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

DOI: 10.1111/gcb.13745

MS. LENA BOYSEN (Orcid ID : 0000-0002-6671-4984)

Trade-offs for food production, nature conservation and climate limit the terrestrial carbon dioxide removal potential

Authors: Lena R Boysen[1,2,3,4*], Wolfgang Lucht[1,2,3], Dieter Gerten[1,2]

Affiliations

[1] *Potsdam Institute for Climate Impact Research, Telegraphenberg A62, 14473 Potsdam, Germany*

[2] *Humboldt-Universität zu Berlin, Department of Geography, Unter den Linden 6, 10099 Berlin, Germany*

[3] *Integrative Research Institute on Transformations of Human-Environment Systems, Unter den Linden 6, 10099 Berlin, Germany*

[4] *Now at Max-Planck Institute for Meteorology, Bundesstraße 53, 20146 Hamburg, Germany.*

*Correspondence to: lena.boysen@mpimet.mpg.de

Keywords: Bioenergy, mitigation, climate change, food production, ecosystem change

Abstract

Large-scale biomass plantations (BPs) are a common factor in climate mitigation scenarios as they promise double benefits: extracting carbon from the atmosphere and providing a renewable energy source. However, their terrestrial carbon dioxide removal (tCDR) potentials depend on important factors such as land availability, efficiency of capturing biomass-derived carbon and the timing of operation. Land availability is restricted by the demands of future food production depending on yield increases and population growth, by requirements for nature conservation and, with respect to climate mitigation, avoiding unfavourable albedo changes. We integrate these factors in one spatially explicit biogeochemical simulation framework to explore the tCDR opportunity space on land available after these constraints are taken into account, starting either in 2020 or 2050, and lasting until 2100. We find that assumed future needs for nature protection and food production strongly limit tCDR potentials. BPs on abandoned crop and pasture areas (~1300 Mha in scenarios of either 8.0 billion people and yield gap reductions of 25% until 2020 or 9.5 billion people and yield gap reductions of 50% until 2050) could, theoretically, sequester ~100 GtC in land carbon stocks and biomass harvest by 2100. However, this potential would be ~80% lower if only cropland was available or ~50% lower if albedo decreases were considered as a factor restricting land availability. Converting instead natural forest, shrubland or grassland into BPs could result in much larger tCDR potentials – but at high environmental costs (e.g. biodiversity loss). The most promising avenue for effective tCDR seems to be improvement of efficient carbon utilization pathways, changes in dietary trends or the restoration of marginal lands for the implementation of tCDR.

Introduction

Terrestrial carbon dioxide removal (tCDR) strategies use the potential of the biosphere to sequester CO_2 from the atmosphere, thereby reducing the rise in global mean temperature (GMT) (Caldeira et al., 2013; Lenton and Vaughan, 2009). For such purpose, highly managed woody and herbaceous bioenergy plantations (BP) could be cultivated and harvested regularly with subsequent storage of the extracted carbon, for example in geological reservoirs, biochar or as building materials. In this manner so-called negative emissions could be achieved, i.e. net extraction of CO_2 from the atmosphere (Fuss et al., 2014; Lenton, 2010; Smith et al., 2016; Vaughan and Lenton, 2011). These are a crucial part of many projected mitigation pathways for ambitious climate protection (Fuss et al., 2014; Klein et al., 2014; Kriegler et al., 2013) and also part of a climate engineering (CE) portfolio (Caldeira et al., 2013; Keller et al., 2014) proposed as a potential counter-measure in case of failed mitigation. Understanding the relationship between land availability for BPs and their potentials, trade-offs and side-effects for the environment, human well-being and climate itself is therefore crucial in determining the properties of such near-future mitigation pathways.

Optimistic studies on tCDR consider biomass plantations and afforestation projects to be a carbon extraction tool that is relatively safe and affordable (Shepherd, 2009) compared to other CE-methods like solar radiation management and, together with the biomass conversion to bioenergy and carbon capture and storage (BECCS), also an effective tool (Klein et al., 2014; Kriegler et al., 2013; Lenton, 2010; Lomax et al., 2015). However, substantial uncertainties remain regarding BP's scalability and the time- and space-consuming properties linked to high carbon extraction potentials which could ultimately turn tCDR into a rather expensive (Caldeira et al., 2013), ineffective (Fuss et al., 2014; Shepherd, 2009) and ecologically and socially intolerable (Dornburg et al., 2010; Smith et al., 2016, 2013) CE method.

Previous studies agree that land availability for tCDR is, among others, tightly linked to food demand and production efficiency, associated land management practices and ecosystem conservation: It will likely be a challenge to simultaneously meet the needs of food production for a growing world population, nature conservation and climate protection through avoided deforestation or BPs (Beringer et al., 2011; Kraxner et al., 2013; Lenton, 2010). Most likely, only a shift towards highly efficient food production systems with low meat consumption would release sizable agricultural areas for tCDR without compromising forest protection and biodiversity conservation (Kraxner et al., 2013; Powell and Lenton, 2012, 2013). Nevertheless, tCDR potentials – generally assumed to be climate-beneficial – identified in these studies could increase if the emissions incurred the conversion of biomass to long-lived carbon products were reduced through technological improvements (Lenton, 2010). Negative biogeophysical effects due to land conversion to BPs (e.g. changes in moisture fluxes and albedo) and biogeochemical effects (e.g. through increased water and nutrient applications) on climate have recently been investigated, too (Davin et al., 2014; Heck et al., 2016; Smith et al., 2016). The potential of tCDR to mitigate climate change is furthermore linked to the timing of their implementation and duration of operation. Implementation of BPs in the near-future rather than later (Bertram et al., 2015; Luderer et al., 2013) increase their accumulation of carbon while emissions might continue to rise. So far, most studies have investigated these land-constraining factors individually, in some form of limited combination or using an integrated assessment model but not within a comprehensive and internally biophysical process consistent single modelling framework as provided by this analysis.

To advance the above-mentioned studies, we ask under what conditions arable land could possibly be available for climate protection through tCDR, with food production secured for a growing population and natural areas preserved. In light of an increasing number of mitigation scenarios relying on tCDR (Fuss et al., 2014), we aim to reduce uncertainties in such scenarios from a biosphere perspective using a well-established biogeochemical process model for natural vegetation and managed land, LPJmL (Bondeau et al., 2007).

Specifically, this study analyses, spatially explicitly, three prioritizations that could severely restrict large-scale land availability for tCDR. First, security of agricultural food production is prioritised over tCDR ("food first") considering different assumptions about food demand (determined mainly by global population growth). Second, (unmanaged) natural areas are prioritized over tCDR depending on a combination of published data sets on areas of conservation concern and simulated biomes ("conservation first"). Third, climate protection is prioritized, i.e. negative emission potentials are maximized ("climate first"). On the one hand, this last factor means increasing tCDR potentials by extending the operational time of BPs (e.g. near-term establishment) and improving the effectiveness of carbon utilization pathways (e.g. reducing the emissions incurred along the subsequent process chain through technological innovations). On the other hand, this simultaneously implies avoiding negative albedo changes induced by land conversion to BPs – one possible affected biogeophysical variable next to moisture and momentum fluxes. Along this line of argumentation, we examine tCDR potentials and trade-offs of BPs that are assumed to be grown from either 2020 (as required, e.g., for near-future projections as in most mitigation scenarios) or 2050 (for the purpose of CE) until 2100. Using these constraints enables us to quantitatively explore the global opportunity space of convertible land for tCDR as shown schematically in Fig. 1a. The link between these foci and tCDR potentials is explained in the following paragraphs. We do not study optimal solutions to these trade-off conundrums but rather analyse their respective influence on tCDR potentials, whereby results for the conversion of natural land or agricultural land are additive

Materials and Methods:

The model LPJmL:

We conduct spatially explicit simulations with the biogeochemical process model LPJmL for vegetation (including agricultural managed land) and the terrestrial carbon and water cycle (Bondeau et al., 2007; Schaphoff et al., 2013). The model is spun up for 5000 years without land use and by cycling the climate of 1901-1930 to reach equilibrium in carbon pools. Then, another spinup of 390 years follows with gross transient historical land-use of 1700-1900 to bring the distribution of potential natural vegetation represented by nine plant functional types (PFTs) into equilibrium. Only after that, the growth and productivity of the dynamic natural and gross transient historical land-use (Bondeau et al., 2007; Fader et al., 2010), including crop and pasture areas and irrigation patterns following Jägermeyr et al. (2015), are simulated for the period 1901-2005. Climate data for this period are monthly data on temperature, precipitation and cloudiness as well as annual CO_2 concentrations (Ostberg et al., 2015) disaggregated to daily time-steps (Gerten et al., 2004). Simulated natural PFTs compete for light, space and water (Sitch et al., 2003), the latter provided by precipitation, snowmelt and permafrost thawing (Schaphoff et al., 2013). Plants can access water by extracting infiltrated soil water through their roots to the extent this is accessible after subtraction of evaporation and (sub)surface runoff (Gerten et al., 2004). Carbon uptake by plants through photosynthesis (Collatz et al., 1992; Farquhar et al., 1982) is allocated in leaves, heart and sapwood and roots and is transferred to the litter and soil carbon pools after leave shedding, disturbances (e.g. wind or fire) or mortality. The model's performance has successfully been evaluated e.g. by Peylin et al. (2005) and Sitch et al. (2003, 2008) for carbon cycling, Cramer et al. (1999) for NPP, Lucht et al. (2006) for LAI, Friend et al. (2014) for turnover rates and Schaphoff et al. (2013) for carbon and water fluxes.

LPJmL simulates 12 crop functional types (CFTs), pastures and a category with "other" non-nutritious plant types (e.g. citrus, cotton or fibre). Crop yields are calibrated with annual national FAO statistics between 1995 and 2005, which assures a realistic representation despite the model assumption that there is no nutrient limitation. This calibration is achieved by adjusting three crop-specific parameters: the harvest index (HI, range of 0-1; Bavec and Bavec, 2002; Krysanova et al., 2000; Neitsch et al., 2005) as an optimum harvest proportion of the storage organ (e.g. grains) and a parameter (α_a, range of 0.4-1) representing photosynthetic activity of plants; which are both internally linked to the maximum leaf area index (LAI_{max}, range of 1-7 in accordance with the majority of observed values (Anten, 2005; Scurlock et al., 2001) as a proxy of plant density defining how efficiently plants capture incoming light. The leaf area index (LAI) for a CFT is calculated following a prescribed sigmoid curve through the year based on heat sum units needed to reach vernalisation, growing phase and senescence. It is limited by the calibrated LAI_{max} and, additionally, downscaled under water stress. This is in contrast to the dynamic LAI calculation of PFTs depending on leaf carbon, transport tissue, specific leaf area and longevity as well as the crown area. LAI_{max} is linked to photosynthetic active radiation absorbed, which levels off when approaching an LAI_{max} value of 7 (Haxeltine and Prentice, 1996; Jung et al., 2007) i.e. the energy gain for the plant is small compared to the increase of LAI. This in turn means, that if, at present, maximum yields are locally reached with a LAI_{max}=7 (and consequently α_a =1) in some regions (Anten, 2005; Scurlock et al., 2001), only new breeds with different carbon allocation rules between leaves and harvestable fruit organs, new leaf structures or photosynthetic pathways could result in even higher yields (Kromdijk et al., 2016; Srinivasan et al., 2017). For example, breeds/species with as little LAI as possible towards higher harvestable organs could be one solution in regions where LAI_{max} is already approached today (i.e. maximum yields shown in Fader et al., 2010 and Neumann et al., 2010). However, we base our analysis on current knowledge of yields and processes but emphasize that e.g. genetic modifications could shift these limits upward by introducing new relationships between plant's use of sunlight and fruit organs.

Crop yield refers to the harvested biomass and is translated to calorific values by first converting biomass carbon to dry matter and further to fresh matter (Wirsenius, 2000) before crop-specific calorific factors are being applied (FAO). The model's performance in simulating agricultural properties has been demonstrated in many applications (Boit et al., 2016; Bondeau et al., 2007; Fader et al., 2010; Jägermeyr et al., 2015; Maiorano et al., 2017; Rolinski et al., 2015; Sakschewski et al., 2014; Schauberger et al., 2017; Waha et al., 2012; Weindl et al., 2015).

We choose a climate forcing reaching 2.5°C of mean global warming above preindustrial in the year 2100 (Heinke et al., 2013) on the basis of simulations with the MPI-ESM climate model (Giorgetta et al., 2013). This forcing is similar to the RCP4.5 trajectory (Thomson et al., 2011) similar to the current internationally agreed national emission reduction pledges (Jeffery et al., 2015). Following this trajectory, we choose to start our tCDR scenarios in 2020 (when +1.1°C is reached) and 2050 (+1.8°C), respectively.

