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Coupled Climate–Economy–Biosphere (CoCEB) model – Part 2: Combining deforestation control with carbon capture and storage technologies.

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Coupled Climate–Economy–Biosphere (CoCEB) model – Part 2: Combining deforestation control with carbon capture and storage technologies

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Abstract. This study uses the global climate–economy–biosphere (CoCEB) model formulated in Part 1 to investigate economic aspects of deforestation control and carbon sequestration in forests, as well as the efficiency of carbon capture and storage (CCS) technologies as policy measures for climate change mitigation. We assume — as in Part 1 — that replacement of one technology with another occurs in terms of a logistic law, so that the same law also governs the dynamics of reduction in carbon dioxide (CO_2) emission using CCS technologies. In order to take into account the effect of deforestation control, a slightly more complex description of the carbon cycle than in Part 1 is needed. Consequently, we add a biomass equation into the CoCEB model and analyze the ensuing feedbacks and their effects on per capita gross domestic product (GDP) growth. The paper indicates that an increased investment in CCS will not suffice to reduce CO_2 emissions, and that a reduction of deforestation would be as effective as investment in low- and zero-carbon or CCS technologies for reducing climate damage. This study also demonstrates that a combined mitigation regime — investment in low-carbon and CCS technologies, as well as deforestation control— enables the most ambitious climate policy scenario considered here to limit warming throughout the 21st century to below 2 °C above pre-industrial levels without a temporal overshoot, as well as reduces impacts to the global per capita GDP by 21.8 % by 2100 relative to the "business-as-usual" pathway which reaches 4.9 °C.

1 Introduction and motivation

The crucial and urgent challenges posed by the reality of societally induced environmental degradation are profound in quantity and space (Chen et al., 2017). Policy makers, investors and the general public need to be adequately and effectively informed of alternative climate change futures so as to guide them in making viable and far-reaching decisions (McMahon et al., 2016). From its causes and impacts to its solutions, the issues surrounding climate change involve multidisciplinary and transdisciplinary science and technology (Steffen, 2012). However, we still lack integrated assessment models (IAMs) that will allow us to effectively handle the complex Earth's climate system with our incomplete understanding of sub-system processes (Nordhaus and Boyer, 2000). As Gaucherel and Moron (2016) rightly point out, steps in this direction are being taken by recent integrated assessment studies; see for example Ogutu et al. (2017b).

The paper is the second part of a two-part study that formulates, tests, and applies a simplified Coupled Climate–Economy–Biosphere (CoCEB) model. Part 1 of the study (Ogutu et al., 2017b; hereafter Paper 1) presents the model structure and the coupling of economic equations and physical equations. The economic activities are represented through a Cobb–Douglas output function with constant returns to scale of the two factors of production: per capita physical capital K and per capita human capital H. The per capita output after tax is allocated among consumption, investment in physical and human capital accumulation, and in carbon dioxide (CO_2) abatement. The climate system evolution is modeled via an energy balance equation for the average global surface air temperature T (SAT) and a carbon cycle equation for the CO_2 concentration in the atmosphere C. The coupling of the two modules, economic and physical, is done via the industrial emission of CO_2 and other gasses, which depend on per capita output relative to per capita abatement activities, and via a damage function that modifies economic activity because of climate change.

Now, unlike many IAMs in the contribution of Working Group 3 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [IPCC; Clarke et al. (2014)], Paper 1 points to the fact that investment in low- and zero-carbon technologies alone is a necessary but not sufficient step towards climate stabilization: no matter how fast CO_2 emissions are reduced, the below 2 °C target will still be violated; see also Klimenko et al. (2016). The inability of low- and zero-carbon technologies alone to produce effective climate change mitigation may partly be ascribed to the warming from the carbon stock already in the atmosphere (Steffen, 2012), the lock-in of carbon-intensive energy infrastructure (Rogelj et al., 2015) and rebound effects from increasing resource use efficiency: gains in efficiency are offset by increased consumption or new uses for energy (Palmer, 2012); see also Santarius et al. (2016) on new perspectives on the rebound phenomenon. This ineffectiveness of low- and zero-carbon technologies can partly be addressed by considering a CO_2 stock reduction strategy: the draw-down of carbon from the stock already emitted to the atmosphere, together with the draw-down of all further additions to that stock that are made during the period of transition; see also Canadell and Schulze (2014).

This paper's main goal is to assess the effects of climate policy on the impacts of climate change, and on the comparative efficacy of different approaches to abatement. To this end we introduce into the CoCEB model a simulation of the reduction of CO_2 emissions due to carbon capture and storage (CCS) technologies and to the control of deforestation. Of course, it cannot go without saying that this is with a reasonable-to-good prospect of remaining on a trajectory that would keep warming below 2 °C, and thus maintaining climate change within the boundaries of manageable risks as well as our ability to adapt to climate change (Rogelj et al., 2016). Actually the availability of negative-emission technologies like CCS is argued as fundamental in achieving an atmospheric CO_2 concentration of no more than 958.5–1171.5 gigatonnes of carbon (GtC, 1 Gt = 10^{15} g) by year 2100, which is pegged to deliver the SAT target of 2 °C (Clarke et al., 2014; Akaev, 2015). However, there is a notable absence in the literature of a focused discussion of both social barriers and implications of the rapid scale-up of CCS (Buck, 2016). Moreover, there are recent concerns that reliance on negative-emission technologies — whose large-scale rollout is often assumed by current scenarios to be technically, economically, and socially viable (Clarke et al., 2014) — locks in humanity's carbon addiction and this could be a recipe for catastrophe (Anderson and Peters, 2016);

see also Tretkoff (2010, and reference therein) and Kirschbaum (2016) who respectively argue that stabilization of SAT deviation may not limit heat wave risk or dangerous sea-level rise.

As in Paper 1 we assume that replacement of one technology with another occurs in terms of the logistic law (Akaev, 2015). Consequently we model the dynamics of reduction in CO_2 emission using CCS technologies by a logistic function (cf. Akaev, 2015), in which growth depends on abatement investment. This is a novel approach with respect to most other IAM studies in the climate change mitigation literature, in which technological change is assumed to be independent of public policy; see the discussion in Paper 1, and references therein. In order to take into account the effect of deforestation control, a slightly more complex description of the carbon cycle than on Paper 1 is needed. Consequently, we add here a biomass equation into the CoCEB model and analyze the ensuing feedbacks and their effects on per capita Gross Domestic Product (GDP) growth.

