Environmental Research Letters

LETTER • **OPEN ACCESS**

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To cite this article: Helene Muri 2018 *Environ. Res. Lett.* **13** 044010

IOP Publishing *Environ. Res. Lett.* **13** (2018) 044010 https://doi.org/10.1088/1748-9326/aab324

Environmental Research Letters

OPEN ACCESS

RECEIVED
30 October 2017

REVISED
27 February 2018

ACCEPTED FOR PUBLICATION
1 March 2018

PUBLISHED
26 March 2018

LETTER

The role of large–scale BECCS in the pursuit of the 1.5°C target: an Earth system model perspective

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Keywords: BECCS, 1.5°C target, Earth system modelling, carbon cycle

Supplementary material for this article is available online

Abstract

The increasing awareness of the many damaging aspects of climate change has prompted research into ways of reducing and reversing the anthropogenic increase in carbon concentrations in the atmosphere. Most emission scenarios stabilizing climate at low levels, such as the 1.5 °C target as outlined by the Paris Agreement, require large-scale deployment of Bio-Energy with Carbon Capture and Storage (BECCS). Here, the potential of large-scale BECCS deployment in contributing towards the 1.5 °C global warming target is evaluated using an Earth system model, as well as associated climate responses and carbon cycle feedbacks. The geographical location of the bioenergy feedstock is shown to be key to the success of such measures in the context of temperature targets. Although net negative emissions were reached sooner, by ~6 years, and scaled up, land use change emissions and reductions in forest carbon sinks outweigh these effects in one scenario. Re-cultivating mid-latitudes was found to be beneficial, on the other hand, contributing in the right direction towards the 1.5 °C target, only by −0.1 °C and −54 Gt C in avoided emissions, however. Obstacles remain related to competition for land from nature preservation and food security, as well as the technological availability of CCS.

1. Introduction

The temperature targets of the Paris Agreement are associated with small and rapidly declining carbon budgets (Millar *et al* 2017, Rogelj *et al* 2015), and indicates a need for carbon dioxide removal (CDR) to compensate from lack of mitigation commitments by nations, cf current National Determined Contributions (NDCs) (Minx *et al* 2017). Of the 400 Intergovernmental Panel on Climate Change (IPCC) climate scenarios that have a 50% or better chance of less than 2 °C warming, 344 assume the successful and large-scale uptake of negative emission technologies such as Bio-Energy with Carbon Capture and Storage (BECCS). The 56 scenarios that do not include negative emissions technologies are deemed unrealistic, as the global emissions peak in around year 2010, which is not supported by available emission data (Anderson 2015). Hence negative emissions technologies like BECCS seem necessary in order to reach 2 °C, and more certainly for 1.5 °C. BECCS involves growing biofuel crops that absorb CO_2 from the atmosphere through photosynthesis and the biomass can be burned in a power plant or converted in another form of energy, producing e.g. electricity. Any CO_2 produced by such biomass conversion is subsequently captured and sequestered for long-term purposes in geological reservoirs (e.g. Smith *et al* 2016, Kemper 2015). The process hence results in net negative emissions and is considered a form of CDR (Shepherd *et al* 2009). For the purpose of BECCS, managed woody and herbaceous bioenergy agricultural estates could be regularly harvested and with coupling to storage of the extracted carbon in geological reservoirs (Lenton 2010, Fuss *et al* 2014).

There are uncertainties around the size of the carbon budget compatible with a warming of 1.5 °C. Rogelj *et al* (2015) found that scenarios corresponding to a 1.5 °C warming have an atmospheric CO_2e concentration of 420–440 ppmv by the end of the century. These scenarios have accumulated carbon emissions over 2011–2100 of 200–415 $GtCO_2$, with an active net removal of CO_2 during the second half of the century, whilst IPCC found 90–310 $GtCO_2$ accumulated emissions permissible for a 1.5 °C warming (Edenhofer *et al* 2014). Millar *et al* (2017) report a somewhat more optimistic cumulative post-2015 carbon budget of 250–540 GtC (or 918–1982 $GtCO_2$). Nonetheless, considering current emission rates of about 9.9 Gt yr^{-1} (Le Quéré *et al* 2016), allowable budgets are running out fast. Notably, all scenarios aligning with the most ambitious temperature target depend on BECCS, primarily, as the negative emissions driver.

