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Carbon implications of converting cropland to bioenergy crops or forest for climate mitigation: a global assessment

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Abstract

The potential for climate change mitigation by bioenergy crops and terrestrial carbon sinks has been the object of intensive research in the past decade. There has been much debate about whether energy crops used to offset fossil fuel use, or carbon sequestration in forests, would provide the best climate mitigation benefit. Most current food cropland is unlikely to be used for bioenergy, but in many regions of the world, a proportion of cropland is being abandoned, particularly marginal croplands, and some of this land is now being used for bioenergy. In this study, we assess the consequences of land-use change on cropland. We first identify areas where cropland is so productive that it may never be converted and assess the potential of the remaining cropland to mitigate climate change by identifying which alternative land use provides the best climate benefit: C_4 grass bioenergy crops, coppiced woody energy crops or allowing forest regrowth to create a carbon sink. We do not present this as a scenario of land-use change – we simply assess the best option in any given global location should a land-use change occur. To do this, we use global biomass potential studies based on food crop productivity, forest inventory data and dynamic global vegetation models to provide, for the first time, a global comparison of the climate change implications of either deploying bioenergy crops or allowing forest regeneration on current crop land, over a period of 20 years starting in the nominal year of 2000 AD. Globally, the extent of cropland on which conversion to energy crops or forest would result in a net carbon loss, and therefore likely always to remain as cropland, was estimated to be about 420.1 Mha, or 35.6% of the total cropland in Africa, 40.3% in Asia and Russia Federation, 30.8% in Europe-25, 48.4% in North America, 13.7% in South America and 58.5% in Oceania. Fast growing C_4 grasses such as *Miscanthus* and switch-grass cultivars are the bioenergy feedstock with the highest climate mitigation potential. Fast growing C_4 grasses such as *Miscanthus* and switch-grass cultivars provide the best climate mitigation option on ≈485 Mha of cropland worldwide with ~42% of this land characterized by a terrain slope equal or above 20%. If that land-use change did occur, it would displace ≈58.1 Pg fossil fuel C equivalent (C_{eq} oil). Woody energy crops such as poplar, willow and Eucalyptus species would be the best option on only 2.4% (≈26.3 Mha) of current cropland, and if this land-use change occurred, it would displace ≈0.9 Pg C_{eq} oil. Allowing cropland to revert to forest would be the best climate mitigation option on ≈17% of current cropland (≈184.5 Mha), and if this land-use change occurred, it would sequester ≈5.8 Pg C in biomass in the 20-year-old forest and ≈2.7 Pg C in soil. This study is spatially explicit, so also serves to identify the regional differences in the efficacy of different climate mitigation options, informing policymakers developing regionally or nationally appropriate mitigation actions.

Introduction

In the past century, the impact of human activities on the global environment has intensified due to increasing population, raw material consumption and increased industrial activity. Globally, agriculture, forestry and other land use together are responsible for just under a quarter of anthropogenic greenhouse gas emissions (Smith et al., 2014). According to the Food and Agricul-ture Organization (FAO) of the United Nations, agricul-tural land occupies approximately 38% of Earth's terrestrial surface, and between 1985 and 2005, it

expanded by approximately 3%, mainly in the tropics where about 80% of new croplands replaced forests (Foley *et al*., 2011). In contrast, in Europe, North America and Asia, agricultural lands have undergone land conversion and have generally been replaced by forests or abandoned, due to lack of economic profitability (FAO-FRA 2010, Gibbs *et al*., 2010; Foley *et al*., 2011). The net redistribution of agricultural land towards the tropics was the result of local, as well as global social and economic drivers (Smith *et al*., 2010), and its impact on carbon dynamics, climate change, hydrology and biodiversity is among the most prominent challenges facing society in the 21st century (Smith *et al*., 2013a).

Delivering food security to a global population of 9–10 billion by 2050 will be an enormous challenge (Smith, 2013), and there will be strong competition for productive cropland. Several studies agree that bioenergy production should not come at the expense of food production or forest: they assume that even if food crop yields increase at high rate, and even more quickly than global population and food demand, cropland will be needed in the future to feed everyone (Wolf *et al*., 2003; Hoogwijk *et al*., 2005, 2009; Smeets *et al*., 2007; Field *et al*., 2008). Biomass developers are strongly incentivized to identify productive low-cost land, and growing biomass feedstocks on grasslands and marginal croplands is becoming an increasingly attractive choice for bioenergy crops (Qin *et al*., 2014; Slade *et al*., 2014). For the reasons discussed below, here we assess the mitigation potential of croplands, including the portion designated as disadvantaged agricultural land (DAL) based on terrain slope above ≥20%, when converted to energy crops or afforested.

In developing countries, trends of land-use and land-cover change (LULCC) are in general driven by the need to satisfy the food and energy demands of an increasing human population and to deliver economic growth. In developed countries (i.e. those countries listed in Annex B of the Kyoto Protocol), the forcing factors behind LULCC are based on local economic profitability factors, government agricultural support and subsidies, and policies that aim to deliver environmental goals such as greenhouse gas (GHG) emission reduction or improved water quality or to provide sustainable and affordable energy sources (Schlamadinger *et al*., 2007). In recent decades, as a result of national and international political actions in Europe, North America and Asia (e.g. the United Nations programmes on land use, land-use change, and forestry (LULUCF), Reducing Emissions from Deforestation and forest Degradation (REDD), the European Commission Renewable Energy Directive (2009/28/EC), Chinese Programs on Conversion of Cropland to Forest and Grassland, and the Natural Forest Protection and Conservation Reserve Program of Unites States), the reforestation of idle or fallow cropland, abandoned farmland and abandoned pastureland (i.e. less-favourable agricultural areas) is the dominant land-use change in temperate regions. Marginal agricultural land (MAL) is increasingly recognized as a potential avenue to reduce net GHG emissions from agricultural land by either increasing terrestrial carbon (C) stocks through increased forest area or by replacing fossil fuels for energy production through increased bioenergy crop production (Gallagher, 2008; Ravindranath *et al*., 2009; FAO, 2010, Wang *et al*., 2013). In Europe, approximately 56% of the utilized agricultural area was classified as MAL in 1996 by the Common Agricultural Policy (CAP), and the majority of this occurred in mountainous zones characterized by steep slope, low accessibility, poor soils, land used as alpine pastures, high cultivation costs and small field size (MacDonald *et al*., 2000; Pointereau *et al*., 2008; Gopalakrishnan *et al*., 2011; Haddaway *et al*., 2013). Campbell *et al.* (2008) reported that about 0.4 billion hectares of MAL were abandoned globally between years 1700 and 2000 due to agricultural intensification, reduction of soil fertility, topographic unsuitability and economic conditions caused by the market globalization such as milk quotas or set-aside (Pointereau et al., 2008, Haddaway *et al*., 2013).

Understanding the spatial location and extent of the cropland areas where forest and bioenergy production might have least impact on cropland production is essential in order to efficiently develop GHG mitigation strategies and to manage ecosystems for multiple goals (West *et al*., 2010). Growing biomass for bioenergy has the potential to mitigate anthropogenic C emissions by replacing fossil fuel use for energy production, thereby reducing the amount of C emitted from fossil fuel burning, as does using land to sequester C in trees and soils (Fig. 1). In general, production of bioenergy from forest biomass occurs when the productivity is low, on poor quality land, or where the costs of harvesting and utilization are high (Cannell, 2003). For dedicated energy crops, the C mitigation potential and profitability increases with the quality of the land, the potential for GHG savings relative to fossil fuels and the ability to create new agricultural markets and rural development opportunities (Cannell, 2003; Gallagher, 2008). Using cropland to grow crops for energy, however, can produce direct and indirect negative effects on, for example, carbon storage and food production, depending on (i) the level of cropland productivity and soil C storage capacity (West *et al*., 2010; Crossman *et al*., 2011), (ii) local climate conditions (Trail *et al*., 2013), (iii) socio-economic constraints affecting food commodity prices and the effect upon food security for the poor, (iv) the displacement of agricultural production onto uncultivated

areas and (v) other environmental hazards due to habitat destruction (Gallagher, 2008; Paterson & Bryan, 2012).