To date, most of the global response and attention — including political and financial commitment — aimed toward combating climate change has been noticeably insufficient and focused primarily on the industrial and energy sectors (Crutzen, 2016; Forsell et al., 2016). In fact, most of the scenario studies that aim to identify and evaluate climate change mitigation strategies (e.g., Morita and Robinson, 2001) focus on the energy sector (Van Vuuren et al., 2006, p. 166) and mostly aim at reducing fossil fuel emissions because they constitute the largest flux driving the global increase of CO_2 (Ciais et al., 2013). Actually, only a subset of current models explicitly model land-use change in scenarios (Clarke et al., 2014). Examples of studies that focus on the energy sector are the "Regional Dynamic Integrated model of Climate and the Economy" and the "Dynamic Integrated model of Climate and the Economy" [RICE and DICE respectively; Nordhaus and Boyer (2000)], which consider emissions from deforestation as exogenous. Nevertheless, greenhouse gas (GHG) emissions from deforestation and current terrestrial uptake are significant and deserve more attention for determining the potential for the success of CO_2 mitigation strategies (Dang Phan et al., 2014; Rakatama et al., 2016). Therefore, including GHG mitigation in the biota sinks has to be considered within IAMs, cf. Wise et al. (2009) and Port et al. (2012).

Several studies provide evidence that forest carbon sequestration can reduce atmospheric CO_2 concentration significantly and could be a cost-efficient way for curbing climate change (e.g., Wise et al., 2009; Eriksson, 2015). In fact, recent studies show that global climate policies should focus on increasing the forest biomass, to sequester and store carbon, rather than increasing the use of forest bioenergy to substitute fossil fuels (Eriksson, 2015). However, it is recognized that there are also trade-offs — between positive and negative effects — associated with controlling deforestation or increasing the forest biomass (Forsell et al., 2016; see also, Sect. 3.4 below). Furthermore, forests reduce the rate at which they accumulate carbon as they age and may be harvested in the future — or affected by disturbances such as fire and insect outbreaks, exacerbated by climate extremes and climate change — thereby re-introducing CO_2 to the atmosphere (Canadell and Raupach, 2008). It is therefore no wonder that, the role of deforestation control as a mitigation option remains a controversial topic in climate policy (McCarl et al., 2007).

Again, most of the earlier studies do not consider the more recent mitigation options currently being discussed in the context of ambitious emission reduction, such as hydrogen and CCS (see Edmonds et al., 2004). Actually, even most of the recent studies in an assessment by Clarke et al. (2014) simply assume that particular high-capital baseload technologies, such as CCS or nuclear power, may not be available. Given current insights into climate risks and the state of the mitigation literature, then, there is a need for comprehensive scenarios that explore different long-term strategies to stabilize GHG emissions at low levels (Morita and Robinson, 2001; Metz and Van Vuuren, 2006).

Our goal — with the above background and motivation — is to build a reduced-complexity model that incorporates the climate–economy–biosphere (CoCEB) interactions and feedbacks, while using the smallest number of variables and equations needed to capture the main mechanisms involved in the evolution of the coupled system. We merely wish to trade greater detail for more flexibility in the analysis of the dynamical interactions between the different variables. The CoCEB model is not a quantitative tool for climate change impacts: it is an exercise in simplicity and transparency — to offer some insights that we hope can inform both policy and future IAM efforts. The modeling framework here brings together and summarizes information from diverse fields in the literature on climate change mitigation measures and their associated costs, and allows comparing them in a coherent way.

In Paper 1, we analyze the abatement share and consider abatement activities to be geared toward investment in increase of overall energy efficiency of the economy and decrease of overall carbon intensity of the energy system. In this paper, we study relevant economic aspects of deforestation control and carbon sequestration in forests, as well as the widespread application of CCS technologies as alternative policy measures for climate change mitigation.

An important caveat, however, is that it is beyond this study to discuss how a reasonable policy, e.g. an appropriate climate change mitigation policy, should look in terms of economic, ethical, philosophical, legal or other arguments. Instead, we seek to put in doubt the assumptions that an increased investment in CCS would go hand in hand with an increased reduction in CO_2 emissions, and a reduction of deforestation would be as effective as investment in low- and zero-carbon or CCS technologies for reducing climate damage; the reader is guided to Jamieson (1991) and Gardiner et al (2010) for an essential reading on environmental philosophy and climate ethics respectively.

We will do this by showing that: (i) low investment in CCS contributes to reducing industrial carbon emissions and to increasing GDP growth, but further investment leads to a smaller reduction in emissions, as well as in the incremental GDP growth. (ii) Enhanced deforestation control contributes to a reduction in both deforestation emissions and atmospheric CO_2 concentration, thus reducing the impacts of climate change and contributing to a slight appreciation of GDP growth, but this effect is very small compared to that of implementing low carbon technologies or CCS. (iii) The result in (i) is very sensitive to the formulation of CCS costs. To the contrary, the results for deforestation control are less sensitive to the formulation of its cost. A large range of hypotheses on CCS costs appears in the literature, and our modeling framework permits to span this range and check the sensitivity of results.

This study will also demonstrate that investment in low-carbon technologies, deforestation control, as well as CCS technologies is essential in limiting warming throughout the 21st century to below 2 °C over pre-industrial levels.

In the next section, we briefly revisit the CoCEB model as developed in Paper 1 for completeness. In Sect. 2.1, we introduce the biomass equation and the effect on the carbon emissions of CCS and of deforestation control. Section 3 presents the numerical simulations and their results. In Sect. 4, we test the sensitivity of the results to the parameters setting the price of CCS and of deforestation control. Section 5 summarizes, discusses the results, and formulates our conclusions with a few caveats and avenues for future research and assessment.

2 Model description

The climate–economy part of the CoCEB model is represented by five variables: per capita physical capital K, per capita human capital H, the average global surface air temperature T, the CO_2 concentration in the atmosphere C, and industrial CO_2 emissions E_Y. These five main variables are governed by a set of nonlinear, coupled ordinary differential equations (ODEs); they are complemented by a number of auxiliary variables, which are connected to them by ODEs and algebraic equations.