Land availability for biofeedstock is limited by the competition from food production, nature conservation and furthermore, with regards to climate change mitigation, avoiding potentially unfavourable surface albedo reductions. BECCS competition with food security and local livelihoods are all context-dependent, and the specific negative effects depend on the project, location, land use history, and societal needs (Smith and Torn 2013). Anthropogenic land use change can have large impacts on the climate not only through changes to the carbon cycle (Canadell *et al* 2007, Bonan 2008), but also changes in biogeophysical processes and alterations to surface energy and moisture fluxes (Betts 2001, Bala *et al* 2007, Lawrence and Chase 2010). Fertilizer use in growing biocrop cultivation is another concern that should be taken into account when considering the total impacts of BECCS. Nitrous oxide is a bi-product of nitrogen fertilizer use, with a global warming effect of 296 times that of CO_2 (Crutzen *et al* 2008). Popp *et al* (2014) and Kato and Yamagata (2014) estimate emissions from fertilizing biocrops to be of 3–24 $GtCO_2$-equivalent and 5.1 Pg C-equivalent (18.7 $GtCO_2$-equivalent), respectively, during the 21st century for ~2 °C global warming scenarios. Fertilizer availability may prove to become a constraint, as well as water scarcity. Biocrop production requires energy inputs for machinery used for soil preparation and seed sowing, cultivation, irrigation infrastructure, harvest, and transportation to the processing plant (Qin *et al* 2006). Fertilizer, pesticides, and herbicides may result in additional carbon costs through its manufacture, transportation and application procedure. Furthermore, energy inputs in the conversion, capture, and storage processes increase the resources required reducing the net negative potential of BECCS (Rhodes and Keith 2005, Qin *et al* 2006). Current biodiversity losses are tied to land use changes (MEA 2005). BECCS could hence be a threat to biodiversity, depending on deployment scale, native ecosystem type, land use history, biocrop specie, and spatial distribution of habitats. Primary forests tend to have higher plant and animal diversity than secondary or plantation forest (Zurita *et al* 2006, Barlow *et al* 2007). Restored grasslands or forests often have lower biodiversity than nearby native ecosystems (Camill *et al* 2004). Such factors need to be taken into account in the total evaluation of approaches to limit climate change.

Boysen *et al* (2017) used a global vegetation model to assess the climate effects of different land use scenarios, prioritizing either food production, nature conservation or terrestrial CDR, not coupled to CCS. It was found that the most effective terrestrial CDR pathway would be to change dietary habits or re-cultivation of abandoned and marginal land. The land use and land cover change impacts on climate in RCP2.6 (representative concentration pathway) in the CMIP5 (Coupled Model Intercomparison Project phase 5) ensemble were assessed by Brovkin *et al* (2013). It was found that biogeophysical effects were not significant on the global scale, though with some regional effects where the land use change exceeded 10%. Cai *et al* (2016) used a regional model centred over North America to assess land use change impacts of biocrops. They found that, through non-linear albedo effects and radiative processes, there was a spatially heterogeneous response to land conversions to the same biocrop. The results are suggestive of highly variable albedo effects from land use change depending on geographical locations and native vegetation. BECCS has furthermore been much discussed as a policy option in the integrated assessment modelling (IAM) literature (e.g. Fuss *et al* 2014, Azar *et al* 2013, Smith *et al* 2016, Klein *et al* 2014, Tavoni *et al* 2017). Vaughan and Gough (2016) found, however, that assumptions concerning the availability of BECCS in future IAM scenarios are too optimistic according to expert judgment, and this could indeed lead to overshoot of temperature targets with a substantial bearing on near-term mitigation options. With this, a closer evaluation of BECCS seems necessary, as also pointed out by Anderson (2015).

There is a lack of Earth system modelling assessment of this approach. To get a more complete picture of the climatic effects of BECCS, fully coupled models are needed, accounting for carbon cycling and biogeochemical cycles. Here, this gap in the literature is abridged with an innovative approach to implementing interactive BECCS code in a state-of-the-art Earth system model. Improving our understanding the relationship between land use for BECCS along with trade-offs and side effects for the climate and environment is essential in determining the potential of such mitigation pathways. This paper assesses the potential of BECCS deployment in contributing towards the ambitious 1.5 °C target by the use of Earth system model simulations, in the first ESM study with interactive CCS, as described in section 2.2. The climate response to two different large-scale BECCS deployment scenarios is evaluated and the carbon cycle—climate feedbacks are assessed. The supply side of bioenergy feedstock is considered, including the climatic drivers, as well as the negative emissions potential from the two different deployment scenarios, also accounting for the net effects by including for carbon lost by change in land use. This paper describes the model and method, including the CCS approach, in section 2, and the results are presented in section 3, with the investigation of the temperature response, in particular, to the land use change and the CCS coupling, before conclusions are drawn in section 4.

2. Model and method

2.1. The Norwegian Earth System Model

The Norwegian Earth System Model with interactive carbon cycle and fully coupled biogeochemistry (NorESM1-ME) is used (Tjiputra *et al* 2013) and run in emission drive mode. This model contributed to CMIP5 and the AR5 (5th Assessment Report) of the IPCC. The horizontal resolution is of 1.9° latitude × 2.5° longitude both for the atmospheric and land modules. The atmosphere model is CAM4-Oslo (Bentsen *et al* 2012), the ocean model is MICOM, coupled to the HAMMOCC ocean carbon cycle module, and CICE4 is the sea ice component.