Quantitative and qualitative global data sets on management practices and the environmental effects of LULCC are still scarce, making climate mitigation analysis difficult. In addition, there is still a lack of information on where, at what rates, and on what type of land cover is affected by LUC. Recently, however, a number of harmonized databases and process-based biogeochemical models have been developed that could be used to estimate the potential biomass productivity at a global scale from cropland, natural ecosystems and bioenergy crop plantations (Sitch *et al*., 2003; Monfreda *et al*., 2008; Portmann *et al*., 2010; Beringer *et al*., 2011; Poulter *et al*., 2011; Kang *et al*., 2014; You *et al*., 2014). Here we use a number of these harmonized geographically explicit data sets on agriculture, forest and bioenergy crop production to assess the global climate change mitigation potential of cropland when converted to bioenergy production or reforested. Our objective is to assess which portions of current cropland could deliver a climate mitigation benefit, and on that land, which of the following options delivers the best climate mitigation option: bioenergy from C_4 grass, short rotation coppice woody (SRCW) crops (e.g. willow and poplar) or C sequestration in forests. Using a database of food crop locations and yields, along with potential rainfed bioenergy crops yields, global forest biomass C stocks and soil C stocks, we highlight the potential extent of cropland that could be used for climate mitigation. In addi-

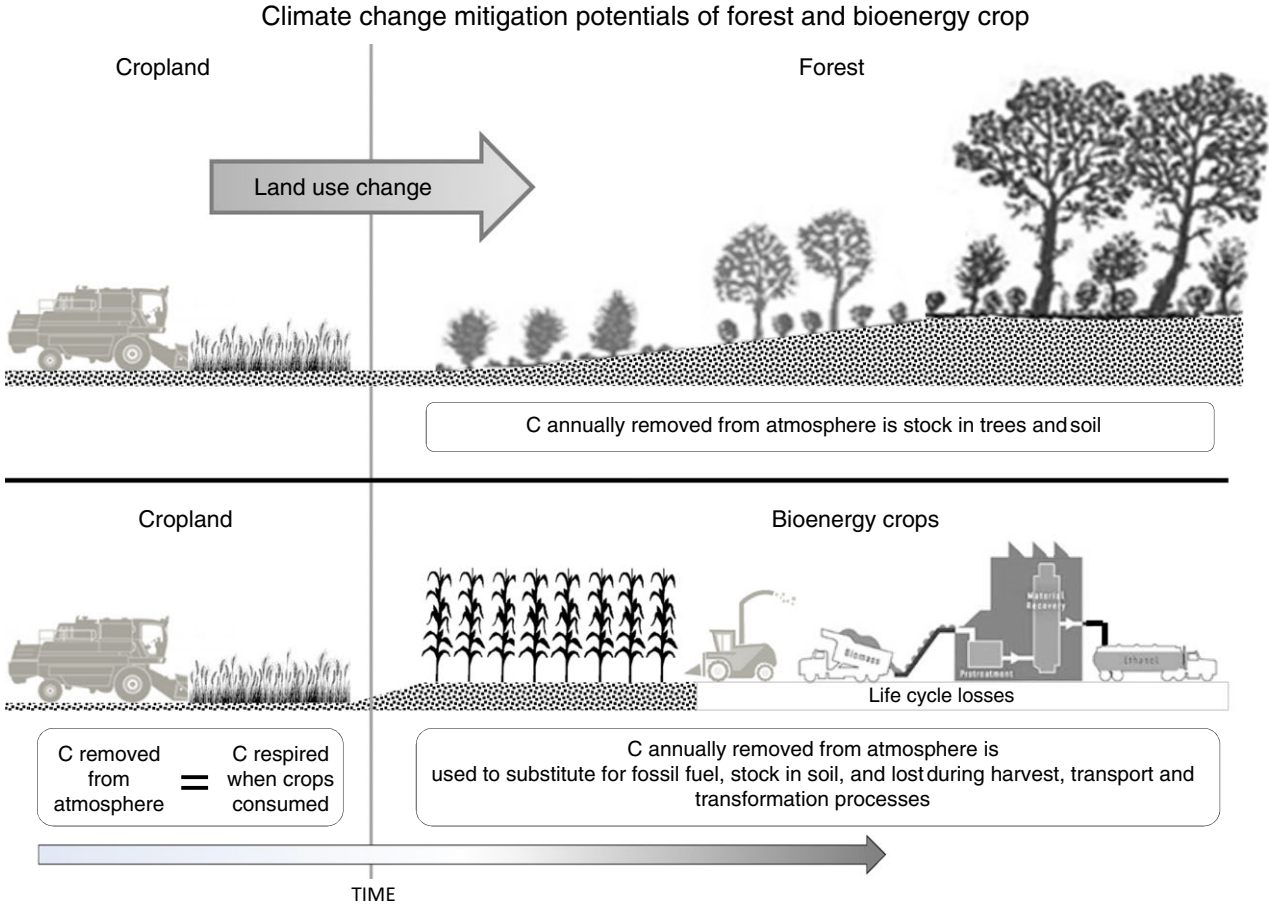


Fig. 1 Croplands do not accumulate carbon for more than a year, as their yields are in general respired within the same year of harvest. The climate change mitigation potential achievable in agricultural land strongly depends on the availability of land for food to be reforested or to be converted to bioenergy production. Forests have been reported to hold up to 50 times more C than a hectare of crop (Houghton, 2002) and depend upon the capacity of sequester C in biomass and soils relative to their agricultural productivity and the risks to be released back into the atmosphere through fire, harvesting and land clearance. The net climate mitigation potential of converting cropland to bioenergy crops is based on the ability of replacing fossil fuels for energy production through bioenergy production and the capacity to sequester additional C in agricultural soils during the 20 years of permanence in the ground. The displaced fossil fuel C equivalent (C_{eq} oil) emissions are equal to the C emissions of the functionally equivalent fossil energy system minus the fossil C_{eq} emissions of the bioenergy system, for example due to harvest, transport and processing of the biomass.

tion, we provide a global estimate of the potential climate mitigation from bioenergy crops and forests across continental regions, climatic regions and on a specific subset of croplands designated as DAL. Our aim is not to show where bioenergy crops or forests should replace cropland, which will depend on many other factors, not least of which is the need to produce food; rather, it is to show where there could be a climate benefit if this land were to be converted.

Material and methods

General description of the data sets

We identified the global above-ground C stocks (i.e. the amount of carbon held by an ecosystem at a given point in time) of rainfed and irrigated high-input croplands, dedicated biomass plantations for bioenergy, and potential forests using the spatial production allocation model (SPAM) (You *et al.*, 2014), the Lund-Potsdam-Jena managed land-dynamic global vegetation model (LPJmL-DGVM) (Bondeau *et al.*, 2007; Beringer *et al.*, 2011), and applying the IPCC Tier-1 method for estimating managed forest vegetation C stocks using the globally consistent default values on above-ground biomass (IPCC, 2006), respectively. The global SOC stock for agricultural areas was derived from the Harmonized World Soil Database (FAO/IIASA/ISRIC/ISS-CAS/JRC v.1.1, 2009) 30-arc second resolution grids (≈1 km at the equator). Here we used the total organic soil C stock density to a depth of 1 m reported by Hiederer & Kochy (2012) (Table 1). Overall, based on the references of the data sets used, the results reported here were assumed to represent the land around the year 2000.

The global maps on eco-floristic zones were obtained from the Carbon Dioxide Information Analysis Center website (Ruesch & Gibbs, 2008; http://cdiac.ornl.gov/), while the global climatic zone map (Fig. S1) was developed using the 5-arc min resolution grids (≈10 km) of CRU thermal and moisture regime baseline data (1961–1990) (Global Agro-Ecological Zones FAO-GAEZ website, Fischer *et al.*, 2008). Following the method reported in Smith *et al.* (2008), we defined four distinct climatic zones based on thermal and moisture regimes: cool, warm, dry and moist zone. The cool zone included the temperate (oceanic, subcontinental and continental) and boreal (oceanic, subcontinental and continental) areas, while the warm zone included the tropics (lowland and highland) and subtropics (summer rainfall, winter rainfall and low rainfall) areas. The dry zone comprised the areas where the annual precipitation was equal or below 500 mm, while the moist zone included areas where the annual precipitation was above 500 mm. The final climatic zone map was produced intersecting the above zones into cool-dry, cool-moist, warm-dry and warm-moist region. Finally, the DAL coverage was obtained using the 5-arc min resolution gridded global terrain slope map (Global Agro-Ecological Zones FAO-GAEZ website, Fischer *et al.*, 2008). The extension of the DAL was based on the occurrence of land with mean terrain slope value ≥20% (Fig. S3).

