The limits to global-warming mitigation by terrestrial carbon removal

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Abstract Massive near-term greenhouse gas emissions reduction is a precondition for staying "well below 2°C" global warming as envisaged by the Paris Agreement. Furthermore, extensive terrestrial carbon dioxide removal (tCDR) through managed biomass growth and subsequent carbon capture and storage is required to avoid temperature "overshoot" in most pertinent scenarios. Here, we address two major issues: First, we calculate the extent of tCDR required to "repair" delayed or insufficient emissions reduction policies unable to prevent global mean temperature rise of 2.5°C or even 4.5°C above pre-industrial level. Our results show that those tCDR measures are unable to counteract "business-as-usual" emissions without eliminating virtually all natural ecosystems. Even if considerable (Representative Concentration Pathway 4.5 [RCP4.5]) emissions reductions are assumed, tCDR with 50% storage efficiency requires >1.1 Gha of the most productive agricultural areas or the elimination of >50% of natural forests. In addition, >100 MtN/yr fertilizers would be needed to remove the roughly 320 GtC foreseen in these scenarios. Such interventions would severely compromise food production and/or biosphere functioning. Second, we reanalyze the requirements for achieving the 160–190 GtC tCDR that would complement strong mitigation action (RCP2.6) in order to avoid 2°C overshoot anytime. We find that a combination of high irrigation water input and/or more efficient conversion to stored carbon is necessary. In the face of severe trade-offs with society and the biosphere, we conclude that large-scale tCDR is not a viable alternative to aggressive emissions reduction. However, we argue that tCDR might serve as a valuable "supporting actor" for strong mitigation if sustainable schemes are established immediately.

Plain Language Summary In 2015, parties agreed to limit global warming to "well below" 2°C above pre-industrial levels. However, this requires not only massive near-term greenhouse gas emissions reductions but also the application of "negative emission" techniques that extract already emitted carbon dioxide from the atmosphere. Specifically, this could refer to the establishment of extensive plantations of fast-growing tree and grass species in combination with biomass conversion to carbon-saving products. Although such deployment is seen as promising, its carbon sequestration potentials and possible side-effects still remain to be studied in depth. In this study, we analyzed two feasibility aspects of such a negative emissions approach using biomass plantations and carbon utilization pathways. First, we show that biomass plantations with subsequent carbon immobilization are likely unable to "repair" insufficient emission reduction policies without compromising food production and biosphere functioning due to its space-consuming properties. Second, the requirements for a strong mitigation scenario staying below the 2°C target would require a combination of high irrigation water input and development of highly effective carbon process chains. Although we find that this strategy of sequestering carbon is not a viable alternative to aggressive emission reductions, it could still support mitigation efforts if sustainably managed.

1. Introduction

The "2°C guardrail" was defined to avoid "dangerous anthropogenic interference with the climate system" [*United Nations Framework Convention on Climate Change (UNFCCC)*, 2009]. There is growing scientific evidence [*Schellnhuber et al.*, 2016] that this limit to global warming is indeed necessary for confining the risks

of disastrous functional changes in the planetary machinery. The goal has now been ratified by 125 nations that signed the Paris agreement in 2015 [*United Nations Framework Convention on Climate Change (UNFCCC)*, 2015]. Current country pledges as described in the intended nationally determined contributions are voluntary mitigation efforts [*Jeffery et al.*, 2015] that would clearly not add up to realize the stated objective. There is an overwhelming expert consensus that substantial near-term emissions reductions are required, instigating a full de-carbonization of the world economy by mid-century to establishing a reasonable probability of staying below 2°C global mean temperature (GMT) rise (above pre-industrial levels) [*Bertram et al.*, 2015; *Rogelj et al.*, 2015a, 2015b; *Sanderson et al.*, 2016; *Schleussner et al.*, 2016]. Should mitigation actions not materialize, not be substantially increased over time, be disrupted, delayed or overpowered by concurrent fossil fuel-based development [*Bertram et al.*, 2015; *Smith et al.*, 2016], then GMT could increase by up to ∼5°C by the end of this century.

Even in the most ambitious mitigation scenarios, including the widely used Representative Concentration Pathway 2.6 (RCP2.6) scenario for limiting GMT rise to <2°C [*van Vuuren et al.*, 2010], there is an additional need for large-scale carbon dioxide removal (CDR) from the atmosphere to offset particularly hard-to-mitigate greenhouse gas emissions and prevent "overshoot" of the 2°C temperature line. Hence, the notion of employing substantial CDR action to complement strong mitigation action is currently reflecting the predominant mind-set of the climate policy discourse. However, with existing mitigation pledges and actions falling far short of what is required in such <2°C scenarios, it seems reasonable to ask whether *even larger-scale* CDR could possibly counteract failures to sufficiently reduce emissions? This returns to the earlier framing of CDR as an ex-post option of managing an overshoot and bringing GMT rise back down to 2°C [*Shepherd*, 2009; *Vaughan and Lenton*, 2011; *Caldeira et al.*, 2013; *Kreidenweis et al.*, 2016].

