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ORIGINAL RESEARCH

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Land suitability for energy crops under scenarios of climate change and land-use

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Abstract

Bioenergy is expected to play a critical role in climate change mitigation. Most integrated assessment models assume an expansion of agricultural land for cultivation of energy crops. This study examines the suitability of land for growing a range of energy crops on areas that are not required for food production, accounting for climate change impacts and conservation requirements. A global fuzzy logic model is employed to ascertain the suitable cropping areas for a number of sugar, starch and oil crops, energy grasses and short rotation tree species that could be grown specifically for energy. Two climate change scenarios are modelled (RCP2.6 and RCP8.5), along with two scenarios representing the land which cannot be used for energy crops due to forest and biodiversity conservation, food agriculture and urban areas. Results indicate that 40% of the global area currently suitable for energy crops overlaps with food land and 31% overlaps with forested or protected areas, highlighting hotspots of potential land competition risks. Approximately 18.8 million km^2 is suitable for energy crops, to some degree, and does not overlap with protected, forested, urban or food agricultural land. Under the climate change scenario RCP8.5, this increases to 19.6 million km^2 by the end of the century. Broadly, climate change is projected to decrease suitable areas in southern regions and increase them in northern regions, most notably for grass crops in Russia and China, indicating that potential production areas will shift northwards which could potentially affect domestic use and trade of biomass significantly. The majority of the land which becomes suitable is in current grasslands and is just marginally or moderately suitable. This study therefore highlights the vital importance of further studies examining the carbon and ecosystem balance of this potential land-use change, energy crop yields in sub-optimal soil and climatic conditions and potential impacts on livelihoods.

KEYWORDS

bioenergy potential, biomass, climate change scenarios, energy crops, energy transition, feedstocks, land availability, land competition, land suitability

1 | INTRODUCTION

With the Paris Agreement, the international community committed to keep the global temperature rise well below 2°C and endeavour to limit it to 1.5°C (UNFCCC, 2015). Bioenergy is expected to play a critical role in emissions mitigation, as it offers options for electricity, heat and transport fuels with low- or even net-negative greenhouse gas (GHG) emissions (Forsell et al., 2016; Fuss et al., 2014; Rogelj et al., 2018; Rose et al., 2014). The International Energy Agency estimates that the supply of biomass feedstocks for modern bioenergy will need to increase fivefold compared to current levels and that wastes and residues can only provide approximately two thirds of the required resources (IEA, 2017). Integrated assessment models (IAMs) consistently foresee an expansion of agricultural land for cultivation of energy crops (Rogelj et al., 2018). With a global high-resolution spatial model, this paper examines the geographic distribution of the land suitable for growing a range of energy crops, and how this changes under scenarios of climate change and other land-use.

Although there is substantial consensus on the need for biomass, estimates of future feedstock resources vary widely, with the highest uncertainty in the estimates of biomass from dedicated energy crops (Creutzig et al., 2015; Smith et al., 2016). Uncertainties on the sustainable resource potential for dedicated energy crops stem from several factors including: the availability of land considering changing food requirements and agricultural practices; the suitability of that land for crop cultivation in a changing climate; the performance of crops which have not yet been cultivated at large scale; the yields that may be expected from abandoned or degraded land; costs associated with improving degraded land; emissions associated with land-use change and transport to processing facilities (Anderson & Peters, 2016; Fajardy, Köberle, Mac Dowell, & Fantuzzi, 2019; Searle & Malins, 2015). Improved understanding of these issues at the global and regional level is vital, as they could have important implications for the potential role of bioenergy and trade of biomass resources.

Land-use for energy crops demands particular attention due to the complex links between energy policies, the food sector and land stewardship as well as water resources and biodiversity (Mirzabaev et al., 2015; Stoy et al., 2018; Tomei & Helliwell, 2016; Zabel et al., 2019). In recent years, major concerns have been raised that using crops for energy can increase food prices, deforestation and biodiversity loss (Committee on Climate Change, 2011; Delzeit, Zabel, Meyer, & Václavík, 2017; Hof et al., 2014; Lotze-Campen et al., 2014). Deforestation due to oil palm cultivation has led the European Commission to impose additional sustainability criteria on biofuel feedstocks (European commission, 2019). Increasing population and meat consumption under growing economies are expected to place additional demands on agricultural land (Popp et al., 2017).

Uncertainties in future energy crop resources are compounded by the impacts of climate change itself through changing temperature and precipitation patterns. Researchers have mainly focussed on the yields of staple food crops, such as maize, rice and sugarcane, under the changing climate at global and regional levels (e.g. Deryng et al., 2016; Porter et al., 2014; Rosenzweig et al., 2014; Warszawski et al., 2014; Zabel, Putzenlechner, & Mauser, 2014). Previous studies have examined the potential performance of certain energy crops for specific regions with field trials (e.g. Dong et al., 2019; Roncucci, Nassi o Di Nasso, Bonari, & Ragaglini, 2015), land suitability (LS) modelling (e.g. Feng et al., 2017; Kahsay, Haile, Gebresamuel, & Mohammed, 2018) and process driven crop models (e.g. Beringer, Lucht, & Schaphoff, 2011; Haberl et al., 2011). However, as food supply and environmental protection should be prioritized over supply of energy crops, it is vital that climate impacts are modelled in the context of land-use scenarios, and that the role of marginal quality land is considered. A comprehensive global study examining the potential distribution of a wide range of energy crops accounting for climate change impacts and land-use scenarios is so far lacking but required.

Looking to reduce the social and environmental issues of direct and indirect land-use change, biomass resource assessments have focussed on the potential for marginal lands to provide the additional areas required (Jia et al., 2019; Mehmood et al., 2017), and second-generation feedstocks (lignocellulosic grasses, short rotation coppice and forestry, crop and forestry residues) are projected to be play an increasing role (Schueler, Fuss, Steckel, Weddige, & Beringer, 2016). It is posited that improvements in food agricultural practices, cropping intensification, multiple harvests per year and more efficient spatial allocation could also liberate land for energy crops, though recent studies disagree as to whether they will be sufficient to ensure future bioenergy demands can be met without expanding cropland (Henry et al., 2018; Mauser et al., 2015). There also remains significant uncertainty over the yields that can be expected from commercial plantations of second-generation energy crops on marginal lands due to the land quality, scaling up of plot-size and the extent to which trends from food crops may be applied to grassy and woody crops (Searle & Malins, 2015).

Key elements of various second-generation bioenergy technologies are still some way off being commercially ready (Workman, Dooley, Lomax, Maltby, & Darch, 2020) and while policy interest in advanced biofuels is strong in Europe, India and the United States, the investment landscape remains challenging (IEA, 2019). The critical role bioenergy is expected to play in the urgent decarbonization challenge requires that the environmental sustainability and economic viability of all potential resources are considered, including those with both new and mature conversion pathways (IEA, 2017). It is therefore now appropriate to consider the potential for a wide range of energy crops on all lands.

This paper presents a comprehensive global assessment of the land suitable for first- and second-generation energy crops under a changing climate with a scenario-based examination of land-use. By identifying hotspots of land competition risk, areas where land is highly or just marginally suitable for energy crops, and how these areas will change over the century, it lays groundwork for further studies on energy crop yields, commercial viability, environmental policy and international trade of biomass.

We address the following questions: (a) What is the current spatial distribution of areas suitable for growing energy crops? (b) How do the suitable areas overlap with other land-uses and where are the hotspots for potential competition between energy crops, food and forestry? (c) When land required for food, urban and protected areas is excluded, how is climate change projected to impact the areas suitable for growing energy crops in the context of socio-economic development?

The following sections describe the spatial modelling methods and the scenarios examined (Section 2), the modelling results for the current and future periods to illustrate the interactions of climate change and land-use (Section 3) and finally a discussion of the results in the context of the questions above (Section 4).