Potential cropland C balance

The cropland yield distribution was derived from the global 5-arc min land-use data set of the spatial production allocation model (SPAM) that distinguishes the area and yield in the year 2000 (average 1999–2001) of 20 distinct crop types into three different production systems: high-input irrigated, high-input rainfed and low-input rainfed (You *et al.*, 2014) (Fig. S2). In this study, we included seven cropland classes representing the potential productivity of annual food crops at global scale (i.e. barley, maize, millet, other fibres, other pulses, other crops, rice and wheat). The total annual harvested crop yield expressed in metric tons dry matter per hectare per year (t DM ha^{-1} yr^{-1}) for each grid was weighted by the harvest area of each crop, including in the harvest area calculation for multicropping systems, and converted to t C ha^{-1} yr^{-1} using the carbon fraction (CF) set at 0.5 (Table 1).

Following the method reported in West *et al.* (2010), the average cropland C loss resulting from LUC was calculated as the difference in C between annual bioenergy crop yields and cropland yields. The croplands on which a negative or neutral C stock difference would occur are highly productive, are assumed to remain under croplands and are excluded from further analysis (West *et al.*, 2010). Cropland exclusion at this stage is based on the comparison between annual extractable C stocks in cropland and annual extractable C stocks in bioenergy crops; forest carbon sequestration is included at the next stage of the analysis. The climate change mitigation calculations focus on the remaining cropland, which then examines whether bioenergy crops or forests provide the best carbon mitigation outcome should they be converted.

Potential bioenergy crop C stocks and fossil fuel displaced

Global potential production values for bioenergy crops were obtained using the LPJmL-DGVM simulations performed over the 1980–2009 period and forced with reconstructed historical climate based on Climate Research Unit (CRU) TS 3.0 climatic data, which contributed to the study published by Beringer *et al.* (2011) (Table 1). The global land availability for bioenergy crop plantation and biomass production was based on a scenario constrained to areas where bioenergy crops could potentially grow under rainfed conditions. Bioenergy annual crop yield (t C ha^{-1} yr^{-1}) was derived from the global 30-arc min resolution (≈50 km) land-cover map comprising three bioenergy crop functional types (CFTs): (i) evergreen tropical trees to represent the performance of Eucalyptus species, (ii) deciduous temperate trees to match the field performance of poplar and willow used for short rotation coppice wood land (SRCW) and (iii) fast growing C_4 grasses such as *Miscanthus* and switch-grass cultivars. When converted to carbon, the yield of C_4 bioenergy crops was adjusted by the DM peak yield factor of 0.66 (Clifton-Brown *et al.*, 2007) that represents a constant decay rate of DM occurring from the onset of plant senescence stage due to cessation of photosynthesis in the autumn to the harvest time in spring.

The net effect of using C_4 crops and SRCW biomass as a source of bioenergy to displace fossil fuel was obtained by mul-

tiplying the area planted by the fossil fuel C offset per area. The displaced fossil fuel C equivalent (C_{eq}) emissions are equal to the C emissions of the functionally equivalent fossil energy system minus the fossil C_{eq} emissions of the bioenergy system, for example due to harvest, transport and processing of the biomass. This value depends on the exact bioenergy technology and displaced fossil energy system; here, we assumed savings of 1.61 tons of oil CO_2-eq per oven dry tons (odt) of biomass (Cannell, 2003; Sims *et al.*, 2006) or 0.878 of oil C_{eq} per unit of biomass-derived C. The amount of delivered energy obtained per unit of biomass-derived fuels (woody biomass) was assumed to be 8 GJ t C^{-1} (Mitchell *et al.*, 2012).

Following standardized GHG life cycle assessment (LCA) guidelines (PAS 2050, 2008), and the EU Renewable Energy Directive (EU, 2009), the mitigation benefit of bioenergy crops in time was aggregated over 20 years. This time horizon corresponds also to the length of the rotation of both grasses and woody energy crops (i.e. establishment phase of three years and a period of 17 years before replanting becomes necessary) and is the timescale considered when decisions to plant energy crop rotations are made. Finally, SOC changes in the LUC transition from annual food crops to bioenergy crop plantations were assumed to increase by 18% (Guo & Gifford, 2002) as annual cultivation is replaced by permanent vegetation, and this is assumed also to occur over a 20-year period.

Potential forest distribution and C stocks

The potential distribution and forest vegetation C stocks for the year 2000 were obtained using the 30-arc min resolution land-cover map from the LPJmL-DGVM v3.1 simulations, which reflected the processes contributing to the dynamics of forest vegetation structure, composition and ultimately their change in ecosystem geography (Poulter *et al.*, 2011; Sitch *et al.*, 2013). In particular, the DGVM simulation was performed over the 1901–2009 period and forced with reconstructed historical climate fields and rising atmospheric CO_2 concentration. Climate forcing was based on a merged product of Climate Research Unit (CRU) observed monthly 0.5° climatology (v3.0, 1901–2009; New *et al.*, 2000) and the high temporal fidelity NCEP reanalysis forcing. Global atmospheric CO_2 was derived from ice core and NOAA monitoring station data and provided at annual resolution over the period 1860–2009. As land-use change was not simulated in these model experiments, models assume a constant land use throughout the simulation period. Atmospheric nitrogen deposition data for CLM4CN and OCN derived from Dentener *et al.* (2006). Gridded fields of Leaf Area Index (LAI) are used in the evaluation of DGVM northern greening trends. These LAI data sets, based on remote sensing data, were generated from the AVHRR GIMMS NDVI3 g using an artificial neural network derived model with a temporal resolution of 15 days over the period 20 1981–2010 and a spatial resolution of 1/12°.

The calculation of global forest C stocks (t C ha^{-1}) (i.e. above- and below-ground components) summarized in Table 1 followed the method reported by Ruesch & Gibbs (2008), and applied IPCC, 2006 Tier-1 method for estimating vegetation C stocks of forests using the IPCC default values provided for above-ground biomass and the root to shoot ratios for natural regeneration by broad categories for below-ground biomass (Tables S1 and S2). We compiled the IPCC default forest C zone using the continental regions, eco-floristic, climatic zone and the spatial coverage of seven DGVM forest plant functional types (PFTs), distinct by their spatially consistent climate distribution: (i) tropical evergreen, (ii) tropical raingreen, (iii) temperate needleleaf evergreen, (iv) temperate broadleaf evergreen, (v) temperate broadleaf summergreen, (vi) boreal needleleaf evergreen and (vii) boreal broadleaf summergreen. The total C stock values of each C zone was adjusted by the human fire induced and forest felling losses for the year 2000 provided by Krausmann *et al.* (2008a) (Table S1) and represented the rate of C accumulation or saturation in forest. In the comparison, the C sequestration in forests after 20 years was calculated by applying the factors representing percentage of final biomass C stock accumulated after 20 years (F_{20}). F_{20} was estimated by integrating, over a 100 year timescale (i.e. saturation point), the IPCC default dry matter biomass annual increments in above-ground biomass in naturally regenerated forest classified below and above 20 years of age (IPCC, 2006). F_{20}, therefore, represents the contribution of the first 20 years of C accumulation of forest biomass C. Table S3 reports the average of F_{20} of each broad forest category among the distinct climatic zones and continental regions. Finally, we assumed that the total SOC change in reforested cropland, over the biomass stabilization time horizon, would be equal to 53% of the initial SOC occurring in cropland (Guo & Gifford, 2002) which was adjusted by the same fraction as given in Table S3 for above-ground biomass, that is F_{20} to give SOC accumulation over 20 years.

