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Constraints on biomass energy deployment in mitigation pathways: the case of water scarcity

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Abstract

To limit global warming to well below 2 ° most of the IPCC-WGIII future stringent mitigation pathways feature a massive global-scale deployment of negative emissions technologies (NETs) before the end of the century. The global-scale deployment of NETs like Biomass Energy with Carbon Capture and Storage (BECCS) can be hampered by climate constraints that are not taken into account by Integrated assessment models (IAMs) used to produce those pathways. Among the various climate constraints, water scarcity appears as a potential bottleneck for future land-based mitigation strategies and remains largely unexplored. Here, we assess climate constraints relative to water scarcity in response to the global deployment of BECCS. To this end, we confront results from an Earth system model (ESM) and an IAM under an array of 25 stringent mitigation pathways. These pathways are compatible with the Paris Agreement long-term temperature goal and with cumulative carbon emissions ranging from 230 Pg C and 300 Pg C from January 1st onwards. We show that all stylized mitigation pathways studied in this work limit warming below 2 °C or even 1.5 °C by 2100 but all exhibit a temperature overshoot exceeding 2 °C after 2050. According to the IAM, a subset of 17 emission pathways are feasible when evaluated in terms of socio-economic and technological constraints. The ESM however shows that water scarcity would limit the deployment of BECCS in all the mitigation pathways assessed in this work. Our findings suggest that the evolution of the water resources under climate change can exert a significant constraint on BECCS deployment before 2050. In 2100, the BECCS water needs could represent more than 30% of the total precipitation in several regions like Europe or Asia.

1. Introduction

In the UN Paris Agreement adopted in 2015, countries agreed to limit global warming to well below 2 ° above pre-industrial levels, and to strengthen global efforts to limit global warming to 1.5 °. The core pledges submitted in the Nationally Determined Contributions (NDCs) would bracket emissions levels within a range of 14.2–16.2 Pg C-equivalent in 2030 (UNFCCC 2015). These levels are to be compared with current emission levels, 13.4 Pg C-equivalent (2014 data), and with levels in 2030 which would be consistent with least-cost pathways to the 2 °C goal

(3–4 Pg C-equivalent lower than NDC levels) and the 1.5 °C goal (4.3–5.2 Pg C-equivalent lower than NDC levels) (UNEP 2017). To reach the Paris Agreement long-term objective, NDC emissions levels thus imply very fast decarbonization post-2030 which would require deliberate human efforts to remove a large amount of CO₂ from the atmosphere (Gasser *et al* 2015). Technologies used to remove CO₂ from the atmosphere, also known as negative emissions technologies (NETs), are therefore present in the majority of the IPCC working group III scenarios that give a more than 50% chance of limiting warming to below 2 °C (Fuss *et al* 2014, Peters *et al* 2017) and all

scenarios that give more than a 50% chance of staying below 1.5 °C (Rogelj *et al* 2016a).

In stringent emission pathways, the presence of NETs nearly cancels out the continued positive emissions from fossil fuels and land-use change, thus strongly reducing the anthropogenic carbon emissions to the atmosphere. In the most ambitious emission pathways, NETs even reverse the sign of the anthropogenic carbon emissions turning the effect of human activities into a net flow of CO₂ out of the atmosphere.

In current Integrated assessment models (IAMs) large-scale afforestation and Bio-Energy combined with Carbon Capture and Storage (BECCS) are commonly used to create net negative emissions, removing CO₂ from the atmosphere. Indeed, Carbon Capture and Storage (CCS) is a negative carbon technology because it extracts CO₂ from the atmosphere and transfers it to geological reservoirs. Out of the 116 IPCC's AR5 scenarios (Clarke *et al* 2014) that were assessed to be consistent with a high probability of achieving the 2 °C target, 104 scenarios use BECCS and most of them at a large scale. In these scenarios, the median estimate of bio-energy used by the IAMs is about 160 EJ y⁻¹ in 2100 except for one model which uses as much as 300 EJ y⁻¹ in the second half of the century. In those scenarios, net negative emissions reach up to 3 Pg C y⁻¹ in 2100 and total cumulative sequestration over the century reaches up to 500 PgC.

In the context of IAMs studies, BECCS is allowed as an option in the production of electricity and heat in power plants, and sometimes for the generation of hydrogen, other transport fuels or bioplastics. This technology is supposed to have cost-competitive potential in order to reduce mitigation costs required to achieve ambitious climate targets (van Vuuren *et al* 2007, Azar *et al* 2010, van Vuuren *et al* 2013, Kriegler *et al* 2013, Rogelj *et al* 2016a).

Current generation of BECCS is based on the use of woody tree species, switchgrass (*Panicum vergatum*) and miscanthus (*Miscanthus x giganteus*) grasses that aim to replace current feedstocks such as corn, sorghum, sugarcane, rapeseed, soy, and oil palm. Although these bioenergy crops are thought to produce usable energy with lower energy, water and nutrient requirements than corn, recent studies indicate that a massive deployment of bio-energy crops such as switchgrass would take enormous water resources. Smith and Torn (2013) estimated that the removal of 1 Pg C per year out of the atmosphere would require about 200 Mha of land—an area of the size of Mexico—and consume 1000 km³ y⁻¹ of water—equivalent of the annual freshwater withdrawals in USA and China combined. More recently, Smith *et al* (2015) revised those estimates in the light of IPCC-AR5 working group III scenarios. This review indicates that in order to remove 1 Pg C per year by 2100, the use of various BECCS technologies would require between 100 and 200 Mha of land, and ~720 km³ y⁻¹ of water—equivalent to the annual freshwater withdrawals in Japan.

So far, the cost-competitive potential of BECCS remains largely debated because of its large array of constraints such as geophysical or climate (i.e. water resources, land surface area, food production), infrastructure (i.e. transportation) and commercial viability in addition to issues with people's perceptions that would limit the large-scale deployment of BECCS (e.g. Court *et al* 2012, Fajardy and Dowell 2017). In terms of geophysical constraints, pioneering model studies have shown that any BECCS deployment has to solve a complex trade-off for food production, nature conservation and climate limits (Boysen *et al* 2017a, Lotze-Campen *et al* 2014, Beringer *et al* 2011), confirming concerns expressed in experts assessments (Vaughan and Gough 2016). However, large uncertainties remain on the large-scale deployment of BECCS (Azar *et al* 2010, Wiltshire *et al* 2015); in particular, the interaction between climate and techno-economic constraints under climate change have received little attention so far (e.g. Heck *et al* 2016b, Boysen *et al* 2017a, 2017b).

In this paper, we explore this specific issue through the combined assessment of techno-economic and water availability factors that could hamper the large-scale deployment of BECCS under a set of stylized stringent mitigation pathways compatible with the Paris Agreement long-term temperature goal with an Earth system model, CNRM-ESM1 (Séférian *et al* 2016), and an integrated assessment model, IMACLIM-R (Waisman *et al* 2012).

An array of 25 stylized mitigation pathways following an exponential decrease in CO₂ emissions after peaking at the NDCs CO₂ emission level in 2030 is used to force IMACLIM-R and CNRM-ESM1. IMACLIM-R is run backwards to estimate the evolution of techno-economic factors governing the deployment of BECCS whereas CNRM-ESM1 is run forward in time to compute the evolution of Earth's climate.