Land-use and irrigation patterns are held constant from 2005 until BPs are introduced in 2020 or 2050 as we aim for a systematic analysis of biogeochemical potentials within today's known spatial and productivity limits without additional (and possibly speculative) assumptions about optimized patterns or socio-economic drivers of land cover change. Any further expansion would cause trade-offs with natural land conservation (Popp et al., 2014) which is, in this study, only analysed in relation with replacement by BPs.

The model simulates two types of bioenergy plants, herbaceous and woody (Heck et al., 2016), with global distributions – as constrained by our diverse assumptions (see below) -- optimized for best net carbon sequestration (see below). Herbaceous and woody BPs are modelled to be harvested on a regular basis (annually or in a 8-year cycle, respectively) to keep productivity rates high. In this study BPs are assumed to be non-irrigated but to have full nutrient supply. The tCDR potentials given here always include the net carbon sequestration potential, that is the net outcome of accumulated biomass harvest carbon depending on the conversion efficiency of the applied biomass carbon utilization pathway (see below) and changes in land carbon pools (soil, litter and vegetation) due to the establishment in 2020 or 2050 and operation of BPs until 2100. The replacement of natural vegetation is accounted for as a one-time tCDR-harvesting event, in that carbon emissions from the conversion are reduced by 50%. This value is assumed to represent a reasonable global average for clearing natural forest with likely less developed infrastructure and long transport ways for processing biomass compared to values assumed for biomass plantations (see below). Annual mean albedo changes from land conversion including snow cover effects are explicitly calculated in LPJmL as described in the Data S1: Section S2.

Scenario setup

The assumptions for the scenario building process prioritizing food security ("food first", Fig. 1a), ecosystem ("conservation first") or climate protection ("climate first") are described in detail in the following sections and listed in Table 1. The basic methodology is simple: First, land grid cells on either crop, pasture or natural land are sorted according to their productivity (given in kcal cap^{-1} day^{-1} on cropland and vegetation carbon in giga tons of carbon GtC on the remaining agricultural and natural land). Second, along this gradient grid cells are protected from conversion to BP to the point where the scenario-specific constraints such as food production for a given global population or intended protection of ecosystems are fulfilled. Third, the remaining, less productive grid cells are considered available for the establishment of BPs (Fig. 1b). We investigate the opportunities and trade-offs for BPs on agricultural and natural areas separately such that the results are additive. However, as in previous studies (Humpenöder et al., 2014; Lenton, 2010; Powell and Lenton, 2013; Smeets et al., 2007; van Vuuren et al., 2011) we first concentrate on the conversion of degraded (Oldemann et al., 1991) or abandoned cropland and pastures before converting natural land to BP, in order to protect still existing natural ecosystems from further human interference through tCDR. The following paragraphs introduce the constraints and the underlying rationale in more detail.

Agricultural food production

The first set of scenarios investigates potential future food demand from agricultural production and possible abandonment of agricultural land for tCDR ("food first" scenarios). The underlying assumption is that food production per unit of arable land (crops, feed and fodder) could be further increased in the future (e.g. through fertilizer input), and thereby, agricultural land be made available for BPs. We apply a range of scenarios of food demand increases (derived from population growth) and crop yield increases up to 2020 and 2050 (see Table 1). For reasons of simplicity we assume that these numbers remain constant for the time after BP implementation (in 2020 or 2050 and lasting until 2100) but account for different levels of yield increases and population growth at these points in time reflecting changes over time.

Our model on average simulates crop yields providing 3240 kcal cap^{-1} day^{-1} given a world population of 6.5 bn in 2005. The calibration also included crops that were used as feed for animals. Further feed and fodder for animals is assumed to be sufficiently provided from residues, pastures and the category "others". We test different levels of global yield increases by assuming relative (percentage-based) decreases in the global yield gap (potential minus actual yield, see also Foley et al., 2011; Godfray et al., 2010; Neumann et al., 2010). This results in a global heterogeneous pattern of yield increases with strongest relative gains in regions with currently largest yield deficits (Foley et al., 2011). Following the yield-gap-approach, yield increases are simulated by decreasing the difference of the current LAI_{max} value to the maximum value of 7 for each crop type in each country by 5, 10 and 25% and 25, 30 and 50% (halving the yield gap) until 2020 and 2050, respectively. These values were chosen systematically to investigate levels of yield increases; they could possibly be reached through breeding, new input resources or management techniques and are comparable to published levels under different preconditions (e.g. based on historical maximum increases or socio-economic estimates Foley et al., 2011; Humpenöder et al., 2014). Climate-driven simulations were carried out with these new management parameters and evaluated while other management parameters (e.g. irrigation) were held constant. This way, global kcal production is simulated to increase by 11, 16 and 31% until 2020 and 36, 45 and 62% until 2050.

We assume that any yield increase on cropland linearly also increases meat production through yield increases on pastures achievable through adequate management options (Rolinski et al., 2015) or feed composition (Havlík et al., 2014; Weindl et al., 2015). We neither explicitly distinguish between vegetal and meat or dairy products which would require a thorough analysis of livestock systems, feed and fodder production and conversion to kilocalories nor consider changes in diet. This simple approach is arguable as future meat demand might increase disproportionally (Bajželj et al., 2014; Erb et al., 2016), but can be justified by studies focussing on abandonment of pasture land due to shifts to e.g. vegetarian diets (e.g. Humpenöder et al., 2014; Riahi et al., 2016; Smith et al., 2013; Thomson et al., 2011; van Vuuren et al., 2011a) or even motivated by climate protection (Smith et al., 2013). We keep the ratio of kcal (crops) and GtC (pastures and others) produced per capita in 2005 on both cropland and pastures constant and take this ratio as a requirement for future food supply which must be met along the gradient of sorted grid cells. Yield increases may thus be seen as opportunities for tCDR if land can be spared where population-driven food demand is outpaced by productivity increases (assuming a globally effective trade system for food supply). These productivity increases could be incentivised by the competition for land as a limited resource (e.g. for food and energy production, recreation, conservation, settlements) and achieved by giving farmer access to knowledge, technology, input resources and infrastructure (Godfray et al., 2010). Additionally, we provide results on tCDR potentials on cropland and pasture land separately.

Global population numbers refer to 2005's status of 6.5 bn, 2017's status of 7.5 bn and a moderate estimate of an increasing population up to 8.0 bn and 8.4 bn in 2020 reaching up to 9.5 bn an 11.0 bn in 2050, respectively (United Nations, 2015). Again, we do not simulate evolving population numbers with time but account for different levels in 2020 and 2050.

Degraded and unproductive soils

Some of agricultural land is rather unproductive and contributes little to food, fibre or cotton production and therefore could be made available for BP (at least theoretically, as it has many other current functions and values). We identify these areas by taking the 90th percentile of least productive cropland and pasture grid cells, which are mainly located at the margins of deserts or mountainous regions and test whether BPs could make this land productive again (possible e.g. through soil amelioration by roots and increased carbon input from litter fall). Vice versa we test what the BP potential would be if BPs were to restore current land classified as degraded (Qin et al., 2011; Xie et al., 2013). For this, we additionally use the Global Assessment of Human-Induced Soil Degradation (GLASOD, Fig. S1; Oldemann et al., 1991) data set to identify severely and extreme degraded land (not suitable for agriculture) as well as slightly and moderately degraded land (reduced agricultural productivity). LPJmL does not simulate degraded soils explicitly and thus, BPs could have higher productivity than crops that were calibrated with observations in that same location. Therefore, we imitate the case that such soils could be fully restored by 2020 or 2050 (e.g. through sufficient resource input) and deduce optimistic potentials for (non-irrigated) BP on these areas.

Natural and areas of conservation concern

To avoid conflicts with food production, natural land might be considered alternatively for conversion to BP. The value of these areas is difficult to measure quantitatively but they play an important role in the climate system and their biodiversity supports resilience to natural disturbances such as pests, fires or droughts (Anderegg et al., 2013; Sakschewski et al., 2016) besides having an intrinsic value to human culture. We therefore classify biomes and overlay spatially detailed biodiversity maps to systematically screen tCDR suitability and potentials of these areas “conservation first” scenarios). We analyse simulated biomes and published data on areas of conservation concern separately and in combination. We consider biomes as well to reflect their values (carbon, heat and moisture fluxes, air quality and cultural meaning) on top of the value of only preserving today’s areas of concern.

Fifteen natural biomes are classified from model simulations until 2020 or 2050 using climatic input data and simulated vegetation carbon at grid-cell level (Ostberg et al., 2013) and grouped into forested areas (F), grassland (G) and shrubland (S) as a way of presenting results in a simplified manner. Potapov et al. (2017) identified intact forest landscapes (IFL) which are considered to be most valuable and which are part of the forest biomes considered here (Fig. 2 a). We further overlay maps of conservation concern (C) such as of biodiversity hotspots (Mittermeier et al., 2011), protected areas (IUCN and UNEP-WCMC, 2015), endangered species (including amphibians, birds, birds small-ranged and mamels, Pimm et al., 2014) and endemism richness (for terrestrial vertebrates and vascular plants, Kier et al., 2009) (Fig. 2 b). We chose these data sets as a subset of all available information on conservation concerns as they cover different aspects such as biodiversity hotspots, already protected areas and range maps. While hotspots and protected areas cover entire grid cells, areas of endangered species and endemism richness were rasterized and normalized by their maximum values and thereby translated to fractional shares of grid cells. The dominant share of all data sets is taken and protected from land transformation as we assume that the areas of conservation concern of different data sets overlap rather than being additive. In all grid cells, at least a fraction of 0.1 was excluded from conversion to BPs.

Biome classes and biodiversity maps are either excluded from transformation to BPs separately (e.g. only forests, shrub land or protected areas) or in combination (e.g. forest plus protected land), while the other classes of natural land are assumed to be available for tCDR. However, grid cells are excluded in which non-irrigated BP saplings do not grow due to climatic conditions. If BPs and areas of conservation concern (C) appear together in one grid cell, it is assumed that BPs always interfere with the conserved areas although these could be located anywhere in the cell which is a very strict assumption.

Albedo changes

Studies show that the conversion of grassland to BP in higher latitudes might shadow bright reflective snow, causing a warming effect (Arora and Montenegro, 2011; Schaeffer et al., 2006). Similarly, albedo might decrease with a replacement of crops by less reflective BPs which, however, also depends on management practices: herbaceous biomass harvest left on the field for drying tends to cover dark soil and thus, increases overall albedo compared to traditional crop management, while a complete or partial - as in LPJmL where only straw and stubble remain on field - removal would decrease albedo (Davin et al., 2014; Horton et al., 2015; Merlin et al., 2013). LPJmL calculates annual mean surface albedo depending on area covered by vegetation and snow cover in each grid cell (Data S1: Section S2 and Fig. S2 and S3a; Forkel et al., 2014; Strengers et al., 2010). In the analysis, we only include changes that exceed -0.02 of the original albedo value to account only for pronounced alterations of the surface reflectivity ("climate first" scenarios) and that therefore exceed the change of historical albedo changes due to the conversion of natural land to crop land in opposite direction (Pongratz et al., 2011).

Carbon conversion pathways

Harvested biomass from BP contains carbon that needs to be further processed to be climatically beneficial: i.e. carbon needs to be extracted from the carbon cycle to achieve negative emissions. Methods include in particular the substitution of fossil fuels by transforming biomass into biofuels in combination with carbon capture and storage (BECCS) to geological reservoirs. Further applications are the increased traditional use of wood as a building material or the production of biochar which is brought back onto fields and might act as a fertilizer and reduce the use of nitrogen and phosphorus (Lenton, 2010). The ultimate carbon extraction depends not only on the decay time of the end product but also on the losses and leakage rates during harvest, transportation and, especially, conversion techniques and feedstocks used (Edenhofer et al., 2011).

Biomass utilization pathways therefore influence tCDR potentials in two ways: First, the conversion efficiency (CEff) defines how much of the biomass carbon is actually immobilized permanently depending on the emissions occurring along the process chain (Lenton, 2010). Second, for higher conversion efficiencies less land will be needed to gain the same amount of carbon extraction. We here span the range of possible conversion efficiencies, including all losses, from a pessimistic 20% (e.g. wood combustion or fermentation; Edenhofer et al., 2011; Lenton, 2010) to a medium level of 50% to improvements up to 70% (e.g. for gasification or pyrolysis processes; Lenton, 2010; Woolf et al., 2010). CEff could in theory be as large as 90% (e.g. biomass to hydrogen, pyrolysis; Edenhofer et al., 2011; Lenton, 2010), however accounting for leakage during transport, processing and storing as well as the large-scale application (Cannell, 2003; Smeets et al., 2007) we assume lower values. In the following, all tCDR potentials refer to values of CEff of 50% unless stated differently which represents a reasonable global average accounting (Lenton, 2010).