In either case, terrestrial CDR (tCDR), mainly via biomass-producing plantations (BPs) combined with subsequent permanent carbon storage (e.g., bioenergy with carbon capture and storage, BECCS) has been considered a feasible technology for achieving *net-negative* emissions by late century [*Fuss et al.*, 2014]: It comprises the three favorable aspects of being (i) a green energy carrier [*Midilli et al.*, 2006]; (ii) a substitution for fossil fuels [*Klein et al.*, 2013]; and (iii) economically attractive [*Cornwall*, 2017]. Thus, it is not only a vital complement to strong emission reductions in mitigation pathways aiming at the 2°C target [e.g., *van Vuuren et al.*, 2010; *Fuss et al.*, 2014], but could also be investigated as a countermeasure to slow down or even reverse CO_2 accumulation on less stringent mitigation pathways [*Riahi et al.*, 2011; *Thomson et al.*, 2011; *Caldeira et al.*, 2013]. However, in both cases large uncertainties remain, not only concerning tCDR availability, effectiveness, economic and technological feasibility but also its likely and rather dramatic environmental consequences [*Fuss et al.*, 2014; *Kato and Yamagata*, 2014; *Smith et al.*, 2016].

Here, we investigate the feasibility of tCDR and its trade-offs from a biosphere point of view. This includes considering different background emissions scenarios (unabated, partially mitigated, or strongly mitigated), different starting points for implementing CDR, the required land extent of BPs, and their respective water and nitrogen requirements. To achieve this, we explore two narratives, the *first* being a systematic analysis of maximum tCDR potentials under insufficient mitigation action (i.e., comparably weak emissions reductions), and the *second* focusing on the land and water demands of tCDR in a strong mitigation scenario.

In particular, we investigate how spatially extensive BPs implemented by 2050 would need to be on an unabated or partially mitigated pathway in order to observe the 2°C guardrail. Accepting that this is not the preferred policy framing of tCDR use, this assessment nevertheless addresses whether tCDR potentials could be a "late-regret" solution if emissions continued to increase and the 2°C line was transgressed around 2050. One can think of this analysis as a severe-risk assessment of an undesirable outcome, which exposes the stark trade-offs it would generate. As such it helps inform policy discussions.

Furthermore, we analyze under what technological and management pre-conditions the biosphere could provide the carbon extraction potentials defined by a strong transient mitigation pathway, namely the RCP2.6 [*van Vuuren et al.*, 2010]. Although the starting point of this scenario lies in the past (2006), we can still investigate what the technological and environmental implications should have been to reach the published tCDR potentials of BPs.

Table 1. Potentials and Impacts for Each tCDR Scenario

(a) tCDR Potentials	Permanent Carbon Sequestration (GtC)		Years Saved (Years)		(b) Impacts			
	Part. Mitigated	Unabated	Part. Mitigated	Unabated	BP Area (Mha)	Forest Extent Remaining (%)	kcal Loss (%)	N Application in Total (Mt yr^{-1})
Needed to reach 2°C (in RCPs)	~320	~1,230	~46	~53				
100NAT	1,130	1,424	165	67	6,899	0		570
100AGR	583	705	67	28	4,267		100	196
100AGR_p	324	391	44	15	2,771			
25NAT	655	816	74	32	3,307	30		328
25AGR	454	549	56	21	2,176		73	151
25AGR_nv	289	291	41	11	2,176			
10NAT	333	414	45	16	1,470	49		160
10AGR	295	354	42	13	1,078		43	96

BP, biomass-producing plantation; RCP, Representative Concentration Pathway; tCDR, terrestrial carbon dioxide removal.
(a) Description of the tCDR scenarios and their potentials in 2100 in terms of permanent carbon extraction (GtC) and years of emissions delayed (years) with respect to RCP8.5's and RCP4.5's 2100 emissions; (b) The impacts of tCDR on land conversion (Mha) and remaining forest extent (reforestation potential), food production (% loss of kcal cap^{-1} day^{-1} production) and estimated nitrogen application (Mt yr^{-1}).

For both narratives, the implications for environment and society are inferred for every tCDR scenario using a state-of-the-art, spatially explicit, biogeochemical-processes-based model as described in the following.

2. Materials and Methods

2.1. The Model LPJmL

We here use the well-established [*Cramer et al.*, 1999; *Gerten et al.*, 2004; *Friend et al.*, 2014] Dynamic Global Vegetation Model including managed land [*Bondeau et al.*, 2007; Text S2, Supporting Information] to simulate the growth of natural and managed vegetation—including BPs—and the associated biogeochemical processes in a single, internally consistent framework. LPJmL embraces nine plant functional types with dynamic distributions based on bioclimatic conditions and competition for light, water, and space, and 12 crop functional types as well as pastures with prescribed distributions and management [e.g., irrigation, *Jägermeyr et al.*, 2015] with calibrated yields until 2005 [*Fader et al.*, 2010]. Furthermore, the model captures two second-generation bioenergy functional types with prescribed distribution in scenarios (as specified in Table 1) producing yields [*Beringer et al.*, 2011]. With daily time steps and on a 0.5° × 0.5° grid, the model evaluates the climate-dependent transient dynamics of carbon fixation, allocation, turnover and loss in vegetation growth while accounting for interactive effects of soil moisture and atmospheric CO_2 content [for a detailed description of model setup please see also Text S2 and *Schaphoff et al.*, 2013]. Bioenergy plantations are either woody (representing the growth characteristics of temperate willows and poplars or tropical *Eucalyptus*) or herbaceous (imitating *Miscanthus* and switchgrass) with harvest cycles of 8 years or multi-annual occurrences, respectively [*Beringer et al.*, 2011; *Heck et al.*, 2016; Text S1]. Simulations of dedicated BPs differ from those of corresponding natural vegetation by assuming higher productivity and harvest at regular or growth-dependent intervals. Our results capture a realistic magnitude of production as verified by a comparison of the uncalibrated simulated woody and herbaceous BP productivity with observations from field data as conducted by *Heck et al.* [2016].