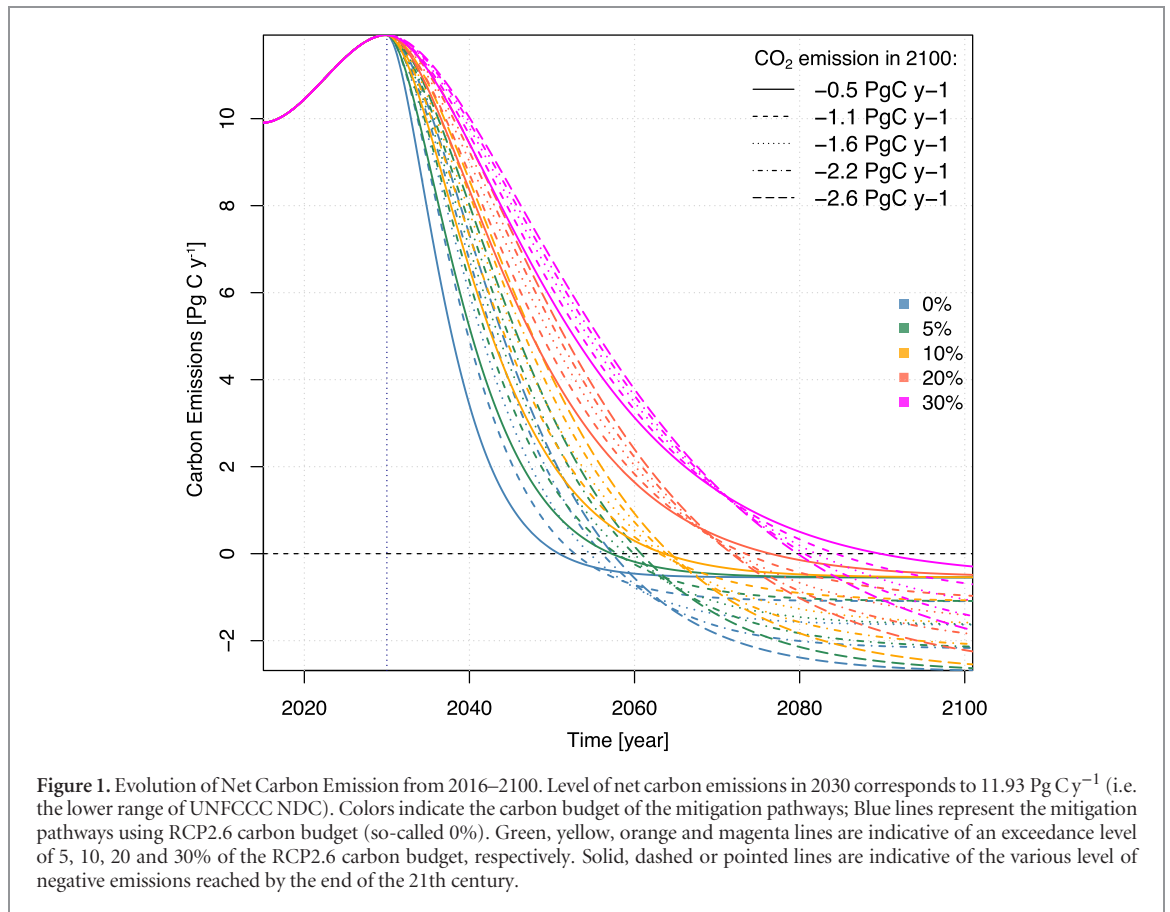
The paper is structured as follows: the experimental set-up and the methodology are explained in section 2, section 3 discusses constraints in techno-economic pathways as simulated by IMACLIM-R; section 4 assesses the climate characteristics of the stylized stringent mitigation pathways and then makes use of CNRM-ESM1 to explore the potential climate constraints in relation to the water resources; section 5 summarizes the key findings of the study.

2. Methodology

2.1. Approach

This study is based on a three-step modelling protocol:

1. A set of stylized carbon emission pathways is produced using the 2015 level of CO₂ emissions (9.91 Pg C y⁻¹, Boden *et al* (2013) and Le Quéré *et al* (2015)), NDC CO₂ emission level by 2030 (11.93–13.60 Pg C y⁻¹) and the cumulative RCP2.6 carbon budget at the end of the 21st century



(1000 Pg C, Peters *et al* (2017)). The emissions of other climate forcers such as aerosols and anthropogenic greenhouse gases followed the standard RCP2.6 scenario from 2010. The method employed to generate these scenarios is detailed in section 2.2.

2. The IMACLIM-R integrated assessment model is forced with the above-mentioned CO₂ emissions to assess economic and technological constraints of these mitigation pathways. IMACLIM-R helps to evaluate the economic and technological feasibility of BECCS technologies' deployment along the pathways. IMACLIM-R is described in section 2.3.1.
3. The Earth System Model CNRM-ESM1 uses the same net carbon emissions used by IMACLIM-R and explicitly resolves atmospheric CO₂ and climate-carbon cycle interactions. CNRM-ESM1 is run with a set of mitigation pathways evaluated as feasible by IMACLIM-R in order to assess climate constraints of those mitigation pathways. CNRM-ESM1 is described in section 2.3.2.
4. The joined use of IMACLIM-R and CNRM-ESM1 results allows to analyze both economic and technological feasibility and climate constraints of the various stringent mitigation pathways.

2.2. Stylized Emissions scenarios

In this study, an array of 25 stylized mitigation pathways was produced using exponential splines satisfying

several key criteria detailed below (figure 1). The exponential relationship has been used in former studies such as Gasser *et al* (2015). It can be expressed as:

$$f^{\text{ANT}} = A \times t \times e^t + b$$

Where f^{ANT} is the net anthropogenic CO₂ emissions, A and b are fitting coefficients in Pg C y⁻¹ and t is the month.

The 25 stylized mitigation pathways have been determined using the following set of key criteria:

1. Historical emissions up to 2015.
From 1985–2014, we use the CO₂ emissions established from the Global Carbon Project (Le Quéré *et al* 2015). We update the CO₂ emissions up to 2015 using Boden *et al* (2013) estimates of 9.89 Pg C y⁻¹ in 2015.
2. Global CO₂ emissions by 2030.
We use the UNFCCC (2015) estimate to compute 2030 global CO₂ emissions. UNFCCC (2015) computed the 2030 global CO₂-equivalent emissions from the NDC's submitted to Paris agreement. By applying the ratio of RCP8.5's CO₂ to CO₂-eq emissions in 2030 (Riahi *et al* 2011).
3. Remaining carbon budget compatible with the Paris agreement.

In order to meet the long-term temperature goal of the Paris Agreement ('well below 2 °C'), we deduce the allowable cumulative anthropogenic

CO₂ emissions or the carbon budget from the linear relationship between global warming and cumulative CO₂ emissions as in Friedlingstein *et al* (2014) and Rogelj *et al* (2016a). Le Quéré *et al* (2015) have evaluated cumulative CO₂ emissions to 414 PgC until 2015. On the other hand, Peters *et al* (2015) have estimated the non-CO₂ greenhouse gases contribution to 210 PgC and for the past land use change to 145 PgC. Altogether, the carbon budget from 2016 to 2100 compatible with 2 °C is 231 PgC. We derived 4 other carbon budgets in order to explore the uncertainties in the carbon budget. We allow deviations of 5%, 10%, 20% and 30% higher from the RCP2.6 carbon budget (van Vuuren *et al* 2011); which leads to cumulative CO₂ emissions in 2100 of 242, 254, 277 and 300 PgC; respectively. We acknowledge that our stylized mitigation pathways differ from those compatible with 1.5 °C as detailed in Rogelj *et al* (2015) which generally display a peak in CO₂ emissions before 2020. However, these latter are not consistent with the range of CO₂ emissions corresponding to the current NDCs. Carbon budgets higher than 231 PgC allow to explore pathways compatible with the level of CO₂ emissions as derived from the current NDCs.

