodiversity sensitive areas (identified by a biodiversity index). For soil protection, we prohibit the use of degraded land for annual crops (food crops) and allocate it for bioenergy crops, assuming a half yield reduction for bioenergy crops following Beringer et al. (2011). In the moderate soil protection scenario, severely degraded land (detailed definition in Section 2.3) is protected; in the enhanced soil protection case, protection is expanded to seriously degraded land (detailed definition in Section 2.3).

2.2.2 Societal transformation measures

Societal transformation measures are important supplementary policies designed to meet growing bioenergy demand by increasing land available for bioenergy production from the supply and demand sides. As compared to the no policy and environmental protection scenarios, three options were considered. These measures were implemented in the AIM/CGE model, affecting the bioenergy potential by decreasing the land demand required for food and livestock production, such as cropland and pasture. All societal transformation scenarios were simulated under the full environmental policy condition.

The first measure is sustainable diet (demand-side policy), that is, dietary preferences evolve towards less animal products as in SSP1 (Hasegawa, Fujimori, Takahashi, et al., 2015). In this study, food consumption was determined according to income (represented by the GDP per capita) and the income elasticity of the food demand. In baseline and environmental protection scenarios (the SSP2 assumption), the relationship between per-capita animal product consumption and income was observed in national level data for 1980–2009 and the future income elasticity of the food demand for meat was changed based on such a relation. In the sustainable diet scenario, the relationship was shifted to inelastic directions within the range of the observed data. There is no assumption concerning the crop products because no relationship was identified between crop consumption and income.

The second measure is the trade openness for food (supply-side policy), that is, international trade increases according to SSP1, with a more globalized economy and reduced trade barriers. In this study, trade openness was characterized by changing trade elasticities. In the baseline and environmental protection scenarios (the SSP2 assumption), the original default trade elasticities of AIM/CGE were employed. For the trade openness measure, the freeness of trade was increased compared to SSP2 by increasing the trade elasticities over time for all regions.

![FIGURE 2 Maps for environmental protection policies: (a) protected area, (b) biodiversity sensitive areas, (c) severely degraded land, (d) seriously degraded land](image-url)
The third option is advanced technology development (supply-side policy). In the baseline and environmental protection scenarios (the SSP2 assumption), the AgMIP assumption of the crop yield changes for rain-fed and irrigation-fed cultivation (von Lampe et al., 2014) were used in AIM/CGE as the default assumptions. For the advanced technology measure, the yield was changing by assuming high irrigation growth rates (0.6%/year) for SSP1 (Hanasaki et al., 2013).

2.3 | Data

2.3.1 | Protected area

Two sources were used for protected area: the World Database for Protected Areas (WDPA) (IUCN & UNEP-WCMC, 2018) and World Database of Key Biodiversity Areas (KBA) (BirdLife International, 2017). As of 2018, WDPA covered an area of 33.6 million km² and KBA covered an area of 19.9 million km². According to the definition and objective of the IUCN category in WDPA (Dudley, 2008), categories with the highest protection value, that is, Ia, Ib, II, and III, were excluded from land use in the baseline scenario. In the biodiversity protection scenarios, we then expand the protected area into all the areas listed in WDPA and KBA (Figure 2a).

2.3.2 | Biodiversity index

Biodiversity sensitive areas were identified by a spatially explicit biodiversity index provided by AIM/Biodiversity. For this index, climate variables and proportion of land use types in 2005 were used to predict the potential habitat of 9,025 species using the MaxEnt model (Phillips, Anderson, & Schapire, 2006), and a biodiversity index for each grid cell was calculated based on the distribution of potential habitat for those 9,025 species (Ohashi et al., 2017). The index, with a range of 0–1, is defined in terms of its conservation priority rank, as determined by a Zonation analysis (Moilanen et al., 2005). The ranking of each grid cell is created via a cell removal process where the Zonation software first assumes all target cells to be protected and then progressively removes cells that cause the smallest loss in potential habitat of 9,025 species. This index represents the percentile of the priority for protection and larger values imply a higher priority. For example, a grid cell with an index of 0.99 indicates that this region is a top 1% priority region for biodiversity protection. In the enhanced biodiversity protection scenario, we further exclude all the bioenergy production from the grid cells with an index above 0.95 (Figure 2b). Concerning the sensitivity of the results to the biodiversity index threshold, we provide a sensitivity analysis in the supplementary information.