Results

tCDR potentials on agricultural land ("food first") depend on two main assumptions in our study: land availability (depending on yield increases and food demand) and time of operation of BPs (from 2020 or 2050 to 2100). Thus, agricultural land can only be spared for BPs if yield increases until 2020 or 2050 will exceed the concurrent food demand for a given world population (given that diets, crop mixes and total agricultural land extent remain constant).

Transforming the 10% least productive agricultural land grid cells (Fig. 3a, 68 Mha) to BP reveals that these areas are also unsuitable for the cultivation of non-irrigated BP, with only 1 GtC sequestered (Fig. 4, Table 2). However, LPJmL simulates sizable biomass production potential on currently observed degraded soils (Oldemann et al., 1991) such that if severely and extremely degraded soils covering about 300 Mha globally were restored until 2020, 67 GtC could be extracted. If all slightly and moderately degraded land was recovered and converted to BP, 109 to 191 GtC could be extracted on 1654 Mha (Table S1).

The assumed yield gap reductions (decreasing the difference of potential minus actual yield by the scenario percentage) in our model deliver enough agricultural food production for up to 8.4 bn people in 2020 and 9.5 bn (but not 11.0 bn) people in 2050 while still releasing land for BPs as shown in Fig. 4 and Table 2. In 2020, a yield gap reduction of 10% would, in our scenarios, be just sufficient to provide food for 7.5 bn people (meeting the calibrated kcal cap^{-1} day^{-1} production) and allow for 53 GtC tCDR by 2100 on 1006 Mha (almost exclusively pastures; 8 GtC on 73 Mha other agricultural land for e.g. fibre. and cotton production, Table S2). Increasing yields by one fourth of the yield gap could enhance food production by 31% and thus meet the food demand of 8 bn people (with a production of still +7% kcal cap^{-1} day^{-1} production). This would double tCDR potentials while additional available area for BPs increases by 300 Mha with contributions of BPs on cropland (13 GtC on 78 Mha) and other land (17 GtC on 116 Mha). As population increases with time, a yield gap reduction of 50% until 2050 would already be needed to produce food for 9.5 bn people (Fig. S4). In this case, BPs could extract 70 GtC on half of today's pastures (1271 Mha), 13 GtC on 112 Mha cropland and 19 GtC on 165 Mha of remaining other agricultural land. tCDR potentials generally decrease in 2050 compared to 2020 as population numbers rise and the run-time of BPs is 30 years shorter which cannot be compensated by land abandonment caused by the chosen yield gap reduction.

In LPJmL, albedo is simulated to decrease on much of the abandoned cropland if converted to BPs (Fig. S5 and S6), since the mean annual albedo of herbaceous BPs (predominantly modelled on cropland) is lower than that of most crops (Fig. S3). For example, in a scenario with a yield gap reduction of 25% and 7.5 bn people in 2020, pasture area assumed to be suitable for tCDR (albedo changes not exceeding -0.02 after land conversion, "climate first") is reduced by one third while suitable cropland is reduced by 90% leaving tCDR potentials of 67 and 5 GtC, respectively (compared to 127 and 25 GtC without this constraint) in 2100 (Table 2; see also Table S3). This excluded land however, could still be used for surplus food production for an even larger world population (see Table S3 for detailed information).

Technical improvement of conversion and storage efficiencies (CEff) could increase the net carbon extraction and reduce the area needed for the effective sequestration of one unit of carbon. In Fig. 4 (and Fig. 5 and Data S1: Sections 3 and 4), values in brackets denote tCDR potentials at the 20-50% range of CEff. The area made available due to an increase of CEff from e.g. 50 to 70% is immense: 50-60% less agricultural land would be needed throughout our scenarios (Table S4). This means that the same amount of carbon could be extracted out of the atmosphere on about 40% of the most productive available land cells if carbon losses during transportation, processing and storage are decreased by at least 20%. Interestingly, for CEff of

20%, carbon losses due to the conversion of land cover to BP cannot be fully offset and thus, the suitable area for BP is reduced by 2-3% compared to higher values of CEff (Table S4). The consequence is that area savings for an efficiency increase from 20 to 50% lie above 70%.

Overall, albeit relatively low, the simulated tCDR potentials studied here are rather optimistic since our scenarios rely on very productive BP characterized by, for example, unlimited nutrient supply and fast implementation. One could argue that this lack of nutrient limitation for BPs could be realized to guarantee high biomass harvest yields which has been tested in several field studies (Heck et al., 2016). Especially the beneficial effects of a moderately warmer climate and elevated CO_2 levels as in our climate scenario increase plant productivity in the second half of the century in our model (productivity increase on cropland: +31% in 2020, +35% in 2050) which is in line with experiments and previous publications (Beringer et al., 2011; Hickler et al., 2008; Norby et al., 2005).

Conversion of natural land

Analogous to the above analysis for abandoned agricultural land, we map the different tCDR potentials following various degrees of nature conservation ("conservation first"). This could be considered if yield increases were too small to balance food demand and thus, release agricultural land and if tCDR was still rated as an option to reduce atmospheric CO_2 concentrations. Figure 5 shows the simulated vegetation carbon for different combinations of conserved biomes and biodiversity maps against the tCDR potential on the released areas for the period 2020-2100 (Fig. S7: results for 2050-2100). In this scenario setup tCDR potentials are mainly a function of run-time until 2100 and beneficial climatic and CO_2 effects on BP productivity. However, forests expand by 264 Mha or 5% in 2050 compared to 2020 and thus, if these additional areas are consistently excluded, the area of land potentially available for tCDR declines (Table S5). We select one scenario combination for illustration: In LPJmL, 690 GtC of vegetation carbon are stored in 7.5 Gha of combined areas of conservation concern and forested land (C+F scenario) in 2050. BP's on the remaining unprotected grass and shrubland (G+S) covering 1673 Mha could then sequester 49 GtC until 2100 (CEff = 50%). This already accounts for half the vegetation carbon stored in G+S (50% of the original vegetation carbon are permanently sequestered, see methods) which amounts to 690 GtC in total in 2050. However, this extracted carbon has to first offset carbon emissions from land conversion and thus, lowers the overall tCDR potential. In general, the tCDR potentials per unit of area converted are much smaller than those achieved on agricultural land since higher land conversion emissions counteract substantial parts of the sequestration potentials. On natural land albedo mostly increases after a conversion to BP (Fig. S3) which is why these effects are not included in the analysis on tCDR potentials on these areas.

Discussion

This study shows that there are, theoretically, options available for implementing BPs in today's landscapes by 2020 or 2050 and that these BPs could sequester up to 250 GtC by 2100 on abandoned agricultural or on natural land outside forests or biodiversity-rich areas. However, the available area for tCDR highly depends on the assumptions about what areas are considered convertible, what yield increases might be possible in the future, how efficient utilization pathways will be, and what food demand is foreseen (here, depending primarily on population numbers).

On agricultural land, our potentials are high as long as pastures may be converted to BPs. Pastures today cover two thirds of total agricultural land with 3.5Gha of 4.5 Gha. Depending on future diets and management intensities (yield gap reductions), this area is projected to either increase substantially or to be partially abandoned and thus, released for BPs. Most studies argue that it is likely that with population growth food demand will increase overproportionally with shifts to more meat and dairy consumption (Bajželj et al., 2014; Lotze-Campen et al., 2014; Sakschewski et al., 2014; Wise et al., 2009). Such developments could drive land expansion into currently natural areas if yield increases, new food sources (e.g. protein from algae) or global trade of products cannot balance the demand. As a consequence, land availability for BPs could be very limited (if they re allowed only on abandoned agricultural areas, as assumed here). On the contrary other studies show, that it could be possible to feed the world on today's agricultural land by closing yield gaps (Dornburg et al., 2010; Erb et al., 2016; Foley et al., 2007, 2011; Godfray et al., 2010) which in combination with diet shifts to less meat consumption – which was found to be the most influential driver – (Erb et al., 2016; Humpenöder et al., 2014; Powell and Lenton, 2012; Smith et al., 2013) would provide land for tCDR. For example, the recent portfolio of land use scenarios in shared socioeconomic pathways (SSPs) SSP1 and SSP2 (Riahi et al., 2016; van Vuuren et al., 2016) as well as RCP2.6 (van Vuuren et al., 2011b) also consider a decrease of pasture land in a globalized world with high yield increases in wealthy regions. Following such a projection, while acknowledging that they are hypothetical compared to present day conditions in the real world, could then indeed allow for upper estimates of tCDR potentials found in this study. Overall, the prospect of sustainably increasing global food production while protecting the environment poses challenges already today (Hertel and Baldos, 2016) – demonstrating the difficulty of freeing land for BPs in the future if expansion is undesirable, yield increases were only moderate (e.g. if maximum plant productivity was indeed limited as in our study) and meat consumption was excessive.

Previous studies estimated tCDR potentials on abandoned agricultural land of 65-133 GtC on 695-1014 Mha between 2000 (Lenton, 2010) and 2100 or even 180-260 GtC on 332-660 Mha between 2000 and 2050 (Powell and Lenton, 2012) (both with CEff=50%). Even though our scenarios assumed an instantaneous (and not transient) conversion of land to BPs, tCDR potentials on similar BP extents sequester less than half the carbon over 50 to 80 years of operation in our biogeochemically advanced simulation. The simulated tCDR potentials in this study could be improved by allowing the use of more productive than least productive land grid cells. For example, converting 25% of the most productive crop and pasture grid cells (1045 Mha) resulted in 341 GtC extraction between 2038 and 2100 in a study by Boysen et al. (2016). A similar BP area is covered in a scenario with 8bn in 2020 and a yield gap reduction by 25% but results only in 55 Gt carbon sequestration until 2100.

If BPs could only be established on abandoned cropland, tCDR potentials would be considerably smaller than if pastures were also considered. One of the reasons lies in our assumption of fixed crop mixes and diets; another may lie in the yield increases chosen. By reducing the yield gap until 2020 by 5, 10 and 25% yields increase on average by 0.3, 0.6 and 1.7% yr^{-1} (and by 0.6, 0.7, 1.1% yr^{-1} until 2050 given yield gap reductions of 25, 30 and 50%). This range might seem to have been chosen somewhat arbitrarily, however, it covers the range of yield increases given by literature and thus, it may be assumed to be suitable for estimating the extent of land available for tCDR. For example, lower-than-current yield increases of 0.48% yr^{-1} are assumed for a business-as-usual pathway (Humpenöder et al., 2014). Current yield increases lie at 0.95% yr^{-1} (1985-2005; Foley et al., 2011) and could possibly even be maintained sustainably at around 1% yr^{-1} if diets shifted towards lower meat shares and production would move to highly efficient schemes (Powell and Lenton, 2012). Highest productivity increases in the recent past (1985-2005) reached 1.4% yr^{-1} (Foley et al., 2011; Lotze-Campen et al., 2010), but it is unclear whether these can be achieved once more and sustained unless genetic modifications or currently unutilized food plants were entered into use (Humpenöder et al., 2014; Lotze-Campen et al., 2010). In LPJmL, plants are supplied sufficiently with nutrients – a condition that might not easily be fulfilled in reality, especially for intensively managed croplands and BPs (Beringer et al., 2011; Boysen et al., 2016; Heck et al., 2016). The simulated tCDR potentials could further be enhanced by introducing irrigation systems to BPs, which in turn would likely increase the pressure on water resources (Gerten et al., 2013; Jägermeyr et al., 2015).

To avoid these trade-offs between tCDR and agricultural food production two possibilities are available. On the one hand, marginal and unproductive agricultural areas could be converted to BPs. However, they did not show to be a good choice for at least non-irrigated BPs either. On the other hand degraded areas were simulated to have been fully restored and then converted to BPs, which resulted in similar results compared to those of BPs on crop land alone, i.e. represent an optimal outcome. There are studies that claim that BP could indeed restore degraded soils (McElroy and Dawson, 1986; Xie et al., 2013) but others hold against that carbon emissions from land conversion and BP operation are high (Qin et al., 2011, 2014).