Results

Global C in cropland, bioenergy crops and forest

The crop yield provided by the SPAM model varied across the globe depending on the crop type, soil type, climate and management (Annex I, Fig. S2). This covered a physical area of 1.11 billion hectares distributed in approximately 205.3 million hectares (Mha) in the Europe, 444.6 Mha in Asia and Russia Federation, 160.9 Mha in Africa, 196.4 Mha in North America and Caribbean, 75 Mha in South America and 26 Mha in Oceania. Overall, the global cumulative extractable C from cropland via annual yields was ≈1.74 Pg C yr^{-1} with 38% located in the warm-moist region, 9% in the warm-dry, 41% in the cool-moist and 12% in the cool-dry region. The annual extractable C from cropland was highest in the parts of Europe in the cool-moist region (where yields are known to be among the highest globally; FAOSTAT, 2014), and the lowest yield density occurred in African countries in the warm-dry region (where yields are known to be among the lowest globally; FAOSTAT, 2014; Table 1). The proportion of agricultural land classified as DAL covered ≈19% in Europe, 12% in North America and Caribbean, 17% in

Table 1 Annual extractable biomass carbon (t C ha^{-1} yr^{-1}) in agricultural land (cropland), C_4 bioenergy crops (C_4 crop) and short rotation coppice woody bioenergy (SRCW), biomass C density in forest and soil organic carbon (SOC) stock (t C ha^{-1}) in 1 metre of soil, separated among climatic and continental regions. Total biomass C density values (BC, mean ± SD) were derived using the data sets from SPAM for the annual cropland, the LPJmL model for the bioenergy crops and the IPCC default C stocks for the forests biomes. SOC stock in annual cropland derived from the HWSD v1.1. Peak yields of C_4 bioenergy crops from LPJmL were adjusted using a correction factor of 0.66 to obtain harvestable yield

	Warm					Cool				
	Cropland		C_4 crop	SRCW	Forest	Cropland		C_4 crop	SRCW	Forest
	BC	SOC	BC	BC	BC	BC	SOC	BC	BC	BC
Moist										
Africa	0.6 ± 0.2	77.9 ± 39	6.1 ± 3.6	2.8 ± 2.4	107.5 ± 45.3	n.d.	n.d	n.d.	n.d.	n.d.
Asia	1.1 ± 0.5	98.4 ± 62	7.1 ± 4	3.3 ± 2.5	115.2 ± 42.3	0.9 ± 0.4	63.8 ± 24	3 ± 2.1	1.8 ± 1.7	75.8 ± 10.6
Europe	2.0 ± 0.6	88.6 ± 47	4.1 ± 1.2	2.2 ± 1.3	76.7 ± 12	1.6 ± 0.9	131.9 ± 60	4.1 ± 1.2	3.5 ± 1.1	67.0 ± 12.3
N.,C. America & Caribbean	1.0 ± 0.4	149 ± 82	10.7 ± 2.3	5.2 ± 1.7	148.1 ± 27.1	1.5 ± 0.4	122 ± 46	3.7 ± 1	3.4 ± 0.7	41.8 ± 30
South America	1.3 ± 0.4	157.8 ± 72	9.9 ± 2.9	5.5 ± 1.6	192.6 ± 42	1.6 ± 0.3	118 ± 7	3 ± 1	4.0 ± 1.4	149.3 ± 4
Oceania	1.6 ± 1.2	136 ± 46	11.6 ± 3.4	6.5 ± 2.1	133.8 ± 24.2	n.d.	n.d	4.6 ± 0.6	5.3 ± 0.3	94.1 ± 3.5
Dry										
Africa	0.5 ± 0.6	49 ± 10	1.1 ± 1	0.3 ± 0.3	71.2 ± 8.3	n.d.	n.d	n.d.	n.d.	n.d.
Asia	1.1 ± 0.5	47.4 ± 15	1.6 ± 0.6	0.3 ± 0.3	76.5 ± 3	1.2 ± 0.8	73 ± 37	1.4 ± 0.3	0.6 ± 0.2	60.7 ± 15.3
Europe	2.0 ± 0.8	64.3 ± 6	2 ± 0.4	0.4 ± 0.1	78.9 ± 0.8	2.1 ± 0.9	141.6 ± 82	1.5 ± 0.3	0.8 ± 0.4	51.6 ± 20.5
N.,C. America & Caribbean	1.8 ± 0.9	96.3 ± 32	1.3 ± 0.3	0.4 ± 0	106.4 ± 19.5	2.7 ± 1.2	133.8 ± 45	1.7 ± 0.2	1.0 ± 0.2	26.3 ± 17.6
South America	1.1 ± 0.5	58.7 ± 24	2.9 ± 1.3	1.3 ± 0.7	95.5 ± 1.2	1.4 ± 0.1	340 ± 95	1.2 ± 0.1	2.4 ± 1.8	n.d.
Oceania	1.0 ± 0.7	54.3 ± 15	1.5 ± 1	0.2 ± 0.2	109.2 ± 12.8	2.3 ± 0.7	92.4 ± 3	n.d.	n.d.	97.8 ± 6.9
Africa	0.5 ± 0.6	49 ± 10	1.1 ± 1	0.3 ± 0.3	71.2 ± 8.3	n.d.	n.d	n.d.	n.d.	n.d.

South America, 7% in Asia and Russia Federation, 47% in Africa and 3% in Oceania (Annex I, Fig. S3).

The annual extractable C from SRCW and C_4 bioenergy crops was highest in the countries located in the warm-moist region of the Oceania (6.5 ± 2.1 and 11.6 ± 3.4 t C ha^{-1} yr^{-1}, respectively) and the lowest values in the African and Asian warm-dry regions (Table 1). In comparison to food crops, in the warm-moist and cool-moist regions, the annual extractable C from rainfed SRCW was on average 55% and 65% higher than for food crops. Conversely, in the warm-dry and cool-dry regions, the annual extractable C from SRCW was, on average, 42% lower than for food crops. For the highly productive rainfed C_4 bioenergy crops, the annual extractable C was between 23% and 82% higher than for food crop yields. In the cool-dry regions of Europe, North America and South America, however, the annual extractable C from C_4 bioenergy crops was, on average, between 19% and 37% lower than for croplands.

Finally, at global level, 55.8% of the saturated C stock of forests was distributed in the warm-moist region, 22.7% in the warm-dry, 10.3% in the cool-moist and 11.2% in the cool-dry region (Table 1).

Excluding highly productive croplands that would yield no climate benefit if converted to energy crops or forests

Figure 3 shows the total cropland area (in red) where only the annual extractable C from C_4 and SRCW bioenergy crops would be equal to or lower than the annual extractable C of the cropland. We assume that if the annual extractable C from croplands (in yield used for food) exceeds the annual increment in C under forestry or annual extractable C from bioenergy crops, then the land is deemed more suitable for food crop production than other uses, and that these areas are assumed to remain under cropland. Globally ≈38% (≈420.1 Mha) of cropland was deemed more suitable for food crop production according to these criteria and was therefore excluded from conversion to bioenergy crops or reforestation. This was distributed as follows: 57.3 Mha in Africa, 179.1 in Asia and Russia Federation, 63.2 Mha in Europe, 95.1 in North America, 10.2 in South America and 15.2 Mha in Oceania. The area where annual extractable C of C_4 bioenergy crops would be equal to or lower than cropland covered ≈12% of the total cropland and occurred mostly in the warm-dry regions of central of Spain, Greece, Western Asia and Sub-Saharan zones where precipitation events are scarce and in the cool-moist regions where agricultural lands have the highest productivity. The geographic locations where the conversion to SRCW would result in equal or lower annual extractable C than cropland occupied more than 35% of current cropland area. The extent of DAL included in the potential coverage of C_4 bioenergy crops was about 202.2 Mha, and ≈11% of this was deemed unsuitable for LUC due to the high cropland yields. The total DAL area where SRCW could potentially grow occupied ≈201.9 Mha, and ≈30% of this area is projected to be unsuitable for LUC to energy crops. Finally, within the ≈219.2 Mha of DAL where forests could potentially grow, only ≈1% would not be suitable for forests due to higher cropland yields.

