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Impacts devalue the potential of large-scale terrestrial CO₂ removal through biomass plantations

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Large-scale biomass plantations (BPs) are often considered a feasible and safe climate engineering proposal for extracting carbon from the atmosphere and, thereby, reducing global mean temperatures. However, the capacity of such terrestrial carbon dioxide removal (tCDR) strategies and their larger Earth system impacts remain to be comprehensively studied—even more so under higher carbon emissions and progressing climate change. Here, we use a spatially explicit process-based biosphere model to systematically quantify the potentials and trade-offs of a range of BP scenarios dedicated to tCDR, representing different assumptions about which areas are convertible. Based on a moderate CO₂ concentration pathway resulting in a global mean warming of 2.5 °C above preindustrial level by the end of this century—similar to the Representative Concentration Pathway (RCP) 4.5—we assume tCDR to be implemented when a warming of 1.5 °C is reached in year 2038. Our results show that BPs can slow down the progression of increasing cumulative carbon in the atmosphere only sufficiently if emissions are reduced simultaneously like in the underlying RCP4.5 trajectory. The potential of tCDR to balance additional, unabated emissions leading towards a business-as-usual pathway alike RCP8.5 is therefore very limited. Furthermore, in the required large-scale applications, these plantations would induce significant trade-offs with food production and biodiversity and exert impacts on forest extent, biogeochemical cycles and biogeophysical properties.

1. Introduction

Terrestrial carbon dioxide removal (tCDR) strategies, as part of a suggested climate engineering (CE) portfolio (Vaughan and Lenton 2011), aim at extraction of CO₂ out of the atmosphere in the process of carbon fixation by plants through photosynthesis. Amongst other CE ideas that intentionally alter the radiative forcing of the atmosphere, tCDR is rated as a relatively 'safe' technology with medium carbon removal potentials at low economic costs (Shepherd 2009). However, efficient tCDR requires large-scale biomass plantations (BPs) or afforestation projects, long implementation periods (Vaughan and Lenton 2011, Caldeira *et al* 2013) and suitable

utilization pathways of the allocated biomass to permanently extract as much carbon as possible (Klein *et al* 2014).

Recent studies (Humpeöder *et al* 2014, 2015, Lomax *et al* 2015) see global re- and afforestation initiatives as well as managed BPs, combined with suitable conversion pathways (e.g. bioenergy with carbon capture and storage, BECCS), as an important component of the mitigation portfolio. This view is supported by the Summary for Policymakers of Working Group I of the International Panel on Climate Change's Assessment Report 5 (Stocker *et al* 2014) in which only the trajectory RCP2.6 (van Vuuren *et al* 2011) trajectory stays below the 2 °C target for global mean temperature (GMT) rise due to the assumed extensive

use of BECCS, whereas the other RCPs imply less or no mitigation based on BPs. Other analyses suggest that this ambitious mitigation pathway is not reliable due to uncertainties in high biomass feedstock supply (Kato and Yamagata 2014), carbon cycle dynamics, technologies and political frameworks (Fuss *et al* 2014).

CE projects are generally being suggested for deployment in the later decades of this century when consequences of unabated global warming might become intolerable for ecosystems and human well-being (Gerten *et al* 2013, Piontek *et al* 2014). For example, there is consensus that the 2 °C or 1.5 °C target will be out of reach if rapid mitigation efforts in the near future fail (Luderer *et al* 2013, Bertram *et al* 2015, Rogelj *et al* 2015). But so far research is lacking quantitative studies on the potential and consequences of later deployment of large-scale BPs as a CE rather than a mitigation method. For example, the deployment of tCDR could be suggested to lower the estimated median change in GMT of 2.7 °C in 2100 as anticipated by the currently pledged so-called intended nationally determined contributions (INDCs, Jeffery *et al* 2015) to 1.5 °C by 2100 once all near-term efforts will have been exhausted. To date, only a few studies contextualize tCDR explicitly as a CE option (Lenton 2010, Vaughan and Lenton 2011, Caldeira *et al* 2013) but their results are based on global estimates of available area and conversion pathways (i.e. not spatially explicit and without support by sound modeling of involved biogeochemical processes).

Our study focuses on the potentials and trade-offs of tCDR in a climate similar to that in RCP4.5 (Thomson *et al* 2011) with a GMT rise of 2.5 °C by 2100 (Heinke *et al* 2013) and similar to the anticipated warming according to the submitted INDCs (Jeffery *et al* 2015). So far, these mitigation pledges still fail to limit GMT rise to 2 °C or even 1.5 °C by the end of the century. In this study we therefore assume a deployment of tCDR with the intention to postpone or counter further emissions once the 1.5 °C target will be reached around 2038 (with ca. 660 GtC of cumulative emissions) using a spatially explicit systematic modeling framework. We create land-use scenarios in which the climatically and biogeochemically most suitable areas for tCDR are either converted to highly productive BP or natural vegetation (NV). Specifically we answer the three following research questions:

- (1) Could tCDR substantially delay the progression of cumulative emissions once a GMT rise by 1.5 °C is reached in a partial mitigation scenario like RCP4.5?
- (2) Could tCDR, deployed at a time when climate projections strongly diverge, even balance additional emissions towards a business-as-usual level of emissions (akin to RCP8.5)?