The model is reproduced below:

$$\frac{\mathrm{d}K}{\mathrm{d}t} = \mathrm{A}\left[1-\tau(1+\tau_\mathrm{b})-c(1-\tau)\right]K^\alpha H^{1-\alpha} D\left(T-\hat{T}\right)-\left(\delta_\mathrm{K}+n\right)K\,, \tag{1a}$$

$$\frac{\mathrm{d}H}{\mathrm{d}t} = \varphi\left\{\mathrm{A}\left[1-\tau(1+\tau_\mathrm{b})-c(1-\tau)\right]K^\alpha H^{1-\alpha} D\left(T-\hat{T}\right)\right\}-\left(\delta_\mathrm{H}+n\right)H\,, \tag{1b}$$

$$\frac{\mathrm{d}T}{\mathrm{d}t} = \frac{\left(1-\alpha_\mathrm{T}\right)\mathrm{Q}}{4c_\mathrm{h}} - \frac{\varepsilon\tau_\mathrm{a}\sigma_\mathrm{T}}{c_\mathrm{h}}T^4 + \frac{(6.3)\beta_1(1-\xi)}{c_\mathrm{h}}\mathrm{In}\left(\frac{C}{\hat{C}}\right), \tag{1c}$$

$$\frac{\mathrm{d}C}{\mathrm{d}t} = \beta_2 E_\mathrm{Y} - \mu_\mathrm{o}\left(C - \hat{C}\right), \tag{1d}$$

$$\frac{\mathrm{d}E_\mathrm{Y}}{\mathrm{d}t} = \left[g_\sigma + g_\mathrm{Y} + n\right] E_\mathrm{Y}, \tag{1e}$$

with:

$$D\left(T - \hat{T}\right) = \left[1 + m_1\left(T - \hat{T}\right)^\chi\right]^{-1}, \qquad \text{(Damage function)} \tag{2}$$

$$\sigma = f_\mathrm{c}\left[1 - \frac{r\exp(\psi t)}{1 + r\left(\exp(\psi t) - 1\right)}\right]\left[c_{-\infty} + \frac{a_\mathrm{c}}{1 + r\exp(-\psi t)}\right], \qquad \text{(Carbon intensity)} \tag{3}$$

$$\psi = \psi_0\left\{1/\left[1 - \alpha_\tau \tau_\mathrm{b}(1 - f)\right]\right\}, \qquad \text{(Energy intensity parameter)} \tag{4}$$

$$g_\sigma = \frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}t}, \qquad \text{(Growth of carbon intensity, } \sigma\text{)} \tag{5}$$

$$g_\mathrm{Y} = \alpha g_\mathrm{K} + (1 - \alpha) g_\mathrm{H} + \frac{1}{D}\frac{\mathrm{d}D}{\mathrm{d}T}\frac{\mathrm{d}T}{\mathrm{d}t}, \qquad \text{(Growth rate of per capita output, } Y\text{)} \tag{6}$$

$$g_\mathrm{K} = \frac{1}{K}\frac{\mathrm{d}K}{\mathrm{d}t}, \qquad \text{(Growth rate of per capita physical capital, } K\text{)}$$

$$g_\mathrm{H} = \frac{1}{H}\frac{\mathrm{d}H}{\mathrm{d}t}. \qquad \text{(Growth rate of per capita human capital, } H\text{)}$$

The evolution of human population is precomputed using the following equations:

$$\frac{\mathrm{d}L}{\mathrm{d}t} = nL\left\{1 - \exp\left[-\left(L/L(1990)\right)\right]\right\}, \qquad \text{(Human population)} \tag{7}$$

$$\frac{\mathrm{d}n}{\mathrm{d}t} = \left(\frac{1}{1 + \delta_\mathrm{n}} - 1\right)n. \qquad \text{(Human population growth rate)} \tag{8}$$

For other parameters definitions and values, and all other details, the reader is referred to Paper 1.

2.1 Active biomass and carbon capture and storage (CCS) inclusion

2.1.1 Inclusion of CCS in the industrial CO_2 emissions equation

Fossil fuels — the main source of CO_2, which is, at the same time, the most common and important gas among the GHG (Chen et al., 2017) — are expected to remain the dominant source of energy for decades to come (Scott et al., 2013). On the other hand, there is uncertainty regarding future deployment of large-scale low-carbon technologies (Akashi et al., 2014). As a result, the as-yet-unproven CCS technologies provide a *tentative solution* — under a precautionary perspective — for continued use of fossil fuels, until the technology to transition to more sustainable energy sources is developed (Herzog, 2001). These energy intensive and expensive technologies are end-of-pipe controls removing pollutants without affecting the emission-producing activity itself (Rao et al., 2016; Raufer et al., 2017). There are several studies in the CCS literature — see e.g., Gale and Kaya (2003) and Kalkuhl et al. (2015) — addressing the problem of capturing CO_2 released during fossil fuel combustion. These studies tend to assume that a certain part of this CO_2 is caught and bound using a special technology for further storing in order to reduce CO_2 emissions into the atmosphere. We similarly assume the same in this paper in accordance with previous literature; see also Keith et al. (2006) for an insightful study about air capture — a form of technology which removes the CO_2 directly from the atmosphere. The reader is also referred to Reiner (2016) for an overview of recent CCS developments and to Kuckshinrichs and Hake (2015) for an integrated technology study discussing and assessing the technical, economic, environmental, and social perspectives of CCS technologies.