2 | METHODS

A two-step modelling approach was employed. First, a high-resolution spatially explicit LS model was enhanced and used to simulate the suitability of land for energy crops under current and future climatic conditions. For this, a database of crop requirements, known as 'membership functions', was developed from LS and agronomy literature. Second, 'land-use masks' representing the land required for other purposes (urban areas, food agriculture, natural or managed forest and protected designations) were constructed from spatial datasets for two scenarios and applied to the suitability maps. The gridded results of LS on potentially available areas were then aggregated for a set of 22 geographic regions and climate model uncertainty was considered. More details of these steps are provided below.

The crops listed in Table 1 were modelled, as literature suggests they are the most promising in terms of their potential cultivation and suitability for conversion to useful energy carriers such as pellets and liquid fuels (Chum et al., 2011; Creutzig et al., 2015; Searle & Malins, 2015). As discussed above, first- and second-generation crops are modelled; third generation feedstocks such as algae are not included as they are still far from being commercially viable on a large scale (IEA Bioenergy, 2017). The crops were modelled individually and the results aggregated into four groups according to their use as feedstocks in bioenergy technologies. In general, starch/sugar crops are converted to first-generation bioethanol, oil crops are converted to first-generation biodiesel and grasses and wood crops are used for combustion, gasification and cellulosic bioethanol (Chum et al., 2011; Creutzig et al., 2015). Residues from several first-generation crops can also be used as cellulosic feedstock. All crops are modelled globally for a comprehensive assessment.

TABLE 1 Energy crops and feedstock groups modelled

Feedstock group	Crop
1. Sugar & starch crops	Sugar cane
	Sugar beet
	Sorghum
	Wheat
	Maize
	Cassava
2. Oil crops	Rapeseed
	Soy
	Oil palm
	Jatropha
3. Grasses	Miscanthus
	Switchgrass
	Reed canary grass
4. Short rotation coppice/forestry crop	Eucalyptus
	Willow/Poplar

2.1 | LS modelling

To ascertain the areas suitable for growing each crop, an advanced version of the fuzzy logic LS model developed by Zabel et al. (2014) was applied. This type of model indicates the spatial distribution of suitable cropping areas with relatively low computational requirements and is suited to modelling crops with uncertain physical growth parameters (Feng et al., 2017; Joss, Hall, Sidders, & Keddy, 2008).

The LS model derives the suitability of each grid cell for the cultivation of a crop by comparing the crop's climate, soil and topographic requirements with global gridded data sets of the same conditions. The mean temperature, total precipitation and minimum radiation requirements inform the climatic suitability, and the following soil properties are considered: soil depth, texture, proportion of coarse fragments, proportion of gypsum, base saturation, pH, proportion of organic carbon, salinity and sodicity. While the soil parameters are assumed to remain constant over time, daily climate data are used to identify an optimal growing period in the year under consideration. The LS for each grid square is effectively determined by the least suitable parameter, based on the Sprengel–Liebig Law of the Minimum (Gleeson & Tilman, 1992).

The application of fertilizers is not considered, as this approach assesses the technical potential for energy crop land, independent of the current land-use and possible management decisions. This is appropriate due to the uncertainty over the economic value of applying fertilizers to energy crops (Field, Marx, Easter, Adler, & Paustian, 2016; Lutes, Oelbermann, Thevathasan, & Gordon, 2019; Nassi O Di Nasso, Lasorella, Roncucci, & Bonari, 2015; Roncucci et al., 2015).

Further details of the LS model are provided in Zabel et al. (2014) and the Supporting Information (S1 and S2). For this study, the LS model was enhanced:

1. Soil depth was added as a parameter, as literature indicates insufficient soil depth can limit physical rooting space and availability of moisture and nutrients (FAO, 1985; Yohannes & Soromessa, 2018). The DAAC dataset of depth to bedrock was selected as it represents the maximum potential depth of permeable soil (Pelletier et al., 2016).
2. The radiation condition was adjusted so that it was not applied for crops with a growing cycle of 365 days, in order that the model did not artificially prohibit the suitability of perennial crops at higher latitudes.
3. The model was adjusted to output the limiting parameter in each cell (for the most suitable crop only) so that the importance of slope, climate, soil, permafrost and soil depth could be investigated.
4. The model was driven by several climate datasets individually with membership functions for an extended set of crops, an improved dataset of irrigated areas was used and climate model uncertainty assessed (see below).

2.1.1 | Membership functions

Membership functions were compiled for each crop based on information from Sys, Van Ranst, Debaveye, and Beernaert (1993), the FAO EcoCrop database (FAO, 2007), a range of LS and agronomy studies and grey literature sources. Where data for a specific crop and parameter could not be found, values were inferred from qualitative comments regarding that crop and data for similar crops. If no comments or similar crop data could be identified, the membership function for that parameter was set to 1 so that it would place no limitation on the suitability. If no indication of suitability was found for a particular soil texture, the suitability was set to the value of the most similar soil texture for which there were data or set to 1. Literature indicates several species of eucalyptus may be promising for bioenergy; to represent these with a single set of model runs, the temperature and precipitation membership functions for eucalyptus were set to the mean values across those species. For crops which are harvested less than once per year, the length of growing season was set to 365 days and the temperature and precipitation requirements set as annual mean and total values respectively. The full membership functions and data sources are given in Supporting Information S3.

2.1.2 | Modelling procedure

The suitability model was run for each crop with climate data representing 30-year averages for the period 1980–2009 and three future periods (2010–39, 2040–69, 2070–99) for two GHG concentration pathways (RCP2.6 and RCP8.5) from five climate models (GFDL, HadGEM2, IPSL, MIROC and NorESM1). These five general circulation models (GCMs) were chosen as they represent a wide range of the global mean temperature and precipitation changes seen in the full CMIP5 model ensemble (Warszawski et al., 2014). The model was run with each GCM individually in order to preserve the spatial and temporal consistency of the temperature and precipitation conditions, as represented by the atmospheric physics in each model. A high spatial resolution of 0.5 arcmin (approximately 1 km^2 at the Equator) was chosen in order that the resulting suitability takes into account local soil, topography and climate conditions, as represented in the input data. Climate data was statistically downscaled from 30 to 0.5 arcmin spatial resolution and bias corrected (Zabel et al., 2014).

To simulate the suitability of land with irrigation, the model was also run without the precipitation constraint, representing a case where water availability is no limitation to growth. These results were taken for the areas which are currently irrigated, as identified from the dataset developed by Meier, Zabel, and Mauser (2018), and combined with the rainfed results for non-irrigated areas. We assume no expansion of irrigation in all of our scenarios because, while recent work has examined water irrigation requirements under socio-economic scenarios (Nechifor & Winning, 2017), literature indicates significant uncertainty over the relative importance of climate and human interference in irrigation water availability considering the competition with other demands (Elliott et al., 2014; Haddeland et al., 2014) and judgements about the changing financial viability of irrigating energy crops are outside the scope of this study.

Rasters were then created representing the suitability of each feedstock group (Table 1): in each cell, for each group, the highest suitability score of the crops in the group was chosen in order to create maps of suitability for the best 'sugar/starch crop', 'oil crop', 'grass crop', 'wood crop', as well as the best overall energy crop. This represents the assumption that farmers choose the most suitable crop for their land in each group, provided a market is available for its sale, and that markets would be available for the sale of crops based on their uses for bioenergy conversion. Suitability results were classified into three bands for each crop type: marginally suitable = 1–32, moderately suitable = 33–74, highly suitable = 75–100.