- (3) What would be some of the non-economic costs of the required excessive land-use and land cover changes for ecosystems and human well-being (e.g. effects on food production, forest extent and biogeochemical flows)?

2. Materials and methods

2.1. The biosphere model LPJmL

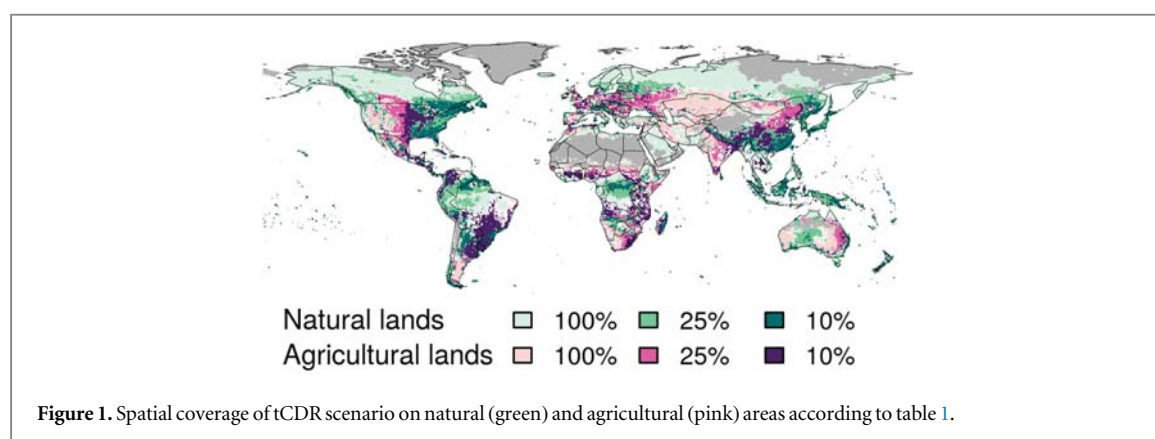
We created land-use scenarios of large-scale tCDR for evaluation with the Dynamic Global Vegetation Model LPJmL (Bondeau *et al* 2007, Schaphoff *et al* 2013) on a 0.5° × 0.5° global grid. The model was driven by monthly observational fields of temperature, precipitation and cloudiness as well as by annual CO₂ concentrations for the historic period of 1901 to 2005 as described in Ostberg *et al* (2015). The model dynamically simulates the biogeographical distribution of nine natural plant functional types depending on light, water and competition. Land-use patterns for 12 crop types and pasture were prescribed from 1901 to 2005 following transient historical changes (Fader *et al* 2010) up to the year 2005 including irrigated areas (Portmann *et al* 2010, Jägermeyr *et al* 2015). Crop yields are calibrated to match national FAO statistics as described in Fader *et al* (2010). To achieve soil carbon equilibrium and distributions of NV, the model was spun up for 5000 years without land-use but under the repeated climate of the years 1901–1930 (Schaphoff *et al* 2013). A subsequent spin-up of 390 years accounted for the influence of land-use changes on the carbon balance.

From 2005 on, we prescribed a climate forcing arriving at 2.5 °C of mean global warming in 2100 (Heinke *et al* 2013), similar to the CO₂ trajectory of RCP4.5. We used climate model output (e.g. precipitation patterns, temperature, wet days, cloudiness and CO₂ concentration) from MPI-ESM simulations prepared for the CMIP3 framework, which lies in the middle range of climate models considered in Heinke *et al* (2013).

Crop and pasture spatial patterns were kept constant between 2005 and 2038, the year in which the 1.5 °C target is crossed in our climate scenario. We assumed that in that year selected land areas would be converted to BP following the framework of table 1 (see next section). Bioenergy trees (BT) are simulated to meet the growth characteristics of poplar and willow in temperate regions and *Eucalyptus* in tropical areas. Bioenergy grasses (BG) imitate the growth behavior of *Miscanthus* and switchgrass. BT are simulated to be initially cultivated from small saplings on the field which grow for eight years when they are partially harvested down to their stump with rapid regrowth due to the remaining root system. Plantations are clear-cut and replanted after five harvest cycles (i.e. 40 years). Contrarily, BG grow much faster and 85% of the above ground biomass can be harvested once at the

Table 1. Scenario definitions, areas covered, and qualitative implications of their implementation.

Scenario	Name	Choice of cells	Area (Mha)	Implication
	LUconst	Constant land-use patterns of 2005	4267	Today's food production
Natural land	100 NAT	All arable cells	6883	Severe elimination or reduction of ecosystems/ biodiversity
	25 NAT	The 25% most productive cells	3245	
	10 NAT	The 10% most productive cells	1431	
Agricultural land	100 AGR	All cells	4267	No or strong reductions in food production (both crop & pasture based)
	25 AGR	The 25% most productive cells	2104	
	10 AGR	The 10% most productive cells	1045	
RCP	RCP2.6	As in van Vuuren <i>et al</i> (2011)	445	Bioenergy on cropland in 2100
	RCP4.5	As in Thomson <i>et al</i> (2011)	954	Afforestation of 468 Mha cropland and 486 Mha pastures in 2100



end of the growing season or several times a year as soon as leaf mass reaches 400 g m^{-2} . These parameter settings for both, BT and BG are chosen and tested to represent good global matches with reported yields on field as described by Heck *et al* (2016). Here, we consider only non-irrigated bioenergy plants. The global distribution of BG and BT in the different tCDR scenarios depends on the highest net accumulated biomass harvest as well as on changes in land carbon pools in each grid cell (SI.1 figure S1). For example, the soil carbon allocation of BT can be more beneficial for the net carbon sequestration than higher harvest rates of BG in some regions which is why BT would be planted in there. This procedure mainly allocates BG in tropical and temperate regions and BT in high latitudes and water stressed tropical regions where the deeper root system of BT are preferential over BG.