4. Level of negative CO₂ emissions by 2100.

In order to explore technological constraints relative to a given carbon budget, we impose 5 different levels of negative CO₂ emissions in 2100: -0.5, -1.1, -1.6, -2.2 and -2.7 PgC y⁻¹. The level of negative CO₂ emissions has been limited to -2.7 PgC y⁻¹ in agreement with the estimates found in the recent literature which give an upper bound of 3 PgC y⁻¹ for the net negative CO₂ emissions. By comparison, the CO₂ emission of the RCP2.6 scenario in 2100 is -0.4 PgC y⁻¹, implying that for some scenarios the level of negative CO₂ emissions by 2100 can be a bit lower than the allowed maximum.

In 2016, CO₂ emissions used in our stylized mitigation pathways differ by less than 5% with observed CO₂ emissions as assessed in Le Quéré *et al* (2018). This difference remains smaller than the uncertainties in historical CO₂ emissions as reported in Le Quéré *et al* (2018).

While all scenarios are evaluated by IMACLIM-R (section 3), only a subset of stylized mitigation pathways, corresponding to pathways reaching -2.2 PgC y⁻¹ of negative emissions by 2100, will be assessed with CNRM-ESM1 (section 4). This subset of scenarios has been chosen because it allows to assess the full range of carbon budgets from 0%–30% (table S1 available at stacks.iop.org/ERL/13/054011/mmedia).

2.3. Models

2.3.1. Earth system model

This study analyzes model outputs of the Earth system model (CNRM-ESM1) developed at the Centre

National de Recherches Météorologiques (CNRM). CNRM-ESM1 is based on the physical and dynamical core of the CNRM-CM5.1 model described in Voldoire *et al* 2013. CNRM-ESM1 employs the Interactions between Soil, Biosphere and Atmosphere land surface model (ISBA (Gibelin *et al* 2008)) and the Pelagic Interaction Scheme for Carbon and Ecosystem Studies (PISCES (Aumont and Bopp 2006)) as terrestrial and oceanic components of the global carbon cycle. The climate physics and the global carbon cycle are resolved at a resolution of about 1°. For further details, see the skill assessment of CNRM-ESM1 against modern observations conducted in Séférian *et al* (2016). In a context of future scenarios, allowable CO₂ emissions as estimated from CNRM-ESM1 compares well to those of derived from other CMIP5 models (figure S1).

In this study, CNRM-ESM1 is forced by net anthropogenic CO₂ emissions (including land-use and land-cover change CO₂ emissions, fossil fuel and cement emissions and negative CO₂ emissions) which are updated every month. The evolution of the atmospheric CO₂ concentration is resolved at global scale assuming that this gas is well-mixed. Its evolution is computed at a monthly time scale as follows:

$$p\text{CO}_2(t + \Delta t) = p\text{CO}_2(t) + \frac{1}{2.12} \sum f^{\text{ANT}}(t) - \frac{1}{2.12} \sum f^{\text{NAT}}(t)$$

Where f^{ANT} is the net anthropogenic CO₂ emissions and f^{NAT} is the sum of global land and ocean carbon flux as simulated by ISBA and PISCES, respectively. The conversion factor from PgC month⁻¹ to ppm month⁻¹ is 2.12.

For each mitigation pathway, we perform 3 member ensemble simulations in order to improve the signal-to-noise ratio. The ensemble members are generated with different initial conditions provided by the model's restarts from the model year 1850, 1900 and 1950 of a preindustrial simulation. A larger ensemble of simulations would have been preferable but a 3 members ensemble represents a reasonable compromise between the ensemble size and the number of mitigation pathways. In the following, global warming (ΔT) is estimated as the difference of the temperature between the future mitigation pathways and the preindustrial control simulation of CNRM-ESM1 as detailed in Séférian *et al* (2016).

2.3.2. Integrated assessment model

The IMACLIM-R model (Waisman *et al* 2012) is a multi-regions and multi-sectors model of the world economy that represents the intertwined evolution of technical systems, energy demand behavior and economic growth. It combines a Computable General Equilibrium (CGE) framework with bottom-up sectoral modules in a hybrid architecture. It describes dynamic trajectories in yearly time steps until 2100

through the recursive succession of top-down static equilibria and bottom-up sectoral modules. The scope of the represented GHG is restricted to CO₂ emissions from fossil fuel combustion. A detailed description of the model is available at http://themasites.pbl.nl/models/advance/index.php/Model_Documentation_-_IMACLIM.

In IMACLIM-R, biomass-energy can be used for power generation and for the production of alternative transport fuels. Carbon capture and storage is an available option for the industry sector and for power generation, such that BECCS can arise in the power generation sector, thus resulting in net negative emissions. The supply of biomass-energy is represented through regional supply curves, calibrated on Hoogwijk *et al* (2009). In the power generation sector, CCS is available for fossil-fuel fired and biomass-fired power plants. The model represents explicitly 26 power generation technologies, and investment choices are modelled according to life-cycle costs of technologies. Further details about the representation of biomass-energy and BECCS are given in Bibas and Méjean (2014).

The IMACLIM-R model parameters are calibrated using a baseline scenario (i.e. a scenario with no carbon prices or other mitigation policies). Such scenarios, with no carbon prices or other mitigation policies are not intended to represent a plausible scenario, because some climate policies are already implemented in parts of the world. However, they are used as points of comparison, to evaluate the costs of mitigation policies and the costs of damage from climate change. The new framework for scenarios for climate change research starts from such baseline scenarios (the Shared Socioeconomic Pathways, SSPs (O'Neill *et al* 2013, Riahi *et al* 2016)), that allow to represent alternative socio-economic evolutions. On the basis on these baseline scenarios, mitigation policies are then assessed. In this study, we use the SSP2 scenario (intermediate challenges for adaptation and mitigation, with a forcing level between 6.0 and 8.0 W m⁻² in 2100) to calibrate IMACLIM-R. It is detailed in Marangoni *et al* (2017).

Mitigation scenarios are built from this baseline, with the CO₂ emissions pathways described in 2.2. To do so, we do not input carbon prices in the model, we force the CO₂ emissions, and the model finds the price trajectory that allows to reach the CO₂ constraint at each time step. Therefore, carbon prices are not an assumption, but a result. For instance, in the subset of stylized mitigation pathways on which this study is focused, i.e. the pathways reaching -2.2 Pg C y^{-1} of net negative emissions by 2100, the carbon prices range from 290 to 1880 US\$₂₀₀₅/tCO₂ in 2040. In this study, carbon prices are identical for all sectors, households and regions.

3. Economic and Technological constraints of mitigation pathways

Here, we assess the 25 stylized mitigation pathways in terms of economic and technological constraints using the IMACLIM-R results.