Climate mitigation potential of C_4 bioenergy crops

If grown on all croplands not excluded due to high productivity, over a 20-year rotation, the biomass production of C_4 bioenergy crops could save ≈58.12 Pg C-eq_{oil} across 484.9 Mha. Approximately 74.4% of this area would occur in the warm-moist region, 0.1% in the warm-dry region, 24% in the cool-moist region and 1.4% in the cool-dry region (Fig. 3). Tables 2 and 3 report the climate mitigation potential from the extractable biomass, the C sequestration in soils and the cropland area where bioenergy crops could be deployed. In Asia (continental and insular), the use of biomass from C_4 bioenergy crops could potentially save ≈27.6 Pg C-eq_{oil} and sequester ≈3.56 Pg of C in soil across ≈66.1 Mha of cropland. While considering the climatic regions, the potential fossil fuel saving in the warm-moist region would be ≈48.6 Pg C-eq_{oil} across ≈273.5 Mha of cropland. Approximately 42% of the agricultural land potentially suitable to be converted to C_4 bioenergy crops (≈204.4 Mha), however, has a terrain slope ≥20%. The portion of agricultural land suitable to C_4 bioenergy crops and classified as DAL was ≈9%, 20.7%, 4.7%, 4.7%, 3% and 0.1% in Africa, Asia, Europe, North America, South America and Oceania, respectively. Except in the continental region of Oceania, the cumulative climate mitigation potential of C_4 bioenergy crops exceeded the savings of both SRCW and reforested croplands. On a per hectare basis, C_4 bioenergy crops always provided higher C savings than 20-year-old forests (Fig. 2).

Climate mitigation potential of SRCW crops

On ≈26.3 Mha of cropland, SRCW has greater or equal C mitigation potential than C_4 bioenergy crops and forest, giving a potential saving of ≈1.6 Pg C-eq_{oil} and ≈0.8 Pg C of soil C. Approximately 64.5% of the C saving from SRCW biomass occurred in the cool-moist region, 26% in the cool-dry region, 8.6% in the warm-moist regions and 0.9% in the warm-dry regions

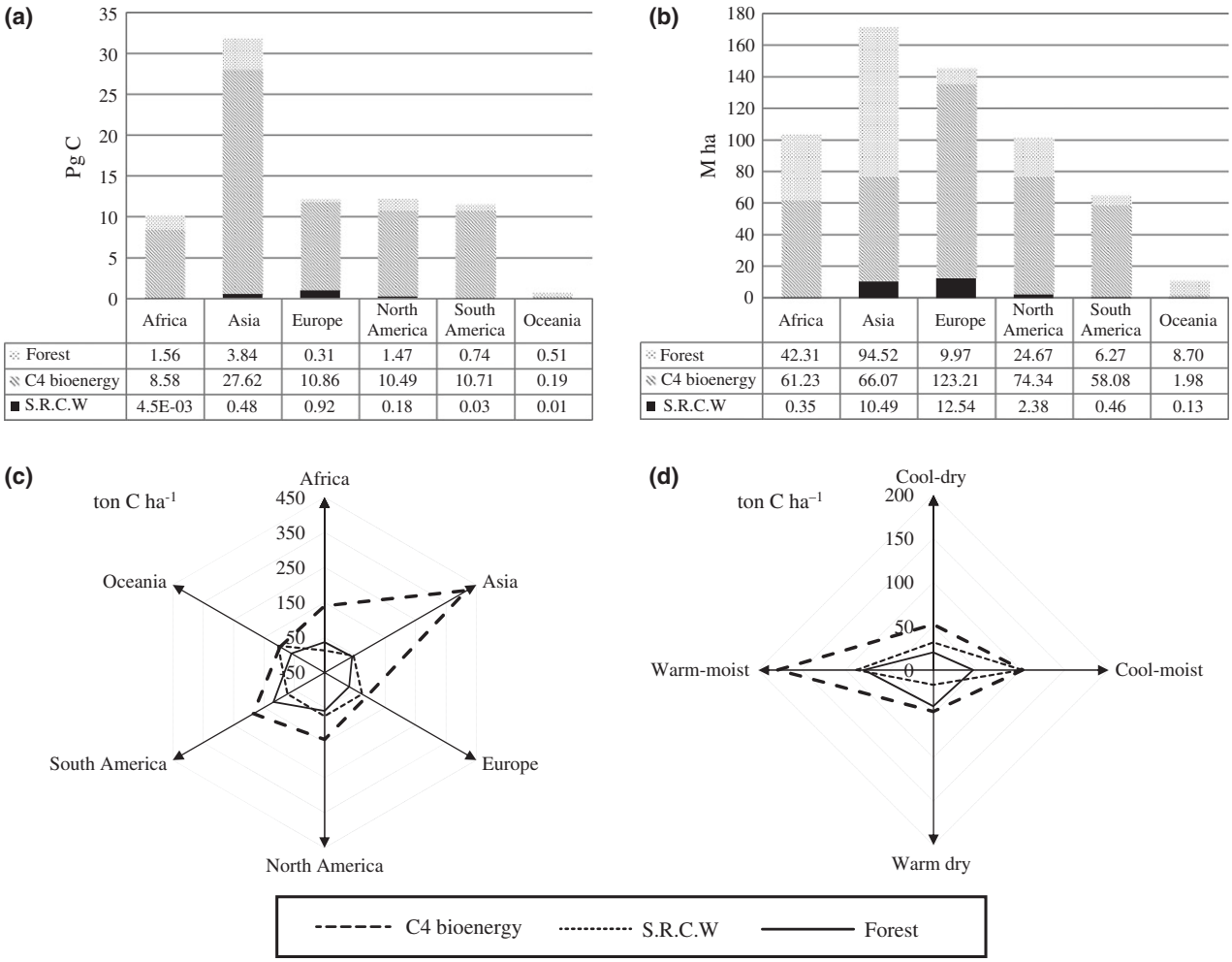


Fig. 2 Potential climate change mitigation of forest, C_4 bioenergy crop and short rotation coppice wood partitioned across global continental regions. In (a), the cumulative climate mitigation potential of forest includes biomass and soil C sequestration (Pg C) over 20 years, while the climate mitigation potential of bioenergy crops includes the fossil fuel C equivalent displaced by the use of bioenergy crop biomass (Pg C_{eq} oil) and the sequestration of C in soil. In (b), the total extent of agricultural land (Mha) depends upon the capacity of each ecosystem to provide the highest climate mitigation potential. In (c), the potential climate mitigation of each ecosystem is reported on a per hectare basis discriminated among continents (for forest t C ha^{-1}, for bioenergy crops t C_{eq} oil ha^{-1}). In (d), potential climate mitigation of each ecosystem is reported on a per hectare basis and discriminated among climatic regions. SOC changes in the LUC transition to bioenergy crops plantations were assumed to increase of 18% and to forests were assumed to increase by 53% (Guo & Gifford, 2002). Peak yields of C_4 bioenergy crops from LPJmL were adjusted using a correction factor of 0.66 to obtain harvestable yield.

(Fig. 3). Globally, the cumulative mitigation potentials from SRCW never exceed those of C_4 bioenergy crops (Table 2). However, on a per hectare basis, the mitigation potential of SRCW plantations produced higher C savings than C_4 bioenergy crops in Oceania (≈102.8 Pg C-eq_{oil} ha^{-1}) and across the cool-moist climatic region (Fig. 2c). Approximately 28.3% (≈7.5 Mha) of cropland where SRCW showed the highest C mitigation potential was classified as DAL. The portion of agricultural land suitable to SRCW classified as DAL was ≈0.1%, 13.5%, 11.5%, 1%, 1.6% and 0.5% in Africa, Asia, Europe, North America, South America and Oceania, respectively.