2.2. Climate and Land Use Scenarios

We investigate the ability of tCDR to counteract future emissions associated with three climate scenarios that generate specific GMT levels by the end of the century. In the first scenario, climate develops on an
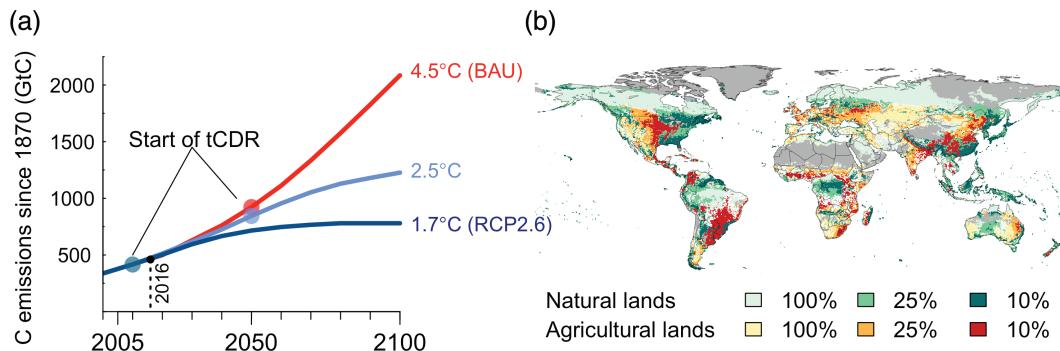
Figure 1. (a) Cumulative emission pathways leading to a mean global warming of 1.7°C (Representative Concentration Pathway 2.6 [RCP2.6]), 2.5°C, and 4.5°C by 2100, respectively. Dots indicate the starting points of terrestrial carbon dioxide removal (tCDR) assumed here. Climate projections for the upper two graphs were retrieved with a pattern-scaling approach applied on five CMIP3 models [*Heinke et al.*, 2013] while the RCP2.6 climate was retrieved from CMIP5 simulations. (b) Areas considered for tCDR in the studied conversion scenarios. Values are given as % fraction of 0.5° × 0.5° grid cells for scenarios listed in Table 1. Note that only the dominant fraction of either natural or agricultural land in each cell is displayed.

unabated business-as-usual pathway resulting in a GMT rise of ∼4.5°C by 2100 [*Heinke et al.*, 2013] and a crossing of the 2°C threshold in 2053 (Figure 1a). This climate forcing is comparable to the RCP8.5 projection [*Riahi et al.*, 2011] with 2,085 GtC cumulative anthropogenic emissions by the end of the 21st century. On the RCP8.5 trajectory, a GMT rise by 2°C above pre-industrial level is reached by 2047 [see figure, SPM.10 in *Stocker et al.*, 2013], hence, we extended our simulations until 2106 to capture a similar timespan (e.g., 2053–2106 instead of 2047–2100). In the second scenario, emissions are partially mitigated, leading to a GMT rise of ∼2.5°C by 2100 (and ∼1.8°C by mid-century). This forcing is comparable to the RCP4.5 scenario with 1227 GtC cumulative anthropogenic emissions by 2100. It is also equivalent to the current mitigation pledges of the Paris accord [*Jeffery et al.*, 2015] and thus still not complies with the internationally agreed objectives. The third climate scenario follows temperature and emissions projections (1.7°C and 780 GtC cumulative emissions by 2100, respectively) of the strong-mitigation, transient RCP2.6 trajectory [*van Vuuren et al.*, 2010].

The climate forcing and CO_2 concentrations for the first two climate scenarios were taken from the MPI-ESM ECHAM5 model and found to give intermediate biosphere responses in LPJmL when compared with four additional climate models participating in the Coupled Model Intercomparison Project Phase 3 (CMIP3) and prepared for our 2.5°C and 4.5°C trajectory following *Heinke et al.* [2013, see Figure S3]. For RCP2.6, climate model inputs were taken from five CMIP5 models [HadGEM2-ES, MPI-ESM-MR, CanESM2, IPSL-CM5A-MR, and MIROC-MR-CHEM; *Taylor et al.*, 2012] and bias-corrected [*Watanabe et al.*, 2012; *Heinke et al.*, 2013]. The sensitivity of BPs' productivity to different levels of CO_2 and climate is rather high but within the range observed in field experiments [Figure S2, *Norby et al.*, 2005; *Hickler et al.*, 2008].