A further aspect are the negative effects on surface albedo on climate ("climate first") from land conversion from crops to BPs (Arora and Montenegro, 2011; Schaeffer et al., 2006; Singarayer et al., 2009). Compared to historical changes of albedo due to land use change (Pongratz et al., 2011), changes simulated here are stronger and thus, tCDR potentials are reduced along with this land conversion restriction. However, studies are not conclusive about the sign of albedo changes which highly depends on management practices and the original land cover (Davin et al., 2014; Merlin et al., 2013). Further analyses with coupled simulations including climate system feedbacks should also focus on what the effective tCDR potential of reducing CO_2 concentrations is (including feedbacks from e.g. oceans, (Jones et al., 2016; Tokarska and Zickfeld, 2015; Zickfeld et al., 2016), whether changes from the extraction of CO_2 by tCDR overcompensate changes in albedo (through changing radiative forcing; Pongratz et al., 2011), whether N2O emissions from increasing fertilizer application cause additional warming or whether changes in moisture and heat fluxes play an important role for the local to regional climate (Brovkin et al., 2013; Noblet-Ducoudré et al., 2012; Pitman et al., 2009).

Land transformation for the purpose of tCDR could also take place outside already cultivated land ("conservation first"). However, rededicating more natural land to BPs is a delicate task considering that the rate of biodiversity loss is already exponentially increasing (Ceballos et al.,

2015) and that ecosystems will likely be exposed to climate change impacts during the next decades (Gerten et al., 2013; Ostberg et al., 2013). There are however studies arguing that corridor-like BP or afforestation projects could favour biodiversity, protect ecosystems and even favour the potential of BP (Jantz et al., 2014). Still, sacrificing natural areas which are rich in carbon storage, biodiversity and needed for ecosystem resilience (Sakschewski et al., 2016) would request delicate decision-making and the added value of tCDR for climate protection against the multi-faceted value of original land cover (e.g. also for recreation and emotional attachment; Chan et al., 2016) would still have to be proven.

Lastly, the utilization pathway chosen for harvested biomass from BPs determines how much area is required to permanently extract one unit of carbon in regions with similar land cover or land use history and bioclimatic conditions. We here envelope conversion efficiencies of a range of technologies that are available today - but not necessarily ready to be deployed at large-scale (e.g. BECCS) due to limitations in storage capacity (e.g. of soils or geological reservoirs; Azar et al., 2010; Humpenöder et al., 2014; Lenton, 2010; Vaughan and Lenton, 2011) or additional non-BP feedstock demand (Fuss et al., 2014; Kato and Yamagata, 2014; Smith et al., 2016). A promising biomass product could be biochar with estimated lifetimes of up to millennia (Woolf et al., 2010) and positive effects on the fertility of soils reducing therefore artificial fertilizer input.

We conclude that land availability for tCDR is very limited if constrained by the simultaneous needs for food production ("food first") as well as nature conservation ("conservation first") and local climate protection through albedo changes ("climate first"). Our scenarios cover a range of food production increases derived from yield gap reductions which, in combination with population outlooks until 2020 or 2050, could theoretically release land for the establishment of BPs. Excluding scenarios with decreasing or stagnating population numbers, tCDR potentials could reach about 100 GtC on abandoned agricultural land by 2100 if population numbers increased moderately or yield gaps were closed substantially (e.g. 8.0 bn people and yield gap reduction of 25% until 2020 or 9.5bn people with yield gap reductions of 50%). These potentials would, however, almost be halved when accounting for undesirable albedo changes leading to local warming effects or be reduced to less than one-fifth if only cropland was available due to increasing feed and fodder demand on pastures. Changes in dietary trends or new, less space-demanding food sources as well as the restoration of degraded soils could release additional land for tCDR. Although the possibly available natural areas cover large areas reported here, land conversion emissions have first to be overcome and the ecological costs such as the loss of biodiversity or pristine forests are considered to be high. The highest potential to approach a satisfaction of all constraints with still substantial tCDR potentials could lie in the improvement of highly efficient carbon utilization pathways which reduce the carbon losses along the process chain and thus, lower the demand for land per unit of carbon extracted. If these are not implemented, rapid mitigation, with only small contributions of BP on selected areas such as degraded land, appears to be inevitable.

Acknowledgements

This study was funded by the German Research Foundation's priority program DFG SPP 1689 on "Climate Engineering – Risks, Challenges and Opportunities?" and specifically the CE-LAND project.

We thank Sibyll Schaphoff for her constant improvements of the model and Julia Pongratz for kindly providing us with data on simulated historical albedo changes.

We thank the referees for their constructive and detailed comments that enabled us to substantially revise and improve the manuscript.

References

Anderegg, W.R.L., Kane, J.M., Anderegg, L.D.L., 2013. Consequences of widespread tree mortality triggered by drought and temperature stress. Nat. Clim. Change 3, 30–36. doi:10.1038/nclimate1635

Anten, N.P.R., 2005. Optimal Photosynthetic Characteristics of Individual Plants in Vegetation Stands and Implications for Species Coexistence. Ann. Bot. 95, 495. doi:10.1093/aob/mci048

Arora, V.K., Montenegro, A., 2011. Small temperature benefits provided by realistic afforestation efforts. Nat. Geosci. 4, 514–518. doi:10.1038/ngeo1182

Azar, C., Lindgren, K., Obersteiner, M., Riahi, K., Vuuren, D.P. van, Elzen, K.M.G.J. den, Möllersten, K., Larson, E.D., 2010. The feasibility of low CO2 concentration targets and the role of bio-energy with carbon capture and storage (BECCS). Clim. Change 100, 195–202. doi:10.1007/s10584-010-9832-7

Bajželj, B., Richards, K.S., Allwood, J.M., Smith, P., Dennis, J.S., Curmi, E., Gilligan, C.A., 2014. Importance of food-demand management for climate mitigation. Nat. Clim. Change 4, 924–929. doi:10.1038/nclimate2353

Bavec, F., Bavec, M., 2002. Effects of plant population on leaf area index, cob characteristics and grain yield of early maturing maize cultivars (FAO 100–400). Eur. J. Agron. 16, 151–159. doi:10.1016/S1161-0301(01)00126-5

Beringer, T., Lucht, W., Schaphoff, S., 2011. Bioenergy production potential of global biomass plantations under environmental and agricultural constraints. GCB Bioenergy 3, 299–312. doi:10.1111/j.1757-1707.2010.01088.x

Bertram, C., Johnson, N., Luderer, G., Riahi, K., Isaac, M., Eom, J., 2015. Carbon lock-in through capital stock inertia associated with weak near-term climate policies. Technol. Forecast. Soc. Change 90, Part A, 62–72. doi:10.1016/j.techfore.2013.10.001

Boit, A., Sakschewski, B., Boysen, L., Cano-Crespo, A., Clement, J., Alaniz, N.G., Kok, K., Kolb, M., Langerwisch, F., Rammig, A., Sachse, R., van Eupen, M., von Bloh, W., Zemp, D., Thonicke, K., 2016. Large-scale impact of climate change versus land-use change on future biome shifts in Latin America. Glob. Change Biol. n/a-n/a. doi:10.1111/gcb.13355

Bondeau, A., Smith, P.C., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W., Gerten, D., Lotze-Campen, H., Müller, C., Reichstein, M., Smith, B., 2007. Modelling the role of agriculture for the 20th century global terrestrial carbon balance. Glob. Change Biol. 13, 679–706. doi:10.1111/j.1365-2486.2006.01305.x

Boysen, L.R., Lucht, W., Gerten, D., Heck, V., 2016. Impacts devalue the potential of large-scale terrestrial CO 2 removal through biomass plantations. Environ. Res. Lett. 11, 095010. doi:10.1088/1748-9326/11/9/095010

Brovkin, V., Boysen, L., Arora, V.K., Boisier, J.P., Cadule, P., Chini, L., Claussen, M., Friedlingstein, P., Gayler, V., van den Hurk, B.J.J.M., Hurtt, G.C., Jones, C.D., Kato, E., de Noblet-Ducoudré, N., Pacifico, F., Pongratz, J., Weiss, M., 2013. Effect of Anthropogenic Land-Use and Land-Cover Changes on Climate and Land Carbon Storage in CMIP5 Projections for the Twenty-First Century. J. Clim. 26, 6859–6881. doi:10.1175/JCLI-D-12-00623.1

Caldeira, K., Bala, G., Cao, L., 2013. The Science of Geoengineering. Annu. Rev. Earth Planet. Sci. 41, 231–256. doi:10.1146/annurev-earth-042711-105548

Cannell, M.G.R., 2003. Carbon sequestration and biomass energy offset: theoretical, potential and achievable capacities globally, in Europe and the UK. Biomass Bioenergy 24, 97–116. doi:10.1016/S0961-9534(02)00103-4

Ceballos, G., Ehrlich, P.R., Barnosky, A.D., García, A., Pringle, R.M., Palmer, T.M., 2015. Accelerated modern human–induced species losses: Entering the sixth mass extinction. Sci. Adv. 1, e1400253. doi:10.1126/sciadv.1400253

Chan, K.M.A., Balvanera, P., Benessaiah, K., Chapman, M., Díaz, S., Gómez-Baggethun, E., Gould, R., Hannahs, N., Jax, K., Klain, S., Luck, G.W., Martín-López, B., Muraca, B., Norton, B., Ott, K., Pascual, U., Satterfield, T., Tadaki, M., Taggart, J., Turner, N., 2016. Opinion: Why protect nature? Rethinking values and the environment. Proc. Natl. Acad. Sci. 113, 1462–1465. doi:10.1073/pnas.1525002113

Collatz, G.J., Ribas-Carbo, M., Berry, J.A., 1992. Coupled Photosynthesis-Stomatal Conductance Model for Leaves of C4 Plants. Funct. Plant Biol. 19, 519–538. doi:10.1071/pp9920519

Cramer, W., Kicklighter, D.W., Bondeau, A., Iii, B.M., Churkina, G., Nemry, B., Ruimy, A., Schloss, A.L., Intercomparison, T.P.O.T.P.N.M., 1999. Comparing global models of terrestrial net primary productivity (NPP): overview and key results. Glob. Change Biol. 5, 1–15. doi:10.1046/j.1365-2486.1999.00009.x

Davin, E.L., Seneviratne, S.I., Ciais, P., Olioso, A., Wang, T., 2014. Preferential cooling of hot extremes from cropland albedo management. Proc. Natl. Acad. Sci. 111, 9757–9761. doi:10.1073/pnas.1317323111

Dornburg, V., Vuuren, D. van, Ven, G. van de, Langeveld, H., Meeusen, M., Banse, M., Oorschot, M. van, Ros, J., Born, G.J. van den, Aiking, H., Londo, M., Mozaffarian, H., Verweij, P., Lysen, E., Faaij, A., 2010. Bioenergy revisited: Key factors in global potentials of bioenergy. Energy Environ. Sci. 3, 258–267. doi:10.1039/B922422J

Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Kadner, S., Zwickel, T., Eickemeier, P., Hansen, G., Schlömer, S., Stechow, C. von, Matschoss, P., 2011. Renewable Energy Sources and Climate Change Mitigation: Special Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Erb, K.-H., Lauk, C., Kastner, T., Mayer, A., Theurl, M.C., Haberl, H., 2016. Exploring the biophysical option space for feeding the world without deforestation. Nat. Commun. 7, 11382. doi:10.1038/ncomms11382

Fader, M., Gerten, D., Krause, M., Lucht, W., Cramer, W., 2013. Spatial decoupling of agricultural production and consumption: quantifying dependences of countries on food imports due to domestic land and water constraints. Environ. Res. Lett. 8, 014046. doi:10.1088/1748-

9326/8/1/014046

Fader, M., Rost, S., Müller, C., Bondeau, A., Gerten, D., 2010. Virtual water content of temperate cereals and maize: Present and potential future patterns. J. Hydrol., Green-Blue Water Initiative (GBI) 384, 218–231. doi:10.1016/j.jhydrol.2009.12.011

Farquhar, G.D., O'Leary, M.H., Berry, J.A., 1982. On the Relationship Between Carbon Isotope Discrimination and the Intercellular Carbon Dioxide Concentration in Leaves. Funct. Plant Biol. 9, 121–137. doi:10.1071/pp9820121

Foley, J.A., Monfreda, C., Ramankutty, N., Zaks, D., 2007. Our share of the planetary pie. Proc. Natl. Acad. Sci. 104, 12585–12586. doi:10.1073/pnas.0705190104

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., Zaks, D.P.M., 2011. Solutions for a cultivated planet. Nature 478, 337–342. doi:10.1038/nature10452