Climate mitigation potential of forests

Over a 20-year time horizon, the rank of cumulative C sink strength in reforested croplands was Asia > Africa > North and Central America > South America > Oceania > Europe. On a per hectare basis, however, due to the influence of tropical forests, the C sequestration strength resulted in a rank of South America > North and Central America > Oceania > Asia > Africa > Europe (Fig. 2). Overall, on ≈186.5 Mha, reforestation of cropland would be the best climate mitigation option, saving a total of ≈8.4 Pg C in biomass and ≈2.7 Pg C in

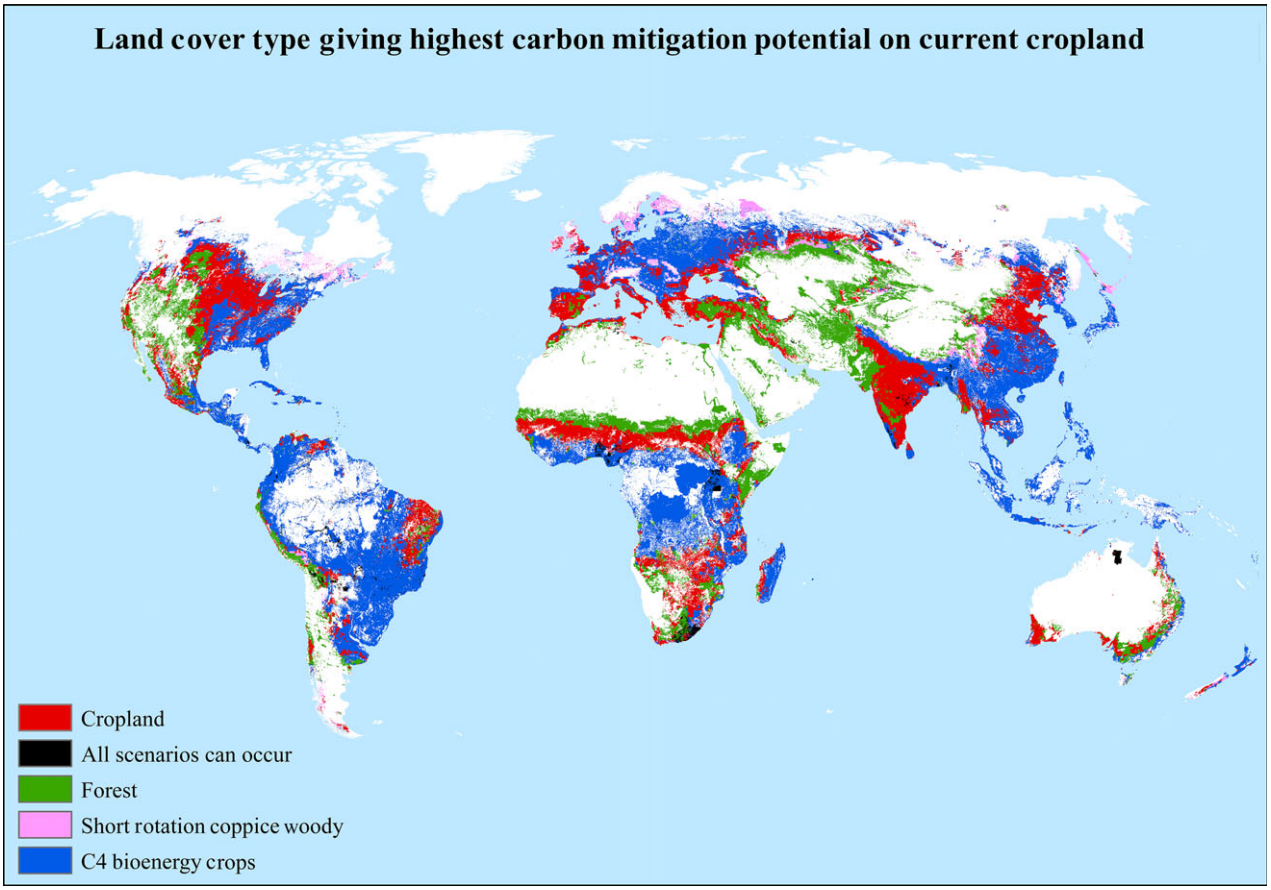


Fig. 3 Five-arc minute (≈10 km at the equator) map of land-cover types giving the highest climate change mitigation potential C_4 bioenergy crops (≈484.9 Mha), short rotation coppice wood (≈26.3 Mha) and forest (≈186.5 Mha). Red pixels indicate highly productive agricultural land not suitable to land-use change due to negative or neutral C stock difference when converted to C_4 bioenergy crops, short rotation coppice wood (≈420.6 Mha). The pixels in black colour report agricultural land where both C_4 bioenergy crops and short rotation coppice wood have similar climate mitigation potential and could potential occur (≈24 Mha).

the soil. Approximately 44.7% of the C saving in forest would be achieved in the warm-dry climatic region and 42.6%, 11.3% and 1.4% in the warm-moist, cool-dry and cool-moist regions, respectively (Table 3). The area where reforestation was the best mitigation included 35.6 Mha of DAL, with a potential climate mitigation of ≈2.2 Pg C in biomass and 0.9 Pg C in soil. Reforested DAL covered ≈5% of the total suitable cropland in Asia, 23.6% in Africa, 1.1% in Europe, 3.6% in North America, 1.7% in South America and 0.2% in Oceania.

Discussion

Potential climate mitigation on current cropland

Identifying the areas where terrestrial ecosystems could contribute to climate mitigation is of great policy importance. Many countries have moved quickly to set up targets for fossil fuel substitution by bioenergy. India has announced a target of 20% petroleum substitution by 2017, the European Union 10% by 2020, and different states in the USA have announced different targets ranging from 7% to 20% over different periods. It was reported that at global scale, the land required in order to substitute 10% of fossil fuels with biofuel by 2020 would vary from 142 to 600 Mha (Ravindranath *et al.*, 2009). In that respect, the potential for bioenergy crops to mitigate climate change and enhance energy security has encouraged many countries worldwide to consider a transition of some grassland and cropland from food production to the production of bioenergy. To date, several bioenergy resource-focused studies, based on the food/fibre and environment principle, where unused and suitable land is calculated after land requirements for food, feed, fibre and other competing land uses have been fulfilled, showed that a significant quantity of abandoned or 'surplus' cropland could become available for bioenergy crop plantations in the future (Bati-

Table 2 Continental C mitigation potential achievable in agricultural land from forest, C_4 bioenergy crops and short rotation coppice woody (SRCW) crops. The C mitigation potential in biomass is reported in Pg C forest and Pg C_{eq} oil for bioenergy crops and SRCW. The C sequestration in soils is reported in Pg C for all land uses. The agricultural land displaced by the four land-use scenarios is reported in Mha

Land use	Continental region	Total C mitigated	C mitigated from biomass use/increment	C stock sequestered in soil	Agricultural land displaced
Forest	Africa	1.56	1.11	0.44	42.31
	Asia	3.84	2.73	1.11	94.52
	Europe	0.31	0.17	0.15	9.97
	North America	1.47	0.96	0.50	24.67
	South America	0.74	0.41	0.34	6.27
	Oceania	0.51	0.39	0.12	8.70
C_4 bioenergy crops	Africa	8.58	7.69	0.89	61.23
	Asia	27.62	24.06	3.56	66.07
	Europe	10.86	7.74	3.12	123.21
	North America	10.49	8.89	1.60	74.34
	South America	10.71	9.58	1.13	58.08
	Oceania	0.19	0.16	0.03	1.98
SRCW	Africa	4.5E−03	1.9E−03	2.6E−03	0.35
	Asia	0.48	0.20	0.28	10.49
	Europe	0.92	0.52	0.41	12.54
	North America	0.18	0.10	0.07	2.38
	South America	0.03	0.03	0.01	0.46
	Oceania	0.01	0.01	0.00	0.13

Table 3 Carbon mitigation potential across global climatic regions achievable in agricultural land from forest, C_4 bioenergy crops and short rotation coppice woody (SRCW) crops. The C mitigation potential in biomass is reported in Pg C for forest and Pg C_{eq} oil for bioenergy crops and SRCW. The C sequestration in soils is reported in Pg C for all land uses. The agricultural land displaced by the four land-use scenarios is reported in Mha