In the first part of our analysis, we investigate the tCDR potential necessary to hold the 2°C line in the high and the partially mitigated emission scenario, respectively, using a set of land-use scenarios differing in terms of the spatial extent of BP plantations and in terms of whether currently cultivated or uncultivated areas are considered for conversion (Figure 1b, Table 1). In these scenarios, land-use patterns for crops and pastures are fixed at year 2005 levels until BPs are implemented according to the following rationale: By utilizing all natural land suitable for growing BPs (7.4 Gha globally, 100NAT) or all present-day agricultural land (4.2 Gha, 100AGR), theoretical upper limits on tCDR potentials are established. Scenarios where 25% of the most productive either natural (e.g., parts of five major biomes, 25NAT) or agricultural land grid cells (e.g., parts of cropland and pastures, 25AGR) are converted to BPs represent very extensive versions of tCDR (3.3 or 2.2 Gha). Conversions of 10% of grid cells (1.4 Gha in 10NAT and 1.1 Gha in 10AGR, respectively) are perhaps more realistic but still very ambitious tCDR scenarios. Grid cells unsuitable for agriculture, e.g., those covered by ice, snow, or desert, were excluded. However, BPs may also be realized in apparently low-productivity regions (e.g., central Australia) as long as they belong to the 25% most productive grid cells of grass- or shrubland [following the biome classification by *Ostberg et al.*, 2013]. For this systematic analysis of *potentials*, we did not adhere to the land-use patterns associated with the studied RCPs [*Riahi et al.*, 2011; *Thomson et al.*, 2011], since we are interested in the effectiveness of BPs to balance additional emissions under different climates and CO_2 concentrations *per se*, i.e., based *only* on production potentials for the selected areas,

irrespective of whether they are considered BP areas in RCP land-use scenarios (see below for our alternative scenario that allows for a feasibility analysis under an RCP2.6 land-use pattern).

Note that grid cells and plantation types are selected for conversion such that the highest global net carbon potential — that is the highest sum of land-carbon changes from land conversion plus carbon extraction by BPs — is achieved in each scenario (global distribution shown in Figure S1).

In the second part, the *feasibility* of a predefined RCP2.6 land-use scenario for crop, pasture, and bioenergy plantations [*van Vuuren et al.*, 2010; http://luh.umd.edu/data.shtml] is analyzed. In this scenario, created by an Integrated Assessment Model (IAM), global population reaches 9 billion in 2050 causing cropland expansion due to increasing food demand. Growing land-use intensity allows for agriculture to concentrate in poorer world regions while the abandoned land in wealthier regions can be used for establishment of BPs. Specifically, this means that BPs are only allowed on abandoned crop and pasture land or natural, non-forested and non-protected land. This in turn causes deforestation to meet the increasing food and energy demand and to compensate for a decreasing CO_2 fertilization effect. Land-use change is therefore only demand-driven and not by climate policies. The provided single crop land distribution was transferred to the spatial patterns of 13 crop types in LPJmL in 2005 and proportionally scaled to meet required areas (as described in *Boit et al.*, 2016; for spatial and temporal patterns see Text S3). According to this scenario, dedicated BP areas increase to 441 Mha between 2006 and 2100 and are assumed to be herbaceous, since these have higher biomass harvest potentials than woody BPs on a global scale [see *Kato and Yamagata*, 2014; *Heck et al.*, 2016]. In contrast to the previous scenarios, irrigation of BPs is explicitly considered, assuming either sustainable or unlimited schemes. For the version assuming sustainable irrigation, water withdrawal is constrained by local renewable water availability from rivers, groundwater baseflow, lakes, and reservoirs. Irrigated cropland area in 2005 [*Jägermeyr et al.*, 2015] is assumed to increase proportionally over time (reaching 362 Mha out of 5005 Mha total agricultural land in 2100), as is the irrigated fraction of BP area (reaching 40 Mha in 2100). In the (thought experiment) scenario of unlimited irrigation, any water demand is assumed to be met in one way or the other.

2.3. Calculation of Carbon Sequestration Potentials

For BPs to be an effective tCDR tool, that is realizing net negative emissions, the extracted carbon from the atmosphere needs to be permanently immobilized and excluded from the carbon cycle. We calculate the cumulative biomass harvest carbon until 2100 but employ a conversion-efficiency rule (CEff) before accounting for land-carbon changes for the overall tCDR potential. That is, we simplify the life-cycle assessment of processed carbon and carbon products by assuming that harvested biomass carbon is passed to a carbon pool with a CEff of 50%: Half of the sequestered carbon is lost during biomass harvest, its subsequent transportation, processing, and storage on longer time scales. This simplification represents a reasonable global averaging in line with the current evidence [*Lenton*, 2010; *Powell and Lenton*, 2012; *Smith et al.*, 2013]. However, there are various schemes by which biomass carbon could be utilized: biofuels with CEff's of ~20%, 50%, or 70% for the processes of fermentation, liquefaction or pyrolysis, respectively [*Edenhofer et al.*, 2011]; bioenergy with carbon capture and storage (BECCS) in geological reservoirs with theoretical CEff's of 70–99% [*Lenton*, 2010; *Edenhofer et al.*, 2011; *Humpenöder et al.*, 2014]; or biochar generation, substituting fertilizers on fields, with potential CEff's of 70–90% (*Lehmann*, 2007; *Woolf et al.*, 2010). Transportation may lead to losses of 2–15% (*Cannell*, 2003; *Smeets et al.*, 2007). We account for this range when analyzing the tCDR potential in the RCP2.6 scenario by applying values of CEff of 50%, 75%, and 90%. Lower values of 20% or less could lead to the unfavorable outcome that land-carbon losses exceed the carbon extraction by BPs, so they are not considered here. The replacement of natural vegetation by land conversion is treated as a one-time harvest with a 50% capture rate. As CO_2 concentrations are prescribed in the model, we cannot account for substituting fossil fuel energy carriers.