2.2 | Land-use modelling

It is assumed that energy crops are the last priority of any land allocation strategy. Land required for other purposes (food agriculture, urban areas, forests and protected areas) was identified and removed from the derived suitability maps, according to the scenarios described in Section 2.3. Note, issues of land tenure are not considered in this modelling. For each scenario and time period, the relevant spatial datasets were resampled to 0.5 arcmin resolution, then used to classify each cell as ‘available’ or ‘unavailable’. If a cell was available in all the layers, it was classified as available in the final mask. More detail is given in Supporting Information S1 and all input data sets are listed in Supporting Information S2.

Protected areas were identified from the World Database of Protected Areas (UNEP-WCMC-IUCN, 2016) and forested land was identified from the ESA GlobCover2009 dataset, which includes both natural and managed forests (Bontemps et al., 2011). It is assumed that all areas that are currently protected or forested will remain so, and so will be unavailable for energy crops. The protection of all current forested land is consistent with the assumption that conversion of forest to cropland would likely result in net positive GHG emissions or other adverse environmental impacts and so is unlikely to be preferable for a climate change mitigation strategy (Harris, Spake, & Taylor, 2015).

Land required for food agriculture and urban areas are considered to change with time, consistent with the shared socio-economic pathways (SSPs; Riahi et al., 2017). Spatially explicit projections of land required for food, fibre, fodder crops and intensive pasture were taken from the IMAGE modelling framework (Doelman et al., 2018). Projections of urban land under the SSPs were derived from the spatially explicit global population density datasets developed by Jones and O'Neil (2016). Cells with population density greater than 140 people/km^2 were masked as unavailable for crops; this threshold was derived by comparing the 2010 population density map from this study with current urban extent polygons (CIESIN, Columbia University, CIDR, IFPRI, The World Bank, CIAT, 2017).

For each scenario, time period and GCM, the relevant land-use mask was applied to the suitability results, then the areas of available land in each of the suitability bands within each of 22 geographic regions (Figure 1) were summed. These areas were averaged over the climate models to create an ensemble mean result. The mean was taken rather than the median in order that the average takes into account all the climate models equally, as none are considered more reliable than the others or outliers (Warszawski et al., 2014). The minimum and maximum areas for each time period are presented as an indicator of climate model uncertainty.

2.3 | Scenarios

Scenarios are used to explore a range of plausible, self-consistent storylines of future climate change and land-use. Results for the period 1980–2009 are the same for all scenarios and are examined to illustrate the ‘current’ situation. Two GHG concentration pathways (RCP2.6 and RCP8.5) are selected to represent a low and high climate change scenario respectively, mapping a wide range of future climate conditions under which the suitability for energy crops could change. RCP2.6 is consistent with an increase in the global average temperature of approximately 1.6°C by 2100 relative to pre-industrial levels; RCP8.5 is consistent with an increase of approximately 4.3°C (Stocker et al., 2013). For the land-use masks, two scenarios are created—forest and protected areas are excluded and food and urban areas are taken for two

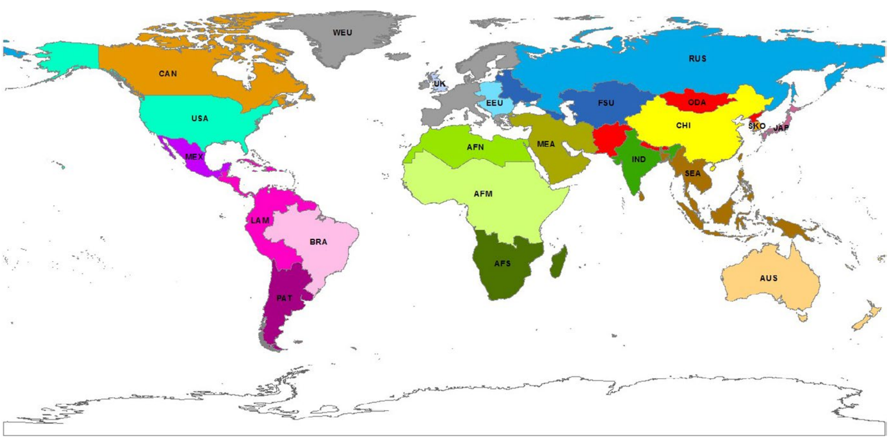

FIGURE 1 Regions for results aggregation. Countries included in each region are shown in Supporting Information S4. As shown, the Former Soviet Union region excludes Russia

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pathways of socio-economic development (SSP2 and SSP5). The three resulting scenarios are summarized in Table 2.

SSP2 depicts a 'middle of the road' pathway of socio-economic development, with medium population growth, medium urbanization and medium land-use for food agriculture. Due to land competition, it is thus expected to result in medium availability of bioenergy feedstocks (Fricko et al., 2017). The baseline SSP2 scenario is considered consistent with a radiative forcing level of approximately 6.5 W/m^2 in 2100 (not as high as RCP8.5), and could be combined with mitigation policies to reduce GHGs down to RCP1.9 (Doelman et al., 2018; Riahi et al., 2017). SSP5 depicts a world with high fossil-fuelled development, high population and GDP growth and meat-heavy, wasteful food consumption (Kriegler et al., 2017). It is considered consistent with the very high radiative forcing pathway RCP8.5 (Riahi et al., 2017) but mitigation down to RCP2.6 is also considered feasible (Doelman et al., 2018). With a strong reliance on technical solutions rather than demand reductions, climate change mitigation under SSP5 is expected to require a large role for forest regulation and a high demand for bioenergy feedstocks. However, among the SSPs, it has the second highest requirement for crop and grazing land and so presents strong risks for land competition should energy crops be required.

In the scenario of moderate climate change (RCP2.6), comparing the SSP2 and SSP5 scenarios indicates the impact of changes in food agricultural areas, and to a lesser extent urban expansion. In the scenario of SSP5 land-use, comparing the RCP2.6 and RCP8.5 cases shows the impact of stronger climate change. *RCP8.5_SSP5* is modelled in order to examine the sensitivity of potential energy crop land in a high climate change case, which could affect countries' potential to deploy rapid mitigation measures in the middle and end of the century in case the 1.5 or 2°C targets are exceeded.

3 | RESULTS

Table 3 shows the global areas suitable and potentially available for each crop type and scenario at the start and end of this century. Table 4 shows the results excluding the marginally suitable land. The full regional results, along with the minimum and maximum areas from the five climate models are provided in Supporting Information S5 and S9. We find that over the century, the total global area suitable and available for energy crops (see the 'All Energy Crops' column) is changed by −1.3% (in RCP2.6_SSP2), −7.5% (RCP2.6_SSP5) and +4.3% (RCP8.5_SSP5).

The following sections present the results for the period 1980–2009 then future periods with a comparison of scenarios to examine the impacts of climate change, socio-economic development and forest conservation.

TABLE 2 Scenario framework in which climate change and land-use cases are combined

	Land-use	
Climate change	**Current protected areas and forests Food agriculture and urban land from SSP2**	**Current protected areas and forests Food agriculture and urban land from SSP5**
RCP2.6	*RCP2.6_SSP2*	*RCP2.6_SSP5*
RCP8.5		*RCP8.5_SSP5*

TABLE 3 Global suitable, potentially available areas for each crop type (million km^2) for the historic period and for the end of the century for each scenario: Including all suitability bands

		Sugar/ starch	**Oil**	**Grassy**	**Wood**	**All energy crops**
Historic period	1980–2009	17.4	17.5	13.2	8.2	18.8
RCP2.6_SSP2	2070–2099	16.9	17.5	12.5	7.0	18.6
RCP2.6_SSP5	2070–2099	15.8	16.4	11.5	6.2	17.4
RCP8.5_SSP5	2070–2099	17.3	17.6	13.5	6.6	19.6

TABLE 4 Global suitable, potentially available areas for each crop type (million km^2) for the historic period and for the end of the century for each scenario: High and moderately suitable areas

		Sugar/ starch	**Oil**	**Grass**	**Wood**	**All energy crops**
Historic period	1980–2009	6.5	6.7	5.1	3.0	9.5
RCP2.6_SSP2	2070–2099	6.0	6.3	4.6	2.4	8.9
RCP2.6_SSP5	2070–2099	5.5	5.8	4.3	2.1	8.2
RCP8.5_SSP5	2070–2099	5.3	5.7	5.0	2.1	8.8

3.1 | Historic period

3.1.1 | Overall suitability

In the period 1980–2009, the total area identified as suitable for energy crops with the current extent of irrigated areas was 76.9 million km^2. (Note: Antarctica and areas with no soil data were not modelled, so the results cover 127.5 million km^2, which is 86% of the total global land area). Figure 2 shows the suitability for each feedstock group, considering no land-use constraints. (See the overall suitability for energy crops in Supporting Information S6). Land suitable for the modelled wood crops is mostly located in Europe, central Africa, central South America, India, South East Asia and the eastern United States. Areas suitable for sugar/starch, oil and grass crops are more extensive, notably stretching across central Asia, western United States and wider areas in Africa and South America.