Simulated yields of herbaceous and woody bioenergy plants (Beringer *et al* 2011) were recently evaluated against field studies (Heck *et al* 2016). The hydrological, agricultural and biogeochemical simulations of LPJmL were thoroughly evaluated and validated in previous studies (Bondeau *et al* 2007, Rost *et al* 2008, Fader *et al* 2010, Schaphoff *et al* 2013).

2.2. Scenarios of tCDR areas

In our baseline scenarios (table 1), either all, a quarter or 10% of the grid cells on agricultural (AGR) or arable (e.g. ice, snow and desert-free) natural land (NAT) were assumed to be converted to BP to cover the range from maximum to more feasible, yet lower potentials (figure 1). To avoid the conversion of solely highly productive rainforest, five major biomes were considered separately for tCDR (tropical, temperate and boreal forest as well as grassland and tundra). Similarly, both cropland and pastures were treated equally to avoid judgment about which of these land use types to convert preferentially.

In an alternative setup, we modified these scenarios by selecting the grid cells with highest biomass harvest only, without considering the land carbon changes through conversion from previous use during the process of selecting grid cells. This allows an analysis of the impact of land conversion emissions on the overall climate potential of tCDR. Furthermore, we compare our results of highly managed BPs to the potentials of (regrowing) NV on the same chosen areas as in our baseline scenarios.

We here explicitly aim at the maximized possible biophysical potentials and therefore neglect

limitations on land-use and land cover transitions through social, economic or political restrictions.

2.3. Calculation of carbon potentials and years delayed

All simulation results, such as carbon pools (vegetation, litter and soil) and accumulated biomass harvests, were smoothed using a 10 year or 16 year moving average (depending on the harvest cycle) up to around year 2100 for herbaceous or woody BPs, respectively. We assumed a 50% capture rate of the carbon stored in the biomass harvest with a backflow of the other half to the atmosphere due to harvest losses, conversion inefficiencies and leakage rates (Lenton 2010, Powell and Lenton 2012, Smith *et al* 2013). Consideration of more detailed and complex conversion pathways or fossil fuel substitutions (Gilbert and Sovacool 2015) are beyond the scope of this study and thus, the tCDR potentials found here are pure carbon extractions to an unlimited storage capacity, reduced by the leakage. The same strategy is applied to the conversion of natural land by treating the replaced biomass as one harvest cycle with 50% loss of carbon to the atmosphere.

To calculate the time delay of tCDR on the cumulative emission trajectory, sequestration potentials of our tCDR scenarios were subtracted from the RCP's cumulative emission budget in 2100. We then counted the years until the reduced budget matches the RCP trajectory backwards in time.

2.4. Calculation of impacts

Following the definition of the planetary boundary for land-system change (PB-L, Steffen *et al* 2015), the loss of forest was estimated for each tCDR scenario and compared to the potential forest extent without human influence. This concept suggests that three major biomes are distinguished: boreal, temperate and tropical forests with boundaries suggesting that 85%, 50% and 85%, of the natural forest are to be preserved, respectively, before leaving the 'safe operating space for humanity'. At present, the global boundary of 75% of remaining forest extent—the average of the three biome-specific values—is already transgressed (62% of forest still existent). The extent of forested land and land-use areas differs between the dataset used in Steffen *et al* (2015) and the simulated extents by LPJmL (Ostberg *et al* 2013). For that reason, forest areas in LPJmL were linearly scaled to fit those calculated in Steffen *et al* (2015), and the percentage changes were calculated.

Our scenarios affect large areas which would induce biogeophysical effects e.g. if the reflectivity of the surface (albedo α) is changed substantially (Arora and Montenegro 2011). BP tend to be darker than cropland (competing effects of longer growing season of darker BG on agricultural land versus less dense bright crops revealing darker soils; Davin *et al* 2014,

DeLucia 2015, Miller *et al* 2015), sparse shrubland or seasonally snow-covered tundra vegetation or cropland, but brighter than dense tropical or temperate forests. To estimate the effect of albedo changes calculated by LPJmL (Forkel *et al* 2014; see SI.2), we compare them to albedo changes caused by historical changes in land-use and land cover (Pongratz *et al* 2011). As changes in moisture fluxes could also induce warming or cooling effects through altered latent heat fluxes (Davin *et al* 2007), we also compared moisture fluxes of unchanged vegetation and managed land in 2100, too.

By converting the LPJmL-simulated (and calibrated) crop yields to dry matter and applying the nutrition values for each crop type (Wirsenius 2000), we also calculated the percentage loss of per-capita calorie production for 7bn people in each tCDR scenario affecting agricultural cropland.