We express the tCDR potentials in terms of cumulative CO_2 uptake and in terms of "years delayed" on the emission trajectories of the similar climate scenarios of the partially mitigated RCP4.5 and unabated RCP8.5 to infer whether tCDR can extend the 2100 emissions budget for a certain period of time into the future. This is achieved by subtracting accumulated tCDR potentials in 2100 from the RCP4.5 or RCP8.5 emissions budget in 2100. By decelerating the emission accumulation with tCDR without actually leaving the trajectory we can bypass the fact that in LPJmL CO_2 concentrations are not affected by tCDR, thus fossil fuel substitution and ocean and climate feedbacks cannot be accounted for.

Under RCP2.6, BPs are required to extract 160–190 GtC from the atmosphere [*van Vuuren et al.*, 2010; *Kato and Yamagata*, 2014]. This should not only refer to the biomass harvest potentials alone but should again take land-carbon changes from conversion to BPs into account. Note that tCDR potentials for RCP2.6 as simulated by LPJmL depend on the specific climate forcing provided by the different climate models. Not only may precipitation patterns differ but also GMT increases may vary, mainly due to the diverse carbon cycle responses arising from different modeling strategies [*Brovkin et al.*, 2013; *Boysen et al.*, 2014]: BP patterns were not uniformly implemented in coupled models' land surface schemes in CMIP5; they were treated as cropland or grassland or entirely ignored, so the resulting climate patterns vary too. These differences provide an uncertainty range for the simulated tCDR potentials presented here.

2.4. Calculation of Impacts of tCDR

We provide a rough assessment of impacts of tCDR on food production (i.e., drawbacks on current production that is estimated to be ~3,000 kcal cap^{-1} day^{-1} for 7 billion people based on simulated crop yields and calorie content [see Text S3 and *Wirsenius*, 2000]), forest extent, and the nitrogen cycle.

Based on the concept of "planetary boundaries" [*Rockström et al.*, 2009; *Steffen et al.*, 2015] we also quantify the impact of further reductions of natural forest cover brought about by tCDR plantations. The land-system boundary defines thresholds of remaining forest extent for three continental forest biomes (boreal, temperate, and tropical) beyond which the Earth system would enter a new state (in a possibly irreversible way). We used this approach according to the fractional forest areas provided by LPJmL, which partly differ from those used in *Steffen et al.* [2015]. By scaling simulated potential forest extents to those in *Steffen et al.* [2015], we were able to analyze the relative change of area in our scenarios and to calculate the position with respect to the planetary boundary for land-system change.

Nitrogen limitation to plant growth is not explicitly modeled in LPJmL. Therefore, we did a *post hoc* estimation of the nitrogen content of the harvested and removed biomass [see *Boysen et al.*, 2016], which can be translated into the required amount of nitrogen fertilization. We do not account here for the possible increase in N$_2$O emissions that could arise from this increased fertilizer application or increased fossil fuel use for producing fertilizer.

3. Results and Discussion

3.1. Sequestration Potentials of tCDR in a Partially Mitigated and in an Unmitigated Scenario

We find that tCDR could potentially push down GMT toward the 2°C line in a partially mitigated climate scenario that would approach 2.5°C above pre-industrial level by 2100 (corresponding to ~320 GtC emissions between mid-century and 2100, following RCP4.5, see Figure 2). This is summarized in Table 1a. However, the required BP area needs to be >1.1 Gha of the most productive agricultural land (10AGR, Figure 2f) or ~1.5 Gha of natural land (10NAT, Figure 2c). The theoretical tCDR potential is as large as 585–1130 GtC, or 67–165 years of delay, if all agricultural or natural land can be converted (100AGR and 100NAT, respectively, Figures 2d and 2a). However, this would have most dire consequences for food production or the biosphere. In order to maintain current global land use patterns for agriculture, the majority of natural ecosystems would be eliminated in the 100NAT scenario. Moreover, the upper ceiling for tCDR potential would be lowered by up to 20% if the conversion of natural vegetation for the sake of tCDR would not make sure that half of the natural-vegetation carbon would be permanently sequestered. Alternatively, converting all cropland and pastures into tCDR area (100AGR) while safeguarding natural ecosystems, would imply that all land-based food and fiber production was abandoned. The implications still remain severe if only a quarter of natural or agricultural land is taken for BPs, thereby stretching 2100's carbon budget by 56–74 years (Figures 2e and 2b). Additionally, simply allowing re-growth of natural vegetation on the same areas as in 25AGR (25ARG_nv, Figure 2e) would reduce potentials by >40% compared to BPs with 454 GtC permanent carbon extraction by 2100.