Limiting factors vary across the continents. Permafrost limits the suitability in northern Canada, Alaska, northern Scandinavia, much of Russia and western China. Soil depth is a key limiting factor in parts of Indonesia, southern Brazil and western Africa. In rainfed conditions, crop suitability is mainly limited by precipitation constraints in Northern Africa, the Middle East, central Asia and central Australia, while soil limits the suitability in most of South America, southern Africa, India and the Australian coastal regions.

The suitability bands show broadly similar patterns across the four crop types, with areas in central United States, central Africa, northern India and eastern China being highly suitable for all groups (Figure 2). The areas suitable for the four crop types overlap heavily, showing that the maximum bioenergy feedstocks cannot be exploited all at once. Within the four groups, the most suitable crops vary across the regions (see Supporting Information S7). We find that the best grass crops (miscanthus, switchgrass and reed canary grass) are largely mixed in all highly suitable regions due to the similarity in their climate and soil requirements. The best sugar/starch crops are more distinct geographically: sorghum and maize are clearly the most suitable in India, central Africa and Brazil, while wheat is the most suitable in the United States of America and China.

The proportions of land falling in each suitability band varies widely between regions. Figure 3 shows the areas in each suitability band in each region, considering all energy crops and no land-use constraints. Southern Africa, Brazil, Eastern Europe, India, Japan, South East Asia, South Korea and the United Kingdom each have over 90% of their land area suitable for energy crops. Much of this is just marginally suitable; when marginal land is excluded, Eastern Europe, India and South East Asia still have over 70% of their areas that are moderately or highly suitable. Northern Africa, Canada, the Middle East and Russia have the smallest proportions of suitable area at less than 30% in each region.

3.1.2 | Land competition

The areas potentially appropriate for energy crops are significantly constrained by other land-uses. Currently, when all urban areas, food agricultural land and protected zones are excluded, the total global area that is suitable and potentially available for energy crops (including all bands of suitability) is halved from 76.9 million km^2 to 37.6 million km^2. When all forests are also excluded, the total area is halved again to 18.8 million km^2, of which approximately half (9.5 million km^2) is highly or moderately suitable and the rest is just marginally suitable.

The overlap between areas suitable for energy crops and other uses indicates potential pressures on land-use as the biomass market develops. Figure 4 shows the current uses of the land that is judged suitable for energy crops: 40.1% of global land suitable for energy crops is currently used for food production, while 7.4% is protected land and 24.1% is unprotected forest. The level of overlap is higher in several regions. In Northern Africa, Eastern Europe, the Former Soviet Union, the United Kingdom and the United States more than half the suitable area is currently used for food agriculture, indicating significant potential risks to food security if this land were to be used for energy crops instead. In absolute terms, the regions with the most overlap with agricultural land are Central and Southern Africa, Australia, Brazil, China and the United States, which each have over 2 million km^2 of overlapping area. In Canada, Japan, Latin America and Brazil, more than half the suitable energy crop land is currently protected or forested, indicating there could be high pressure in these regions on land that is valuable for biodiversity, carbon sequestration other ecosystem services.

Other regions have significant potential to cultivate land for energy crops which is not currently urban, cultivated, forested or protected. Australia, the Middle East and the Other Developing Asia region have the largest percentage of suitable land that is potentially available (each over 39%). In absolute terms, this area is largest in the regions of Central Africa, Southern Africa and Australia—each over 2 million km^2. The land that is considered potentially available for energy crops in this study, i.e. which don't overlap with urban, food, protected for forested land, is currently a variety of land types. The current land cover of these areas, derived by comparison with data from IMAGE (Doelman et al., 2018), is shown in Supporting Information S8. Globally, 19%, 18% and 12% of the suitable, potentially available land is identified as non-intensive pasture, savannah and grassland-steppe respectively. The carbon balance, impact on ecosystem services and social and economic implications of converting these types of land must be carefully considered.