In Paper 1, the formulation of industrial CO_2 emissions uses the Kaya–Bauer identity (Kaya, 1990; Bauer, 2005), in which the CCS growth term g_{ccs} is set equal to 0 (cf. Eq. 1e above), so that $E_Y = E_{tot}$. Now, we consider the full identity, with $g_{ccs} \neq 0$; thus Eq. (1e) becomes:

$$\frac{dE_Y}{dt} = \left[g_\sigma + g_Y + n + g_{ccs} \right] E_Y \, . \tag{9}$$

In order to express the term g_{ccs}, and for simplicity purposes, we also assume the leakage of captured carbon to be zero — see also Bauer (2005, pp. 97 and 241) and Ha-Duong and Loisel (2009), with the latter authors concluding that zero is the only acceptable leakage rate — and use Akaev's (2015) formula to define the reduction of emissions by the CCS as a fraction κ_{ccs}:

$$\kappa_{ccs} = \frac{2\exp(-\omega t)}{1+\exp(-\omega t)} \, . \tag{10}$$

In this equation, $\omega = \omega_0 \left\{ 1 - \left[1/\left(1+\alpha_\omega \tau_b f\right) \right] \right\}$, with ω_0 and α_ω constant, and the parameter f represents the share of investment in CCS; the investment in low- and zero-carbon technologies is $1-f$ and appears in the energy intensity parameter ψ in Eq. (4). Taking the natural logarithms and differentiating both sides of Eq. (10), we get the growth rate of κ_{ccs} as

$$g_{ccs} = \frac{(-\omega)}{\left[1+\exp(-\omega t)\right]} \, . \tag{11}$$

Cost of CCS

There is uncertainty regarding the costs of carbon capture, transportation and storage (Morita and Robinson, 2001; IPCC, 2005, p. 354; Kalkuhl et al., 2015). The total cost of abating carbon through CCS is subject to research: very diverse estimates have been reported in the recent literature. These estimates span the wide range given by USD 71–615 $(tC)^{-1}$ by the year 2100 (McFarland et al., 2004; Riahi et al., 2004; IPCC, 2005; Van Vuuren et al., 2006, p. 271, Table F.1; Bosetti, 2010; Metz, 2010, p. 141; Al-Fattah et al., 2011, p. 296; Stephenson, 2013, p. 132; IPCC, 2014, p. 770; Kalkuhl et al., 2015); here and elsewhere, we use dollar amounts normalized as USD_{1990}.

The estimated CO_2 emissions reduction due to CCS for the time interval 2020–2050 is 0.0038–0.7 GtC yr^{-1} (IPCC, 2005; Bosetti, 2010; Galiana and Green, 2010). Metz (2010, p. 216), on the other hand, projected the 2030 CCS reduction potential of CO_2 emissions at 0.0273–0.0545 GtC yr^{-1} with a possibility of growing to 0.1364–0.409 GtC yr^{-1} by 2050; see also Uyterlinde et al. (2006).

Keeping in mind this range of emissions reduction and of prices, we calibrate the parameter α_ω in that affects ω in Eq. (10) above, in order to obtain similar values. For $\alpha_\omega = 46.1$, the scenario (see Sect. 3.3 below) corresponding to the abatement share $\tau_b = 0.075$ and with f = 1.0, gives aggregate carbon emissions reduction from Business As Usual (BAU) of 0.4 GtC yr^{-1} by 2050 and 0.17 GtC yr^{-1} by 2100. This emissions reduction comes at an approximate aggregate cost of USD 124 $(tC)^{-1}$ by 2050 and USD 558 $(tC)^{-1}$ by 2100. The cost is computed as $fG_E L = f\tau_b \tau Y L$, i.e. the product of the share of investment in CCS (in this case f = 1.0) and the aggregate abatement costs; see Eq. (5) in Paper 1, and Eq. (4) above. These costs lie within the range of the CCS costs in the literature, as given above. Given the large uncertainty in this range of costs — see also Hannart et al. (2013) and Wesselink et al. (2015) for insightful uncertainty assessments — we conduct in Sect. 4.1 below a sensitivity study to changes in the α_ω value.

2.1.2 Inclusion of a biosphere module: CO_2-biomass interactions

Uzawa (1991, 2003) extends the analysis of the CO_2 cycle by including forests, represented by a state variable B (biomass). Biomass absorbs CO_2, so that an additional carbon sink appears in Eq. (1d). Thus, the forest acreage augments the absorption of CO_2 from the atmosphere. The only function of the stock of biomass in Uzawa's work was to sequester CO_2 and its stock could only be increased by net forestation activities, which use constrained resources. We did include here, though, the benefits of CO_2 fertilization, as suggested by Rosenberg (1991) in his commentary to Uzawa's (1991) paper.

In order to include fertilization effects in the Uzawa model, Van Wassenhove (2000) proposes a model of the interaction between biomass and CO_2 that is an adaptation of the Lotka–Volterra predator–prey model (Lotka, 1925; Volterra, 1931). Including fertilization effects and deforestation, our system of equations for this adaptation is:

$$\frac{\mathrm{d}B}{\mathrm{d}t} = g_{\mathrm{b}} B\left(1 - \frac{B}{\Lambda_{\mathrm{b}}}\right) + \gamma_{\mathrm{b}} B\left(C - \hat{C}\right) - \mathrm{d}_{\mathrm{for}}, \tag{12}$$

$$\frac{\mathrm{d}C}{\mathrm{d}t} = \beta_2\left(E_{\mathrm{Y}} + E_{\mathrm{B}}\right) - \mu_{\mathrm{o}}\left(C - \hat{C}\right) - \gamma_{\mathrm{b}} B\left(C - \hat{C}\right), \tag{13}$$

where C is the CO_2 concentration in the atmosphere, B is the terrestrial photosynthetic biomass, Λ_{b} is biomass carrying capacity, g_{b} is the intrinsic colonization rate, and γ_{b} is the fertilization parameter. The term d_{for} stands for deforestation efforts and E_{B} denotes emissions from deforestation, both these are defined in the next subsection. Here E_{Y} are industrial emissions as in Eq. (9), and $\hat{C}$ the pre-industrial concentration of atmospheric CO_2.

Equation (13) is not different from the CO_2 equation of Paper 1; cf. Eq. (1d) above, apart from the addition of the fertilization term. In this case, the "excess" CO_2 is absorbed into the ocean (second term on the right-hand side of Eq. 13) but also into the terrestrial biomass (third term on the right-hand side of Eq. 13). Biomass change and CO_2 sequestration – via photosynthesis – is represented by the logistic Eq. (12) described by Clark (2010) as a population growth model.

Carbon flux from deforestation and deforestation control

This section follows the work of Eriksson (2015) who investigates the role of the global forest in an IAM of the climate and the economy — FOR-DICE. In that work, deforestation does not change the growth rate but leads to a smaller stock of biomass — which is subject to that growth — as well as to a smaller carrying capacity, i.e., a smaller area where forest can potentially re-grow.