The land model, Community Land Model version 4 (CLM4) (Lawrence *et al* 2012a, 2012b), includes ecosystem cycling and the land surface is represented in a sub-grid cell hierarchy of multiple land units, columns, and plant functional types (PFTs). The land unit describes the large-scale shapes of the landscape including vegetated areas, wetlands, lakes, glaciers, and urban spaces. The potential variability in the soil and snow state variables within a land unit is represented at the column level. The PFT level declares exchanges between the land surface and atmosphere. Furthermore, vegetation state variables and treatment of bare ground are computed at the PFT level. Soil are represented down to 50 m, with the upper 3.8 m being hydrologically active (top 10 levels), whilst five bedrock layers below 3.8 m act as thermal reservoirs. The carbon-nitrogen cycle model represents the biogeochemistry of carbon and nitrogen in vegetation, litter and soil-organic matter (Thornton *et al* 2007). The assimilated carbon is estimated from photosynthesis. The nitrogen availability for plants comes from nitrogen uptake in soils and retranslocation from senescing plant tissues, and affects the gross primary production (GPP). The vegetated land unit is divided into a mosaic of PFTs (Oleson *et al* 2010). Land use transitions are based on four classes of primary vegetation (undisturbed natural vegetation), secondary vegetation (regrowth vegetation following human disturbance, or a period of alternative land use), crop, and pasture (Hurtt *et al* 2011). The spatial distribution of PFTs is prescribed annually.

2.2. Experiment design

The land cover change scenarios of CMIP5 include details on the land cover transformations and wood harvest based on natural land cover distributions, anthropogenic land cover and land use conversions, and account for the carbon releases associated with such changes. The data provides historical land cover and wood harvest changes on an annual basis from 1850–2005 (Hurtt *et al* 2006, 2011), as well as future representative concentration pathways from 2006–2100 (van Vuuren *et al* 2011). The *RCP2.6* scenario is used as baseline in this study. *RCP2.6* is chosen as the background scenario out of the CMIP scenarios available for use in Earth system models, as it is deemed the scenario most in line to reach the Paris Agreement target of 1.5 °C. It would be even more challenging to reach such a target with extra BECCS alone in the higher GHG emissions scenarios; *RCP4.5*, *RCP6* and *RCP8.5*. *RCP2.6* already contains some level of deployment of BECCS, at levels for net fossil fuel emissions to become negative towards the end of the century (figure 2(*b*)). *RCP2.6* has a decrease in forested areas and a substantial increase in crops. This is accompanied by a small decrease in pasture, and the use of some crop areas for biofuels, scaled up to around 0.5 Gha in year 2100–∼one quarter of the area used for food crops (van Vuuren *et al* 2011). The main drivers of the RCP2.6 scenario emissions include improvement of energy efficiency, replacement of fossil fuel use by combined fossil fuel use with CCS, nuclear and renewable energy, in addition to BECCS, as already mentioned (van Vuuren *et al* 2007, 2011). BECCS in the standard RCP2.6 CMIP5 scenario uses input data as prepared for the MIP, based on output from integrated assessment model IMAGE, including land properties and emissions accounting for the deployment of BECCS.

Two different land use change scenarios were implemented in the model on the background of the *RCP2.6* scenario. In these land use scenarios, increasing areas are used for biofuel harvest expansion start in year 2020 of *RCP2.6,* increasing until year 2100. In the first scenario, *Aban*, cropland that becomes abandoned, and marginal land is here used for increased harvesting for BECCS (figure 1(*a*)) (Thomson *et al* 2010, 2011). This means a gradual expansion into areas previously used for agriculture mostly, and since abandoned. This includes in particular land areas across Eurasia, mid-latitudinal North America, Central America, and southern Brazil, covering ∼4% of the non-glaciated land surface by year 2100. In a second BECCS deployment scenario, *Defor*, (figure 1(*b*)), fertilized croplands are taking over from woodlands (A2r case in Riahi *et al* 2007, 2011). This is largely in tropical and extratropical areas, including Africa, east Australia and South America, covering ∼5% of the non-glaciated land surface by 2100. Land that was cleared for grazing and agriculture for food in scenario A2r in Riahi *et al* (2007) is here instead assumed cleared for the purpose of bioenergy (figure 1(*b*)). These areas of additional biofeedstock are added to the land already dedicated to BECCS in the RCP2.6 land use scenario. In this way the new land use scenarios with increasing areas of biofeedstock were developed to assess the potential for