These tCDR potentials could be increased by 10–15% if BPs were implemented earlier under the same climate conditions, e.g., when the 1.5°C warming line was reached around 2038 [*Boysen et al.*, 2016]. However, starting BPs mid-century when CO$_2$ levels and additional fertilization are higher, as in the unabated climate scenario, can also be beneficial for BPs leading to similar tCDR potentials as in *Boysen et al.* [2016] (see supporting information [*Leipprand and Gerten*, 2006; *Luo et al.*, 2008] and Figure S2). For example, the 100AGR
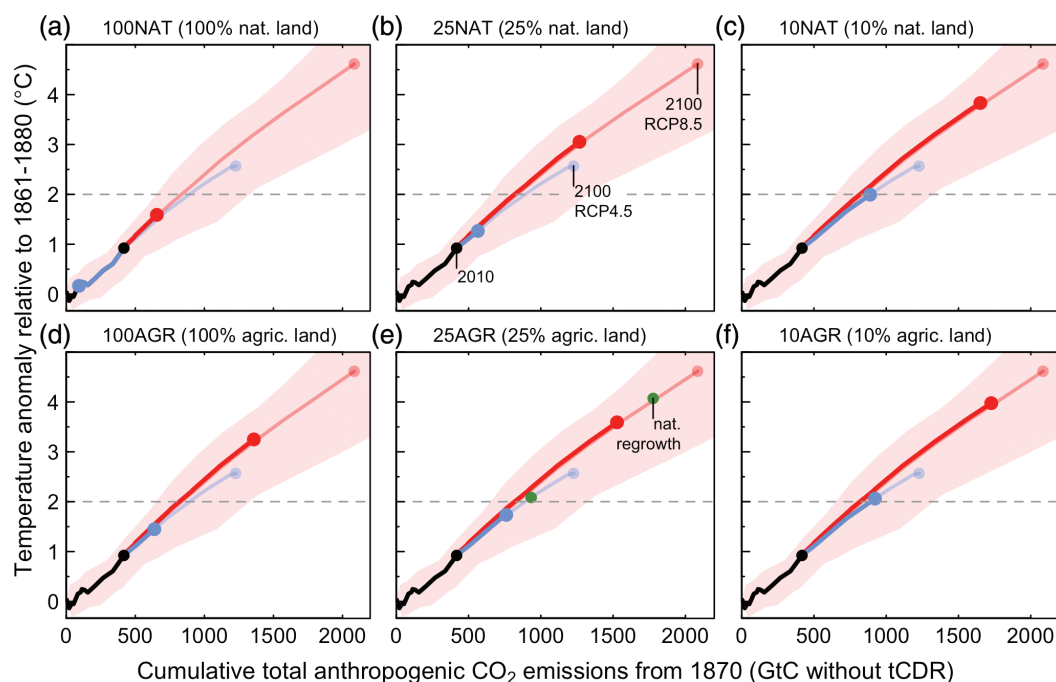
Figure 2. Potentials of terrestrial carbon dioxide removal (tCDR) along the Representative Concentration Pathway 4.5 (RCP4.5) and RCP8.5 trajectories for different biomass plantations scenarios implemented by mid-century: Bright and dark lines indicate the end of trajectory without and with tCDR in 2100. The difference between RCP's endpoint and the modified trajectory's endpoint refers to the tCDR potential in GtC or years saved. (a–c) Results for converting 100%, 25%, and 10% of the most productive grid cells on natural land; (d–f) results for converting 100%, 25%, and 10% of the most productive grid cells on agricultural land to BPs. A conversion efficiency of 50% is applied. Exact end-point values for each scenario are listed in Table 1. (Adapted figure SPM.10 from the IPCC AR5 Summary for Policymakers [*Stocker et al.*, 2013] with permission of WG1 TSU.)

scenario removes 649 GtC between 2038 and 2100 on a partially mitigated pathway, while the 100AGR on an unabated pathway captures 705 GtC between mid-century and 2100. However, tCDR is much less effective in postponing the pertinent carbon-budget exhaustion: The maximum achievable tCDR potential translates into a delay by 28–67 years in the 100AGR and 100NAT scenarios, respectively. The more conservative but still extensive scenarios (10AGR and 10NAT) can only provide 13–16 years of delay—on average three times less than in the partially mitigated scenario. This shows that even though the CO_2 "fertilization" effect on plant growth is about 17–20% higher on the unabated mitigated pathway, strong emissions abatement efforts are necessary as well as carbon extraction technologies such as tCDR. Staying on the unabated pathway would mean not only a failure of mitigation in the first place, but would also predetermine tCDR to fail its ultimate objective!

These results allow us to investigate the upper theoretical ceilings of tCDR following systematic land conversion scenarios by minimizing the uncertainties from the development of complex, actual land-use patterns (as done in the RCP2.6 study below). However, they also show that "realistic" tCDR potentials, following multi-dimensional optimal pathways of land transformation are likely to remain far below scenarios such as the 100%, 25%, or 10% scenarios used in this study.

3.2. Side-Effects of Large-Scale Biomass Plantations

Irrespective of the underlying emissions scenario, large-scale tCDR deployment would be associated with impacts that are likely to be ecologically intolerable and socially unacceptable (Table 1b). The land conversion towards tCDR following 25NAT implies widespread loss of habitats, thus further reducing biodiversity and modifying ecosystems which are already under pressure [*Ostberg et al.*, 2015] and face severe risks of change under anthropogenic global warming [*Ostberg et al.*, 2013; *Warszawski et al.*, 2014]. The global forest extent, currently estimated to consist of 62% natural sub-systems [*Steffen et al.*, 2015], would be halved in this tCDR scenario. When converting "only" 10% of natural land, still almost 1.4 Gha of habitats would be lost or degraded—an area corresponding to half of today's pasture extent.