LPJmL implicitly assumes optimal nutrient supply to vegetation. Studies argue that fertilizers for BPs are only required during establishment in view of modern management techniques with a natural backflow of nitrogen (N) into the soils (Himken *et al* 1997, Brosse *et al* 2012). In the absence of long-term studies, we estimated the needed N fertilizer demand based on the removed biomass (C:N ratio). We assumed N contents of both plantation types of $5 \text{ kgN t}^{-1} \text{ C}^{-1}$ dry mass (Beringer *et al* 2011). With this, we approximated literature values of 4.9 gN kg^{-1} (Pennington 2012) and 4.8 gN kg^{-1} (Karp and Shield 2008) for BG and of 5 g kg^{-1} (Karp and Shield 2008) for BT. The carbon content of dry matter is approximated with 45% for herbaceous (Kato and Yamagata 2014) and 50% for woody biomass (Lenton 2010, Powell and Lenton 2012).

3. Results

3.1. The carbon sequestration potentials of tCDR

Figure 2 shows that the spatially most extensive, only theoretical scenarios (2.5–7.4 Gha, 100AGR, 25AGR + 25NAT, 25NAT, 10AGR + 10NAT and 100NAT) could fully compensate for the cumulative emissions on the RCP4.5 trajectory between 2038 and 2100 (i.e. the tCDR trajectories allow for higher sequestration potentials than the ongoing cumulative emissions). This would delay the carbon budget otherwise reached in year 2100 under RCP4.5 of 1227 GtC by 73 years (corresponding to 649 GtC, table 2) in the 100AGR scenario (figure 2(b)). Even more than 220 years could be balanced in the 100NAT scenario since in such a scenario even more carbon could be extracted than has been emitted since 1880 (1361 GtC). tCDR on smaller, more likely convertible areas of 1.0–2.1 Gha (25AGR, 10NAT, 10AGR) could translate into a postponement of 46–61 years (341–514 GtC). This implies that the maximal permitted amount of emitted carbon to stay below 2°C