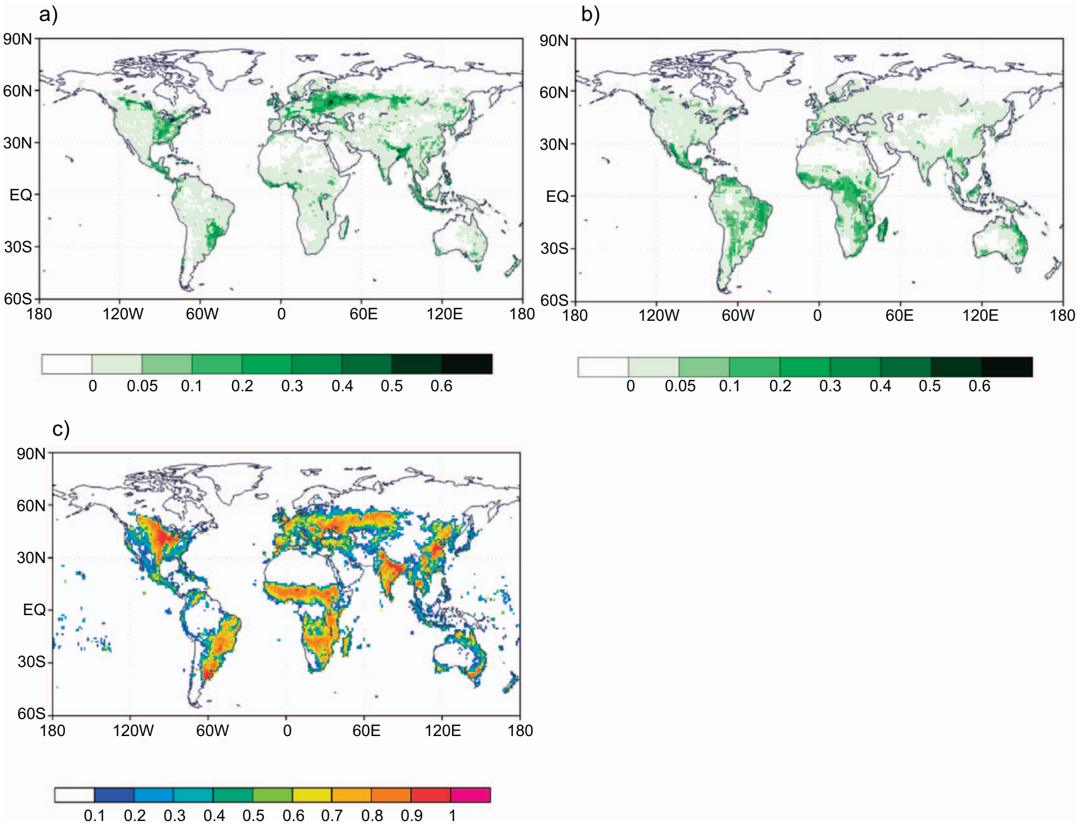

Figure 1. The fractional gridbox cover increase in bioenergy feedstock in year 2100 compared to year 2005 in (*a*) the *Aban* and *AbanCCS* scenarios, and (*b*) the *Defor* and *DeforCCS* scenarios. (*c*) The fractional grid box cover of crop and pasture areas reserved for food production in year 2005, which was kept constant throughout the BECCS simulations.

Table 1. Description of the scenarios used in this study.

Scenario	Description
Pre-industrial	Pre-industrial CMIP5 simulation.
RCP2.6	Emission driven CMIP5 RCP2.6.
Aban	As RCP2.6, but land-use changed to re-cultivate abandoned and marginal land over years 2020–2100.
AbanCCS	As *Aban*, coupled to interactive CCS code.
Defor	As *RCP2.6*, but with land use change deforesting tropics and extra-tropics in favour of biocrops over years 2020–2100.
DeforCCS	As *Defor*, coupled to interactive CCS code.

negative emissions. And these two different land-use scenarios were coupled to CCS in one set of simulations (*AbanCCS* and *DeforCCS*), whilst they were also run without CCS to assess the land—use change feedbacks on climate. With the inclusion of an interactive carbon cycle, carbon emissions from land use change are taken into account and calculated prognostically. See table 1 for an overview of simulations.

BECCS in RCP2.6 in Earth system models in CMIP5 is done in an implicit manner and is prescribed by the input data from IAMs. This includes prescription of properties within the land model; such as plant functional types and associate biogeophysical properties, with the corresponding changes in the terrestrial carbon uptake due to the use of BECCS. In addition, the fossil fuel emissions from industry and transport changes with the use of BECCS. Hence, through the use of the fossil fuel emission profile developed by the IAMs, with the associated changes to the land model, BECCS can be simulated by the ESMs. Though this is not done in the interactive way presented in this paper; the *AbanCCS* and *DeforCCS* cases. These two cases have some implicit BECCS as per the CMIP5 method, with additional explicit BECCS, as developed here and described above.