From calculating the nitrogen content in the globally harvested biomass under unabated conditions, we find that this harvesting would extract 96–151 TgN yr^{-1} on 10–25% of the agricultural area (in addition to the demand on the remaining cropland). This is of a magnitude comparable to today's worldwide nitrogen demand of 147 TgN yr^{-1} in 2014 [*Food & Agriculture Organization of United Nations*, 2015; *Steffen et al.*, 2015], which already has led to transgression of the suggested planetary boundary for nitrogen by a factor of two [*Steffen et al.*, 2015; *Food and Agricultural Organisation United Nations*, .]. As another consequence, substantial extra amounts of non-CO_2 greenhouse gases would be released into the atmosphere after fertilizer application or during the process of fertilizer generation. Thus, our simulated tCDR potentials may be overestimated since we neither account for nutrient limitation of plant growth (nitrogen and phosphorus), nor for the emissions associated with producing and applying fertilizers.

Agricultural calorie production on cropland would be reduced by 43–73% when converting the most suitable 10–25% of cropland for the purpose of tCDR. In view of a world inhabited by at least 9 billion people in 2050, it is unlikely that such deficits could be overcome by sheer management intensification or improvement [*Bajželj et al.*, 2014]. Transforming merely all pastures (i.e., keeping all cropland while eliminating the entire production of meat and dairy products, 100AGR_p) would not result in substantial climate benefits: While pastures are more extensive than croplands, they are also less productive for BP plantations.

Further impacts could arise from generating biogeophysical and biogeochemical effects through the land conversion towards large-scale BPs [*Pongratz et al.*, 2011; *Arora and Montenegro*, 2011; *Brovkin et al.*, 2013]. These effects could include reductions in surface albedo and alterations of moisture fluxes [see Text S1 and *Boysen et al.*, 2016] or additional greenhouse gas emissions from fertilizer applications. Evidently, fully coupled simulations are needed to assess these climate feedbacks (including changing atmospheric CO_2 concentrations and ocean responses [*Zickfeld et al.*, 2013; *Tokarska and Zickfeld*, 2015], something that currently cannot be accomplished because most Earth system models still lack a process-based implementation of BPs in the way LPJmL does.

3.3. Carbon Sequestration Potentials of tCDR in a Transient Mitigation Scenario (RCP2.6)

Harvested biomass carbon on 441 Mha BPs accumulates on climate-model average 152, 325, and 449 GtC under rain-fed, sustainable, and unlimited irrigation conditions, respectively (Table S2). While these results are uniform across the models, the same is not true for land-carbon changes after the conversion of original land cover to BPs, i.e., the resulting tCDR potential by 2100 varies strongly (Table 2). Applying a conversion efficiency of 50% (as before) delivers for instance ranges of 10–64 GtC (mean 57 GtC) net carbon sequestration for non-irrigated BPs (Figure 3a). The reason is that the prescribed climate forcing retrieved from each single climate model might cause unfavorable growing conditions for BPs in some cases. If CEff was not increased, unlimited irrigation would be necessary to achieve the required tCDR potential of 160–190 GtC in 2100. An increase of CEff to 75% in combination with sustainable irrigation on selected areas (40 Mha)

Table 2. Potential tCDR (GtC) Under the Transient RCP2.6 Scenario

	Rain-Fed			Sustainable Irrigation			Unlimited Irrigation		
	50%	75%	90%	50%	75%	90%	50%	75%	90%
MPI	57	94	117	141	222	270	208	320	387
Had	16	54	76	103	184	233	172	286	354
MIR	15	54	78	103	187	237	168	282	350
Can	10	49	72	97	180	229	164	277	345
IPSL	64	103	126	150	232	282	215	327	394
Mean	57	94	117	141	222	270	208	320	387

BPs, biomass-producing plantations; Can, CanESM2; CEff, conversion-efficiency; Had, HadGEM2-ES; IPSL, IPSL-CM5A-MR; MIR, MIROC-MR-CHEM; MPI, MPI-ESM-MR; RCP2.6, Representative Concentration Pathway 2.6; tCDR, terrestrial carbon dioxide removal.
Given are the net carbon sequestration potentials (that is, land-carbon changes are accounted for) for rain-fed (no irrigation), sustainably and unlimited irrigated BPs in combination with different levels of conversion efficiencies (CEff in %). Results were calculated by LPJmL driven by five climate model inputs.
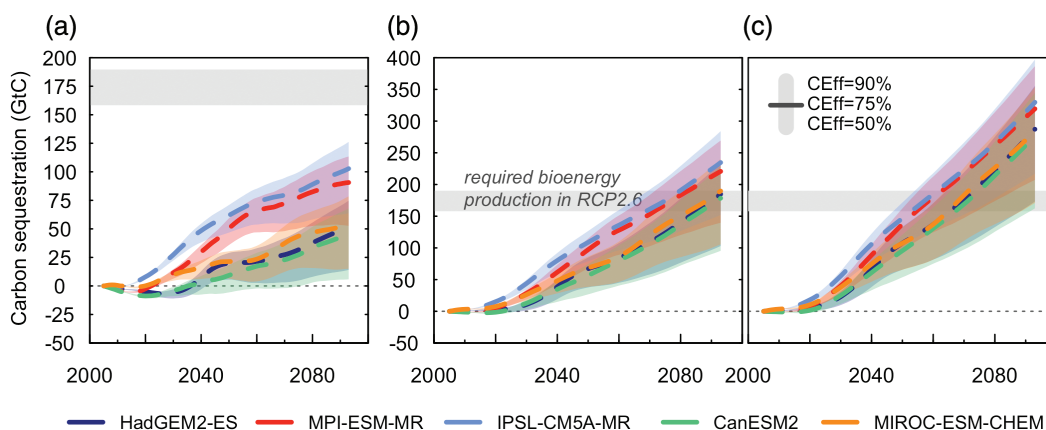
Figure 3. Terrestrial carbon dioxide removal (tCDR) potentials (GtC) for rain-fed (a), sustainably (b) and unrestrictedly irrigated (c) biomass-producing plantations in combination with conversion efficiencies (CEff) of 50%, 75%, and 90% (shading) and for different climate models input for LPJmL (colors). The gray horizontal bar denotes the required tCDR of Representative Concentration Pathway 2.6 of 160–190 GtC.