2.3.3 | Degraded land

We used the Global Land Degradation Information Systems (GLADIS) dataset (Freddy & Monica, 2011) to identify soil protection areas. The original data have a resolution of 0.0833 degree. For soil protection, previous estimations relied mostly on GLASOD (Oldeman, Hakkeling, & Sombroek, 1991), but GLADIS has advantages in that (a) it was more recently compiled in 2011; (b) it describes both the land status and degradation processes, and thereby contains information about future land quality; and (c) it provides continuous indices. GLADIS uses two indices, the Biophysical Status of...
Land Index (BSI) and Biophysical Land Degradation Process Index (BLDI), to describe the current land quality and degradation processes, respectively. BSI ranges from 0 to 100, with larger numbers indicating better quality; BLDI ranges from 0 to 1, and numbers closer to 1 represent severer degradation. In this study, we considered two degrees of soil protection. In the moderate soil protection scenario, severely degraded land (land with a low-quality status and under strong degradation, i.e., BSI 0–25 and BLDI 0.7–1, Figure 2c) is excluded from the allocation to food crops and only used for bio-crops. In the enhanced soil protection scenario, land protection is expanded to cover seriously degraded land (land with a low-quality status and under medium to strong degradation, i.e., BSI 0–25 and BLDI 0.55–1, Figure 2d). Because the protection practice is more stringent for protected areas, land, both degraded and classified as protected areas, is treated as protected areas. The combinations of soil and biodiversity protected area under full environmental policy is shown in Figure 3.

2.3.4 | Yield data

Spatially explicit yield data are required for land use allocation. Food crop yield is derived from the Lund-Potsdam-Jena managed Land Dynamic Global Vegetation and Water Balance Model (Bondeau et al., 2007), which was provided for the Inter-Sectoral Impact Model Inter-comparison Project (Rosenzweig et al., 2014). Details of food crop yield data are presented in Hasegawa et al. (2017). Bio-crop yield (Figure 4) was proxied by averaging yield for rainfed miscanthus and switchgrass from the H08 model (Hanasaki et al., 2008a, 2008b; Hanasaki, Yoshikawa, Pokhrel, & Kanae, 2018).

Yield of bio-crops in H08 model was estimated by the crop-growth sub-model which estimates crop yield (total above-ground biomass for bio-crops) by accumulating daily biomass growth. Daily biomass growth is primarily determined by sunshine (photosynthesis), the suitability of climatic conditions (stress due to high/low temperature and water constraint), and crop-specific characteristics (crop parameters) (see Hanasaki et al. (2008a, 2008b, 2018) for detailed formulations). The potential (theoretical) bioenergy crop yield derived by the H08 model was simulated under ideal conditions (e.g., fertilizer, pesticide use, and management). We assume that the practical yield in each region changes over time and that catch-up exists between income groups, which is driven by technological factors assumed according to their economic condition based on van Vuuren et al. (2009). Figure S1a shows the change of regional average yield over time.

3 | RESULTS

3.1 | Global potential

In the absence of any environmental protection policy implementation, global technical potential in 2050 could reach 245 EJ/year (Figure 5). Under the moderate and enhanced soil protection scenarios, potential decreased slightly to 244 EJ/year and 229 EJ/year, respectively. Biodiversity protection affected bioenergy potential to a greater extent; potential production was 172 EJ/year and 160 EJ/year under the

FIGURE 4 Bioenergy crop potential yield from the H08 model (tonne ha\(^{-1}\) year\(^{-1}\))
moderate and enhanced biodiversity protection scenarios, respectively. These differences were mainly due to the difference in protection implementation and wider coverage of protected and biodiversity sensitive areas as compared with the area of degraded land considered in this study (see Figure 2). When both enhanced soil protection and enhanced biodiversity protection policy were combined (the full environmental policy scenario), the total potential production decreased to 149 EJ/year. Societal transformation measures did effectively promote production: demand- and supply-side policy increased the total potential amount to 167 EJ/year and 183 EJ/year, respectively. When both demand- and supply-side policies were applied, the final bioenergy potential was 186 EJ/year under full environmental policy (enhanced soil protection and enhanced biodiversity protection). A sensitivity analysis for the biodiversity index threshold for enhanced biodiversity protection is shown in Figure S5, which indicates that further strengthening the protection level would continuously reduce the bioenergy potential. For example, if we aim to protect the top 20% of biodiversity sensitive areas (a biodiversity index of 0.8), the bioenergy potential under demand- and supply-side policy scenario would be reduced to 143 EJ/year.

The reduction of potential under each environmental policy is mainly attributed to the decrease of available land, especially high-yield land, which usually has rich ecosystem to be protected. Figure 6 depicts the cumulative area-yield curve for each scenario. In general, curves under the...
environmental policy scenarios were to the left of the one without an environmental policy, implying a shrinkage of high-yield areas. At extremely high yields, the available area decreased slightly with the intensification of environmental policies. The increase of the area gap that started at the middle yield level was primarily responsible for the gaps in potential production between scenarios. As expected, when the full environmental policy was imposed, the area-yield curve was farthest left because of the large reduction in the use of high-yield land. In contrast, societal transformation measures pushed the area-yield curve to the right of the full environmental policy curve, which suggested that more productive areas became available for bioenergy production through the implementation of demand- and supply-side policies.