Deforestation is formulated in terms of forest biomass volume and not in terms of land area. The maximum forest biomass carrying capacity is modeled to decrease with deforestation as follows:

$$\frac{\mathrm{d}\Lambda_{\mathrm{b}}}{\mathrm{d}t} = -\frac{\Lambda_{\mathrm{b}}}{B}\mathrm{d}_{\mathrm{for}}, \tag{14}$$

where d_{for} is deforestation effort, as in Eq. (12), while the fraction Λ_{b}/B is a rescaling to convert biomass deforestation into biomass carrying capacity.

Deforestation is considered exogenous; we model it in our CoCEB model in agreement with Nordhaus and Boyer (2000), who prescribe carbon emissions from deforestation to decrease in time according to:

$$E_{\mathrm{B}} = \left[E_{\mathrm{B0}} \exp\left(-\delta_{\mathrm{b}} t\right)\right]\left(1 - R_{\mathrm{d}}\right), \tag{15}$$

where the parameter E_{B0} represents the initial carbon emission, δ_{b} is the rate of decline of deforestation emissions, and $R_{\mathrm{d}} \geq 0$ is the deforestation control rate. These emissions can be converted into biomass deforestation by means of a global carbon intensity parameter θ_{for} (Eriksson, 2015). The carbon intensity parameter, in this case, represents the average amount of carbon per volume of growing forest biomass. The total biomass deforestation in GtC at any time period is then given by

$$d_{\mathrm{for}} = \left[\frac{E_{\mathrm{B0}}}{\theta_{\mathrm{for}}}\exp(-\delta_{\mathrm{b}}t)\right](1-R_{\mathrm{d}}) . \tag{16}$$

When $R_{\mathrm{d}} = 0$, we have the baseline deforestation. The deforestation control rate can either reduce or increase deforestation. When net deforestation is prevailing, $d_{\mathrm{for}} > 0$ or $0 \le R_{\mathrm{d}} < 1$, and when net afforestation or reforestation is prevailing, $d_{\mathrm{for}} < 0$ or $R_{\mathrm{d}} > 1$.

The total carbon emissions are hence assumed here to be the sum of industrial fossil fuel use emissions E_{Y} from Eq. (9) and of deforestation emissions E_{B} from Eq. (15).

Cost of the deforestation activity

The rental cost — that is, the rental payment to the landowner to hinder conversion of forested land — of avoiding direct release of carbon in one time period is given by the marginal cost function (Kindermann et al., 2008; Eriksson, 2015):

$$\bar{V}_{\mathrm{mc}} = \pi_1 (R_{\mathrm{e}})^{\pi_2} + \left\{[\pi_3 + \pi_4 t]^{(\pi_5 R_{\mathrm{e}})} - 1\right\} , \tag{17}$$

where the π's are the estimated cost parameters and R_{e} is the reduction of direct carbon emission from deforestation. From Eq. (15) this reduction is given by

$$R_{\mathrm{e}} = \left[E_{\mathrm{B0}} \exp(-\delta_{\mathrm{b}} t)\right] R_{\mathrm{d}} . \tag{18}$$

The marginal cost or R_{d} increases with the level of reduction of carbon emission due to deforestation. The land under forest is assumed to carry primarily a low opportunity cost. As more land under forest is targeted for deforestation control, its opportunity cost and hence its marginal cost increases over time. This is due to the fact that as the deforestation level declines, the land under forest that remains carries a high opportunity cost.

The total cost of avoiding deforestation can be written as

$$\frac{\mathrm{d}\bar{V}}{\mathrm{d}t} = \int_t \bar{V}_{\mathrm{mc}}(s)\, ds . \tag{19}$$

Rental payment occurs each time period and land under forest saved from conversion will not be deforested in future time periods. We assume forested land conversion, for example to agricultural land, as an investment in the primary input land, viewing land in the capital stock as a representative for the capital value of land devoted to production of non-forest goods.

The physical capital is hence assumed to grow with investment in land, i.e., conversion of land to agricultural land and urbanization or infrastructure. Deforestation is mainly caused by these two types of conversions, and hence the physical capital increases with deforestation. The accumulated investment in land is here assumed to be implicit in the total physical capital and does not affect the development of the total physical capital when following the baseline deforestation pattern. Reducing the baseline deforestation is here equivalent to a disinvestment of land capital resulting in a smaller net investment in the total physical capital. The per capita cost of avoiding deforestation is thus $V = \bar{V}/L$.

Through a meta-analysis of published works, Dang Phan et al. (2014) estimate the cost of carbon emissions reduction due to deforestation control to range from USD 0.11 $(\mathrm{tC})^{-1}$ to USD 246 $(\mathrm{tC})^{-1}$ with a mean of USD 19 $(\mathrm{tC})^{-1}$; see also Rakatama et al. (2016). Actually, Kindermann et al. (2008) use three economic models of global land use and management — Global Timber Model (GTM), Dynamic Integrated Model of Forestry and Alternative Land Use (DIMA), and Generalized Comprehensive Mitigation Assessment Process Model (GCOMAP) — to analyze the economic potential contribution of deforestation control activities to reduced GHG emissions. The latter authors find that a 10 % deforestation control could be feasible within the context of current financial flows.

Following latter result, we assume $R_{\mathrm{d}} = 0.1$ as the standard value in this study, but will test the robustness of our results by also using other R_{d} values. In the CoCEB model, with 100 % investment in low- and zero-carbon technologies and with

$\tau_b = 0.075$, the value of $R_d = 0.1$ gives an approximate aggregate cost of deforestation emissions reduced of USD 164 $(tC)^{-1}$ by 2100. We notice that the CoCEB total cost for $R_d = 0.1$ is within the range of deforestation control costs given by Dang Phan et al. (2014).

Finally, including the biosphere module and deforestation control, the evolution of total per capita physical capital accumulation K in Eq. (1a) can be written as

$$\frac{dK}{dt} = A[1-\tau(1+\tau_b)-c(1-\tau)]K^{\alpha}H^{1-\alpha}D(T-\hat{T})-(\delta_K+n)K-V. \tag{20}$$

Given the large uncertainty of the estimated cost of deforestation control, a sensitivity analysis to the values of the parameters in Eq. (17) is performed in Sect. 4.2 below.