Forkel, M., Carvalhais, N., Schaphoff, S., v. Bloh, W., Migliavacca, M., Thurner, M., Thonicke, K., 2014. Identifying environmental controls on vegetation greenness phenology through model–data integration. Biogeosciences 11, 7025–7050. doi:10.5194/bg-11-7025-2014

Friend, A.D., Lucht, W., Rademacher, T.T., Keribin, R., Betts, R., Cadule, P., Ciais, P., Clark, D.B., Dankers, R., Falloon, P.D., Ito, A., Kahana, R., Kleidon, A., Lomas, M.R., Nishina, K., Ostberg, S., Pavlick, R., Peylin, P., Schaphoff, S., Vuichard, N., Warszawski, L., Wiltshire, A., Woodward, F.I., 2014. Carbon residence time dominates uncertainty in terrestrial vegetation responses to future climate and atmospheric CO2. Proc. Natl. Acad. Sci. 111, 3280–3285. doi:10.1073/pnas.1222477110

Fuss, S., Canadell, J.G., Peters, G.P., Tavoni, M., Andrew, R.M., Ciais, P., Jackson, R.B., Jones, C.D., Kraxner, F., Nakicenovic, N., Le Quéré, C., Raupach, M.R., Sharifi, A., Smith, P., Yamagata, Y., 2014. Betting on negative emissions. Nat. Clim. Change 4, 850–853. doi:10.1038/nclimate2392

Gerten, D., Lucht, W., Ostberg, S., Heinke, J., Kowarsch, M., Kreft, H., Kundzewicz, Z.W., Rastgooy, J., Warren, R., Schellnhuber, H.J., 2013. Asynchronous exposure to global warming: freshwater resources and terrestrial ecosystems. Environ. Res. Lett. 8, 034032. doi:10.1088/1748-9326/8/3/034032

Gerten, D., Schaphoff, S., Haberlandt, U., Lucht, W., Sitch, S., 2004. Terrestrial vegetation and water balance—hydrological evaluation of a dynamic global vegetation model. J. Hydrol. 286, 249–270. doi:10.1016/j.jhydrol.2003.09.029

Giorgetta, M.A., Jungclaus, J., Reick, C.H., Legutke, S., Bader, J., Böttinger, M., Brovkin, V., Crueger, T., Esch, M., Fieg, K., Glushak, K., Gayler, V., Haak, H., Hollweg, H.-D., Ilyina, T., Kinne, S., Kornblueh, L., Matei, D., Mauritsen, T., Mikolajewicz, U., Mueller, W., Notz, D., Pithan, F., Raddatz, T., Rast, S., Redler, R., Roeckner, E., Schmidt, H., Schnur, R., Segschneider, J., Six, K.D., Stockhause, M., Timmreck, C., Wegner, J., Widmann, H., Wieners, K.-H., Claussen, M., Marotzke, J., Stevens, B., 2013. Climate and carbon cycle changes from 1850 to 2100 in MPI-ESM simulations for the Coupled Model Intercomparison Project phase 5. J. Adv.

Model. Earth Syst. n/a–n/a. doi:10.1002/jame.20038

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food Security: The Challenge of Feeding 9 Billion People. Science 327, 812–818. doi:10.1126/science.1185383

Havlík, P., Valin, H., Herrero, M., Obersteiner, M., Schmid, E., Rufino, M.C., Mosnier, A., Thornton, P.K., Böttcher, H., Conant, R.T., Frank, S., Fritz, S., Fuss, S., Kraxner, F., Notenbaert, A., 2014. Climate change mitigation through livestock system transitions. Proc. Natl. Acad. Sci. 111, 3709–3714. doi:10.1073/pnas.1308044111

Haxeltine, A., Prentice, I.C., 1996. BIOME3: An equilibrium terrestrial biosphere model based on ecophysiological constraints, resource availability, and competition among plant functional types. Glob. Biogeochem. Cycles 10, 693–709. doi:10.1029/96GB02344

Heck, V., Gerten, D., Lucht, W., Boysen, L.R., 2016. Is extensive terrestrial carbon dioxide removal a “green” form of geoengineering? A global modelling study. Glob. Planet. Change 137, 123–130. doi:10.1016/j.gloplacha.2015.12.008

Heinke, J., Ostberg, S., Schaphoff, S., Frieler, K., Müller, C., Gerten, D., Meinshausen, M., Lucht, W., 2013. A new climate dataset for systematic assessments of climate change impacts as a function of global warming. Geosci. Model Dev. 6, 1689–1703. doi:10.5194/gmd-6-1689-2013

Hertel, T.W., Baldos, U.L.C., 2016. Global Change and the Food System in 2050, in: Global Change and the Challenges of Sustainably Feeding a Growing Planet. Springer International Publishing, pp. 141–160. doi:10.1007/978-3-319-22662-0_11

Hickler, T., Smith, B., Prentice, I.C., Mjöfors, K., Miller, P., Arneth, A., Sykes, M.T., 2008. CO2 fertilization in temperate FACE experiments not representative of boreal and tropical forests. Glob. Change Biol. 14, 1531–1542. doi:10.1111/j.1365-2486.2008.01598.x

Horton, D.E., Johnson, N.C., Singh, D., Swain, D.L., Rajaratnam, B., Diffenbaugh, N.S., 2015. Contribution of changes in atmospheric circulation patterns to extreme temperature trends. Nature 522, 465–469. doi:10.1038/nature14550

Humpenöder, F., Popp, A., Dietrich, J.P., Klein, D., Lotze-Campen, H., Bonsch, M., Bodirsky, B.L., Weindl, I., Stevanovic, M., Müller, C., 2014. Investigating afforestation and bioenergy CCS as climate change mitigation strategies. Environ. Res. Lett. 9, 064029. doi:10.1088/1748-9326/9/6/064029

IUCN, UNEP-WCMC, 2015. The World Database on Protected Areas (WDPA) [WWW Document]. URL http://www.protectedplanet.net/ (accessed 10.20.15).

Jägermeyr, J., Gerten, D., Heinke, J., Schaphoff, S., Kummu, M., Lucht, W., 2015. Water savings potentials of irrigation systems: global simulation of processes and linkages. Hydrol Earth Syst Sci 19, 3073–3091. doi:10.5194/hess-19-3073-2015

Jantz, P., Goetz, S., Laporte, N., 2014. Carbon stock corridors to mitigate climate change and promote biodiversity in the tropics. Nat. Clim. Change 4, 138–142. doi:10.1038/nclimate2105

Jeffery, L., Fyson, C., Alexander, R., Gütschow, J., Rocha, M., Cantzler, J., Schaeffer, M., Hare, B., Hagemann, M., Höhne, N., van Breevoort, P., Blok, K., 2015. Climate pledges will bring 2.7°C of warming, potential for more action - Climate Action Tracker [WWW Document]. Clim. Action Tracker. URL http://climateactiontracker.org/news/253/Climate-pledges-will-bring-2.7C-of-warming-potential-for-more-action.html (accessed 2.9.16).

Jones, C.D., Ciais, P., Davis, S.J., Friedlingstein, P., Gasser, T., Peters, G.P., Rogelj, J., Vuuren, D.P. van, Canadell, J.G., Cowie, A., Jackson, R.B., Jonas, M., Kriegler, E., Littleton, E., Lowe, J.A., Milne, J., Shrestha, G., Smith, P., A Torvanger, Wiltshire, A., 2016. Simulating the Earth system response to negative emissions. Environ. Res. Lett. 11, 095012. doi:10.1088/1748-9326/11/9/095012

Jung, M., Vetter, M., Herold, M., Churkina, G., Reichstein, M., Zaehle, S., Ciais, P., Viovy, N., Bondeau, A., Chen, Y., Trusilova, K., Feser, F., Heimann, M., 2007. Uncertainties of modeling gross primary productivity over Europe: A systematic study on the effects of using different drivers and terrestrial biosphere models. Glob. Biogeochem. Cycles 21. doi:10.1029/2006GB002915

Kato, E., Yamagata, Y., 2014. BECCS capability of dedicated bioenergy crops under a future land-use scenario targeting net negative carbon emissions. Earths Future 2014EF000249. doi:10.1002/2014EF000249

Keller, D.P., Feng, E.Y., Oschlies, A., 2014. Potential climate engineering effectiveness and side effects during a high carbon dioxide-emission scenario. Nat. Commun. 5. doi:10.1038/ncomms4304

Kier, G., Kreft, H., Lee, T.M., Jetz, W., Ibisch, P.L., Nowicki, C., Mutke, J., Barthlott, W., 2009. A global assessment of endemism and species richness across island and mainland regions. Proc. Natl. Acad. Sci. 106, 9322–9327. doi:10.1073/pnas.0810306106

Klein, D., Luderer, G., Kriegler, E., Strefler, J., Bauer, N., Leimbach, M., Popp, A., Dietrich, J.P., Humpenöder, F., Lotze-Campen, H., Edenhofer, O., 2014. The value of bioenergy in low stabilization scenarios: an assessment using REMIND-MAgPIE. Clim. Change 123, 705–718. doi:10.1007/s10584-013-0940-z

Kraxner, F., Nordström, E.-M., Havlík, P., Gusti, M., Mosnier, A., Frank, S., Valin, H., Fritz, S., Fuss, S., Kindermann, G., McCallum, I., Khabarov, N., Böttcher, H., See, L., Aoki, K., Schmid, E., Máthé, L., Obersteiner, M., 2013. Global bioenergy scenarios – Future forest development, land-use implications, and trade-offs. Biomass Bioenergy 57, 86–96. doi:10.1016/j.biombioe.2013.02.003

Kriegler, E., Tavoni, M., Aboumahboub, T., Luderer, G., Calvin, K., Demaere, G., Krey, V., Riahi, K., Rösler, H., Schaeffer, M., Van Vuuren, D.P., 2013. What does the 2°c target imply for a global climate agreement in 2020? the limits study on durban platform scenarios. Clim. Change Econ. 04, 1340008. doi:10.1142/S2010007813400083

Kromdijk, J., Głowacka, K., Leonelli, L., Gabilly, S.T., Iwai, M., Niyogi, K.K., Long, S.P., 2016. Improving photosynthesis and crop productivity by accelerating recovery from photoprotection. Science 354, 857–861. doi:10.1126/science.aai8878

Krysanova, V., Wechsung, F., Arnold, J., Srinivasan, R., Williams, J., 2000. SWIM (Soil and Water Integrated Model) user manual (version SWIM-8) (PIK report No. 69).

Lenton, T.M., 2010. The potential for land-based biological CO2 removal to lower future atmospheric CO2 concentration. Carbon Manag. 1, 145–160. doi:10.4155/cmt.10.12

Lenton, T.M., Vaughan, N.E., 2009. The radiative forcing potential of different climate geoengineering options. Atmos Chem Phys 9, 5539–5561. doi:10.5194/acp-9-5539-2009

Lomax, G., Lenton, T.M., Adeosun, A., Workman, M., 2015. Investing in negative emissions. Nat. Clim. Change 5, 498–500. doi:10.1038/nclimate2627

Lotze-Campen, H., Popp, A., Beringer, T., Müller, C., Bondeau, A., Rost, S., Lucht, W., 2010. Scenarios of global bioenergy production: The trade-offs between agricultural expansion, intensification and trade. Ecol. Model., Model-based Systems to Support Impact Assessment - Methods, Tools and Applications 221, 2188–2196. doi:10.1016/j.ecolmodel.2009.10.002

Lotze-Campen, H., von Lampe, M., Kyle, P., Fujimori, S., Havlik, P., van Meijl, H., Hasegawa, T., Popp, A., Schmitz, C., Tabeau, A., Valin, H., Willenbockel, D., Wise, M., 2014. Impacts of increased bioenergy demand on global food markets: an AgMIP economic model intercomparison. Agric. Econ. 45, 103–116. doi:10.1111/agec.12092

Lucht, W., Schaphoff, S., Erbrecht, T., Heyder, U., Cramer, W., 2006. Terrestrial vegetation redistribution and carbon balance under climate change. Carbon Balance Manag. 1, 6. doi:10.1186/1750-0680-1-6

Luderer, G., Bertram, C., Calvin, K., De Cian, E., Kriegler, E., 2013. Implications of weak near-term climate policies on long-term mitigation pathways. Clim. Change. doi:10.1007/s10584-013-0899-9

Maiorano, A., Martre, P., Asseng, S., Ewert, F., Müller, C., Rötter, R.P., Ruane, A.C., Semenov, M.A., Wallach, D., Wang, E., Alderman, P.D., Kassie, B.T., Biernath, C., Basso, B., Cammarano, D., Challinor, A.J., Doltra, J., Dumont, B., Rezaei, E.E., Gayler, S., Kersebaum, K.C., Kimball, B.A., Koehler, A.-K., Liu, B., O'Leary, G.J., Olesen, J.E., Ottman, M.J., Priesack, E., Reynolds, M., Stratonovitch, P., Streck, T., Thorburn, P.J., Waha, K., Wall, G.W., White, J.W., Zhao, Z., Zhu, Y., 2017. Crop model improvement reduces the uncertainty of the response to temperature of multi-model ensembles. Field Crops Res. 202, 5–20. doi:10.1016/j.fcr.2016.05.001

McElroy, G.H., Dawson, W.M., 1986. Biomass from short-rotation coppice willow on marginal land. Biomass 10, 225–240. doi:10.1016/0144-4565(86)90055-7

Merlin, O., Chirouze, J., Olioso, A., Jarlan, L., Chehbouni, G., Boulet, G., 2013. An image-based four-source surface energy balance model to estimate crop evapotranspiration from solar reflectance/thermal emission data (SEB-4S).