With regards to agricultural land available for food production and grazing, this was preserved at the same level throughout the *Aban, AbanCCS, Defor* and *DeforCCS* scenarios (figure 1(*c*)) and kept at the observed 2005 levels (FAO 2005), which amounts to about 30% of the global land area. PFTs C3 non-Arctic grass, C4 grass and C3 crops were used for this purpose. Agricultural intensification and optimization of current agricultural practices on given land, as well as a reduction in meat consumption, is hence implied, given the population increase to 9 billion by the end of the century in the *RCP2.6* baseline scenario. An increase in agricultural intensity has been observed over the past few decades, a trend which is expected to continue to increase (Rudel *et al* 2009).

The carbon removal capacity of the biocrops was calculated as following: the net primary production (NPP) in the areas used for bio-harvest is used,

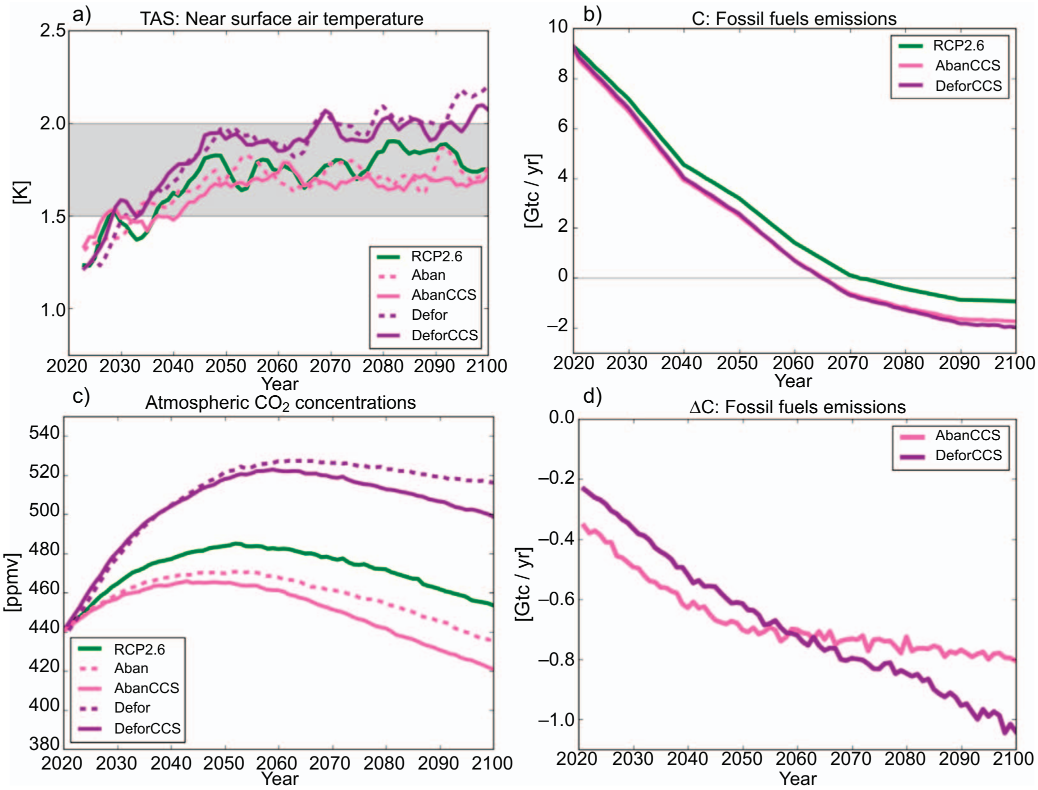

Figure 2. (*a*) Global four-year running mean near surface air temperature difference from the pre-industrial simulation. The grey shading indicates the 1.5 and 2 °C temperature targets of the Paris Agreement. (*b*) Fossil fuel and cement emissions in the three scenarios. (*c*) Atmospheric CO_2 concentrations. (*d*) The difference in carbon emissions from *RCP2.6* (GtC yr^{-1}). Green solid line: *RCP2.6*, pink solid: *AbanCCS*, pink dashed: *Aban*, purple solid: *DeforCCS*, and purple dashed line: *Defor*.

with the assumption of a harvesting efficiency of 48%, following Haberl *et al* (2007), considering not all of the NPP can be completely harvested. This estimate is on the conservative side and one could assume that this efficiency would increase with time. Furthermore, the value is representative of the global mean, and regional variation might be expected, though not taken into account here. A CCS efficiency of 85% was assumed in the biofuel production phase, following Sanchez *et al* (2015) and IPCC (2005). This is at the low end of the range cited in IPCC (2005). Considering industrial—scale BECCS is not yet in place, these estimates must be considered to be uncertain. If less conservative efficiencies were used in this study, with improved negative emissions potential, atmospheric CO_2 concentrations could possibly go down faster though there might be compensating feedbacks from reduced carbon fertilization of the vegetation. The harvesting of the biocrops and implicit production of biofuels then result in a reduction in fossil fuel emissions the following year after harvest (figure 2(*b*)), as it is assumed that fossil fuel consumption is replaced, based on the new availability of biofuels. The CCS code runs interactively with the model in its emission driven mode. There is no actual geological carbon storage in the model and we are hence assuming this part of the technology works, as well as infrastructure being in place. The effectiveness of the BECCS rollout is dependent on further factors that are accounted for in the model, including any soil—and vegetation carbon losses when converting forest into cropland, biogeophysical changes such as albedo and roughness length, as well as any impacts on large-scale sinks and the oceanic biogeochemical cycle.