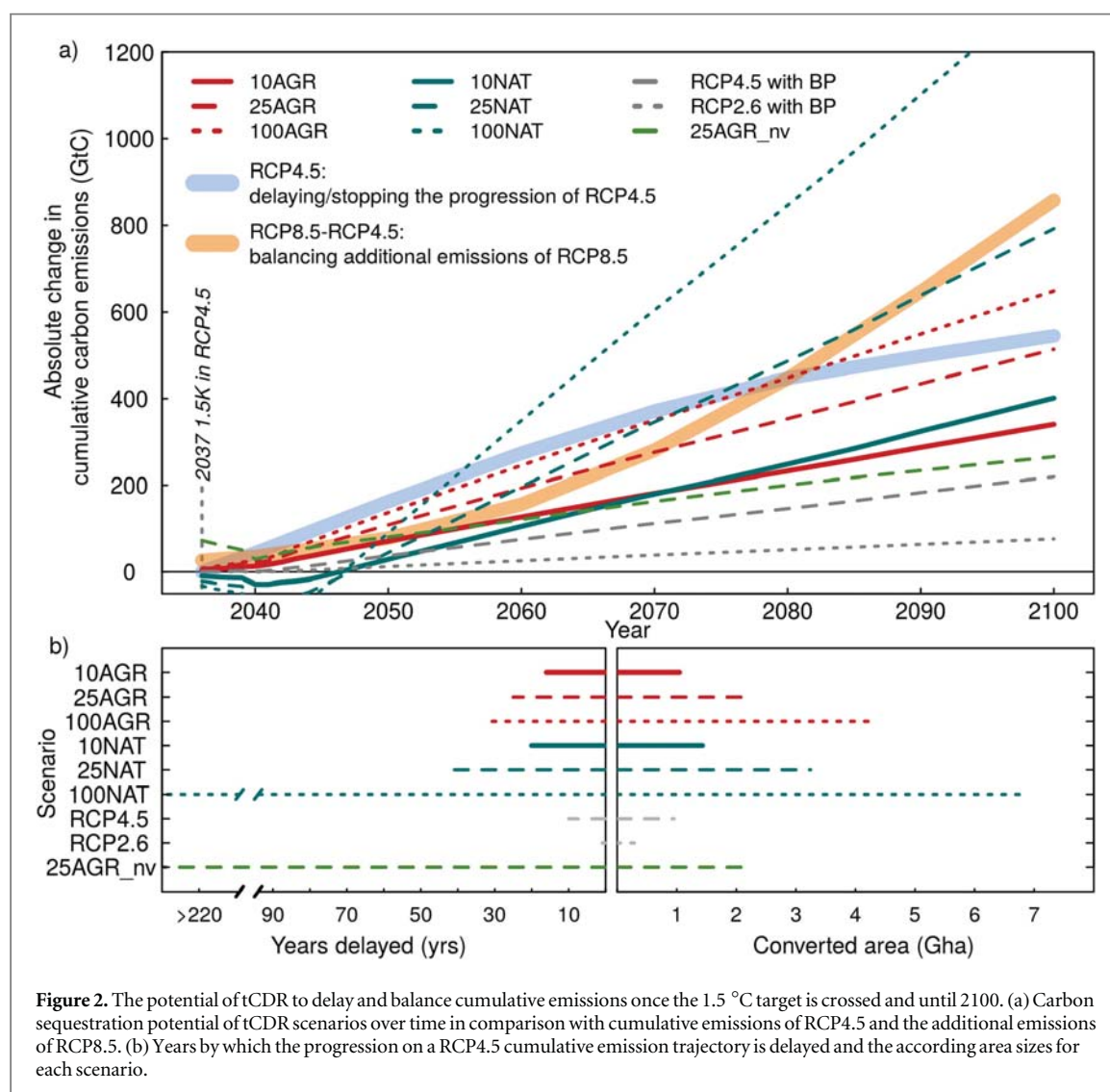


Figure 2. The potential of tCDR to delay and balance cumulative emissions once the 1.5 °C target is crossed and until 2100. (a) Carbon sequestration potential of tCDR scenarios over time in comparison with cumulative emissions of RCP4.5 and the additional emissions of RCP8.5. (b) Years by which the progression on a RCP4.5 cumulative emission trajectory is delayed and the according area sizes for each scenario.

Table 2. Potentials of tCDR in year 2100 in terms of carbon extracted (GtC) and years of emissions saved (yrs). All results are based on an RCP4.5-like emission pathway. 25AGR_h refers to the 25AGR scenario chosen by highest harvest only; 25AGR_nv refers to the 25AGR scenario with natural vegetation instead of BP and 25NAT_nv on the potential of standing natural vegetation on the 25NAT area.

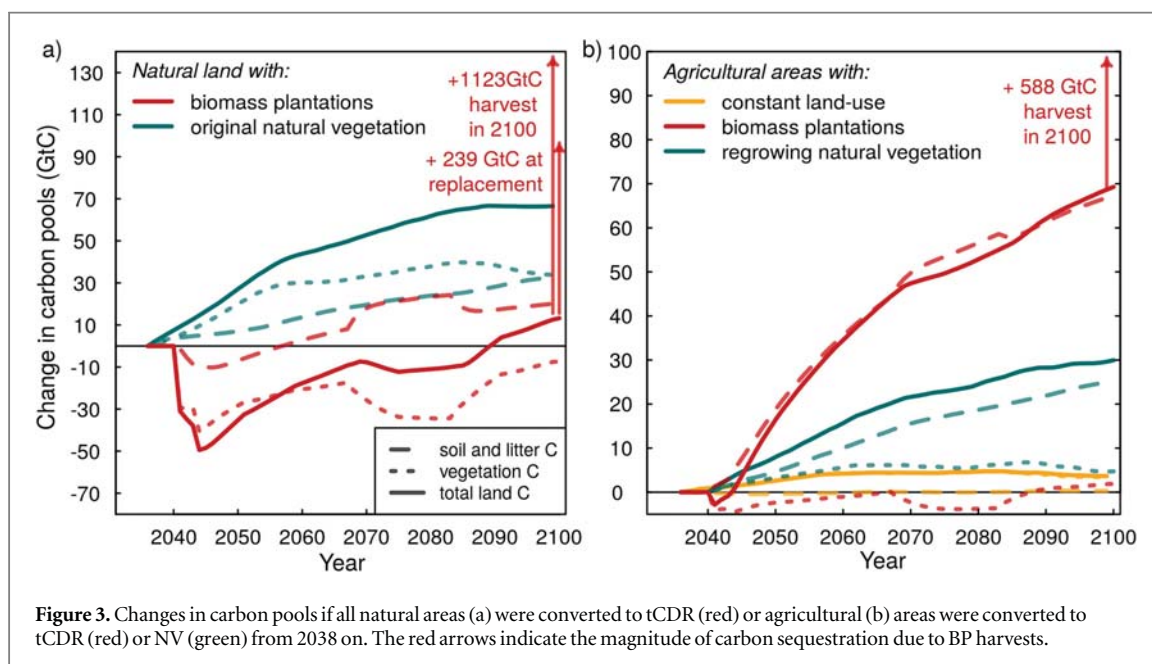
Scenario	C extraction (GtC)	Years delayed (yrs)
100NAT	1361	>220
100AGR	649	73
25NAT	792	88
25AGR	514	61
10NAT	401	51
10AGR	341	46
25AGR_nv	266	39
25NAT_nv	61	12
25AGR_h	502	60
RCP2.6	76	15
RCP4.5	220	34

(ca. 220 GtC from 2038 on in RCP4.5) could just be balanced by the end of this century.

However, these ambitious sequestration potentials of tCDR would only be sufficient following a RCP4.5

climate trajectory but not under unabated emissions as in RCP8.5. This becomes clear when looking at the trajectory of additional cumulative emissions (858 GtC more in 2100) leading towards a RCP8.5 pathway (orange line). tCDR could only balance these additional emissions if plantation sizes reached 7.4 Gha on natural land (100NAT with 1361 GtC) or large parts of natural and agricultural land (25AGR + 25NAT, 5.4 Gha) would be converted (1306 GtC). All scenarios of a smaller global BP area could only partly balance these additional emissions of a BAU pathway.