Figure 2 and table S1 show that IMACLIM-R finds a solution for 17 of the 25 emissions pathways, i.e. socio-economic and technological pathways meet the net CO₂ emission constraint. Figure 2 shows that these 17 pathways display reduction in CO₂ emissions by 0.2–0.5 Pg C y⁻¹ between 2030 and 2040 and reach carbon neutrality between 2056 and 2090. Most of these stylized mitigation pathways exhibit a level of negative emissions by 2100 ranging between 1.6 and 2.2 Pg C y⁻¹ in 2100, a figure that lies within the lower range of IPCC-AR5 WGIII scenarios (Clarke *et al* 2014, Fuss *et al* 2014). The eight remaining stylized mitigation pathways are identified as unfeasible by IMACLIM-R (table S1): for those stylized mitigation pathways as the algorithm of IMACLIM-R does not find a carbon price level that would meet the CO₂ emissions constraint after a given year. These mitigation pathways identified as unfeasible are characterized by: (i) very fast emissions decrease in the two decades after 2030 (reductions of emissions between 2030 and 2040 are higher than 5 Pg C y⁻¹, figure 2), or (ii) very high levels of net negative emissions before the end of the 21st century (more than 1.8 Pg C y⁻¹ net negative emissions in 2080, table S1). Because the CO₂ emission abatement options exhibit are path dependent, there is no absolute maximum decrease in CO₂ emission. It all depends on previous investment choices, technological and structural change. If 2030 CO₂ emission corresponds to the lower bound of NDC estimates (11.93 Pg C y⁻¹), our results indicate that a reduction of more than 0.5 Pg C y⁻¹ after 2030 would be difficult to exceed.

In the 17 feasible mitigation pathways, the deployment of biomass-energy and BECCS produces between 60 and 150 EJ y⁻¹ in 2050 and between 200 and 250 EJ y⁻¹ in 2100 (figure 3(a) and figure S2 and S3). The energy production from biomass overcomes that of conventional energy and in particular fossil fuel after 2080. We analyze the emissions pathways using the Kaya decomposition:

$$\text{EmCO}_2 = \text{GDP} \times \frac{E}{\text{GDP}} \times \frac{\text{EmCO}_2}{E}$$

Where EmCO₂, GDP and E represent the anthropogenic CO₂ emissions, the gross domestic product and the energy production, respectively. $\frac{E}{\text{GDP}}$ represents the energy intensity of the gross domestic product, i.e. the amount of energy that must be used to produce goods or services, and $\frac{\text{EmCO}_2}{E}$ indicates the carbon intensity of energy, i.e. the amount of CO₂ that is

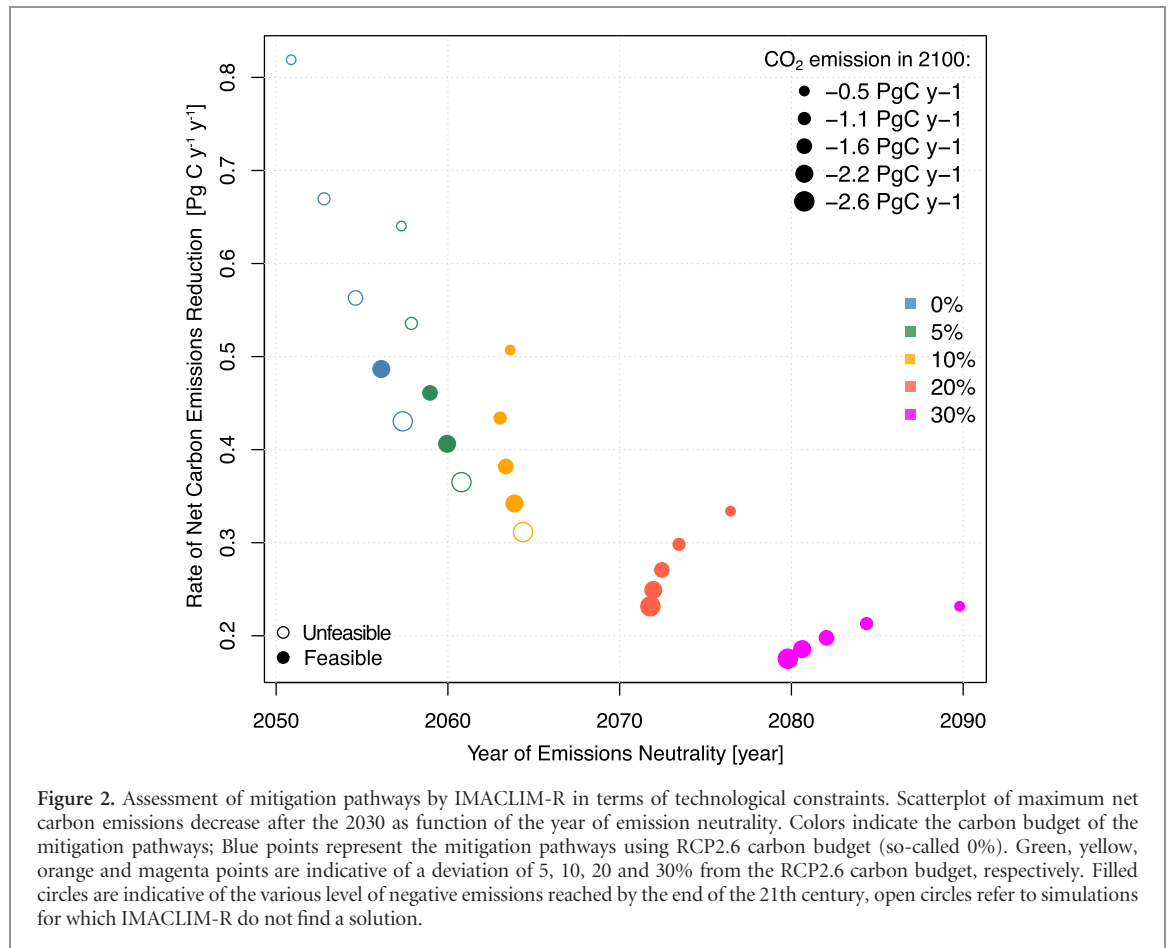


Figure 2. Assessment of mitigation pathways by IMACLIM-R in terms of technological constraints. Scatterplot of maximum net carbon emissions decrease after the 2030 as function of the year of emission neutrality. Colors indicate the carbon budget of the mitigation pathways; Blue points represent the mitigation pathways using RCP2.6 carbon budget (so-called 0%). Green, yellow, orange and magenta points are indicative of a deviation of 5, 10, 20 and 30% from the RCP2.6 carbon budget, respectively. Filled circles are indicative of the various level of negative emissions reached by the end of the 21th century, open circles refer to simulations for which IMACLIM-R do not find a solution.

emitted to produce a given amount of energy. In our stylized mitigation pathways, the major difference arises from the carbon intensity of the energy whereas the energy intensity of the growth domestic product remains roughly independent from the various carbon budget (figure 4). In agreement with Peters *et al* (2017), our results highlight the consistency in terms of energy intensity across the IPCC-AR5 WGIII scenarios compatible with 2 °C and emphasize even further the key role of the carbon intensity in the most stringent mitigation pathways.

We would like to stress that other definitions of feasibility of a pathway exist (see for instance Gambhir *et al* (2017)) and a mitigation pathway that is feasible in modelling terms may still be impossible to implement in social and political terms. However, the feasibility criteria (both economic and technological) chosen in this study allow to remove the most unrealistic mitigation pathways.