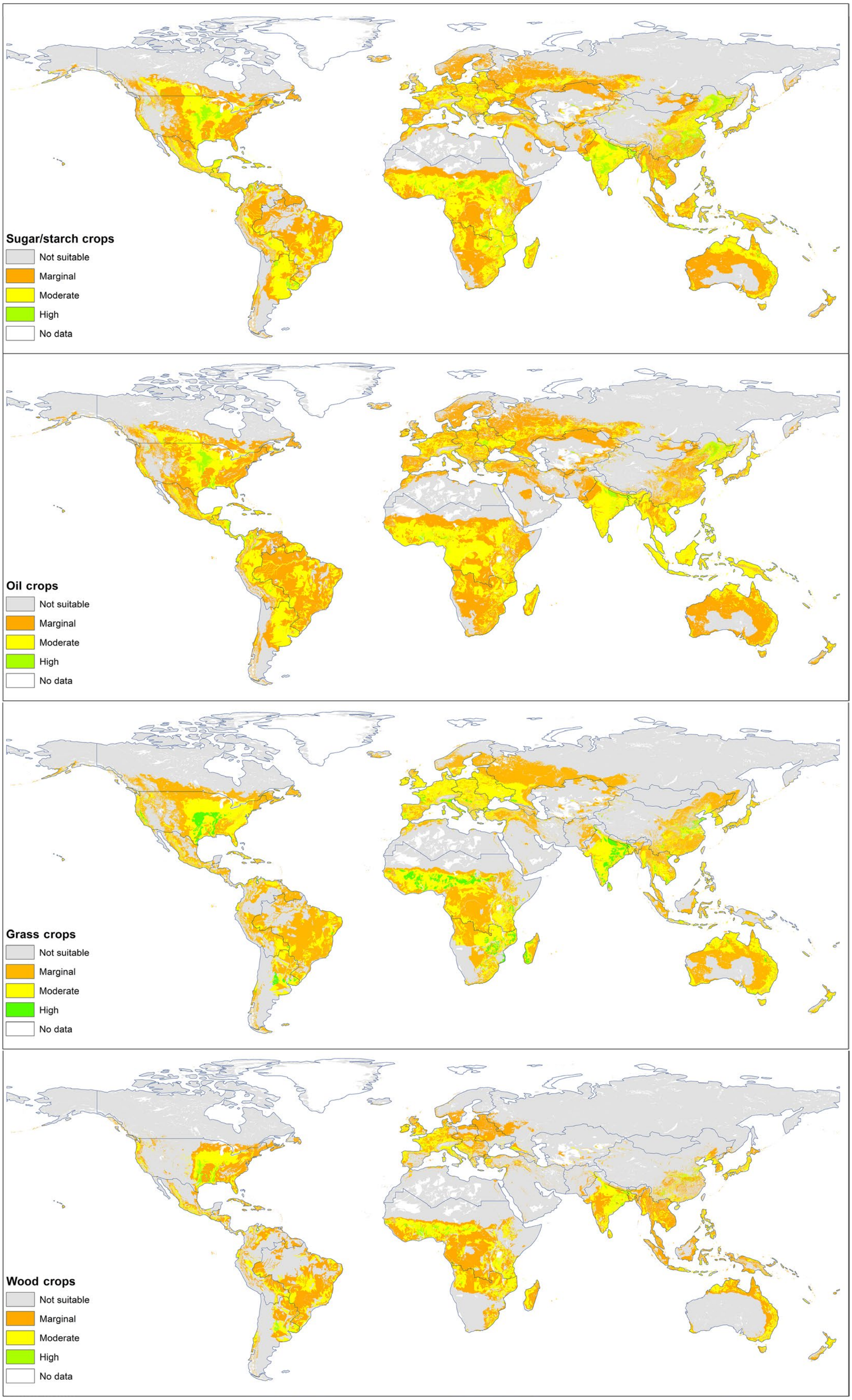

FIGURE 2 Suitability for energy crops, grouped by crop type: sugar/starch, oil, grass, wood crops (1980–2009)

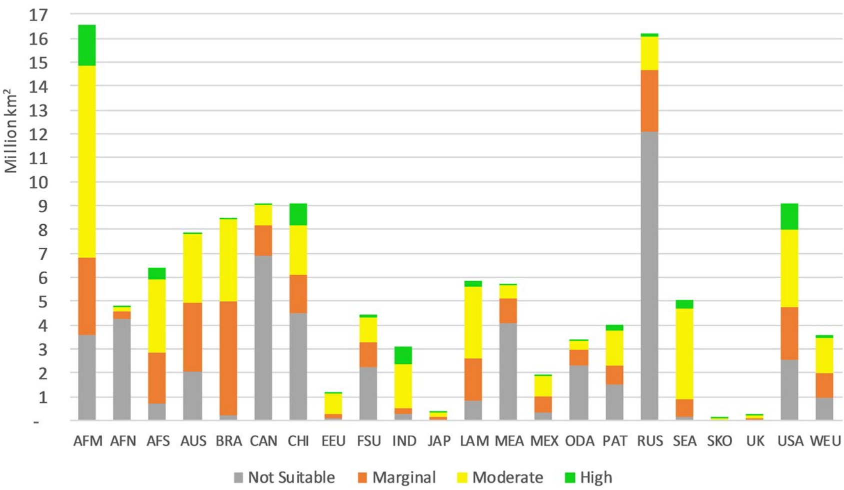

FIGURE 3 Area of land in each suitability band for energy crops in each region (1980–2009), with no land-use constraints (see Figure 1 and Supporting Information S4 for region codes)

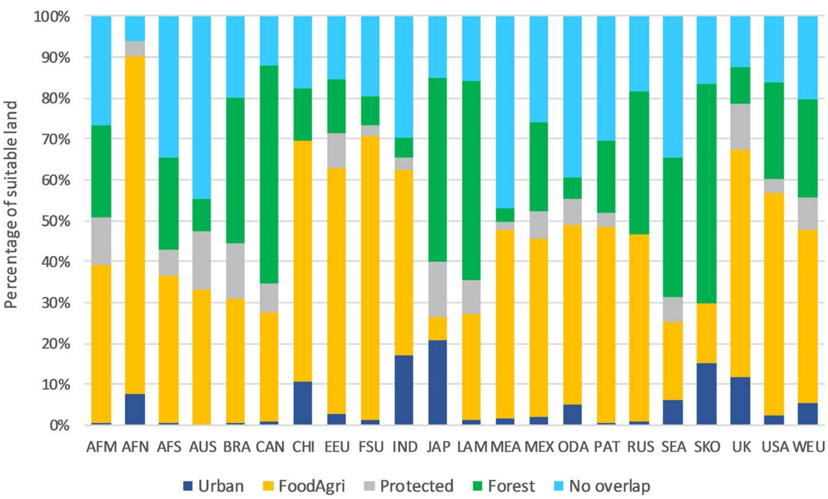

FIGURE 4 Current land-use for areas that are suitable for energy crops, 1980–2009. If land was identified as more than one land cover type, it was allocated its land-type in the following order of preference: urban, food agriculture, protected area, forest

3.2 | Future suitability: Impacts of climate and land-use change

The following paragraphs describe changes in the overall energy crop suitability and the four crop groups in the scenarios of climate change and socio-economic development.

3.2.1 | Overall suitability

Considering no land-use constraints, climate change has an overall positive effect on the global suitability for energy crops, increasing the total area suitable for energy crops over the century by 5.6% under *RCP2.6* and by 13.2% under *RCP8.5*. However, the areas required for food agriculture and urban land increase under SSP2 and SSP5 to support the growing population. This means the total area potentially available for energy crops is reduced over the century in both land-use scenarios: by 4.0% under *SSP2* and by 6.8% under *SSP5*.

The land-use constraints and climate impacts balance out differently across the scenarios (Figure 5). Under moderate climate change and central socio-economic development (*RCP2.6_SSP2*), the positive impact of moderate climate change on LS almost balances the negative impact of higher land-use constraints so the total area that is suitable and available decreases by only 1.3%. Under the high growth socio-economic scenario, the higher land-use constraints clearly outweigh the positive impacts of moderate climate change, as the total suitable-available area decreases by 7.5% over the century (*RCP2.6_SSP5*). Under the scenario of strong climate change and high growth development (*RCP8.5_SSP5*), the improved LS more than makes up for the higher land-use constraint, so the global suitable-available area increases by 4.3%.

Within the total suitable-available land, there is a shift in the suitability levels (Figure 5). In all scenarios, the global area of potentially available land that is highly or moderately suitable decreases (most significantly by 13.7% over the century under *RCP2.6_SSP5*), whereas the area of marginal land stays almost constant (in *RCP2.6_SSP5*) or increases (most significantly by 16.9% under *RCP8.5_SSP5*). We see that overall, the area of marginally suitable land is increased globally but the area of the best land is decreased. The following

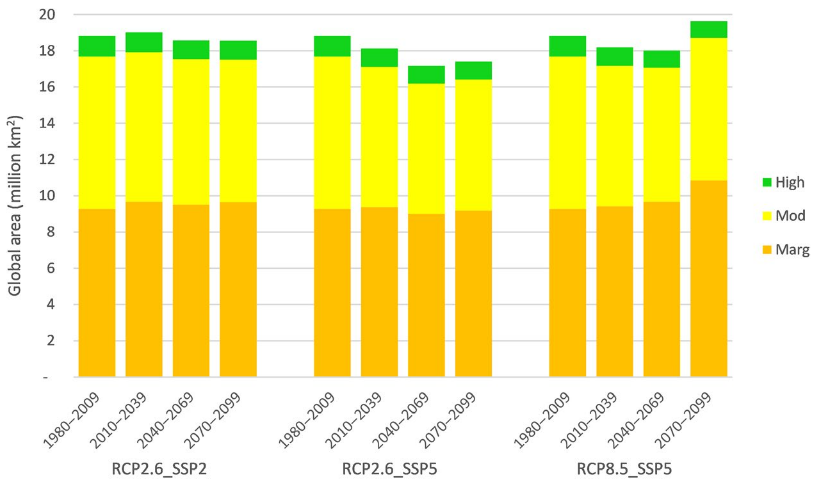

FIGURE 5 Global areas suitable and available for energy crops to the end of the century

paragraphs examine the breakdown of this global trend between crop types and regions, and the practicality of exploiting the newly suitable land.