The sequestration potential of tCDR after 62 years of operation (2038–2100) highly depends on the plantation size and history of the land being converted. While converted natural areas are much larger than in the AGR scenarios, the carbon loss from soils and biomass partly diminishes the BP sequestration potentials (figure 3(a), red lines). This loss can however be compensated for if 50% of both the replaced natural biomass and the accumulated harvest are accounted for as sequestration potential (figure 3(a), red arrows). tCDR on agricultural land (figure 3(b), red lines) in contrast



increases the small current land carbon stocks (yellow lines) almost as much as if potential NV was to regrow on these areas (green lines). In both cases, BP harvest overcompensates any conversion losses by far (red arrows).

A variant of the 25AGR scenario in which afforestation rather than BP is chosen (25AGR_nv; figure 2) would sequester 266 GtC until 2100—almost half the potential of BP. As shown in figure 3(a), the land carbon restoration (i.e. the increase of soil and litter carbon) is also half to that under BPs and the additional BP harvest results in significantly higher potentials than under NV. The standing NV on the area of the 25NAT (25NAT_nv) scenario would sequester 61 GtC—substantially less than with BP on this land despite prevented land cover change emissions.

By neglecting land carbon changes while selecting grid cells, the sequestration potential of tCDR is reduced slightly since land conversion emissions diminish parts of the higher harvest potentials, especially on natural land (see figure S2). This also transfers to the potentials of the dedicated bioenergy areas in RCP2.6 and re- and afforestation areas in RCP4.5 which were chosen by Integrated Assessment Models for agro-economical reasons (figure 2(a)). Although the afforestation areas of RCP4.5 cover a similar area size of agricultural land as the 10CP scenario, the tCDR extraction is 181 GtC smaller. RCP2.6 approximately affects half of the 10AGR area but the sequestration potential is reduced to one fifth.

3.2. Impacts of large-scale tCDR implementation

The transformation of land for the purpose of tCDR would have various impacts as qualitatively listed in table 1 and quantified here with measures described in table 3. Figure 4 maps the impacts of converting large-

scale areas for tCDR on albedo changes, food production, forest extent and biodiversity.

Biogeophysical effects of large-scale land conversions to BP could decrease possible GMT reductions because albedo effects may cause local warming. By comparing albedo (α) values of original and BP land cover (figure 4(a)), we find that converting pastures and cropland could generally induce a positive radiative forcing which is likely stronger than the induced reduction in radiative forcing due to historical land use and land cover changes (Pongratz *et al* 2011). Converting NV to BP would likely increase the reflectivity resulting in a local cooling. We find that moisture fluxes could even be enhanced, leading to additional cooling effects through increased evaporation (table S2) due to the replacement of shrubland by BP, longer growing seasons and higher vegetation densities.

Converting forests to tCDR plantations shifts the status of land-system change (PB-L) from currently being at increasing risk (Steffen *et al* 2015) towards being at high risk with a reduction from 62% global forest cover left (current status) to 31%–49% in the 10NAT and 25NAT scenarios, respectively (table 3; figure 4(b)). For example, temperate and tropical forests in Asia found to be most suitable for tCDR would face massive replacements.

Food production would also be affected by tCDR on agricultural land (figure 4(c)). Kilocalorie losses would range from 43% to 73% for the 10AGR and 25AGR scenarios, respectively.

In our model, BG and BT BPs on all current agricultural areas would result in 56 kgN ha⁻¹ yr⁻¹ and 30.79 kgN ha⁻¹ yr⁻¹, respectively. According to Karp and Shield (2008; 50 kgN ha⁻¹ yr⁻¹ for switchgrass, 30–80 kgN ha⁻¹ yr⁻¹ for willows), Kering *et al* (2011; 120–168 kgN ha⁻¹ yr⁻¹) and Beringer *et al* (2011; 50–70 kgN ha⁻¹ yr⁻¹), these values lie at the lower end

Table 3. Impacts of tCDR on the remaining natural forest extent (%), the planetary boundary for land-system change (PB-L), global kilocalorie production (%) and nitrogen application (Mt yr^{-1} and, respectively, $\text{kg ha}^{-1} \text{yr}^{-1}$) in 2100.

Scenario	Remaining natural forest extent (%)	Risk of transgressing PB-L ^a	Change in kcal cap ⁻¹ day ⁻¹ (%)	Total N application (Mt yr^{-1})	N application ($\text{kg ha}^{-1} \text{yr}^{-1}$)
100NAT	0	High	—	589	57
25NAT	31	High	—	345	99
10NAT	49	High	—	169	114
100AGR	(100)	(Safe)	−100	200	47
25AGR	(85)	(Safe)	−73	160	126
10AGR	(73)	(Incr.)	−43	108	181

^a Note on PB-L: High refers to beyond the uncertainty zone, safe refers to within the safe operating space and increasing (incr.) refers to beyond planetary boundary but within the uncertainty zone. Brackets indicate a possible increase of forest extent if BP were assumed to be semi-natural vegetation.