4. Climate constraints of mitigation pathways

4.1. Earth system response to mitigation pathways: global mean temperature, atmospheric CO₂ concentrations and remaining carbon budgets

In this section, we briefly assess the different climates derived from CNRM-ESM1 when forced by a subset of stylized stringent mitigation pathways

reaching -2.2 PgC y^{-1} of negative CO₂ emission by 2100.

Table 1 shows that all stylized mitigation pathways limit warming to below 2 °C above the 1850–1900 level. It is interesting to note that climate derived from MAGICC (Meinshausen *et al* 2011) as used in Rogelj *et al* (2016b) lead to a higher global mean temperature in 2100 (1.75 °C–1.91 °C for likely 2 °C scenarios and 1.41 °C–1.47 °C for likely 1.5 °C scenarios) than CNRM-ESM1 (1.34 °C–1.75 °C) whereas both models simulations show comparable atmospheric CO₂ concentrations in 2100. On the contrary, all stylized mitigation pathways used in this study exhibit temperature overshoots that exceed 2 °C or 1.5 °C threshold with atmospheric CO₂ concentrations higher than 450 ppm. This means that all of the stylized emissions pathways compatible with NDCs emissions level in 2030 exceed the Paris Agreement long-term temperature goal. The timing of the temperature overshoot as simulated by CNRM-ESM1 under our 0% mitigation pathways compares well to that estimated from MAGICC under various mitigation pathways.

4.2. Tracking regions facing water scarcity

In the following, we investigate potential limitation to BECCS deployment as simulated by CNRM-ESM1 in the context of stringent mitigation pathways. We break down land water in two terms: available water and BECCS water needs (W_{BECCS}). Available water

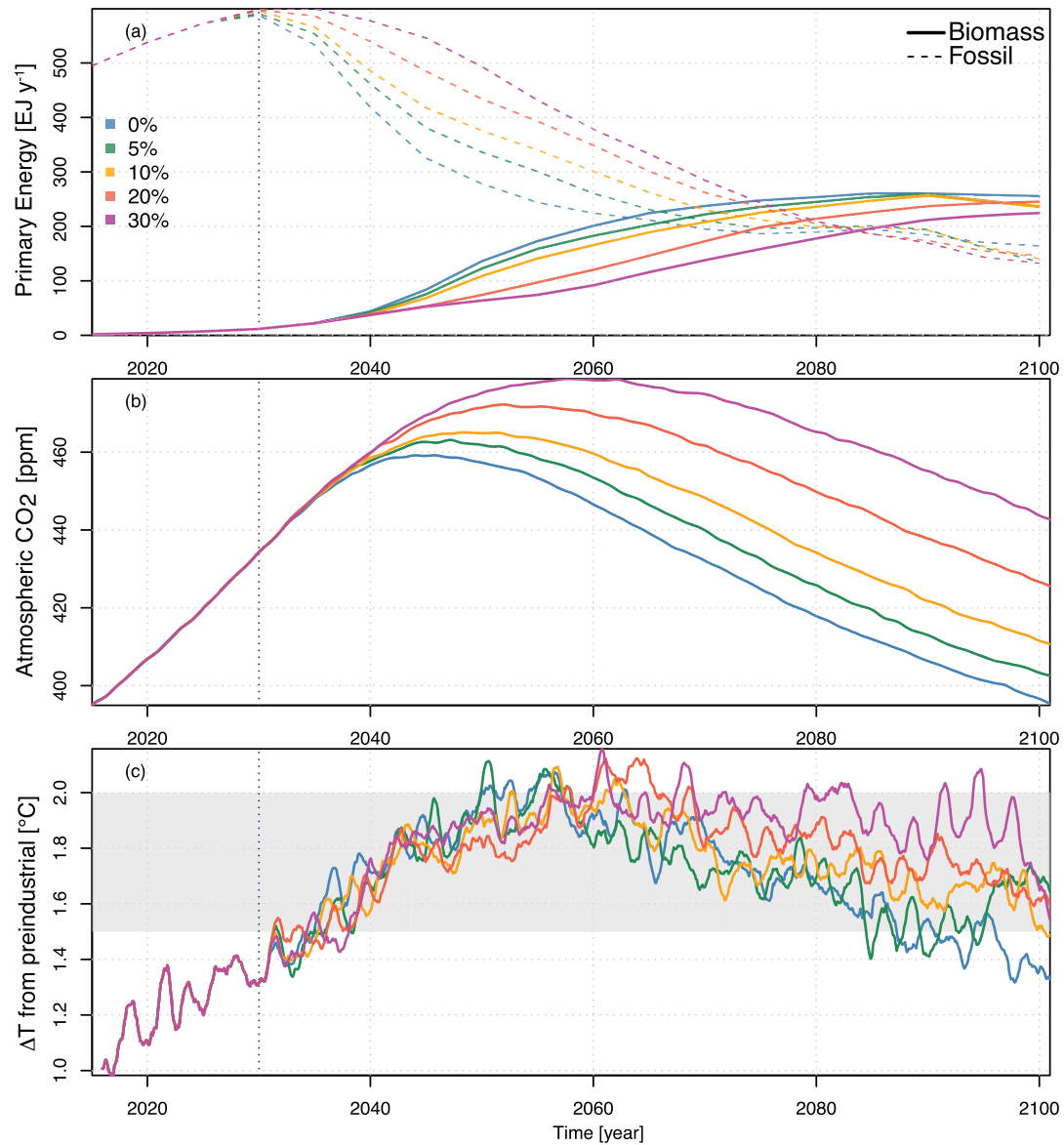


Figure 3. Time-series of yearly global indicators from 2015–2100. Time-series for Energy production (a) are derived from IMACLIM-R simulation; time series for atmospheric CO₂ (b) and temperature anomaly relative to preindustrial levels (c) are derived from CNRM-ESM1 simulations. For the sake of clarity, time series for each global indicator are only represented for mitigation pathways reaching $-2.2 \text{ Pg C yr}^{-1}$ of negative emissions in 2100 as shown in figure 1. Atmospheric CO₂ and temperature anomaly relative to preindustrial levels have been estimated from the ensemble mean across 3 independent CNRM-ESM1 simulations. ΔT has been estimated using the difference in global mean surface temperature between the future projection and the preindustrial simulation of CNRM-ESM1. Refers to figure 2 for colors.