Mittermeier, R.A., Turner, W.R., Larsen, F.W., Brooks, T.M., Gascon, C., 2011. Global Biodiversity Conservation: The Critical Role of Hotspots 3–22. doi:10.1007/978-3-642-20992-5_1

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., King, K.W., 2005. Soil and Water Assessment

Tool (Version 2000)—theoretical documentation. Temple, Texas, USA.

Neumann, K., Verburg, P.H., Stehfest, E., Müller, C., 2010. The yield gap of global grain production: A spatial analysis. Agric. Syst. 103, 316–326. doi:10.1016/j.agsy.2010.02.004

Noblet-Ducoudré, N., Boisier, J.P., Pitman, A., Bonan, G., Brovkin, V., Cruz, F., Delire, C., Gayler, V., van den Hurk, B., Lawrence, P., others, 2012. Determining robust impacts of land-use induced land-cover changes on surface climate over North America and Eurasia; Results from the first set of LUCID experiments. J. Clim.

Norby, R.J., DeLucia, E.H., Gielen, B., Calfapietra, C., Giardina, C.P., King, J.S., Ledford, J., McCarthy, H.R., Moore, D.J.P., Ceulemans, R., Angelis, P.D., Finzi, A.C., Karnosky, D.F., Kubiske, M.E., Lukac, M., Pregitzer, K.S., Scarascia-Mugnozza, G.E., Schlesinger, W.H., Oren, R., 2005. Forest response to elevated CO2 is conserved across a broad range of productivity. Proc. Natl. Acad. Sci. U. S. A. 102, 18052–18056. doi:10.1073/pnas.0509478102

Oldemann, L.R., Hakkeling, R.T.A., Sombroek, W.G., Batjes, N.H., 1991. Global Assessment of Human-induced Soil Degradation (GLASOD). Wageningen University & Research.

Ostberg, S., Lucht, W., Schaphoff, S., Gerten, D., 2013. Critical impacts of global warming on land ecosystems. Earth Syst. Dyn. 4, 347–357. doi:10.5194/esd-4-347-2013

Ostberg, S., Schaphoff, S., Lucht, W., Gerten, D., 2015. Three centuries of dual pressure from land use and climate change on the biosphere. Environ. Res. Lett. 10, 044011. doi:10.1088/1748-9326/10/4/044011

Peylin, P., Bousquet, P., Le Quéré, C., Sitch, S., Friedlingstein, P., McKinley, G., Gruber, N., Rayner, P., Ciais, P., 2005. Multiple constraints on regional CO2 flux variations over land and oceans. Glob. Biogeochem. Cycles 19. doi:10.1029/2003GB002214

Pimm, S.L., Jenkins, C.N., Abell, R., Brooks, T.M., Gittleman, J.L., Joppa, L.N., Raven, P.H., Roberts, C.M., Sexton, J.O., 2014. The biodiversity of species and their rates of extinction, distribution, and protection. Science 344, 1246752. doi:10.1126/science.1246752

Pitman, A.J., de Noblet-Ducoudré, N., Cruz, F.T., Davin, E.L., Bonan, G.B., Brovkin, V., Claussen, M., Delire, C., Ganzeveld, L., Gayler, V., van den Hurk, B.J.J.M., Lawrence, P.J., van der Molen, M.K., Müller, C., Reick, C.H., Seneviratne, S.I., Strengers, B.J., Voldoire, A., 2009. Uncertainties in climate responses to past land cover change: First results from the LUCID intercomparison study. Geophys. Res. Lett. 36, L14814. doi:10.1029/2009GL039076

Pongratz, J., Reick, C.H., Raddatz, T., Caldeira, K., Claussen, M., 2011. Past land use decisions have increased mitigation potential of reforestation. Geophys. Res. Lett. 38, L15701. doi:10.1029/2011GL047848

Popp, A., Rose, S.K., Calvin, K., Vuuren, D.P.V., Dietrich, J.P., Wise, M., Stehfest, E., Humpenöder, F., Kyle, P., Vliet, J.V., Bauer, N., Lotze-Campen, H., Klein, D., Kriegler, E., 2014. Land-use transition for bioenergy and climate stabilization: model comparison of drivers, impacts and interactions with other land use based mitigation options. Clim. Change 123, 495–509. doi:10.1007/s10584-013-0926-x

Potapov, P., Hansen, M.C., Laestadius, L., Turubanova, S., Yaroshenko, A., Thies, C., Smith, W., Zhuravleva, I., Komarova, A., Minnemeyer, S., Esipova, E., 2017. The last frontiers of wilderness: Tracking loss of intact forest landscapes from 2000 to 2013. Sci. Adv. 3, e1600821. doi:10.1126/sciadv.1600821

Powell, T.W.R., Lenton, T.M., 2013. Scenarios for future biodiversity loss due to multiple drivers reveal conflict between mitigating climate change and preserving biodiversity. Environ. Res. Lett. 8, 025024. doi:10.1088/1748-9326/8/2/025024

Powell, T.W.R., Lenton, T.M., 2012. Future carbon dioxide removal via biomass energy constrained by agricultural efficiency and dietary trends. Energy Environ. Sci. 5, 8116. doi:10.1039/c2ee21592f

Qin, Z., Zhuang, Q., Cai, X., 2014. Bioenergy crop productivity and potential climate change mitigation from marginal lands in the United States: An ecosystem modeling perspective. GCB Bioenergy n/a-n/a. doi:10.1111/gcbb.12212

Qin, Z., Zhuang, Q., Zhu, X., Cai, X., Zhang, X., 2011. Carbon Consequences and Agricultural Implications of Growing Biofuel Crops on Marginal Agricultural Lands in China. Environ. Sci. Technol. 45, 10765–10772. doi:10.1021/es2024934

Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J.C., KC, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humpenöder, F., Da Silva, L.A., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Strefler, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J.C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A., Tavoni, M., 2016. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Glob. Environ. Change. doi:10.1016/j.gloenvcha.2016.05.009

Rolinski, S., Weindl, I., Heinke, J., Bodirsky, B.L., Biewald, A., Lotze-Campen, H., 2015. Pasture harvest, carbon sequestration and feeding potentials under different grazing intensities. Adv. Anim. Biosci. 6, 43–45. doi:10.1017/S2040470014000521

Sakschewski, B., Bloh, W. von, Boit, A., Poorter, L., Peña-Claros, M., Heinke, J., Joshi, J., Thonicke, K., 2016. Resilience of Amazon forests emerges from plant trait diversity. Nat. Clim. Change 6, 1032–1036. doi:10.1038/nclimate3109

Sakschewski, B., von Bloh, W., Huber, V., Müller, C., Bondeau, A., 2014. Feeding 10 billion people under climate change: How large is the production gap of current agricultural systems? Ecol. Model. 288, 103–111. doi:10.1016/j.ecolmodel.2014.05.019

Schaeffer, M., Eickhout, B., Hoogwijk, M., Strengers, B., van Vuuren, D., Leemans, R., Opsteegh, T., 2006. CO2 and albedo climate impacts of extratropical carbon and biomass plantations. Glob. Biogeochem. Cycles 20, GB2020. doi:10.1029/2005GB002581

Schaphoff, S., Heyder, U., Ostberg, S., Gerten, D., Heinke, J., Lucht, W., 2013. Contribution of permafrost soils to the global carbon budget. Environ. Res. Lett. 8, 014026. doi:10.1088/1748-9326/8/1/014026

Schauberger, B., Archontoulis, S., Arneth, A., Balkovic, J., Ciais, P., Deryng, D., Elliott, J., Folberth, C., Khabarov, N., Müller, C., Pugh, T.A.M., Rolinski, S., Schaphoff, S., Schmid, E., Wang, X., Schlenker, W., Frieler, K., 2017. Consistent negative response of US crops to high temperatures in observations and crop models. Nat. Commun. 8. doi:10.1038/ncomms13931

Scurlock, J.M.O., Asner, G.P., Gower, S.T., 2001. Worldwide Historical Estimates and Bibliography of Leaf Area Index, 1932-2000 (No. TM-2001/268). Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A.

Shepherd, J.G., 2009. Geoengineering the climate: science, governance and uncertainty [WWW Document]. URL http://eprints.soton.ac.uk/156647/ (accessed 2.18.14).

Singarayer, J.S., Ridgwell, A., Irvine, P., 2009. Assessing the benefits of crop albedo bio-geoengineering. Environ. Res. Lett. 4, 045110. doi:10.1088/1748-9326/4/4/045110

Sitch, S., Huntingford, C., Gedney, N., Levy, P.E., Lomas, M., Piao, S.L., Betts, R., Ciais, P., Cox, P., Friedlingstein, P., Jones, C.D., Prentice, I.C., Woodward, F.I., 2008. Evaluation of the terrestrial carbon cycle, future plant geography and climate-carbon cycle feedbacks using five Dynamic Global Vegetation Models (DGVMs). Glob. Change Biol. 14, 2015–2039. doi:10.1111/j.1365-2486.2008.01626.x

Sitch, S., Smith, B., Prentice, I.C., Arneth, A., Bondeau, A., Cramer, W., Kaplan, J.O., Levis, S., Lucht, W., Sykes, M.T., Thonicke, K., Venevsky, S., 2003. Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. Glob. Change Biol. 9, 161–185. doi:10.1046/j.1365-2486.2003.00569.x

Smeets, E.M.W., Faaij, A.P.C., Lewandowski, I.M., Turkenburg, W.C., 2007. A bottom-up assessment and review of global bio-energy potentials to 2050. Prog. Energy Combust. Sci. 33, 56–106. doi:10.1016/j.pecs.2006.08.001

Smith, P., Davis, S.J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R.B., Cowie, A., Kriegler, E., Vuuren, D.P. van, Rogelj, J., Ciais, P., Milne, J., Canadell, J.G., McCollum, D., Peters, G., Andrew, R., Krey, V., Shrestha, G., Friedlingstein, P., Gasser, T., Grübler, A., Heidug, W.K., Jonas, M., Jones, C.D., Kraxner, F., Littleton, E., Lowe, J., Moreira, J.R., Nakicenovic, N., Obersteiner, M., Patwardhan, A., Rogner, M., Rubin, E., Sharifi, A., Torvanger, A., Yamagata, Y., Edmonds, J., Yongsung, C., 2016. Biophysical and economic limits to negative CO2 emissions. Nat. Clim. Change 6, 42–50. doi:10.1038/nclimate2870

Smith, P., Haberl, H., Popp, A., Erb, K., Lauk, C., Harper, R., Tubiello, F.N., de Siqueira Pinto, A., Jafari, M., Sohi, S., Masera, O., Böttcher, H., Berndes, G., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E.A., Mbow, C., Ravindranath, N.H., Rice, C.W., Robledo Abad, C., Romanovskaya, A., Sperling, F., Herrero, M., House, J.I., Rose, S., 2013. How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? Glob. Change Biol. 19, 2285–2302. doi:10.1111/gcb.12160

Srinivasan, V., Kumar, P., Long, S.P., 2017. Decreasing, not increasing, leaf area will raise crop yields under global atmospheric change. Glob. Change Biol. 23, 1626–1635. doi:10.1111/gcb.13526

Strengers, B.J., Müller, C., Schaeffer, M., Haarsma, R.J., Severijns, C., Gerten, D., Schaphoff, S., van den Houdt, R., Oostenrijk, R., 2010. Assessing 20th century climate–vegetation feedbacks of land-use change and natural vegetation dynamics in a fully coupled vegetation–climate model. Int. J. Climatol. 30, 2055–2065.