3.2 | Regional potential

Results showed a large variation in bioenergy potential and in the impact of environmental policy and societal transformation measures across regions. In the no policy scenario, Brazil was projected to be the largest supplier of bioenergy in 2050 (68 EJ/year), accounting for 28% of the global amount, followed by the Rest of South America (67 EJ/year, 27%) and the Rest of Africa (54 EJ/year, 22%). These three regions accounted for about three-fourths (74%-79%) of global production for almost all scenarios (Figure 7).

The implementation of environmental policy had varied effects on reducing bioenergy potential among the regions. For example, the global ratio of the amount of bioenergy potential production in the full environmental policy scenario to the amount produced under the no policy scenario was 61%, but the regional ratios varied from 49% to 82%. Bioenergy potential in China, the Former Soviet Union, and North Africa was less affected by the environmental protection targets, whereas the protection targets had a greater effect in India, the Rest of Africa and Brazil (Figure 7). India has relatively larger percentages of degraded land and the other two regions are mainly affected by protected areas (Figure 3). Actually, there is also large amount of degraded land in OECD countries (US, Turkey, Australia and Europe); however, its impact was less pronounced due to overlapping with protected area.

Societal transformation measures promoted bioenergy potential differently at the regional level (Figure 7). Notably, the Rest of Africa had the largest growth in both demand and supply side policy scenarios. And it contributed 29 EJ/year of the 37 EJ/year global increase in the demand- and supply-side policy scenario; other main producers, such as Brazil and the Rest of South America, showed little increase. For the demand side policy, this was due to the higher income elasticity of animal products in Africa caused by its present low income level and its higher reliance on increase in land intensity for producing more agriculture and livestock.

FIGURE 7 Regional bioenergy potential in 2050 under each scenario
products. In other regions, such as South America, either due to the low income elasticity or high productivity, the effect of dietary change was not as pronounced. For the supply side policy, this was also caused by the relatively lower productivity in Africa. Under trade openness, production in the Rest of Africa decreased and its consumption was complemented by imports. When the two policies were combined, the effect was not as pronounced as the direct summation of the two. This is primarily due to the overlapping effect of these two policies in the Rest of Africa. The shrinkage of the cropland and pasture land in the Rest of Africa by demand side policy (approaching the optimal allocation globally) was coincident with the mechanism of the supply side policy. In OECD, China, and Former Soviet Union, demand- and supply-side policy does not promote, or even decrease the potential. Such counterintuitive result was caused by the increase of afforestation demand in this scenario for these regions (Figure S4).

Figure S4 shows the regional land use composition in base year (2010) and 2050. Regional bioenergy potential was determined by the amount of available land as well as by yield. Some regions, such as Brazil and the Rest of South America, produced substantial amounts of bioenergy in relatively small land areas (Figure S3) owing to the high biomass yield in these regions (see Figure 4). The quantity produced was small in some regions due to low biomass yield, such as North Africa and the Former Soviet Union (Figure 7), even though the land available for bio-crops was large (Figure S3). Bioenergy potential map (Figure 8) showed that bio-crops could be produced intensively in the north and south of the Amazon Plain, in some parts of the Brazil Highlands, west of
the La Plata Plain, and north and south of the Congo Basin in Africa.

3.3 | Production cost

In Figure 9, the supply curves show the amount of available energy below a certain cost for the various scenarios in 2050. Under the demand- and supply-side policy scenario, 80 EJ/year was available at a production cost of US$3/GJ, which is 43% of the total possible potential in this scenario. At a higher cost, such as US$5/GJ, 143 EJ/year (77% of the total potential) could be produced.

Supply curves were pushed to the left by environmental policies (Figure 9, blue curves). This means that the price will be higher for a given production potential and that, for a given price level, the economically feasible quantity will be lower. For example, at a production cost of US$5/GJ, more than 192 EJ/year of bioenergy could be provided under the no policy scenario, whereas only 110 EJ/year could be produced under the full environmental policy scenario. Similar to the situation with global potential production, the biodiversity protection policy had a larger effect on increasing production cost than the soil protection policy because of the larger coverage area in the biodiversity protection scenarios. Societal transformation measures offset some of the cost increase and pushed the supply curves to the right (Figure 9, yellow curves).

Production cost differed drastically among regions. Under demand- and supply- policy scenario, the medium price was below US$5/GJ for the Rest of Africa, Rest of Asia, Southeast Asia, the Rest of South America, Brazil, and India; whereas the medium price ranged from US$18/GJ to US$70/GJ in China, Middle East, OECD (also in Oceania, Turkey and USA), North Africa, and the Former Soviet Union. Production cost in some OECD regions was especially high, for example, Europe, Japan, and Canada (more price quantiles could be found in Table S2 and the supply curves are available in Table S3).