2.2 Summary: CoCEB, the Coupled Climate–Economy–Biosphere model

The model is now described by equations (1b), (1c), (9), (12), (13), and (20). The equations are grouped for the reader's convenience below:

$$\frac{dK}{dt} = A[1-\tau(1+\tau_b)-c(1-\tau)]K^{\alpha}H^{1-\alpha}D(T-\hat{T})-(\delta_K+n)K-V, \tag{21a}$$

$$\frac{dH}{dt} = \varphi\left\{A[1-\tau(1+\tau_b)-c(1-\tau)]K^{\alpha}H^{1-\alpha}D(T-\hat{T})\right\}-(\delta_H+n)H, \tag{21b}$$

$$\frac{dT}{dt} = \frac{(1-\alpha_T)Q}{4c_h}-\frac{\varepsilon\tau_a\sigma_T}{c_h}T^4+\frac{(6.3)\beta_1(1-\xi)}{c_h}\ln\left(\frac{C}{\hat{C}}\right), \tag{21c}$$

$$\frac{dC}{dt} = \beta_2(E_Y+E_B)-\mu_o(C-\hat{C})-\gamma_b B(C-\hat{C}), \tag{21d}$$

$$\frac{dB}{dt} = g_b B\left(1-\frac{B}{\Lambda_b}\right)+\gamma_b B(C-\hat{C})-d_{for}, \tag{21e}$$

$$\frac{dE_Y}{dt} = [g_\sigma+g_Y+n+g_{ccs}]E_Y. \tag{21f}$$

The parameters used in the model are as described in Paper 1, in this study and are continued in Table 1 below.

3 Numerical simulations and abatement results

3.1 Experimental design

As in Paper 1, we confine our investigations to the transition path for the next 110 years from the baseline year 1990. In Paper 1, we studied the abatement share and how investment in low-carbon technologies affected industrial carbon emissions. We now consider the effect of including CCS technologies as well as biomass and deforestation control into the model. The goal is to understand how the different mitigation measures compare and which is more effective.

The scenarios studied herein are summarized in Table 2. We perform 33 integrations: the first is a control integration, with biomass evolution included but no CCS and no deforestation control. This run is equivalent to a Business as Usual (BAU) simulation in the IPCC terminology, but not the same as the BAU run described in Paper 1. The difference lies in the presence of interactive biomass that exchanges carbon with the atmosphere.

Next we perform 12 integrations using CCS investments but no deforestation control, $R_d = 0$. The 12 runs correspond to a matrix of four values of the share f of investment in CCS, f = 0, 0.3, 0.6, and 1.0, times three values of total abatement share τ_b, τ_b = 0.075, 0.11, and 0.145. Last, 20 integrations with inclusion of deforestation control are performed; they correspond to a matrix of five values each of deforestation control R_d = 0, 0.1, 0.5, 1.0, and 1.2, times four values of abatement share τ_b = 0, 0.075, 0.11, 0.145, with the share of investment in CCS f = 0.

The values of CO_2 emissions and concentration, biomass, temperature, damage and GDP growth at the end of the integrations (year 2100) are shown in Tables 3–5, respectively, for the BAU runs, the CCS runs, and the deforestation control runs.

3.2 Control integration

In Table 3, a summary of the behavior of the BAU integration with inclusion of the biomass is shown. The results of the BAU integration of Paper 1 (reported in the 1st line of the table for comparison) and in the present paper's BAU are qualitatively similar, yet the new BAU has CO_2 emissions of 34 GtC yr^{-1} by year 2100. This is an increase of approximately 4.7 from the 29.3 GtC yr^{-1} of the BAU of Paper 1. From our calculations (not shown) industrial CO_2 contributes to about 92 % of this increment, due to increased per capita GDP growth, while emissions from deforestation, which are declining over time, contribute about 8 % — agreeing quite well with current scientific literature; see e.g., Ciais et al. (2013) and Forsell et al. (2016).

There is no contradiction in the fact that these higher CO_2 emissions are accompanied by lower temperature increase. The increase of emissions is due to the appreciation in per capita GDP, in turn due to a decrease in atmospheric CO_2 through its sequestration owing to biomass fertilization and hence a decline in global SAT and consequently damages. Atmospheric CO_2 decreases from 1842 GtC to 1729 GtC, i.e., about 113 GtC by 2100, which implies a sequestration of approximately 1 GtC yr^{-1} between 1990 and 2100. Our model is in fair agreement with the estimate of Ni et al. (2016); see also Scott (2014).

The model also agrees with Mackey et al.'s (2013) claims that the capacity of terrestrial ecosystems to store carbon is finite and therefore avoiding emissions from land carbon stocks and refilling depleted stocks reduces atmospheric CO_2 concentration, but the maximum amount of this reduction is equivalent to only a small fraction of potential fossil fuel emissions.

3.3 Using CCS methods but no deforestation control

The effects of including CCS into the model, via a fraction f of the total abatement share τ_b, are summarized in Table 4. Deforestation control is not implemented in these runs, $R_d = 0$. Note that the first column of Table 4 repeats for comparison the results of the new BAU run of Table 3; since the abatement share $\tau_b = 0$ in this column, the same results are obviously obtained for all values of the share of investment in CCS f.

On the other hand, when the share of investment in CCS f = 0, i.e. for the first row of Table 4, all the abatement share goes into investment in low- and zero-carbon technologies as in Paper 1; varying the value of the abatement share τ_b in this case, we obtain results that are qualitatively similar to those obtained in Paper 1, although not exactly equal to them, due to the inclusion of the interactive biomass.

The inclusion of CCS investment tends to reduce industrial CO_2 emissions from BAU. When the share of investment in CCS is increased (f = 0.3, second row), one notes that for the abatement share $\tau_b = 0.075$, the 2100 deforestation emissions are 0.4 GtC yr^{-1} (value in parentheses) while industrial CO_2 emissions slightly decrease. This contributes to a slight decline in SAT and consequently, to a small increment in per capita GDP. Further investment share in CCS, namely f = 0.6 and 1.0, causes CO_2 emissions to increase back slightly. This increase, in turn, contributes to a small increment in SAT and consequently, to a slight decline in per capita GDP.