Land use	Climate region	Total C mitigated	C mitigated from biomass use/increment	C stock sequestered in soil	Agricultural land displaced
Forest	Cool-Dry	0.95	0.59	0.36	47.38
	Cool-Moist	0.12	0.04	0.08	2.67
	Warm-Dry	3.77	2.84	0.93	90.96
	Warm-Moist	3.60	2.30	1.30	45.44
C_4 bioenergy crops	Cool-Dry	1.69	0.84	0.85	32.47
	Cool-Moist	18.06	13.94	4.12	176.74
	Warm-Dry	0.10	0.08	0.02	2.20
	Warm-Moist	48.59	43.26	5.33	273.49
SRCW	Cool-Dry	0.42	0.06	0.36	13.53
	Cool-Moist	1.05	0.68	0.38	10.37
	Warm-Dry	0.01	0.01	0.01	0.85
	Warm-Moist	0.14	0.12	0.02	1.60

dzirai *et al*., 2012). Hoogwijk *et al.* (2005) reported that between 600 and 1500 Mha of abandoned agricultural land and 300–1400 Mha of rest land could be available for bioenergy production. Smeets *et al.* (2007) estimated that 0.7–3.6 Gha of surplus agricultural land could be available if improvements in agricultural management are achieved. Van Vuuren *et al.* (2009) reported that biomass potential on abandoned agricultural lands and natural grasslands could reach 1500 Mha, and the German Advisory Council for Global Environmental Change (2009), using the LPJmL model, estimated that between 240 and 500 Mha of land could be available for energy crop production. Sims *et al.* (2006), based on the IPCC scenarios for 2025 (IPCC, 2000), reported that the potential contribution of energy crops to climate mitigation would range from 1.6 to 79.6 Pg C-eq_{oil} across an area varying from 58 to 141 Mha. The conversion of cropland to energy crops or forest, however, is highly

sensitive to food crop yields and land quality and will not occur unless the LUC provides higher economic gains or other benefits to land owners. In this study, we estimated the *maximum* net availability of cropland for conversion to bioenergy crops using the C stock difference between the yields of perennial bioenergy crops and yield of annual food crops. West *et al.* (2010) used a similar approach to assess the losses of C resulting from deforestation. We assume that if the annual extractable C from croplands (in yield used for food) exceed the annual increment in C under forestry or annual extractable C from bioenergy crops, then the land is more suitable for food crop production than other uses, and that these areas will remain under cropland. Our approach, therefore, excludes much of the most productive cropland, and we then assess the best use of the remaining land from a climate mitigation perspective. It is highly unlikely that even much of the less productive cropland will be used to bioenergy production, but here we have provided an analysis of the best climate mitigation options for that land should it be converted.

We show that if all of the 485 Mha of global cropland most suitable for highly productive C_4 bioenergy crops were converted, the oil C savings would be ≈58.1 Pg C-eq_{oil} over 20 years. In energy terms, this land could supply ≈529.5 EJ, which corresponds roughly to current global primary energy supply. Excluding the agricultural land with the terrain slope ≥20%, the oil C savings from the biomass of C_4 bioenergy would decrease by ≈27.5 Pg C-eq_{oil} or 250 EJ. By comparison to other global biomass studies, if we include all croplands where C_4 bioenergy crops could potentially be deployed, our results coincide with so-called estimates in excess; studies assuming that the increases in food crop yields could significantly outpace demand for food making more than 1000 Mha of cropland available and 500 Mha of MAL at global scale. Note though that our results do not represent a scenario for biomass supply; instead they reflect a technical potential on the land considered. Assuming instead that only the DAL would be available to C_4 bioenergy crop plantations (≈204.4 Mha), our results coincide with estimates of studies assuming limited good quality agricultural land available for energy crop production, with MAL ranging from 100 to 500 Mha, and decrease of global forested area up to 25% (i.e. estimates falling within the 100–300 EJ range) (Creutzig *et al.*, 2014; Slade *et al.*, 2014). Our estimates, however, do not model changes in forest extent.

Since the Manomet (2010) study, forest bioenergy has been considered by some researchers as an inefficient renewable energy source to mitigate climate change. To date, a number of studies have reported concerns regarding the assumption of 'C neutrality' over the rotation times and highlighted how dedicated harvest of stemwood might result in GHG emissions higher than fossil fuels (Johnson, 2009; Searchinger *et al.*, 2009; Holtsmark, 2010; Cherubini *et al.*, 2011; Zanchi *et al.*, 2011; Mitchell *et al.*, 2012; Pingoud *et al.*, 2012; Schulze *et al.*, 2012). In addition, despite most of the forest feedstocks used for bioenergy originating from sources considered sustainable (e.g. industrial residues, waste wood, and residual wood), for which GHG savings may be achieved in the short to medium term, an increased use of forest products for bioenergy might indirectly increase the pressure on natural forests and stimulate harvest levels elsewhere in the world (Schwarzbauer & Stern, 2010; Agostini *et al.*, 2013). These issues become particularly important in boreal and temperate regions where the net C sink of forests may continue to grow for a very long time, sometimes far beyond the recommended rotation length (Hynynen *et al.*, 2005; Luyssaert *et al.*, 2008; Pingoud *et al.*, 2012). Given the above concerns, however, the maintenance of high C stock densities in forest at high risk of disturbance or in land with low productivity may result in a lower climate mitigation potential than forest intensively managed to displace fossil emissions (Pingoud *et al.*, 2010). In addition, when the foregone landscape carbon stock and the fossil C displacement factor are low, and the biomass growth rate is high, forest stemwood harvested for bioenergy purposes could reach fossil fuel parity and then generate GHG savings in the longer term. We showed that based on the foregone C in cropland yield, SRCW bioenergy would be suitable on just ≈2.4% of the global agricultural land or 26.3 Mha, and overall it would save only 19% of the C sink achievable in reforested croplands. However, approximately 90.7% of the agricultural land most suitable to SRCW would potentially occur in cool-dry and cool-moist climatic regions (i.e. northern or southern countries of Europe and Asia) saving ≈0.74 Pg C-eq_{oil} over one rotation. On a per hectare basis, the C saving from SRCW in the cool-moist climate region would be 65% higher than in forest and superior to the climate benefits of C_4 bioenergy crops (Fig. 2c and d).

Reforested food croplands showed a potential C sink of 8.4 Pg C a global scale over the first 20 years of forest growth, excluding the croplands on which food crops provided a higher carbon stock than energy crops of forest (red area in Fig. 3). The climate mitigation benefits of forest over 20 years were comparable or superior to the highly productive C_4 bioenergy crops on only 186.5 Mha. Importantly, more than 63% of this area was confined in the dry climatic regions of south and central Asia and North America with terrain slope ≥20% (Fig. 3 and S3). If more rotations were considered (i.e. >20-year time horizon), bioenergy would become ever more favourable than reforestation, as fossil fuel offsets from

bioenergy continue to accrue at the same rate indefinitely, compared to forest C sequestration which declines over time as forests approach C saturation at maturity (Schlamadinger *et al*., 2007). The rationale for using a 20-year time horizon in this analysis is that (i) this is the standard timeframe in LCA assessments (e.g. PAS 2050, 2008; EU, 2009) and (ii) 20 years is the timescale at which decisions to plant energy crop rotations (1 rotation length) are made.

Limitations of the global data sets used

The climate mitigation potential of bioenergy crop systems, compared to forest alternatives, must take into consideration the time frame adopted in the analysis. In this study, the global mitigation benefit of bioenergy crops in time was assessed over a 20-year time horizon, which corresponds to the typical timeframe considered in studies of permanence discounting for land based C sequestration in reforested agricultural land (Kim *et al*., 2008; Haim *et al*., 2014), and in standardized GHG-LCA on the mitigation benefit of bioenergy crops. Forests have been reported to hold up to 50 times more C than a hectare of crop (Houghton, 2002), and the time to sink saturation of reforested cropland may vary depending by the climate conditions, forest types, forest management and soil characteristics. Bird *et al.* (2010) and Jandl *et al.* (2011) reported that temperate biomes have, in general, longer accumulation times than tropical biomes, and the equilibration of above- and below-ground C accumulation rates in forest vary across climate zone, cover type (i.e. secondary forest or plantation), previous land use and forest stand age. In that respect, Silver *et al.* (2000) and Marín-Spiotta *et al*. (2008) reviewed the C dynamics of afforestation of abandoned agricultural lands in tropical biomes and reported that the rates of forest biomass regrowth on abandoned croplands in the first 20 years could range from 60% to 75% of the total regrowth achieved after 80 years. Nevertheless, their reviews pointed out that more than half of the studies on forest included only the first 20 years after abandonment and only limited information on the behaviour of older forests is available in the literature.