Different patterns are observed across geographic regions (Figure 6; Supporting Information S5). In all three cases, suitable-available areas generally increase in northern regions, and decrease for regions at lower latitudes. Notably, under the scenario *RCP2.6_SSP2*, in addition to substantial increases in marginally suitable land, the highly and moderately suitable area in Russia and the Former Soviet Union region is almost doubled by the end of the century, while it is increased by 35%–65% in Canada, China, Eastern Europe, the United Kingdom and the Other Developing Asia region. This is due to the rising temperatures bringing climatic conditions within suitable ranges. Losses of suitable-available land are projected in southern regions. At the start of the century, there was over 0.6 million km^2 of moderately and highly suitable-available land in each of Central and Southern Africa, Australia, Brazil, India and South East Asia, but these areas are projected to decrease by 7%–35% over the century.

In the lower climate change scenario (*RCP2.6_SSP5*), the land-use change associated with the SSP5 storyline is projected to have a larger effect in southern regions than in northern regions. In southern regions, the additional requirements for food land under SSP5 compound the negative impacts of climate change, indicating potential energy crop resources are vulnerable to both climate impacts and land-use constraints in these regions. Conversely, the increases in the northern regions are not substantially affected by the different land-use scenarios, as the additional suitable land does not compete with food or urban land.

In the higher climate change scenario (*RCP8.5_SSP5*), areas in the northern regions are strongly increased, particularly for marginal land, showing that the changing climatic conditions dominate in these high-latitude regions. Very substantial increases in marginally and moderately suitable-available land are seen for China, Canada and Russia. Over the century, in these three regions together, an additional 2 million km^2 of potentially available land becomes marginally suitable and 1.1 million km^2 becomes moderately and highly suitable.

3.2.2 | Suitability for each crop type

Figure 7 shows how the impacts of climate and land-use change vary for the four crop types. This analysis indicates the regions in which different crops could be prioritized in the coming decades. As for the overall suitability discussed above, over the century, the areas are mainly increased in northern regions and decreased in southern regions for all crop types. For most regions, similar changes are projected for sugar/starch and oil crops, as there is large overlap between the areas suitable for these crop types. The regional increases are notably smaller for wood crops than the other crop types. The following paragraphs examine the balance between climate and land-use change impacts for the different crop types.

In the northern regions, changing land-use constraints due to socio-economic development combine differently across scenarios, crop types and regions. In the scenario of lower climate change, the suitable areas increase in Canada, China, the Former Soviet Union and Russia by very similar amounts in *RCP2.6_SSP2* and *RCP2.6_SSP5*, indicating that climate change expands suitable areas for all crop types into regions which do not compete with food and urban land. In the scenario of stronger climate change (*RCP8.5_SSP5*), there are large increases in Canada, China and Russia for sugar/starch, oil and grass crops, showing the potential to cultivate those crops in these regions would increase substantially in a scenario of strong climate change, even if demand for agricultural land is high. However, in the Former Soviet Union region, the increase in area is limited by the land-use requirements. In the United States and Western Europe, land competition with food crops is high. Climate change increases the

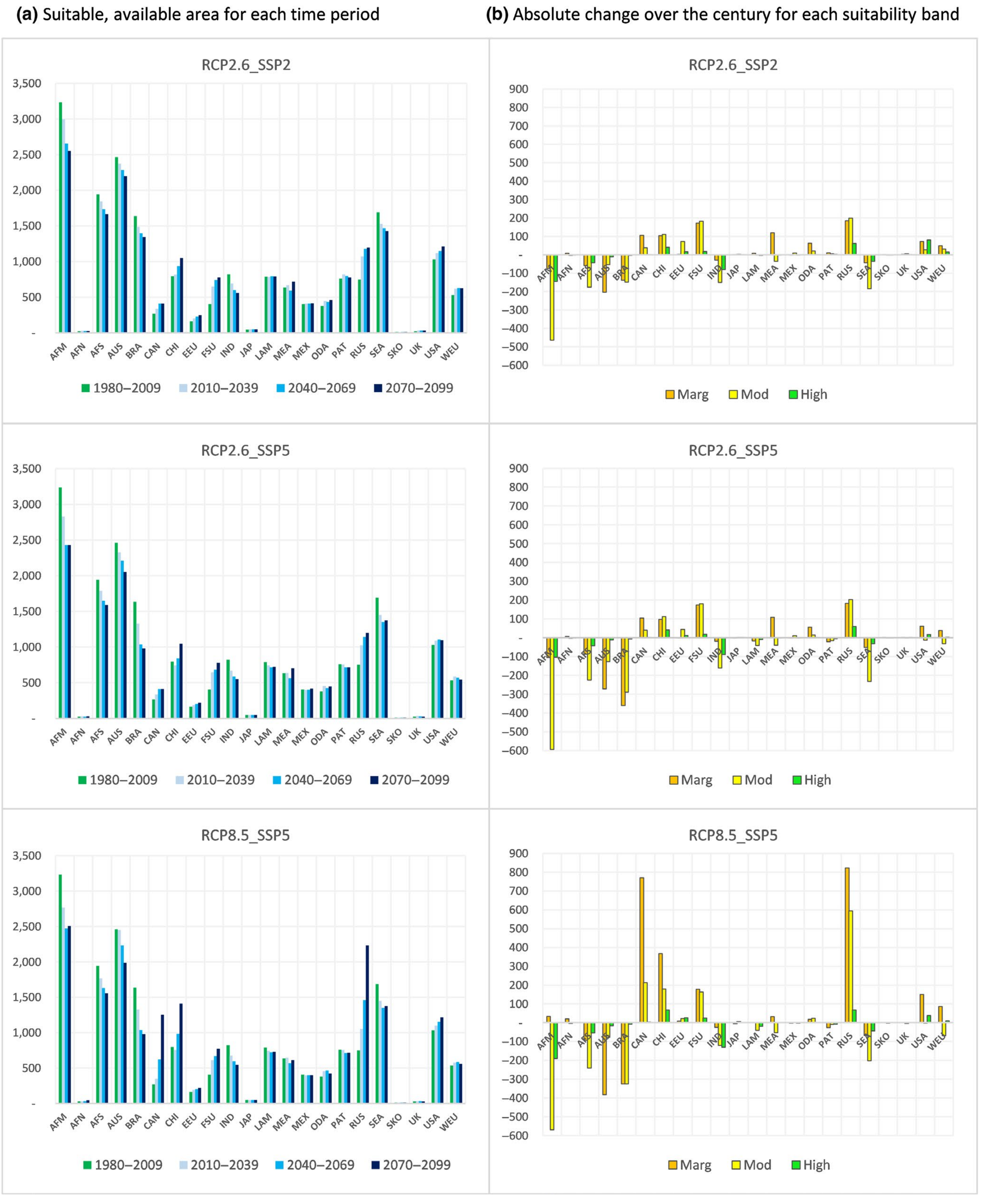

FIGURE 6 (a) Total area of suitable land for each region for each time period (including all suitability bands; thousand km^2) and (b) the change in suitable area between the beginning and end of the century for each suitability band (thousand km^2)

suitability of marginal land for all crop types but under *SSP5* the increased demand on agricultural land means most of that land is unavailable for energy crops. So for wood crops in the United States and all crop types in Western Europe, almost no change is seen in *RCP2.6_SSP5* and *RCP8.5_SSP5* over the century.