From the table, we notice that 100 % investment in CCS, i.e. f = 1.0, is slightly less efficient than the combined investment in both low- and zero-carbon technologies and CCS technologies. A higher rate of GDP growth is observed when f = 0.3 and $\tau_b = 0.075$. This corresponds to total emissions reduction from BAU of approximately 0.19 GtC yr^{-1} at a total CCS cost of about USD 149 (tC)$^{-1}$ by 2100. This cost is within the range of the cost of CCS as given in the literature, cf. Section "Cost of CCS" and references there. Note that more investment in CCS (f = 0.6 and 1), along with an increasing abatement share (τ_b = 0.11 and 0.145), also contributes to a decline in per capita GDP growth rate from what is found in the f = 0.3 row and $\tau_b = 0.075$ column.

In the f = 1.0 row, we note that inclusion of CCS without abatement in the energy sector also has potential for global change mitigation, although a little less efficiently.

In Fig. 1, the time-dependent evolution of the reduction in CO_2 emissions from BAU for the different values of f is shown, from 1990 to 2100, keeping the deforestation control equal to 0. Figure 1a shows that initial investment in CCS of 30 %, when the abatement share is $\tau_b = 0.075$, leads to CO_2 emissions that are below control by 2100. Further investment in CCS, of 60 and 100 % respectively, leads to an initial reduction, followed by an increment in CO_2 emissions by 2100. We also note that, with an increased abatement share of τ_b = 0.11 (Fig. 1b) and 0.145 (Fig. 1c), this effect is amplified, i.e. the emissions decrease at the beginning and then increase even more by 2100. This result agrees quite well with other studies in the literature (e.g., Kalkuhl et al., 2015; Rao et al, 2016).

3.4 Integrations with inclusion of deforestation control

In Table 5, the CCS investment share is taken to be 0 and we analyze the effect of increasing deforestation control with different values of the abatement share τ_b, in the absence of CCS investments, f = 0. We first consider the $\tau_b = 0.075$ column and note that, generally, an increase of deforestation control R_d contributes to an increase of biomass; such an increase, in turn, contributes to the sequestration of atmospheric CO_2 due to photosynthesis, as evidenced by the reduction in the $C/\hat{C}$ ratio.

For instance, we note that increasing deforestation control R_d from 0 to 1.2 gives a per annum sequestration of atmospheric CO_2 of 0.26 GtC yr^{-1} between 1990 and 2100. Comparing with other studies on biomass photosynthetic sequestration of atmospheric CO_2 due to afforestation, this particular annual amount of CO_2 fertilization agrees quite well with the average range of 0.16–1.1 GtC yr^{-1} by 2100 in Canadell and Raupach (2008), and with the range of 0.1–0.4 GtC yr^{-1} obtained by Luo and Mooney (1996); see also Polglase et al. (2013), Canadell and Schulze (2014) and Scott (2014).

The reduction in atmospheric CO_2 due to biomass photosynthesis contributes to a slight attenuating effect on SAT (see also Port et al., 2012) and consequent damages. These reductions actually increase the GDP growth slightly. The improvements due to deforestation control R_d are nevertheless small compared to the effect of low- and zero-carbon technologies or CCS; see also Canadell and Schulze (2014) and Tokimatsu et al. (2016). In accordance with our results, Canadell and Schulze (2014) also conclude that with current technologies, the potential for land mitigation is significant, but relatively small when compared with the overall mitigation requirements for climate stabilization.

It has to be said, however, that besides reducing carbon emissions or generating sequestration gains, reduced deforestation also delivers other benefits, such as cleaner water, biodiversity conservation with enhanced hunting opportunities, watershed and soil quality protection, increased recreational land, a potential decrease in the prevalence and distribution of a large number of vectorborne diseases, and reduced insect-driven deforestation (Gitz et al., 2006; McCarl et al., 2007; Dunn and Crutchfield, 2009; Kitayama, 2013; Dang Phan et al., 2014; Eriksson, 2015; Ebi et al., 2016). Elbakidze and McCarl (2004) show that such co-benefits might represent 50 to 78 % of the cost of sequestration for the United States of America. Moreover, Liang et al. (2016) estimate the economic value of global biodiversity due to forest conservation — excluding the contribution of forest biodiversity to carbon sequestration, wildlife habitat, and aesthetic and cultural values — to be more than six times the conservation cost. We implicitly contend that inclusion of these multiple socio-economic benefits remove the doubt that reduction of deforestation is as effective as low- and zero-carbon or CCS technologies in mitigating and ameliorating climate change; see also Canadell and Raupach (2008), Rao et al. (2016) and Seddon et al. (2016). However, since there is no credible comprehensive study of these latter side effects at a world level (Gitz et al., 2006; Seddon et al., 2016), we do not account for them in the present version of our CoCEB model. In fact, little attention has been paid so far in the literature — and mainstream decision-making — to the presence of these co-benefits of deforestation control when calculating its cost (Dang Phan et al., 2014, Table 1; Seddon et al., 2016). Whereas, land opportunity costs could be in part offset by the economic co-benefits of deforestation control (Gitz et al., 2006).

3.5 A mix of mitigation measures

Even though it is beyond this study's ability to predict a realistic international emissions mitigation regime, CoCEB simulations suggest that best results — due to comparatively improved per capita GDP growth together with decreased CO_2 emissions — are obtained by combining the various mitigation measures discussed. This is found in Table 4 and Fig. 1, where we note that 100 % investment in CCS or low- and zero-carbon technologies is slightly less efficient than the combined investment in both technologies.

For illustration purposes, we choose now a 30 % investment in CCS technologies and a deforestation control of $R_d = 0.1$, while the other parameter values are as in Table 1. The values of CO_2 emissions and concentration, temperature, damage and GDP growth at year 2100 are shown in Table 6 for the four scenarios corresponding to the abatement share τ_b = 0, 0.075, 0.11 and 0.145. From the table, the scenario corresponding to $\tau_b = 0$ attains total emissions of 34.2 GtC yr^{-1} by 2100. This leads to an atmospheric CO_2 concentration of 1727 GtC, i.e. about 2.9 times the pre-industrial level at that time. As a consequence, global average SAT will rise by 4.9 °C from the pre-industrial level with a corresponding damage to the per capita GDP of 24.4 % and a GDP growth of 1.42 %. This compares well with the results of IPCC's Representative Concentration Pathway (RCP) 8.5 scenario (Riahi et al., 2007; IPCC, 2013, p. 23, Table SPM.2 and p. 27, Table SPM.3) and the impacts, adaptation, and vulnerability (IAV) community's Shared Socio-economic Pathway (SSP) 3 scenario (Riahi et al., 2017).