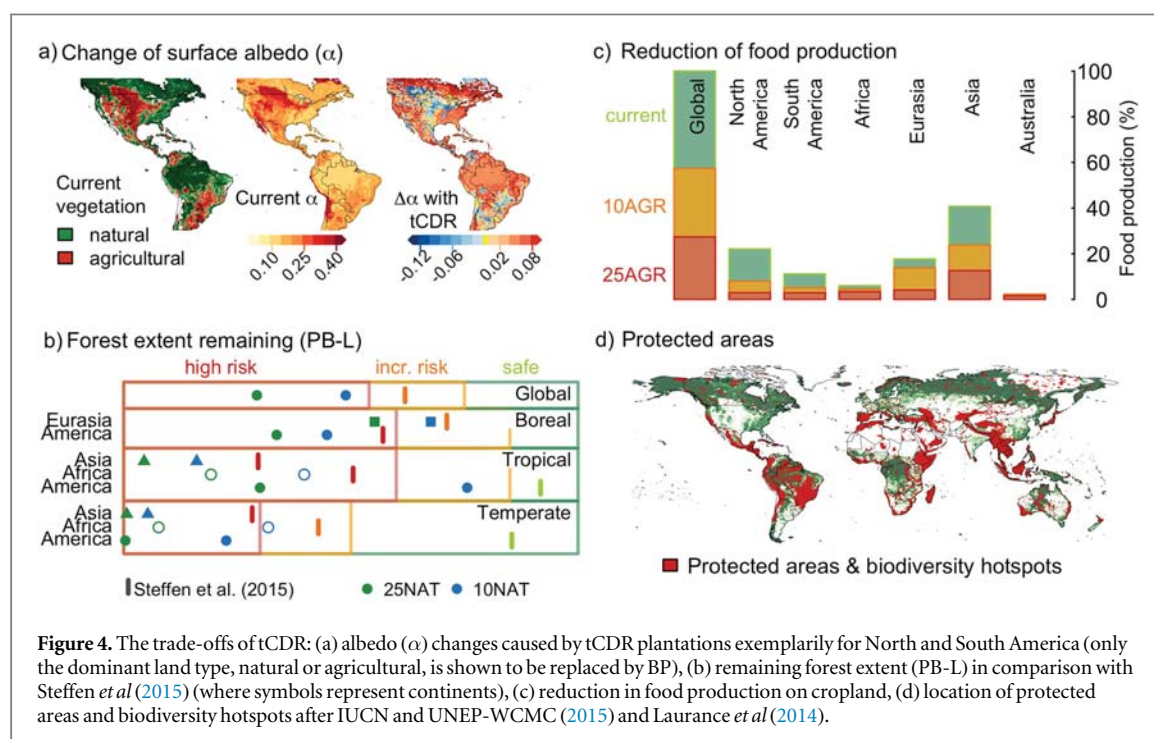


Figure 4. The trade-offs of tCDR: (a) albedo (α) changes caused by tCDR plantations exemplarily for North and South America (only the dominant land type, natural or agricultural, is shown to be replaced by BP), (b) remaining forest extent (PB-L) in comparison with Steffen *et al* (2015) (where symbols represent continents), (c) reduction in food production on cropland, (d) location of protected areas and biodiversity hotspots after IUCN and UNEP-WCMC (2015) and Laurance *et al* (2014).

of former study results. Nitrogen demand for BP ranges from 169 to 589 MtN yr^{-1} on natural areas and from 108 to 200 MtN yr^{-1} on agricultural land. N demand increases over-proportionally: the smaller the selected areas become the more productive they are due to our scenario set up (most productive cells chosen first). For example, 25AGR and 10AGR need much more nitrogen per hectare than the 100AGR scenario. Already the 10AGR scenario demands about three quarters of the current global nitrogen demand of 147 MtN (FAO 2015) enhancing the pressure on the planetary boundary for biogeochemical flows (44–62 MtN yr^{-1}).

The areas dedicated to tCDR in our scenarios also partly interfere with biodiversity hotspots (Laurance *et al* 2014), protected areas (IUCN and UNEP-WCMC 2015) (both figure 4(d)) and areas of endangered species (Pimm *et al* 2014), which might already be affected by climate change impacts at the levels of warming studied here (Gerten *et al* 2013, Ostberg *et al* 2013).

4. Discussion

4.1. The ability of tCDR to delay partially mitigated cumulative emissions

Our simulations demonstrate that the tCDR potential of BP could be substantial (i.e. up to several decades) if they were implemented immediately at large scale on suitable land as soon as the 1.5 °C target is reached around 2038 in a RCP4.5 climate. Our scenarios covering smaller areas could delay the progression on the cumulative emission pathway by almost half a century. If the aim was to balance all cumulative emissions from transgression of the 2.0 °C or even 1.5 °C target until 2100 on a RCP4.5 trajectory, ca. 330 or 550 GtC would have to be compensated, respectively. While the 2 °C target could already be achieved by more restricted (still large-scale) tCDR scenarios, the more ambitious 1.5 °C target could only be achieved by the most spatially extensive and far-fetched tCDR scenarios considered here which would imply severe impacts on ecosystems and food

production. However, if the INDCs could enforce stronger mitigation results (e.g. if conditional options were fulfilled, air pollution reduced and planned coal fired power plants be canceled; Edenhofer 2015, Jeffery *et al* 2015), tCDR could possibly reduce the remaining emission gap if the environmental costs incurred were deemed acceptable.