3. Results

RCP2.6 gives a temperature change of 1.79 °C during the last decade of this century compared to the pre-industrial simulation (figure 2(*a*)), i.e. 0.29 °C off the most ambitious goal of the Paris Agreement (UNFCCC 2015). *RCP2.6* exceeds 1.5 °C for the first time in the late 2020s and is consistently above from year 2035 onwards. The 1.5 °C target is exceeded by 0.26 °C on average over 2035–2100 in *RCP2.6* (table 2). Increasing the biofuel harvesting and coupling to CCS in the *AbanCCS* case, lowers the temperatures closer to the 1.5 °C target, and remains on average 0.17 °C above 1.5 °C over the 2035–2100 period when *RCP2.6* is overshooting this target. *Aban is* 0.21 °C above 1.5 °C during this time. The CCS hence enhances the cooling by 0.02 °C. For the *Defor* scenario, a warming is seen compared to the *RCP2.6* scenario, both with and without the CCS coupling. *DeforCCS* is 0.43 °C above the 1.5 °C target during the 2035–2100 period, and even

Table 2. Global annual means of key variables. ΔTas: temperature difference from RCP2.6 over years 2035–2100. ΔTas—1.5 °C: temperature difference from the 1.5 °C target over years 2035–2100. ΔPr: global mean precipitation rate difference from *RCP2.6* (2020–2100) (mm yr^{-1}). CO_2 peak: maximum atmospheric CO_2 concentrations (ppmv). ΔQVEGT: canopy transpiration difference from *RCP2.6* (2020–2100) (mm yr^{-1}). ΔTOTVEGC: total vegetation C difference from *RCP2.6* (PgC). ΔSoil C Loss difference from *RCP2.6* (PgC yr^{-1}) (2020–2100). ΔAR: autotrophic respiration difference from *RCP2.6* (PgC yr^{-1}) (2020–2100). ΔNEP: net ecosystem production difference from *RCP2.6*, excl. fire flux; positive for sink (PgC yr^{-1}) (2020–2100). ΔGPP: gross primary production difference from *RCP2.6* (PgC yr^{-1}) (2020–2100).

	RCP2.6	*AbanCCS*	*Aban*	*DeforCCS*	*Defor*
ΔTas	–	−0.095	−0.047	0.167	0.201
ΔTas—1.5 °C	0.26	0.17	0.21	0.43	0.46
ΔPr	–	0.703	0.988	5.711	6.856
CO_2 peak	485	465	470	523	527
ΔQVEGT	–	2.057	1.642	−4.360	−4.934
ΔTOTVEGC	–	37.82	37.51	−127.24	−126.41
ΔSoil C Loss	–	−0.412	−0.396	0.317	0.368
ΔAR	–	−0.743	−0.317	0.422	0.670
ΔNEP	–	0.764	0.811	1.026	1.038
ΔGPP	–	−0.732	−0.227	1.799	2.156

exceeds 2 °C during the last five years of this century. *Defor* overshoots the 2 °C target several years during the last part of the century. The temperature change from the land use change is larger than the CCS cooling effect in both land use change scenarios, which is linked to the carbon cycle, as discussed below.

The emissions from fossil fuels and industry become net negative 6 years earlier than *RCP2.6* in the two large-scale BECCS scenarios; year 2066 compared to 2072 (figure 2(*b*)). *AbanCCS* increases the net negative emissions by −0.81 Gt C yr^{-1} by the end of this century, whilst *DeforCCS* furthers this to −1.04 Gt C per year (figure 2). Despite the larger net negative emissions, a larger fraction of CO_2 remains in the atmosphere from the land use change emissions, and the reduction in carbon sink from loss of tropical forest in particular, in the *DeforCCS* scenario. The atmospheric CO_2 concentrations peak at 485 ppmv in *RCP2.6*, 465 ppmv in *AbanCCS*, and 523 ppmv in *DeforCCS* (figure 2(*c*), and table 2), i.e. above the 1.5 °C scenarios of Rogelj *et al* (2015). These changes to the carbon cycle indicate that the geographical location of the bioenergy feedstock is key to the success of such measures in the context of climate targets. Though net negative emissions can be reached sooner and scaled up, the land use change emissions firstly and reductions in forest carbon sinks secondly may outweigh these effects. The coupling to CCS reduces the CO_2 fertilization effect. The accumulated carbon emissions from fossil fuels and industry in *RCP2.6* is of 197.5 GtC over years 2020–2100. 53.8 and 54.6 GtC of these anthropogenic emissions are avoided in the *AbanCCS* and *DeforCCS* scenarios, respectively, not accounting for land use change emissions. Emissions from land use change and changes to carbon sinks amount to −39.0 GtC in the *Aban* scenario and 130.6 Gt C in *Defor*. The reduction in atmospheric CO_2 concentration in *Aban* is from a higher uptake by vegetation, with a lesser amount being taken up by soils (table 2, figures S1 and S2 available at stacks.iop.org/ERL/13/044010/mmedia).