Here we assumed that the time to sink saturation of reforested cropland would correspond to the IPCC C stock default values and estimated the contribution of the first 20 years over the total saturated forest biomass using the corresponding IPCC default dry matter biomass annual increments (IPCC, 2006). The IPCC default C stock values, however, were reported to be heavily biased by limited references in developing countries (Petrescu *et al*., 2012). The uncertainty in the IPCC data set on forests reflects the UNFCCC reporting obligations for full land reporting by Annex I Parties and partial reporting of forestry-related sources by Non-Annex I Parties. Keith *et al.* (2009) showed that in cool temperate moist forests and tropical moist forests, IPCC default values were <1 standard deviation from the averaged site data measurements in primary forests and comparable to tropical and boreal biome measurements. Depending on the continental zone and the canopy cover threshold, in the warm climatic region, the IPCC default C stock provided values from 49% higher to 61% lower than the forest C stock density of tropical regions reported by Saatchia *et al.* (2011). Pan *et al.* (2011, 2013) reported forest C stock densities in tropical forests ranging from 18 to 198 t C ha^{-1}, from 30 to 339 t C ha^{-1} in temperate forests and from 1 to 72 t C ha^{-1} in boreal forests. Our saturated C values in forest biomass (Table 1), discriminated per continental and climatic regions, reached a mean C density of from 76.7 to 192.6 t C ha^{-1} in warm-moist climatic regions, between 41.8 and 149.3 t C ha^{-1} across the cool-moist climatic regions where in general temperate forest occurs and from 26.3 and 97.8 t C ha^{-1} in the cool-dry climatic regions of northern and southern countries.

Another potential uncertainty in our analysis resulted from the biomass allocation models. Here, we opted to use the global crop production distribution of the SPAM model based on its power to combine various data sources (satellite-based land cover, ground-based data and modelling results). Anderson *et al.* (2014), however, explored the similarity and differences among four major global cropping system models (SPAM, M3, MICRA and GAEZ) and concluded that, depending by the crop type and the latitude, the differences among their final crop yields were higher than the differences among the harvested area. As the true global crop distribution is still unknown, the large discrepancies between the cropping system models would depend on the input data and the methodology used, and the review of Anderson *et al.* (2014) was unable to provide a conclusive judgement on which model is more accurate than the other.

The potential occurrence of bioenergy crops systems and forest biomes on current cropland was assessed using the LPJmL-DGVM simulations. Due to the inherent uncertainty in the global distribution, and that the performance of lignocellulosic energy crops is still unknown, here we used the modelled biomass allocation of bioenergy crops from Beringer *et al.* (2011) which was calibrated using data from existing controlled experimental sites of *Miscanthus*, switchgrass, poplar, willow and Eucalyptus. This study, in particular, showed differences against observed values from Europe, North America and South America ranging from −24% to +18%. In C_4 bioenergy crop systems such as *Miscanthus*, the differences against observed values var-

ied from −19% to +34%. An important uncertainty of the LPJmL bioenergy crop yield projections, however, is related to the upscaling of yields measured in small, controlled experimental plots to commercial production scale. Although our bioenergy C_4 crop C saving included a field peak yield reduction of 34% of the bioenergy crop yields, a number of studies reported that small-plot yields could be up to 7 times higher than in semicommercial field trials (Hansen, 1991; Fales *et al*., 2008; Searle & Malins, 2014). If real energy crop yields are lower than those projected by LPJmL, the area where food crops and forests are more competitive could be greater than presented in this analysis.

Pavlick *et al.* (2013) reported that, in general LPJmL-DGVM simulations tend to simplify the diversity of vegetation forms and ecosystem functioning into predefined PFT schemes. In that respect, Poulter *et al.* (2011) reported that the changes in ecosystem geography simulated by the LPJmL model in the warm-dry climatic region resulted in a wider distribution of C_3 and C_4 PFT grassland ecosystems (i.e. heterogeneous mixtures of grasslands, savannah and shrublands systems) in these regions, and uncertainties of up to 30% in the sensitivity of Gross Primary Productivity (GPP) to precipitation, mostly comprised in the dryland biome systems. These uncertainties reflect the urgency for new global, spatially explicit and observation-based database of ecosystem C stock and C change in LUC (Smith *et al*., 2012) to move the climate mitigation potentials reported here to higher tiers.

Concluding remarks

Whether or not land is converted to bioenergy crops or forestry, or remains in use for food production, depends upon many factors, and we do not attempt to project which areas will or will not be converted. Instead, we determine the most effective use of the land for climate change mitigation, should conversion occur. While bioenergy cropping provides the best climate mitigation on the majority of land not excluded by unfavourable carbon consequences of land-use change, forestry is the best option on a large area. This suggests that any areas considered for conversion for energy cropping should also be assessed for carbon sequestration potential in forestry, and it could be argued that any incentives for bioenergy crops in forms of targets and subsidies should be matched with a corresponding (on carbon-saved basis) financial incentive for carbon sequestration via forestry. Landowners could then decide which whether to deploy bioenergy or reforestation depending on their local conditions, know-how and other considerations. A full assessment of the net impacts of LUC in agricultural land would require multiple ecosystems services to be considered (Smith *et al*., 2013b), but that is beyond the scope of this study. Climate mitigation is just one possible service provided by land, with the main use of agricultural land use being the provision of food. As this study is spatially explicit, it also serves to identify the regional differences in the efficacy of different mitigation options, providing the basis for the development of regionally or nationally appropriate mitigation actions (NAMAs; Bockel *et al*., 2010).

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Supporting Information

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

Figure S1. Climate zones map developed using the 5 arc-min resolution grids of CRU thermal and moisture regime baseline data (1961–1990) (Global Agro-Ecological Zones FAO-GAEZ website, Fischer *et al.*, 2008).

Figure S2. High-input irrigated, high-input rainfed, and low-input rainfed cropland yield distribution derived from the global 5-arc min land-use data set of the Spatial Production Allocation Model (SPAM) in the year 2000 (You *et al.*, 2014). Here we included seven cropland classes representing the potential productivity of food annual crops at global scale (i.e. Barley, Maize, Millet, other-Fibers, other-Pulses, other-crops, Rice, and Wheat).

Figure S3. Cropland yield distribution within the Disadvantaged Agricultural Areas (DAL) obtained using the 5 arc-min resolution grids global terrain slope map (Fischer *et al.*, 2008). DAL is based on the occurrence of land with mean terrain slope value ≥20%.

Table S1. Average IPCC default dry matter biomass increment in aboveground biomass, and belowground to aboveground biomass ration (Root : Shoot ratio) in natural regeneration by broad categoriy (IPPC-GBP-LULUCF, 2006). Forest felling losses and human fire induced for the year 2000 were sourced from Krausmann *et al.* (2007).

Table S2. Average carbon zone (t C ha^{-1}) specific to each continent, country, climatic region and eco-floristic zone, derived from the IPCC default values on aboveground biomass, and belowground biomass using the root to shoot ratios for each vegetation type. Living vegetation biomass was converted to C fractions using the factor 0.5. Global continental and eco-floristic zones maps were obtained from the Carbon Dioxide Information Analysis Center website (Aaron and Gibbs, 2008; http://cdiac.ornl.gov/), while the global climate zones map was developed using the 5 arc-min resolution grids of CRU thermal and moisture regime baseline data (1961–1990) (Global Agro-Ecological Zones FAO-GAEZ website, Fischer *et al.*, 2008).

Table S3. Percentage of biomass stock in the first 20 years (F_{20}) in naturally regenerated forest distinct among climatic zones and continental regions. Values were estimated averaging the the IPCC default dry matter biomass increment in aboveground biomass in naturally regenerated forest by broad categoriy reported in IPCC, 2006.