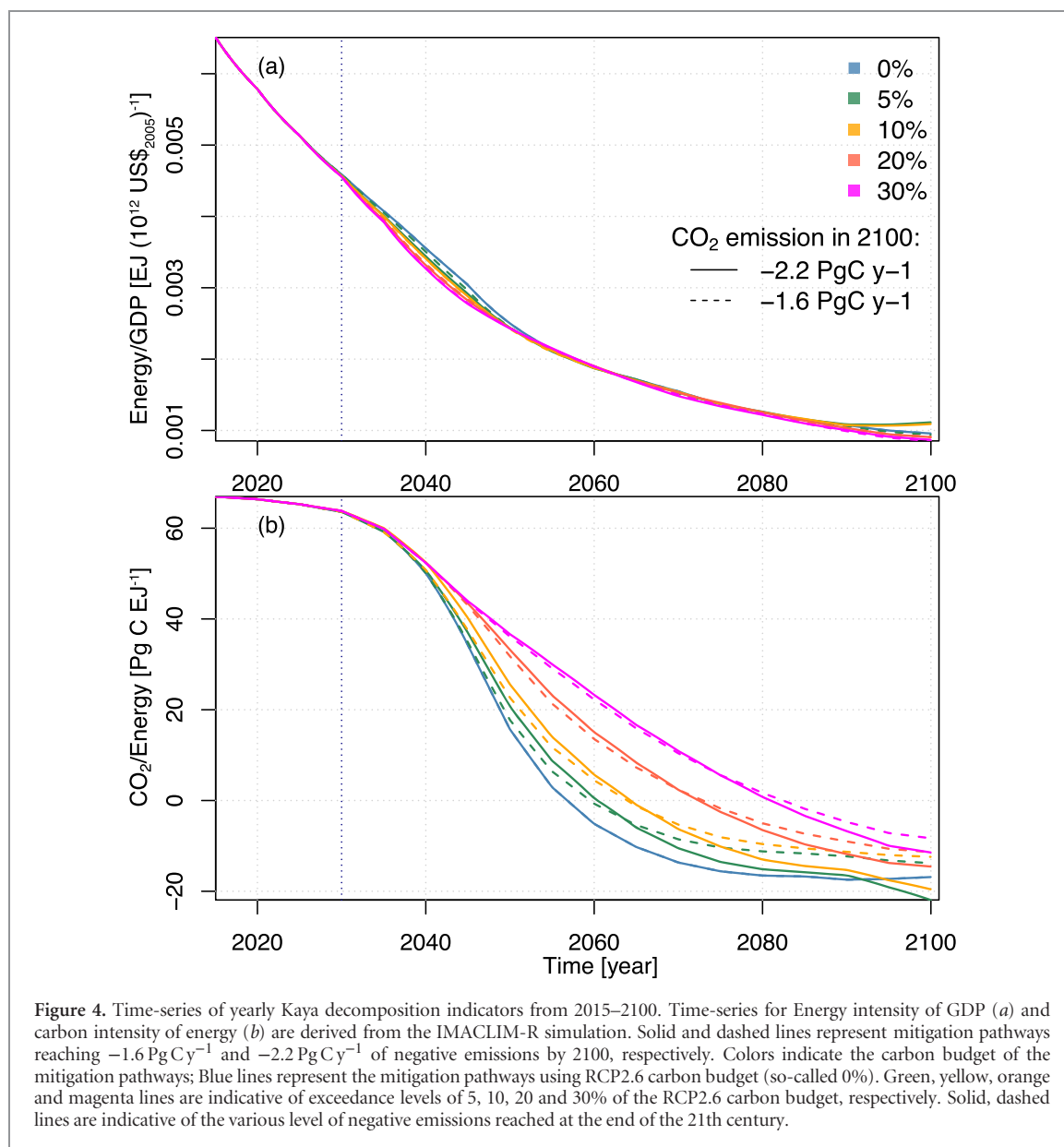


Figure 4. Time-series of yearly Kaya decomposition indicators from 2015–2100. Time-series for Energy intensity of GDP (a) and carbon intensity of energy (b) are derived from the IMACLIM-R simulation. Solid and dashed lines represent mitigation pathways reaching -1.6 Pg C y^{-1} and -2.2 Pg C y^{-1} of negative emissions by 2100, respectively. Colors indicate the carbon budget of the mitigation pathways; Blue lines represent the mitigation pathways using RCP2.6 carbon budget (so-called 0%). Green, yellow, orange and magenta lines are indicative of exceedance levels of 5, 10, 20 and 30% of the RCP2.6 carbon budget, respectively. Solid, dashed lines are indicative of the various level of negative emissions reached at the end of the 21th century.

Table 1. Earth system response to stringent mitigation pathways. Temperature anomalies from the pre-industrial period, in Celsius degree, and atmospheric CO_2 concentration, in ppm, in relation with stringent mitigation pathways reaching -2.2 Pg C y^{-1} of negative emissions in 2100. The last two lines of the table show well-below 2°C and well-below 1.5°C scenarios that are derived from simulations performed from with MAGICC forced by an extended IPCC-WGIII scenario database (Rogelj *et al* 2016b). Percentages are indicative of the carbon budget used in the mitigation pathways with respect to the RCP2.6 carbon budget; 0% represent the mitigation pathways using RCP2.6 carbon budget and deviations of +5%, +10%, +20% and +30% from the RCP2.6 carbon budget are also given. Years in column two refers to the timing of overshooting.

| Exceedance of RCP2.6 carbon budget | Overshoot | | 2100 | | |
|------------------------------------|-----------|----------------------------------|---------------------|----------------------------------|---------------------|
| | Year | ΔT ($^\circ \text{C}$) | CO_2 (ppm) | ΔT ($^\circ \text{C}$) | CO_2 (ppm) |
| | | | CNRM-ESM1 | | |
| 0% | 2050–2059 | 2.1–2.13 | 449–453 | 1.34–1.36 | 395–396 |
| 5% | 2054–2059 | 2.08–2.15 | 454–458 | 1.61–1.63 | 403–404 |
| 10% | 2061–2065 | 2.1–2.16 | 451–457 | 1.44–1.55 | 411–412 |
| 20% | 2061–2065 | 2.1–2.2 | 466–470 | 1.56–1.7 | 426–429 |
| 30% | 2064–2081 | 2.18–2.32 | 462–476 | 1.58–1.75 | 442–443 |
| Warming threshold | | | MAGICC | | |
| $< 2^\circ \text{C}$ | 2074–2078 | 1.86–1.95 | 430–446 | 1.75–1.91 | 403–433 |
| $< 1.5^\circ \text{C}$ | 2051–2053 | 1.61–1.68 | 416–424 | 1.41–1.47 | 359–366 |

is computed in each CNRM-ESM1 grid point as the difference between total land precipitation and surface runoff. This estimate represents the maximum value of water that can infiltrate the soil, as it neglects canopy interception and bare soil evaporation terms. On the other hand, it excludes irrigation, water that could be extracted from rivers, lakes, man-made reservoirs, and aquifers. W_{BECCS} is derived from the IMACLIM-R negative emissions technology-induced carbon flux and from the mean ratio between water requirement and net carbon uptake of crop-based BECCS published in the review of Smith *et al* 2015 ($\sim 720 \text{ km}^3$ for 1 Pg C y^{-1}). W_{BECCS} is distributed to the CNRM-ESM1 grid cells using the following algorithm:

1. We select the grid cells that have a non-zero cropland fraction
2. Over these grid cells, BECCS water needs are computed as:

$$w_{\text{BECCS}}(x, y) = W_{\text{BECCS}} / \int \int S(x, y)$$

$$(\text{BareSoil}(x, y) + \text{Grass}(x, y) - \text{Crop}(x, y)) dx dy$$

where S , BareSoil , Grass and Crop represent the land surface area, bare soil, grass and crop fraction of each grid-cell, respectively. With this formulation, we assume that BECCS would only be grown in regions that are currently cultivated but that BECCS would not replace present-day crops.

With these two terms, we compute the water availability as the difference between available water (estimated from CNRM-ESM1) and the BECCS water needs (W_{BECCS} , estimated from IMACLIM-R). Water scarcity corresponds to negative values of water availability, representative of a decline in water resources for natural and human ecosystems, whereas positive values indicate sustainable water resources for BECCS deployment.