Thomson, A.M., Calvin, K.V., Smith, S.J., Kyle, G.P., Volke, A., Patel, P., Delgado-Arias, S., Bond-Lamberty, B., Wise, M.A., Clarke, L.E., Edmonds, J.A., 2011. RCP4.5: a pathway for stabilization of radiative forcing by 2100. Clim. Change 109, 77–94. doi:10.1007/s10584-011-0151-4

Tokarska, K.B., Zickfeld, K., 2015. The effectiveness of net negative carbon dioxide emissions in reversing anthropogenic climate change. Environ. Res. Lett. 10, 094013. doi:10.1088/1748-9326/10/9/094013

United Nations, 2015. World Population Prospects: The 2015 Revision, Methodology of the United Nations Population Estimates and Projections (Working Paper No. No. ESA/P/WP.242). Department of Economic and Social Affairs, Population Division, New York, NY.

van Vuuren, D.P., Stehfest, E., den Elzen, M.G.J., Kram, T., van Vliet, J., Deetman, S., Isaac, M., Klein Goldewijk, K., Hof, A., Mendoza Beltran, A., others, 2011a. RCP2. 6: exploring the possibility to keep global mean temperature increase below 2° C. Clim. Change 1–22.

van Vuuren, D.P., Stehfest, E., Elzen, M.G.J. den, Kram, T., Vliet, J. van, Deetman, S., Isaac, M., Goldewijk, K.K., Hof, A., Beltran, A.M., Oostenrijk, R., Ruijven, B. van, 2011b. RCP2.6: exploring the possibility to keep global mean temperature increase below 2°C. Clim. Change 109, 95–116. doi:10.1007/s10584-011-0152-3

van Vuuren, D.P., Stehfest, E., Gernaat, D.E.H.J., Doelman, J.C., van den Berg, M., Harmsen, M., de Boer, H.S., Bouwman, L.F., Daioglou, V., Edelenbosch, O.Y., Girod, B., Kram, T., Lassaletta, L., Lucas, P.L., van Meijl, H., Müller, C., van Ruijven, B.J., van der Sluis, S., Tabeau, A., 2016. Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. Glob. Environ. Change. doi:10.1016/j.gloenvcha.2016.05.008

Vaughan, N.E., Lenton, T.M., 2011. A review of climate geoengineering proposals. Clim. Change 109, 745–790. doi:10.1007/s10584-011-0027-7

Waha, K., van Bussel, L.G.J., Müller, C., Bondeau, A., 2012. Climate-driven simulation of global crop sowing dates. Glob. Ecol. Biogeogr. 21, 247–259. doi:10.1111/j.1466-8238.2011.00678.x

Warszawski, L., Friend, A., Ostberg, S., Frieler, K., Lucht, W., Schaphoff, S., Beerling, D., Cadule, P., Ciais, P., Clark, D.B., Kahana, R., Ito, A., Keribin, R., Kleidon, A., Lomas, M., Nishina, K., Pavlick, R., Rademacher, T.T., Buechner, M., Piontek, F., Schewe, J., Serdeczny, O., Schellnhuber, H.J., 2013. A multi-model analysis of risk of ecosystem shifts under climate change. Environ. Res. Lett. 8, 044018. doi:10.1088/1748-9326/8/4/044018

Weindl, I., Lotze-Campen, H., Popp, A., Müller, C., Havlík, P., Herrero, M., Schmitz, C., Rolinski, S., 2015. Livestock in a changing climate: production system transitions as an adaptation strategy for agriculture. Environ. Res. Lett. 10, 094021. doi:10.1088/1748-

9326/10/9/094021

Wirsenius, S., 2000. Human Use of Land and Organic Materials: Modeling the Turnover of Biomass in the Global Food System (Doctoral thesis). Chalmers University of Technology.

Wise, M., Calvin, K., Thomson, A., Clarke, L., Bond-Lamberty, B., Sands, R., Smith, S.J., Janetos, A., Edmonds, J., 2009. Implications of Limiting CO2 Concentrations for Land Use and Energy. Science 324, 1183–1186. doi:10.1126/science.1168475

Woolf, D., Amonette, J.E., Street-Perrott, F.A., Lehmann, J., Joseph, S., 2010. Sustainable biochar to mitigate global climate change. Nat. Commun. 1, 56. doi:10.1038/ncomms1053

Xie, J., Guo, J., Yang, Z., Huang, Z., Chen, G., Yang, Y., 2013. Rapid accumulation of carbon on severely eroded red soils through afforestation in subtropical China. For. Ecol. Manag., Shaping Forest Management to Climate Change 300, 53–59. doi:10.1016/j.foreco.2012.06.038

Zickfeld, K., MacDougall, A.H., Matthews, H.D., 2016. On the proportionality between global temperature change and cumulative CO 2 emissions during periods of net negative CO 2 emissions. Environ. Res. Lett. 11, 055006. doi:10.1088/1748-9326/11/5/055006

Supporting Information Caption

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

Data S1. Additional information on data sets used, scenario and detailed results with Figures S1–S7 and Tables S1–S5.

Conflict of interest statement

The authors declare no conflict of interest.

Table 1: Presentation of the dependency of tCDR on the underlying assumptions on prioritizing food demand ("food first"), nature conservation ("conservation first") or climate protection ("climate first") as well as the methodologies applied (e.g. on food demand or data sets used).

	Assumptions	**Methodology**
Food first (1)	tCDR on abandoned agricultural land possible (cropland, pastures, other agricultural land)	Yield gap reductions: 5, 10 and 25% until 2020; 25, 30 and 50% until 2050 Population development: 6.5, 7.5, 8.0 and 8.4 bn people until 2020; 6.5, 7.5, 9.5 and 11.0 bn people until 2050.
	tCDR on least productive land possible	10% of least productive agricultural grid cells
	tCDR on currently degraded land (restored by BPs)	Extremely, severely, moderately and slightly degraded areas (Oldemann et al., 1991)
Conservation first (2)	tCDR outside selected biomes	Intact forest landscapes (IFL)(Potapov et al., 2017) Forests (F) Shrub land (S) Grass land (G)
	tCDR outside of areas of conservation concerns (C)	biodiversity hotspots (Mittermeier et al., 2011) protected areas (IUCN and UNEP-WCMC, 2015), endangered species (Pimm et al., 2014) endemism richness (Kier et al., 2009)
		Combinations of both
Climate first (3-5)	tCDR is not allowed on areas with unfavorable **albedo** decreases to avoid biogeophysical warming.	Grid cells with albedo changes exceeding -0.02 after conversion to BPs are excluded.

	Conversion efficiencies (CEff) define the amount of C ultimately captured per unit of harvested biomass.	20% 50% (default) 70%
	Timing of implementation of BPs defines time for C accumulation in harvested biomass and land carbon pools.	2020 or 2050 until 2100

Table 2 Results for tCDR on abandoned agricultural land are listed according to the chosen yield gap reduction and population numbers. Kilocalories per capita and day increase and release land for BPs (Mha). tCDR potentials (GtC) on total agricultural land can further be separated to tCDR on available crop land alone (potentials on pasture and other land are given in Table S2). Unfavorable albedo changes due to the conversion of land to BPs reduce available land and tCDR potentials (detailed information in Table S3). tCDR potentials are also given for a range of conversion efficiencies (20-70%; with detailed information on area savings in Table S4).

			tCDR 50%						**20%**	**70%**
population	**Yield gap reduction**	**Kcal/ cap/ day production**	**Total tCDR (GtC)**	**Area (Mha)**	**Thereof on Crop land (GtC)**	**Area (Mha)**	**Total tCDR_ albedo (GtC)**	**Area (Mha)**	**Total tCDR (GtC)**	**Total tCDR (GtC)**
2020										
	Unproductive		1	68					0	1

6.5	5%	+11%	149	1573	23	128	71	1040	61	207
6.5	10%	+16%	177	1714	30	167	79	1085	73	247
7.5			53	1009	0	0	35	817	24	72
6.5	25%	+31%	251	2057	49	250	99	1184	103	350
7.5			153	1592	25	142	72	1045	63	212
8.0			99	1303	13	78	54	944	41	138
8.4			55	1019	4	24	35	815	24	75
2050										
6.5	25%	+36%	200	2215	37	272	68	1159	86	276
7.5			139	1805	21	170	55	1056	59	192
6.5	30%	+45%	220	2354	42	305	71	1194	96	304
7.5			165	1988	28	213	61	1105	71	229
6.5	50%	+62%	253	2571	50	360	76	1241	111	348
7.5			206	2258	38	280	69	1173	89	284
9.5			102	1548	13	112	45	984	44	141

Figure captions

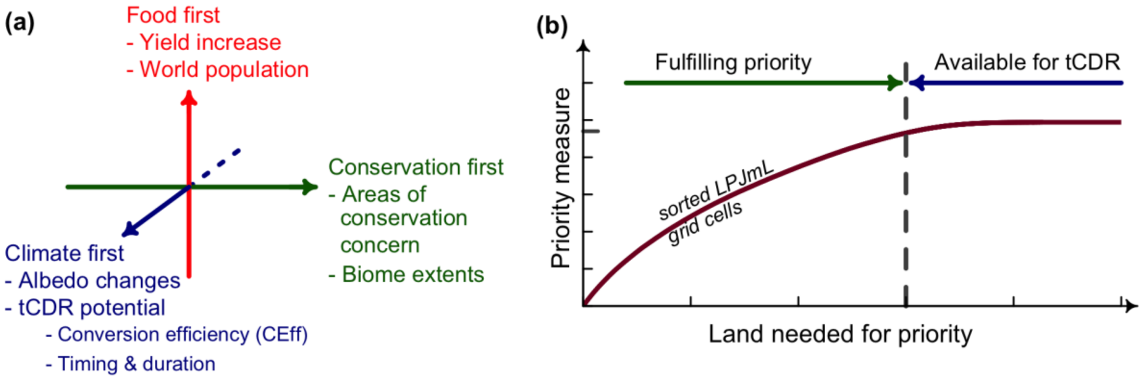
Figure 1 Schematic presentation of this study's framework. a) space of opportunities for tCDR framed by the trade-offs between food production, ecosystem conservation and climate protection where tCDR interacts with the other components (e.g. "food first", "conservation first" or, specifically, with albedo changes); results on natural and agricultural land are additive; b) detection process of land available for tCDR.

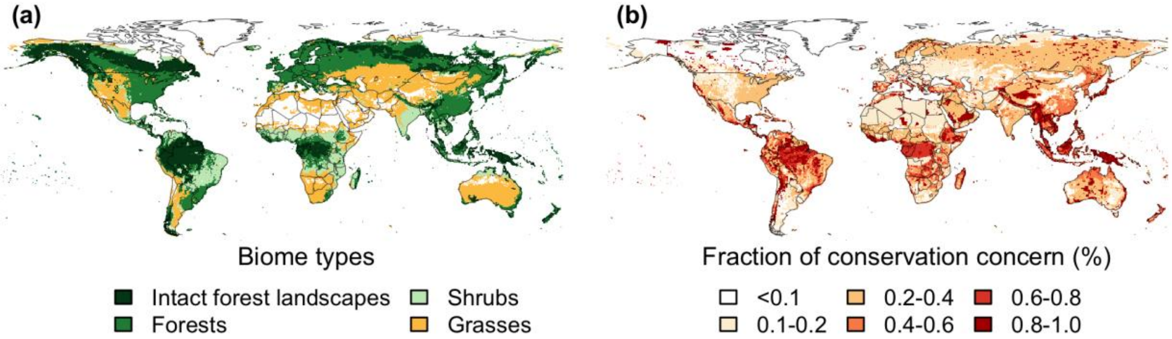
Figure 2 Maps displaying the distribution of major biomes in 2020 (a) and grid cell fractions of conservation concern (b) considered for protection or the establishment of BP in this study.