could produce the desired tCDR outcome though. However, such an increase in the sustainably irrigated area would in turn put substantial pressure on global water use. In fact, the water consumption on dedicated BP land would increase the total water consumption on agricultural land [∼1,000 km^3 yr^{-1} in 2090–2100] by 13% on model average (see Table S3, comparable to *Heck et al.*, 2016). This would strongly increase by a factor of 20 (up to 2,500 km^3 yr^{-1}) if all BPs were equipped with unlimited water supply.

Remarkably, increasing CEff to 90% without any irrigation would still not be sufficient to get close to the desired tCDR amount. This means that very strong efforts regarding water (and fertilizer) management, infrastructure, and technical development would be globally necessary to fulfill the promises of this widely used scenario for successful mitigation. Our result agrees with a previous study claiming that highly productive BPs, supported by heavy irrigation and fertilization, would be needed in the RCP2.6 narrative [*Kato and Yamagata*, 2014]. The implications would again include biogeophysical and biogeochemical effects, which were not considered in the land-selection process of the underlying IAM, while food production would need to increase by ∼20% until 2050 compared to 2005 levels in our model. Thus, tCDR potentials on the RCP2.6 pathway are found to be smaller than anticipated. This finding reveals significant trade-offs when trying to reach the total tCDR volume necessary for holding the 2°C line — even more so, as that scenario was meant to "start" about one decade ago! Hence, assumptions made by IAMs need to be carefully assessed regarding the true abilities of the biosphere, which are independent of any socio-economic considerations.

4. Conclusions

Based on our detailed simulation results, we maintain that tCDR is not an effective tool to balance emissions from unmitigated or only partially mitigated scenarios, regardless of spatial scales, timing, and background mitigation pathways. In particular, substantial *post-factum* carbon removal on an unabated emission pathway would require utilizing a major fraction of the global land surface (natural or agricultural areas), with intolerably large environmental and social costs. Under a partially mitigated climate scenario, the utilization of tCDR from mid-century on would be much more effective. However, the spatial scale of BPs would still need to be very large and might cause comparable environmental costs. An earlier start of tCDR activities on an ambitious mitigation pathway would definitely increase tCDR potentials, although BPs would be less productive due to lower CO$_2$ concentrations. Even in the strong mitigation scenario (RCP2.6), high inputs of managed water and fertilizers would be needed in order to avoid fierce competition for land — with potentially negative side-effects for climate and society.

This leaves us with a rather clear, but hardly comforting overall conclusion: Holding the 2°C line seems only feasible if two sets of climate action work hand in hand. On the one hand, greenhouse gas emissions need to be reduced as early and as effectively as possible [*Luderer et al.*, 2016; *Smith et al.*, 2016]. In fact, an even more aggressive strategy than reflected by the RCP2.6 scenario should be pursued, aiming at the "induced implosion" of most fossil fuel-driven business cases in the next couple of decades [*Rockström et al.*, 2016;

Schellnhuber et al., 2016]. On the other hand, tCDR can significantly contribute as a "supporting actor" of the mitigation protagonist, if it gets started and deployed immediately. This means that the biological extraction of atmospheric CO_2 as well as the suppression of CO_2 release from biological systems must draw upon all possible measures—whether they are optimal or not, whether they are high- or low-tech. We therefore suggest fully exploring the pertinent options available now [*Rockström et al.*, 2017a], which include reforestation of degraded land [*Lamb et al.*, 2005; *Chazdon*, 2008; *Reij and Winterbottom*, 2015; *Morrison*, 2016] and the protection of degraded forests to allow them to recover naturally and increase their carbon storage, e.g., within the Bonn Challenge initiative (http://www.bonnchallenge.org/) or the New York Declaration on Forests [*International Union for Conservation of Nature (IUCN) (n.d.) Streck et al.*, 2016]. Further options range from up-scaled agro-forestry approaches [*Faße et al.*, 2014; *Lasco et al.*, 2014; *Zomer et al.*, 2016] to the application of biochar [*Woolf et al.*, 2010; *Crombie et al.*, 2015; *Smith*, 2016] and various no-tillage practices for food production on appropriate soils [*Lal et al.*, 2012; *Davin et al.*, 2014; *Mangalassery et al.*, 2014; *Rockström et al.*, 2017b]. Also, it becomes overwhelmingly evident that humanity cannot anymore afford to waste up to 50% of its agricultural harvest along various consumption chains [*Smith et al.*, 2013; *Hiç et al.*, 2016] or to go on operating ineffective irrigation systems [*Jägermeyr et al.*, 2015].

So the bottom line is: Do not wait for first-best solutions, neither in emissions reductions action nor in tCDR practice!

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