Overall, the areas sizes considered and carbon extraction potential of our scenarios (except for the 100NAT scenario) lie within the range of suggested in previous studies (table S1). Generally, potentials differ due to a broad range of factors such as economic drivers of land allocation, conversion efficiencies, carbon storage options, yield potentials, fertilizers, methodological simplifications or the treatment of the history of the converted land. To our knowledge, only five studies consider tCDR to be a CE method but assume its implementation already in the near future which typically leads to more optimistic outlooks. Caldeira *et al* (2013) estimated a carbon extraction rate of 1 GtC yr^{-1} on 3% of the land surface ($\sim 437 \text{ Mha}$) using temperate trees. Our BPs are simulated to be more productive and thus, tCDR on 50% of the 10AGR (523 Mha) could extract $\sim 2.5 \text{ GtC yr}^{-1}$. The conversion of areas as large as today's agricultural land to tCDR is estimated to yield different potentials: 150–900 GtC under mitigated climate in Lenton (2010), 583–913 GtC in van Minnen (2008), 277–309 GtC in Heck *et al* (2016) leaving our result at a medium level (616 GtC), partly due to the simplified utilization pathway of carbon.

4.2. The ability of tCDR to balance additional emissions

The potentials of tCDR scenarios would likely still not be sufficient to balance additional emissions associated with a business-as-usual emission pathway like the RCP8.5. Carbon emissions would still increase more strongly than tCDR could compensate despite our carbon sequestration estimates being optimistic due to the preferential selection of most productive grid cells, rapid implementation, beneficial effect of elevated CO_2 on plant growth and the absence of nutrient limitation and biogeochemical feedbacks (e.g. emissions from fertilizers). For example, our model is sensitive to high CO_2 concentrations (Leipprand and Gerten 2006, Luo *et al* 2008, Beringer *et al* 2011) acting as fertilizer on plant productivity, and thus, yields may be somewhat overestimated. tCDR potentials would increase by 10%–12% on BP between simulations reaching 390 ppm and our climate forcing of 546 ppm in 2100. An increase of CO_2 concentrations to 1050 ppm as in the RCP8.5 would enhance productivity 17%–20% compared to our climate forcing. Natural vegetation is less sensitive to changing CO_2 concentrations with only 4%–9%.

4.3. The non-economic 'costs' of tCDR

We find that the non-economic 'costs' resulting from the land conversions for BP will be high. While it is the purpose of tCDR to possibly go back into the 'safe operating space' for climate change (Steffen *et al* 2015), it may thus hamper efforts to stay within the planetary boundaries for land-system change, freshwater use (if irrigated), biogeochemical flows and biosphere integrity. A recent study by Wieder *et al* (2015) states that the nutrient supply for cultivated land throughout the century is not even secured following the land-use scenarios of the RCPs and thus, neither for our large-scale tCDR scenarios. Our spatially least demanding scenarios (1.0–1.4 Gha) would still restrict food production, reduce forests extents critically and certainly threaten biodiversity. The competition for arable land is already high today (Searchinger and Heimlich 2015) and in view of an increasing world population and its growing demand for food, the obstacles for food production are unlikely to be overcome. Optimistic outlooks on food production and yield increases on currently cultivated land (Lotze-Campen *et al* 2010, Alexandratos and Bruinsma 2012, Powell and Lenton 2012) suggest that such increases will likely not be higher than 27% globally (Bajželj *et al* 2014). According to Ellis *et al* (2010) only one fourth of the Earth surface is still pristine and should therefore remain untouched if those areas are to be preserved. Even the conversion of agricultural land to tCDR would not induce a more natural state than today's agriculture (Heck *et al* 2016) and the effect of changing albedos cannot be neglected (Arora and Montenegro 2011, Davin *et al* 2014, Keller *et al* 2014, Miller *et al* 2015). Other studies claim that land availability is not constrained (Souza *et al* 2015) and that e.g. corridor-like and sustainably managed plantations might also increase biodiversity (Smith *et al* 2013, Jantz *et al* 2014, DeLucia 2015). tCDR would likely increase the already existing and intensifying pressure on managed and natural land.

Our scenarios depict only a small range at the margins of a very diverse space of possible future land-use trajectories, but they still draw ceilings to the achievable potentials and, especially, the bearable non-economic costs for the environment and human well-being. Realistic obstacles for tCDR such as smaller plantation sizes, later and gradual establishment of BP, climate change impacts on plant growth and water and nutrient limitations would decrease the potential of BP to sequester atmospheric carbon loading.

5. Conclusion

Our study shows that tCDR as a CE method could substantially slow down the progression of cumulative emission on a mitigation trajectory reaching $2.5 \text{ }^\circ\text{C}$ in 2100. However, this can only be achieved if BPs are implemented immediately once the $1.5 \text{ }^\circ\text{C}$ target is

crossed and if immense costs for food production and ecosystems were tolerated. Furthermore, it is likely that the extensive conversion of land induces positive feedbacks with the climate system itself (not explicitly modeled here), compromising the purpose of tCDR: to lower the global carbon budget and GMT changes. If tCDR was implemented to counter additional emissions on a RCP8.5 trajectory, this potential would be insufficient despite our rather optimistic sequestration calculations. In view of limited space to reduce side-effects, tCDR can thus be considered as an ineffective CE tool to reverse carbon emissions. We show that we cannot bet on tCDR to supply negative emissions (Fuss *et al* 2014, Zickfeld and Herrington 2015) and that early mitigation, even with sustainably managed tCDR, is inevitable (Smith *et al* 2016).

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