Figure 5 shows the results obtained for two of the feasible mitigation pathways with different carbon budget (i.e. +0% and +30% deviations from the RCP2.6 carbon budget) at the beginning (2025–2030), the middle (2045–2050) and the end (2095–2100) of the 21st century. It indicates that while water resources remain sufficient for the deployment of BECCS around 2030, they are reduced in mid-century (~ 2050) and even more so at the end of the century (figures 5(a)–(f)). Water scarcity occurs earlier in the most stringent mitigation pathway consistent with the carbon budget of RCP2.6 (+0%), than the less stringent mitigation pathway (+30%). But at the end of the century, almost all the regions where BECCS would be deployed face water scarcity in both scenarios. Only Amazonia and equatorial Africa remain spared in the +30% scenario, with a severe lack of water resource in the most stringent pathway (+0%). Further analysis indicate that the scarcity is essentially due to an increase in the BECCS needs over time, as they are deployed

over increasingly larger areas to meet the scenarios objectives in terms of global warming and carbon budget (see figure S6).

Because of both the regions distribution of cropland and the region distribution of precipitations and runoffs, CNRM-ESM1 projects that BECCS deployment will induce regional disparities in terms of water availability. In the most stringent mitigation pathways, Europe and Australia for example will face water scarcity due to BECCS deployment by 2046 and 2050, respectively, because these regions exhibit a small decline in precipitation from 2030 onwards. In contrast, regions which benefits from a large amount of precipitation such as South America won't encounter water scarcity before 2065 in the most stringent mitigation pathways and by 2089 in the less stringent scenarios.

We now present a more integrative view of water scarcity over six key regions: Europe, North America, South America, Australia, Africa and Asia. For each of these region, we computed the amount of available water (in km^3) as the difference between the total yearly rainfall and runoff, integrated over the area where BECCS are deployed in the region. The corresponding integrated BECCS water needs, W_{BECCS} , were computed in the same manner. Figure 6 shows these regional water budgets in the year 2100 for five mitigation pathways. In agreement with the results presented on figure 5, we find that in all 6 key regions, the amount of water needed for the deployment of BECCS largely exceeds the local water resources, which amount for only 6%–30% of the BECCS requirements depending on the regions and scenarios—these are substantially larger than that estimates of Smith *et al* (2015). Looking at the temporal evolution of this water balance between the BECCS needs and the amount of available water (figure S6), one can see that the occurrence of water scarcity is due to the increase in the BECCS demand over time, rather than the decrease of available water which remains stable in comparison. For the 0%, 5% and 10% scenarios, the BECCS water needs outstrip the resources sometime during the 2040's; whereas it happens in the 2050's (2060's) for the +20% (+30%) scenario (see figure S7).

Part of this water scarcity could be alleviated with irrigation. This additional supply is not taken into account in our estimate of available water, as the Earth System model CNRM-ESM1 does not include an irrigation scheme. To address this issue, we computed the total yearly rainfall (in km^3) over each of the six regions in 2100 (figure 6) and over the whole scenarios period (figure S6). We argue that this quantity can give a fair estimate of the maximum amount of available water as it integrates the runoff volumes eventually flowing into the surface water network, as well as the annual recharge of groundwater. In equatorial Africa, South America, Australia and North America, the BECCS water needs remain compatible with this upper bound of water resources (figure 6), but this is

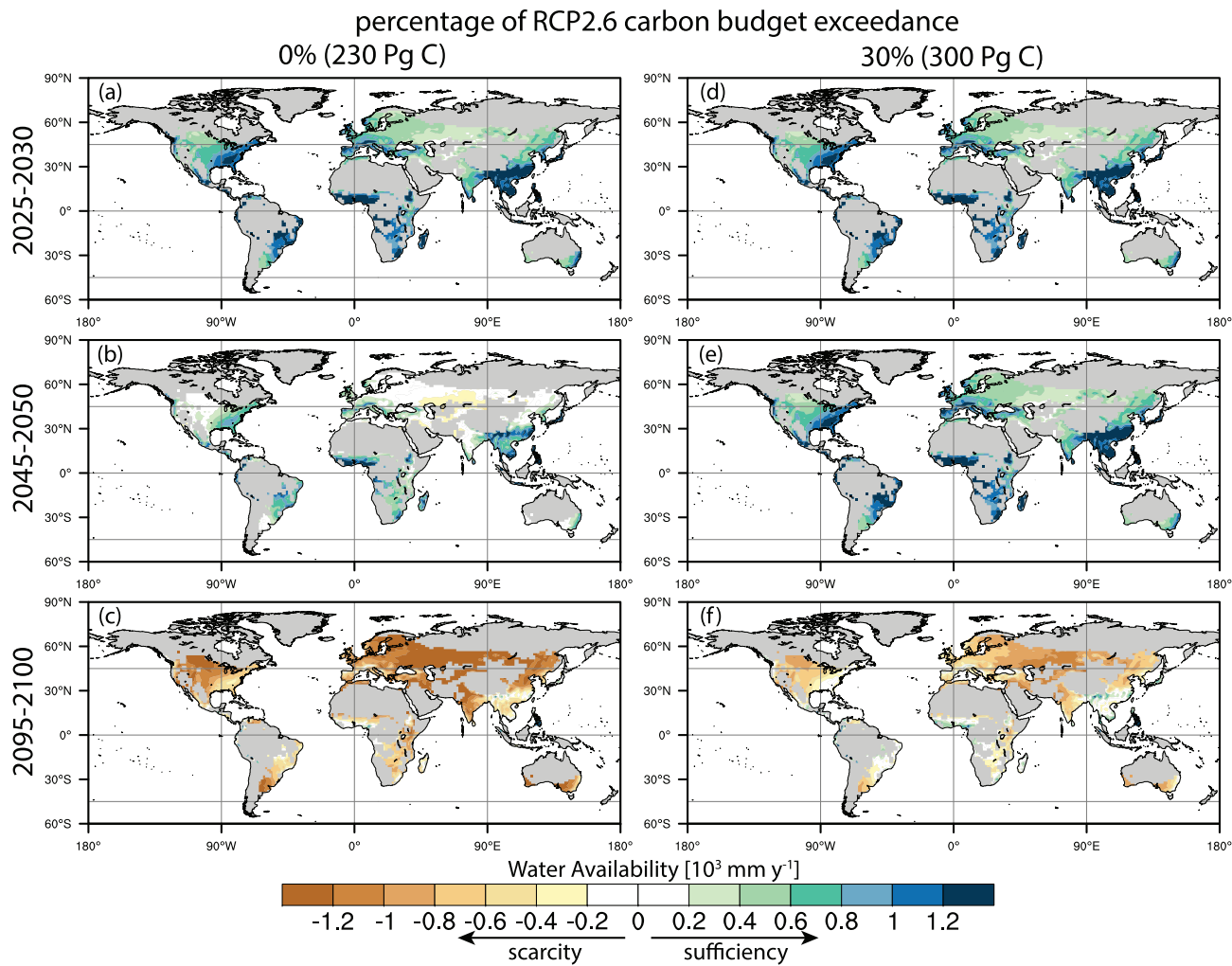
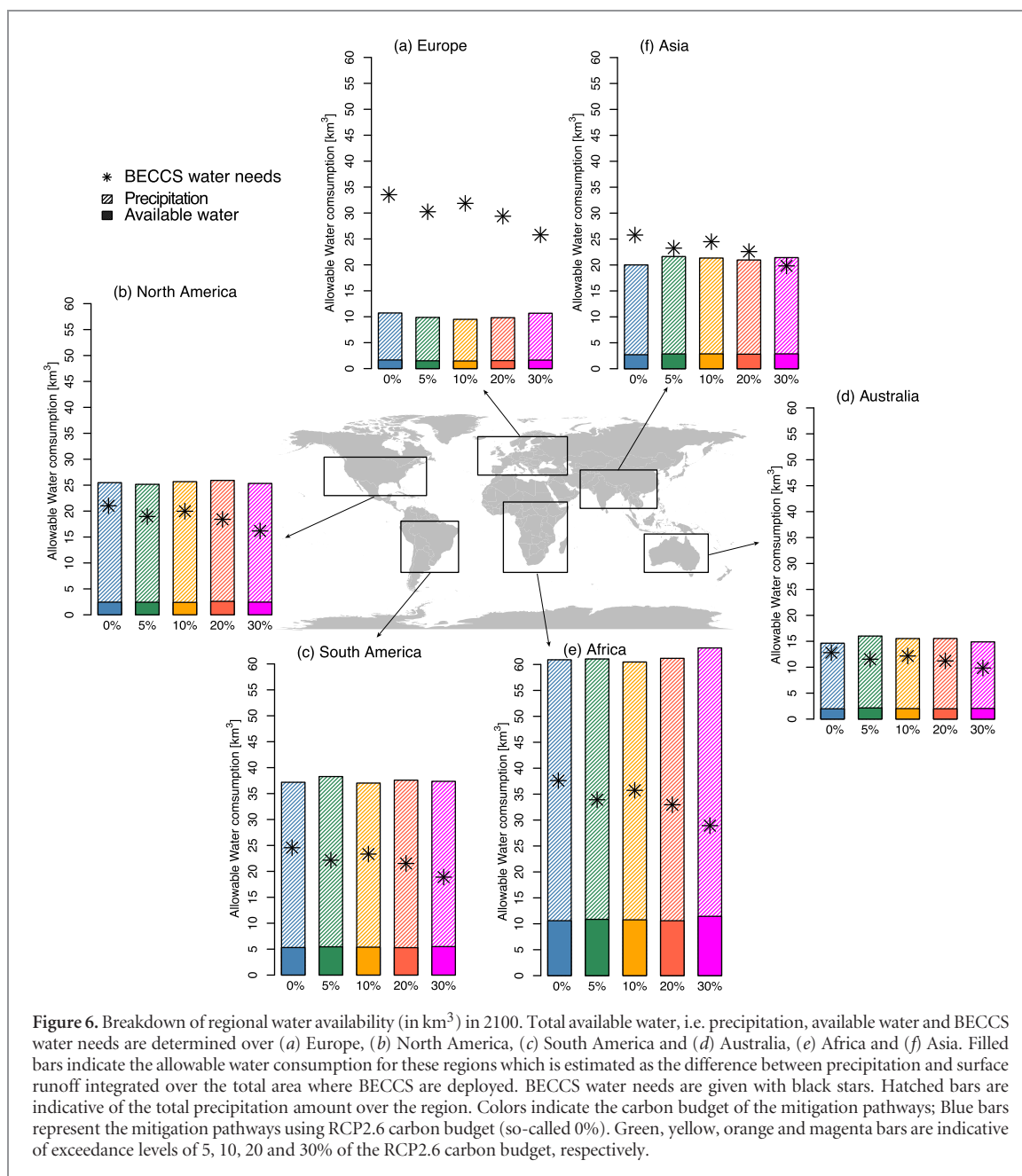