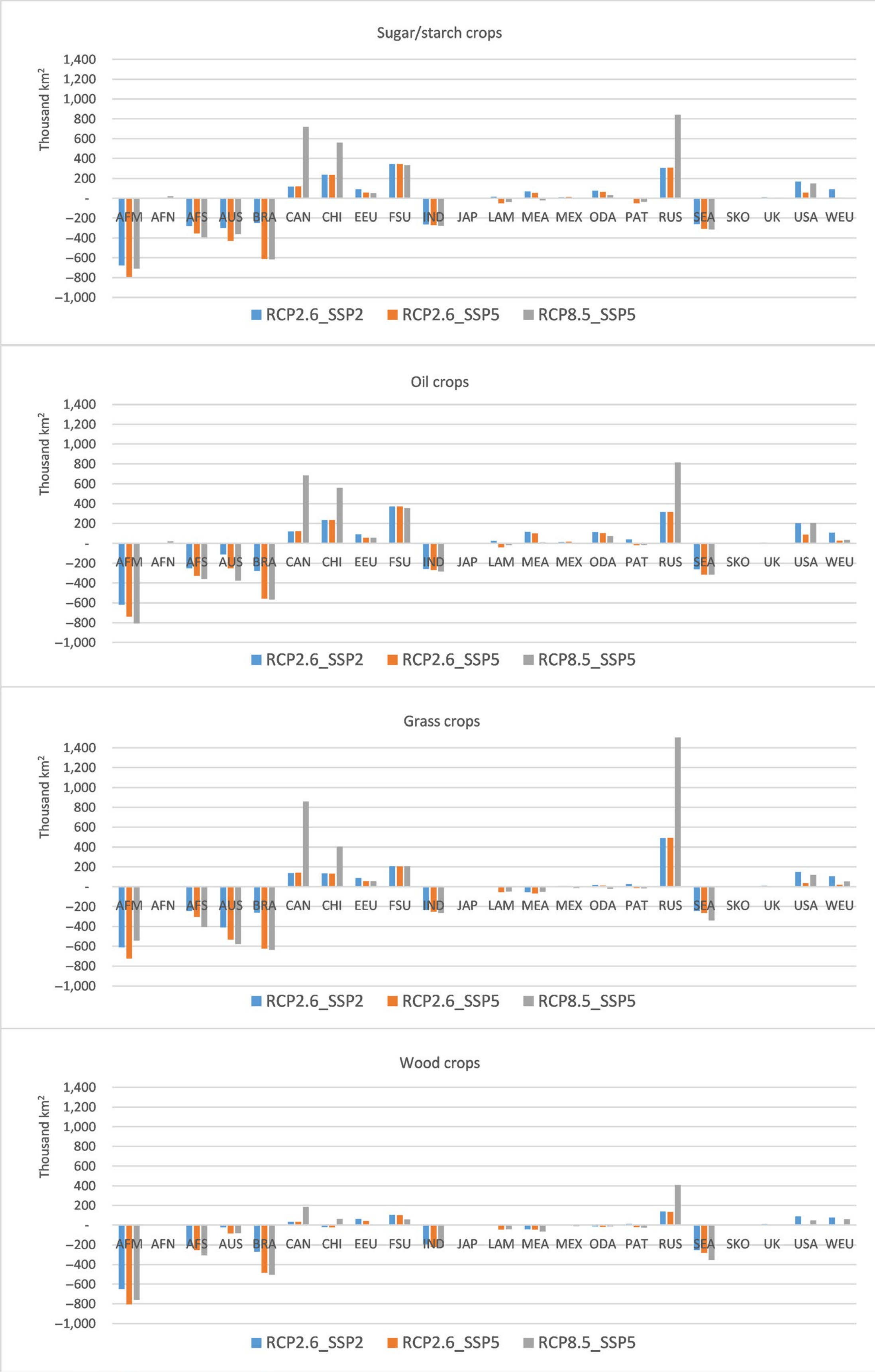

FIGURE 7 Change in the total suitable area of each crop group in each region between 1980–2009 and 2070–2099, including all suitability bands

In the southern regions (Central and Southern Africa, Australia, Brazil, India and South East Asia), both climate change and land-use requirements reduce the areas for all crop types. In Central Africa for sugar/starch, grassy and wood crops, the area is most reduced in the *RCP2.6_SSP5* scenario; moderate climate change and SSP5 land-use constraints decrease the suitable-available land substantially, but stronger climate change in fact slightly mitigates the loss of suitable land.

The largest absolute losses are projected for wood crops in Central Africa (−0.6 million km^2) and Brazil (−0.4 million km^2), and the other crop types in Central and Southern Africa, Brazil, South East Asia, Australia and India. Some regions have relatively small areas of currently suitable-available land (see Figure 6a and Supporting Information S5) but are projected to undergo large percentage changes by the end of the century. For example, in Northern Africa, the area for sugar/starch and oil crops is projected to increase by 30%–95% but decrease by up to 57% for grassy and wood crops.

The largest increases are projected for grass, sugar/starch and oil crops in the most northern regions in the scenario of strong climate change. Under *RCP8.5_SSP5*, the suitable-available areas increase by 0.4–0.8 million km^2 in Canada and China by the end of the century, and by over 0.8–1.5 million km^2 in Russia. The changes in Canada and Russia for wood crops under the strong climate change scenario represent the biggest proportional changes (688% and 1,125% respectively). These changes are accounted for by substantial increases in marginal and moderately suitable land due to rising temperatures.

3.2.3 | Land competition

As for the period 1980–2009, the current land cover of the areas identified as suitable and potentially available in 2070–2099 was examined by comparison with the IMAGE data as described in Section 3.2. This was done for the high climate change scenario (*RCP8.5_SSP5*). Globally, by the end of the century, 19%, 10% and 9% of the suitable, potentially available land is identified as non-intensive pasture, grassland-steppe and savannah respectively. In Africa, Australia, the Middle East, Mexico and the Other Developing Asia region, over 30% is currently non-intensive pasture, indicating important choices to be made regarding food production and energy crops. In each of Central and Northern Africa, the Middle East and the Other Developing Asia regions, over 30% of the suitable-available land for energy crops at the end of the century is in areas currently identified as hot desert. In Canada and Russia, over 50% of the energy crop land is identified as lying what is currently boreal forest (the dataset from IMAGE used in this comparison differs somewhat from the higher resolution forest data used in the land availability modelling).

3.2.4 | Climate model uncertainty

As described in Section 2, the land-use masks were applied to the suitability results from each GCM individually and the areas of suitable-available land summed for each of the geographic regions. Uncertainty due to the inter-model variation is indicated by the range of results across the ensemble of GCMs, represented by the percentage differences between the maximum or minimum and the mean. These are shown in Supporting Information S9.

There is no consistent trend of the model variation being larger below or above the mean, indicating there is no clear skew in the distribution of models (Supporting Information S9.1). The climate model uncertainty generally increases with time across the century, and the uncertainties increase more under RCP8.5 than under RCP2.6, reflecting the divergence of the GCMs, consistent with the trend in the CMIP5 ensemble (IPCC, 2013). Considering the suitability results for the four crop groups with no land-use constraints applied, results from the individual GCMs vary from the mean by up to ±9% under *RCP2.6*, and up to ±16% in *RCP8.5*.

The uncertainties are higher for each of the four crop groups than for the overall suitability results, in which the best of the 15 crops is chosen in each grid cell, as the results are smoothed out more when the best crop is selected in each cell. Similarly, uncertainties on the regional results are higher than on the global results, due to there being less averaging out of the geographic variations. The inter-model uncertainty is greater when more land-use constraints are applied. While insights from this are limited as the land-use masks are unaffected by climate change in this analysis, it is noted that the uncertainties on the grass, sugar and oil crop areas are increased more than on the wood crop areas, due to the stronger overlap between the suitable areas for wood crops and forest. On the global areas the maximum inter-model variation is ±28% (grass crops in RCP8.5_SSP5 for 2070–2099). The uncertainty is under ±40% for most regions (Supporting Information S9.3), but is higher for a few, notably Northern Africa and the Middle East due to their small suitable areas.

4 | DISCUSSION

A high-resolution spatially explicit LS model was enhanced and applied to assess the land that could potentially be used for the cultivation of dedicated energy crops under scenarios of climate change and land-use change due to socio-economic development. Three main findings emerged relating to the research questions, which have implications for the potential supply of biomass, environmental risks and social impacts.