As the biogeochemical effects in the *Aban* scenario lead to reductions in atmospheric CO_2 concentrations, this is indeed accompanied by cooling. The biogeophysical effects, however, can be a cooling or a warming. The spatial pattern of annual mean temperature differences from *RCP2.6* over the years when RCP2.6 overshoots the 1.5 °C target, i.e. from 2035 onwards (figure 3) are cooler over land, with −0.5 to −1 °C over Eurasia, and parts of the ocean in the *Aban* scenario (figure 3(*a*)). Any regions with a warming, e.g. North American land, are mostly not statistically significant as per Student's *t*-test. The biogeochemical effects of the land use change are hence largely dominating. This has previously been found by Pongratz *et al* (2010). Coupling to CCS (figure 3(*c*)), amplifies the cooling pattern. For the *Defor* scenario (figure 3(*b*)), there is a statistically significant warming over land, peaking at 1 °C–2 °C over the North Siberian Lowlands, and Laptev Sea, across the Arctic and also a small warming over the ocean. The warming pattern exhibits typical polar amplification signs, as seen in the CMIP5 ensemble (Collins *et al* 2013). The increase in the atmospheric CO_2 concentrations from the land use change is driving this global warming. When coupling *Defor* to CCS, the warming is reduced everywhere (figure 3(*d*)). Cooling is seen over southern Brazil, which could be related to increased evapotranspiration from the vegetation changes, with intensified water cycling and precipitation rates (figure S3).

With these warmer temperatures, the precipitation rates are increased, by 5.7 and 6.9 mm yr^{-1} in *DeforCCS* and *Defor* respectively (table 2, and figure S3. Global means of further key variables can be seen in table 2). Cultivating abandoned and marginal land as per the other land use change scenario, only increases the precipitation negligibly, by less than 1 mm yr^{-1} in both *AbanCCS* and *Aban*. The warmer and wetter climate in *DeforCCS* and *Defor* increases the soil carbon losses somewhat (0.3 PgC yr^{-1}). The total vegetation carbon is reduced quite substantially in *DeforCCS* and *Defor*, from the loss of forest in particular, as also relected in the reductions in canopy transpiration (table S1). The losses are of −126 and −127 PgC in *DeforCCS* and *Defor*, respectively (table 2). On the other hand, re-cultivating land in *Aban* and *AbanCCS* increases