4 | DISCUSSION

We estimated that the global maximum bioenergy potential under a full environmental protection policy complemented by societal transformation measures would be 186 EJ/year in 2050, 143 EJ/year of which could be supplied at a price of US$5/GJ. Biodiversity protection policies had a greater effect on reducing potential and increasing production cost than soil protection policies. Societal transformation measures effectively promoted bioenergy potential and lowered production costs. Specifically, combined demand- and supply-side policy increased total potential by 37 EJ/year, 33 EJ/year of which could be produced at a price below US$5/GJ.
are possible solutions for improving bioenergy potential and lowering production costs. An annual productivity growth rate of 1.2%–1.4% was found to be required to produce 100 EJ/year in 2055 (Lotze-Campen et al., 2010). Significant agricultural yields improvement was also necessary to ensure bioenergy supply compatible with 1.5 degree target (Daioglou et al., 2019). Prospect for bioenergy will be more optimistic if this level of productivity growth could be realized. Through yield growth and management improvements during plantation and post-harvest conversion (Kampman et al., 2010), it is possible to lower the production cost of bioenergy.

Bioenergy potential, production cost, and sensitivity to environmental policy varied notably among regions. Such regional disparity poses challenges for the global implementation of a bioenergy strategy. It implies that first, each region should consider its production potential and cost when designing a bioenergy strategy. Second, considering the prospect of international trade in bioenergy, a cost-efficient logistic system for the inter-regional export and import of bioenergy should be developed. For regions with large potential and relatively low production costs, such as Brazil, the Rest of South America, and the Rest of Africa, bioenergy production could become an important part of the national economy and an alternative income source for farmers in terms of rural development.

Although our study provided quantitative estimates for bioenergy policy formation, there are some caveats and additional vital factors interacting with bioenergy supply that need to be studied. First, this study focused on the production of herbaceous biomass, but feedstock from woody biomass could also constitute part of the bioenergy supply. Although the yield of woody biomass is generally lower than that of herbaceous biomass (Amaducci et al., 2017; Klein, Humphenöder, et al., 2014; Schaphoff et al., 2018), the total bioenergy potential could be increased if an optimal plantation scheme of herbaceous and woody biomass was determined based on maximum yield. In addition to the bioenergy from dedicated crops, other feedstocks, such as agricultural and forest residues, may be a valuable source of bioenergy. Agricultural residues have been estimated to provide 10–66 EJ/year and forestry residues another 3–35 EJ/year by 2050 (Slade et al., 2014). Second, emission from direct and indirect land use change induced by bio-crops has been found to be huge (Daioglou et al., 2017; Popp, Humphenöder, et al., 2014). Policies aimed at reducing emissions from land use and land use change will be an important determinant of bioenergy supply. Third, although not included in this study, nitrogen leakage and freshwater consumption due to irrigation are also key aspects in determining the planetary boundaries to bioenergy and are worth exploring (Heck, Gerten, Lucht, & Popp, 2018; Popp, Lotze-Campen, et al., 2011). In addition, bioenergy potential and its negative emission effect face uncertainties in conversion technology and conversion efficiency (Heck et al., 2018). Finally, our assessment uses a food-first approach, which assumes no competition with other land uses, such as food crops. However, market dynamics with other factors is relevant to biomass production, therefore altering the potential and supply curve. Such dynamics will be investigated in our future studies.

The results of our study imply that, without compromising other environmental protection, most bioenergy-based climate mitigation scenarios aiming at the 2°C or 1.5°C target are not feasible. A reduction in the bioenergy potential by 96 EJ under the full implementation of environmental protection policies implies a possible trade-off between climate targets and other environmental issues. However, as noted previously, other feedstocks, such as wastes and agriculture and forest residues are estimated to provide several dozens to around one hundred EJ (Slade et al., 2014). Moreover, alternative mitigation scenarios have been explored that do not rely heavily on bioenergy (far less than 100 EJ in 2050) but instead count on low energy demand, high energy efficiency, lifestyle change, additional reduction of non-CO₂ greenhouse gases, and more rapid electrification of energy demand based on renewable energy (Grubler et al., 2018; Vuuren, Stehfest, & Gernaey, 2018). Our paper’s results in conjunction with these articles’ findings suggest that there are still possible pathways through which we can simultaneously harmonize climate change and environmental issues.

Our findings are valuable for the integrated assessment modelling community in highlighting the nexus of environmental protection targets, societal transformation measures, and bioenergy potential. From the perspective of SDGs, this study provides an avenue for balancing multiple development goals, such as affordable and clean energy (Goal 7), climate action (Goal 13), and terrestrial ecosystem conservation (Goal 15) though a combination of relevant policies.

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