Figure 5. Evolution of water availability in early, mid, late 21th century in two stringent emissions scenarios. water availability in early (a), mid (b) and late (c) 21th century under the emissions scenarios 0% is estimated from the 5 year averaged difference between land total precipitation and surface runoff over years 2025–2030, 2045–2050 and 2095–2100; panels (d), (e) and (f) represent the water availability under scenario 30% over the same time windows. Negative (positive) values given in reddish (blueish) colors are indicative of water scarcity (sufficiency). Grey shading indicates land surface areas that are not affected by BECCS deployment. Water availability is derived from mitigation pathways reaching -2.2 Pg C y^{-1} of negative emissions by 2100.



not the case in Europe and Asia where the total precipitation represents respectively 30% and 90% of the BECCS water needs. In any case, it is worth noting that massive irrigation implies tapping of groundwater reserves, reduces access to clean water for human settlements and ecosystems (Postel *et al* 1996, Siebert *et al* 2010, Wada *et al* 2012) and competes with food production water demands (Falkenmark 1997, Rockström *et al* 2009). Furthermore, the use of irrigation techniques would ultimately add a cost to BECCS (Fernández García *et al* 2016, Raudales *et al* 2017), which would in turn hamper the technology competitiveness and would potential slow its deployment compared to the trajectory modelled without this additional cost (Hejazi *et al* 2014).

Previous studies concluded that a large deployment of BECCS can be considered as unrealistic in regards of planetary boundaries (e.g. Running 2012, Heck

et al 2016a, Gerten *et al* 2013, O'Neill *et al* 2018). Here, we confirm this assessment and offer a first quantification of the water availability constraint on the deployment of BECCS. Within our modelling framework, we have identified that the limited amounts of available water (present and future) might substantially restrict the achievement of mitigation pathways based on BECCS.

5. Conclusions

In this work, we explore both technological and water constraints of large-scale deployment of BECCS under an array of 25 stylized mitigation pathways compatible with a 2°C warming. With a parallel approach, we assess those mitigation pathways using an Integrated assessment model (IAM), IMACLIM-R and an Earth

system model (ESM), CNRM-ESM1, to evaluate both the eco-technological limitations and the water scarcity, respectively.

Our evaluation of these mitigation pathways confirms that a massive emission reduction and a massive deployment of BECCS are therefore required to limit global warming below 2 °C in 2100. However, it seems that a massive emission reduction and a massive deployment of BECCS are not sufficient to halt global warming below 1.5 °C or 2 °C over the 21st century.

Our assessment of the water supply required to support such a BECCS deployment questions the feasibility of those mitigation pathways in regards of water constraints. Indeed, when confronting BECCS water needs as estimated from IMACLIM-R and water availability as derived from CNRM-ESM1, our analysis highlights that most of the cropland areas would encounter water scarcity before 2100 because of BECCS water needs. This water scarcity could be alleviated using a larger fraction of precipitation but this will ultimately threaten natural ecosystems and human settlements. We identify that BECCS deployment has to be reduced by about 90% in order to meet water constraints as simulated by CNRM-ESM1, hampering our ability to reduce CO₂ emissions by the use of BECCS.

Our work highlights that the chronology of climate constraints such as water scarcity can feedback on BECCS deployment scenarios in stringent mitigation pathways and hence suggests that the coupling between key technological and economic variables and key climate variables as achieved in Collins *et al* (2015) would improve reliability of those scenarios. In absence of such coupling, we recommend a systematic assessment of stringent mitigation pathways in terms of climate constraints such as the water availability.

Our results suggest that water scarcity induced by climate change would hinder the scale of BECCS deployment necessary to follow CO₂ emissions trajectories that peak in 2030 at a level corresponding to the NDC estimates. This finding questions the feasibility of such mitigation pathways. Therefore, to increase the likelihood of meeting the Paris Agreement long-term target, the peak in CO₂ emissions should be lower than the lower bound of estimations for current NDCs and occur as early as possible.

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