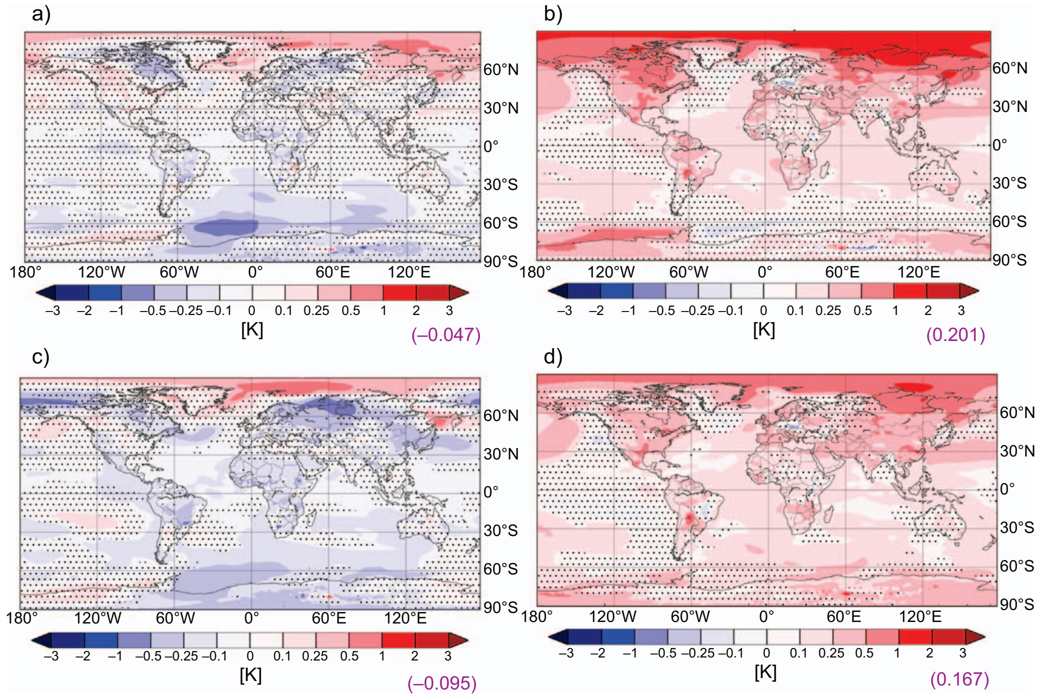

Figure 3. The annual mean temperature difference from RCP2.6 over years 2035–2100, i.e. the years when *RCP2.6* is overshooting the 1.5 °C target. (*a*) *Aban*, (*b*) *Defor*, (*c*) *AbanCCS*, and (*d*) *DeforCCS*. The global annual mean values are shown in purple. Non-stippling indicates a confidence level higher than 90% following student's *t*-test.

the total vegetation carbon by 37 PgC. At the same time, the autotropic respiration is reduced, as the climate is cooler. The global mean land albedo over land is reduced somewhat in all cases (table S1), and the small changes in downwelling shortwave radiation at the land surface (table S1) indicates that biogeophysical feedbacks play a smaller role. There are, however, some local impacts, where shortwave radiation is increased at the surface in deforested regions of around +2 Wm^{-2}, where the local water recycling and cloudiness has been reduced (not shown).

4. Discussion and conclusions

BECCS is an essential technology in the future scenarios that aim at stabilizing climate warming at low levels (Fuss *et al* 2014). The potential contribution from large-scale BECCS deployment in reaching the 1.5 °C target of the Paris Agreement was assessed using an Earth system model. In these fully coupled simulations with an interactive carbon cycle and including the effects of climate on yields, it was found that making use of mid-latitudinal land, a slight cooling was achieved of about −0.1 °C. On the other hand, replacing tropical forest with biocrops reduced the carbon sink, increased land use change emissions, and warmed the climate by +0.17 °C. The most ambitious target was hence overshot by 0.17 °C and 0.43 °C (in *AbanCCS* and *DeforCCS* respectively). A higher fraction of CO_2 remained in atmosphere in the deforestation scenarios (*Defor* and *DeforCCS*), hence what land areas are geographically prioritized to bioenergy is key to the net climate effect it will have.

Some regional cooling from the biocrops was found, but also warming, from biogeophysical feedbacks. The overall climate warming or cooling, however, is dominated by the atmospheric CO_2 concentrations—the biogeochemical effect. The atmospheric CO_2 concentrations are dependent on the net reduction in fossil fuel emissions resulting from NPP harvesting, combined with resulting emission of carbon to the atmosphere from the land use changes. The emissions became net negative 6 years earlier in the BECCS cases, with potentials of −0.81 and −1.04 GtC yr^{-1} by the end of this century, and accumulated avoided fossil fuel emissions of ~54–55 Gt C over years 2020–2100. Land use change emission and changes to carbon sinks came to −39 GtC in *Aban* scenario, and as much as +130 GtC in the *Defor* scenario. *Aban* is indicative of substantial mitigation potentials from managing land areas. *Defor*, on the other hand, results in a need for increased simultaneous efforts like mitigation to achieve the climate targets of COP21 (21st Conference of the Parties). Land use change emissions and available land areas are leading constraints and uncertainties when it comes to the net negative potentials of BECCS. Possibilities of meaningful contributions towards the climate targets are possible, if such constraints are taken into consideration.

Rosenzweig *et al* (2014) suggest that regionally, crops may be sensitive to changes in climatic conditions such as heat stress and water availability and CO_2 fertilization effects. Further studies of the climate effects of agricultural production, including biocrops, and regional crop model studies are needed to assess the viability of bioenergy plantations under future scenarios, such as those stabilizing at the Paris Agreement targets. This will help inform mitigation strategies and planning.

Deploying BECCS at a large enough scale to significantly contribute towards the 1.5 °C target within the surrounding constraints may be highly challenging. The results presented here indeed suggest that due to geophysical limitations, substantial strengthening of the NDCs are needed in 2020 to protect against dangerous climate change and the social, economic, technological and political restrictions of the unprecedented scale-up of options such as BECCS.

Acknowledgments

This work was funded by Research Council of Norway project 1.5C-BECCSy (grant no. 261862/E10). The simulations were performed on resources provided by UNINETT Sigma2—the National Infrastructure for High Performance Computing and Data Storage in Norway; accounts nn9083k, NS9083K. Thanks to Andy Wiltshire (UK Met Office Hadley Centre) for useful input and to Asbjørn Torvanger and Glen Peters (CICERO) for interesting discussions around BECCS.

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