First, regarding the current distribution of suitable areas. Excluding current food and urban land, protected areas and forests, 18.8 million km^2 is currently suitable for energy crops, of which approximately half is at least moderately suitable. For reference, studies recently reviewed by the IPCC (Jia et al., 2019) indicate that 3.2–14.0 million km^2 of degraded or abandoned land are currently considered available for energy crops, depending on the sustainability criteria, land class definitions, land mapping methods and environmental and economic considerations included.

These areas are widely distributed across the world, with only areas in Patagonia, mountainous western United States, deserts in Northern Africa, the Middle East and central Australia, northern Asia and Canada being completely unsuitable. Highly suitable areas are concentrated in central United States, central Africa, northern India and eastern China. The similarity between the suitability distributions for the four crop types shows they cannot all be exploited to their full potential, and so crops should be prioritized considering the regional down-stream requirements for biomass feedstocks.

Second, regarding land competition. The overlaps between areas which are suitable for energy crops in terms of soil and climate conditions but are required for other uses indicate potential hotspots for land competition should a strong demand for biomass arise. Large proportions of the suitable energy crop land in Northern Africa, the Former Soviet Union, Eastern Europe, United Kingdom and United States are currently used for food, fibre and fodder agriculture (over 50% in each), suggesting that increased cultivation of energy crops in these regions could impact food prices, so careful regulation is likely needed to protect food security. The large proportions of suitable land which are currently forested in Canada, Japan, Latin America and Brazil (over 50% in each), suggest that large-scale cultivation of energy crops could drive deforestation in these regions. As the demands for biomass feedstocks increase and the international market develops, strong regulation is likely needed in these regions to avoid the loss of forests that are vital for carbon sequestration and biodiversity.

The areas found to be currently suitable for energy crops and not overlapping with protected areas, forests or other agricultural land are mainly grasslands, savannah and steppe. For regional and global-scale biomass resource projections and appropriate land policy design, comprehensive assessment of the carbon, ecosystem and livelihood implications of converting these land types for energy crops is needed.

Third, regarding how climate change and land-use due to socio-economic development affect potential cropping areas. Climate change is projected to have an overall positive impact on the total global area of land suitable for energy crops. However, in all scenarios the requirements for urban and other agricultural land grow over the century, which increases the constraints on land availability. Accounting for these changing constraints, the global area that is suitable and potentially available for energy crops changes by +1.3%, −7.5% and +4.3% over the century in the scenarios *RCP2.6_SSP2*, *RCP2.6_SSP5* and *RCP8.5_SSP5* respectively. The changes are larger in several regions; areas are mainly increased in northern regions, and decreased in southern regions in all three scenarios.

Comparing the three scenarios in this study indicates the relative importance of climate change and land-use change in affecting the potential cropping areas in the different regions. The increases in the northern regions are more sensitive to climate change than the decreases in the southern regions, as the southern regions are more constrained by other land requirements, indicating that particular attention should be paid to land competition in southern regions, and that cultivation of energy crops could be focussed in northern regions in a high climate change scenario with strong land-use regulation.

Considering these three sets of findings provides insights on the regions that could have a high potential for the cultivation of energy crops. In areas which do not overlap with current protected areas, forest and other agriculture. Accounting for these land-use constraints, Sub-Saharan Africa, Australia, Brazil and South East Asia currently have the greatest areas potentially suitable for energy crops. Together these regions account for 58% of the global suitable area (12 million km^2). By the end of the century, this share declines to 49% under RCP2.6 and 43% under RCP8.5. Due to climate change, Canada, Russia, the Former Soviet Union, China and the United States are projected to substantially increase their potential for sugar/starch, oil and grass crops, increasing their share of the global energy crop land from 17% to 26% under RCP2.6 and 35% under RCP8.5. By the end of the century, despite negative impacts of climate change, the largest potential land areas for wood crops are projected to be in Central Africa and South East Asia, followed by Australia and Brazil.

Along with the environmental and social implications of this potential land-use change, the yields that could be achieved on these areas, potential yield improvements over the coming decades and the likelihood of land far from current settlements being cultivated require further examination. Profitability of energy crops will depend on the yields, as well as the infrastructure and labour investments required to turn previously un-used areas to arable land then transport and process the feedstocks. The majority of the additional land in the northern regions is marginally and moderately suitable; this reiterates the importance of studying the potential yields of energy crops on sub-optimal land, as well as in large commercial-scale plots, rather than in small-scale field trials in ideal soil and climate conditions.

Certain factors make this modelling likely to be conservative. In the LS model, suitability is effectively limited by the least suitable parameter and it is assumed that each parameter is independent. In some cases conditions may mitigate each other, for example, jatropha is thought to be suitable in some very sandy soils as long as there are few heavy precipitation events (Obiero, Birech, Joyce, Kibet, & Freyer, 2013). The effect of CO_2 fertilization, thought to be important for C_3 crops (Allen, Baker, & Boote, 1996; Deryng et al., 2016; Nowak, 2017), is not accounted for here because it is not thought to affect suitable areas, but it could stimulate crop growth if the other requirements of the crop are sufficiently met. Key uncertainties in the study include the crop membership functions, the use of a single IAM to provide the gridded data of food agricultural land, and the assumption that soil parameters and irrigated areas are unchanged in the future. To reduce these uncertainties, studies should explore future changes in the soil parameters due to soil erosion and nutrient loss, the financially and environmentally sustainable use of irrigation for energy crops considering future water competition and climate, and more detailed consideration of adaptation options such as crop breeding and fertilizers for energy crops.

It is vital that the potential synergies and trade-offs between climate change mitigation, energy access and multiple other Sustainable Development Goals (Fuso Nerini et al., 2018) are kept in mind when planning the expansion of bioenergy pathways. Protecting and improving livelihoods, food security and biodiversity must be central to energy and land-use policy. While this study represents land parcels as single-use, in reality, land and crops are multi-functional and the decision-making of cultivators complex (Tomei & Helliwell, 2016). It may be possible to place limitations on the use of certain high-risk biofuels or feedstocks (EU, 2018), however global markets mean cultivators may convert existing food land for energy crops (by either diverting flex crops to the bioenergy market or changing crops), and convert other land for food production. So direct and indirect land-use change can occur at various scales (Di Lucia, Sevigné-Itoiz, Peterson, Bauen, & Slade, 2019; Tokgoz & Laborde, 2014; Valin et al., 2015; van der Hilst, Verstegen, Woltjer, Smeets, & Faaij, 2018). Careful regional planning and regulation are needed to avoid negative impacts on food security, livelihoods, biodiversity through land-use change or introduction of non-native species, and carbon balance, particularly in the regions highlighted, and particularly with relation to the potential expansion of cropping into grasslands. Mixed agricultural systems could offer opportunities for biodiversity, soil enrichment and mitigating risks to food security while still providing energy feedstocks (John & McIsaac, 2017).

Finally, the regional impacts of climate and land-use change on potential bioenergy crop land could have implications for domestic bioenergy use, inter-regional trade of resources and the costs of climate change mitigation. Through the role of biomass in the wider energy system, there is likely to be a feedback effect with climate change itself. It is therefore vital that climate impacts feature in IAMs. Further work will focus on converting these projections of suitable-available land into projections of resource by analysing the overlap of suitable areas, considering the practicality of cultivation in remote areas, grassland sustainability constraints and incorporating the energy content of individual crops, along with yield projections for the future scenarios. Regional feedstock availabilities accounting for climate change impacts will be integrated into the global energy system model TIAM-UCL as a climate feedback mechanism, in order to investigate the effects on the long-term role of bioenergy in energy system decarbonization.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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