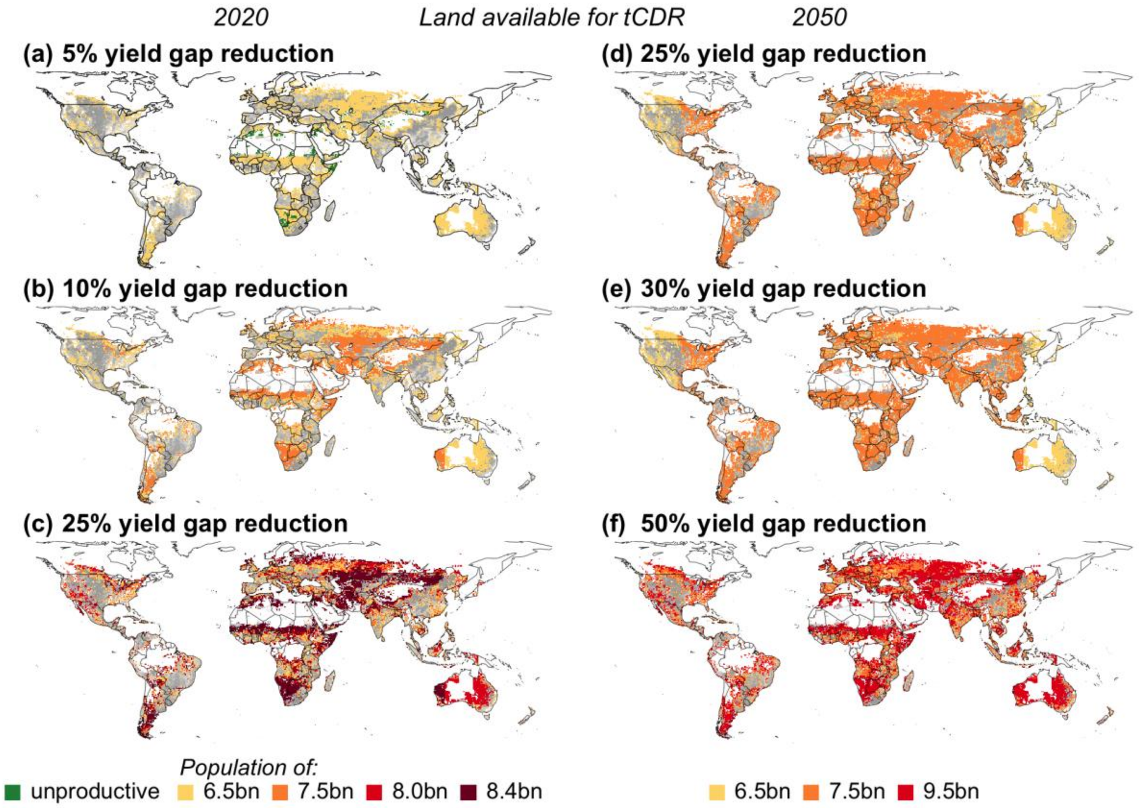
Figure 3 Available land for tCDR on agricultural areas (grey) according to the scenario-specific food demand met by increases in food production from field through yield gap reductions and population growth (red shades) in 2020 (a-c) and 2050 (d-f), respectively. Unproductive land (green) refers to the 10% of least productive agricultural land grid cells in LPJmL.

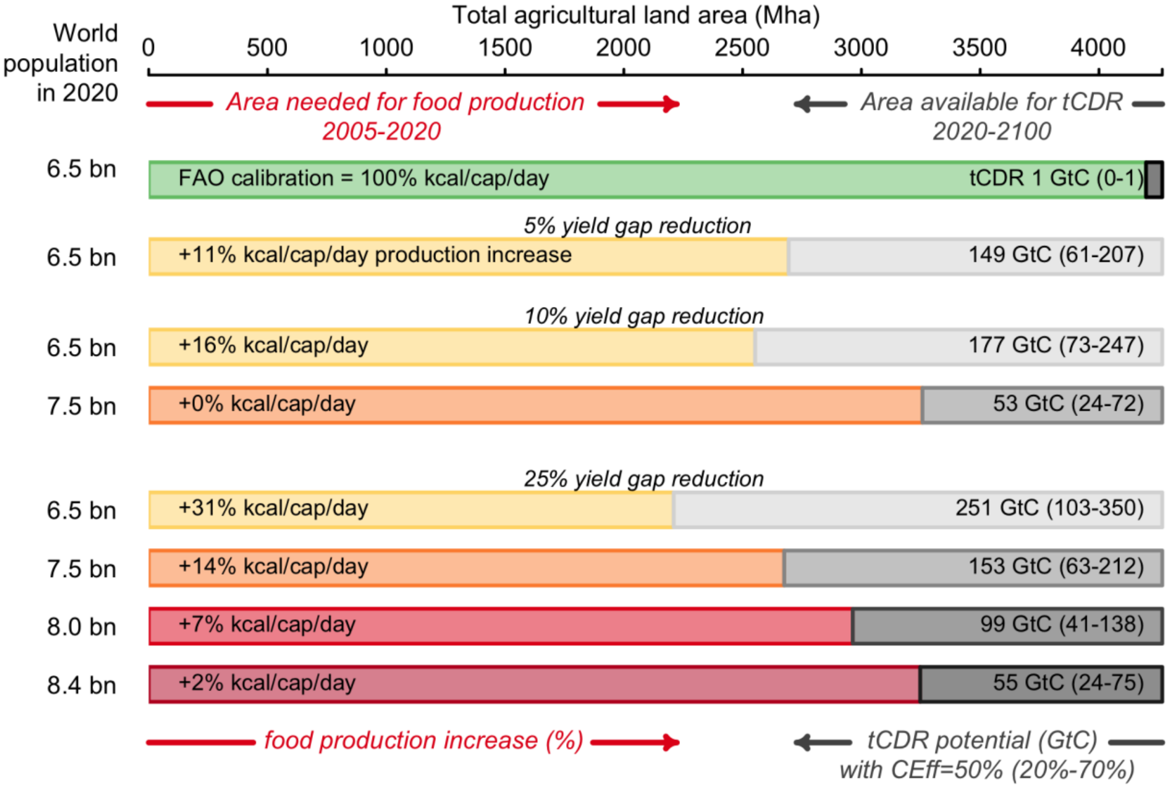
Figure 4 The colored horizontal bars show the agricultural land needed to meet global food demand given surplus agricultural food production increases in kcal per capita per day according to yield gap reductions of, respectively, 5, 10 and 25% by 2020. The coloring is in accordance with the maps in Fig. 3. The green bar shows the initial crop area extent and productivity to feed 6.5bn people (in 2005). Grey bars indicate the area available for BPs and their tCDR potential until 2100 (GtC) assuming a conversion efficiency of 50% (and the range of 20-75% given in brackets). The results for 2050-2100 and the effect of albedo changes can be found in Fig. S4 and Table S2.

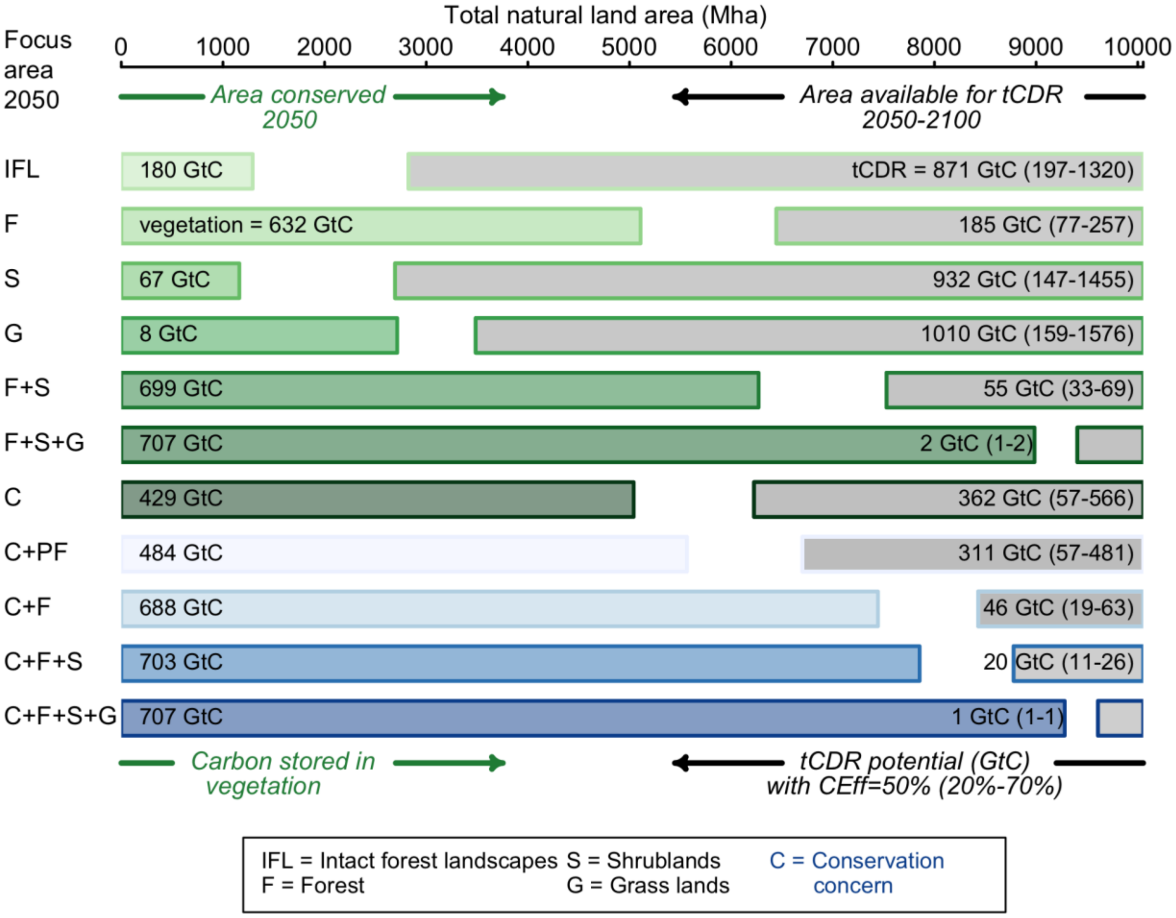
Figure 5 Horizontal colored bars show the area covered by different combinations of biomes and/or areas of conservation concerns with the stored vegetation carbon in 2050 (GtC). Grey bars show the extent of BPs on available land and the tCDR potential by 2100 for a conversion efficiency of 50% (range of 20-70% is given in brackets). White spaces between bars are unsuitable for establishment of BPs due to too dry or cold conditions. Results for the period 2020-2100 are given in Data S1: Section S4.


(a)
Food first
- Yield increase
- World population
Conservation first
- Areas of conservation concern
- Biome extents
Climate first
- Albedo changes
- tCDR potential
- Conversion efficiency (CEff)
- Timing & duration
(b)
Fulfilling priority
Available for tCDR
Priority measure
sorted LPJmL grid cells
Land needed for priority


(a)
(b)
Biome types
Intact forest landscapes
Forests
Shrubs
Grasses
Fraction of conservation concern (%)
<0.1
0.1-0.2
0.2-0.4
0.4-0.6
0.6-0.8
0.8-1.0


2020
Land available for tCDR
2050
(a) 5% yield gap reduction
(b) 10% yield gap reduction
(c) 25% yield gap reduction
(d) 25% yield gap reduction
(e) 30% yield gap reduction
(f) 50% yield gap reduction
Population of:
unproductive
6.5bn
7.5bn
8.0bn
8.4bn
6.5bn
7.5bn
9.5bn


World population in 2020
Total agricultural land area (Mha)
0
500
1000
1500
2000
2500
3000
3500
4000
Area needed for food production 2005-2020
Area available for tCDR 2020-2100
6.5 bn
FAO calibration = 100% kcal/cap/day
tCDR 1 GtC (0-1)
5% yield gap reduction
6.5 bn
+11% kcal/cap/day production increase
149 GtC (61-207)
10% yield gap reduction
6.5 bn
+16% kcal/cap/day
177 GtC (73-247)
7.5 bn
+0% kcal/cap/day
53 GtC (24-72)
25% yield gap reduction
6.5 bn
+31% kcal/cap/day
251 GtC (103-350)
7.5 bn
+14% kcal/cap/day
153 GtC (63-212)
8.0 bn
+7% kcal/cap/day
99 GtC (41-138)
8.4 bn
+2% kcal/cap/day
55 GtC (24-75)
food production increase (%)
tCDR potential (GtC) with CEff=50% (20%-70%)


Total natural land area (Mha)
Focus area 2050
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
Area conserved 2050
Area available for tCDR 2050-2100
IFL
180 GtC
tCDR = 871 GtC (197-1320)
F
vegetation = 632 GtC
185 GtC (77-257)
S
67 GtC
932 GtC (147-1455)
G
8 GtC
1010 GtC (159-1576)
F+S
699 GtC
55 GtC (33-69)
F+S+G
707 GtC
2 GtC (1-2)
C
429 GtC
362 GtC (57-566)
C+PF
484 GtC
311 GtC (57-481)
C+F
688 GtC
46 GtC (19-63)
C+F+S
703 GtC
20 GtC (11-26)
C+F+S+G
707 GtC
1 GtC (1-1)
Carbon stored in vegetation
tCDR potential (GtC) with CEff=50% (20%-70%)
IFL = Intact forest landscapes
F = Forest
S = Shrublands
G = Grass lands
C = Conservation concern