For the scenarios corresponding to abatement share τ_b = 0.075, 0.11 and 0.145, the results obtained in Table 6 are slightly better than those in Table 4 when the share of investment in CCS f = 0 or 1.0. We also note that, for abatement share $\tau_b = 0.075$ and 0.11, the CO_2 emissions per year, as well as the CO_2 concentrations and SAT deviations from pre-industrial levels in year 2100, agree fairly well with the IPCC's RCP6.0 and RCP4.5 respectively (Hijioka et al., 2008; Wise et al., 2009; IPCC, 2013, p. 23, Table SPM.2 and p. 27, Table SPM.3) and the IAV's SSP2 and SSP1 respectively (Riahi et al., 2017).

It is also noted in Table 6 that for the scenario corresponding to the highest abatement share $\tau_b = 0.145$, the global anthropogenic GHG emissions reduction via investment in low- and zero-carbon technologies, deforestation control, as well as CCS technologies limits temperature change over the course of the 21st century to below 2 °C above pre-industrial levels without a temporal overshoot; see also Akaev (2015). This is unlike most emission pathways labeled as 2 °C scenarios which allow for a temporal overshoot in SAT and a decline below 2 °C by 2100 (Clarke et al., 2014). Our analysis also suggests that the most ambitious emissions policy considered here — which limits SAT over the course of the 21st century to below a 2 °C temperature rise target — reduces impacts to the per capita GDP by 21.8 % by 2100 relative to the BAU pathway which reaches 4.9 °C. This agrees quite well with current literature on global assessment of the effects of climate policy on the impacts of climate change (see e.g., Arnell et al., 2013).

Figure 2 plots the per capita GDP growth curves with time for the share of investment in CCS f = 0 and deforestation control $R_d = 0$ scenario (Fig. 2a) and for the share of investment in CCS f = 0.3 and deforestation control $R_d = 0.1$ scenario (Fig. 2b). In both panels, we notice that per capita GDP growth on the paths with nonzero abatement share, $\tau_b \neq 0$, lies below growth on the BAU path, i.e., when using $\tau_b = 0$, for the earlier time period, approximately between 1990 and 2060 in Fig. 2a and approximately between 1990 and 2058 in Fig. 2b.

Later though, as the damages from climate change accumulate on the BAU path, GDP growth in the BAU scenario slows down and falls below the level on the other paths, i.e. the paths cross and mitigation strategies pay off in the longer run. We also observe that the growth in Fig. 2b — with 30 % investment in CCS technologies and 70 % investment in low- and zero-carbon technologies, together with a deforestation control of 10 % — is slightly higher than that in Fig. 2a.

4 Sensitivity analysis

The estimates for the cost of CCS and of deforestation control are still very uncertain in the mitigation literature. For this reason, we conduct an analysis to ascertain the robustness of the CoCEB model's results and to clarify the degree to which they depend on two key parameters: the CCS abatement efficiency parameter α_ω, and the π parameters of Eq. (17). These parameters effectively govern the cost of CCS and of deforestation control. The values of these parameters are varied below in order to gain insight into the extent to which particular model assumptions affect our results.

4.1 Robustness to changes in the CCS abatement efficiency parameter α_ω

We modify the value of the abatement efficiency parameter α_ω by −84 and +84 % from the standard value of $\alpha_\omega = 46.1$ used in Tables 1–6 above, and examine in Table 7 how that affects the model emissions reduction and the GDP growth from BAU by the year 2100. The idea is to check how the results are affected by the hypothesis that the costs of CCS were much higher or much lower than the ones used here, and compared to the cost uncertainties found in the literature. The low value of the abatement efficiency parameter α_ω is equivalent to USD 615 $(\mathrm{tC})^{-1}$ by 2100, while the high value is equivalent to USD 548 $(\mathrm{tC})^{-1}$; these values agree quite well with those given in the literature, cf. Section "Cost of CCS" and references there. We recall once more that the costs everywhere in this paper are expressed in constant 1990 USD.

Each entry in the table — for total emissions reduced, CCS abatement cost, and the per capita GDP growth — appears as three numbers: the standard integrated values for the abatement efficiency parameter $\alpha_\omega = 46.1$ (in parentheses) in the middle, the modified values for the standard +84 % on the left-hand side, and the modified values for the standard −84 % on the right-hand side. From the observed span of the expected values, we notice that in the case of cheap CCS, at USD 548 $(\mathrm{tC})^{-1}$, the share of investment in CCS $f = 1.0$ case gives more or less the same emissions reduction and GDP growth as the share of investment in CCS $f = 0$.

Comparing the efficiency of CCS and low- and zero-carbon technologies, which depend on their cost estimation, we note that given the uncertainties (see also, Wesselink et al., 2015), low- and zero-carbon can be either slightly more efficient or equally efficient. The qualitative result that a mix of the two is better than 100 % of the one or 100 % of the other is quite robust; see also Akashi et al. (2014), Kalkuhl et al. (2015) and Rao et al. (2016).

4.2 Robustness to changes in the deforestation control cost parameters

Taking abatement share $\tau_b = 0.075$, the share of investment in CCS $f = 0.3$, and with the standard values (given in Table 1) of the deforestation control R_d cost parameters π_1, π_2, π_3, π_4, and π_5, we note that by increasing deforestation control R_d from 0 to 0.1, the deforestation emissions are reduced from approximately 0.4 to 0.3 GtC yr^{-1} at a total cost of USD 164 $(\mathrm{tC})^{-1}$, while the per capita GDP growth would be of 2.40 % yr^{-1} by 2100.

We now vary simultaneously the deforestation control R_d cost parameters from the standard values so as to span the range of costs given by Dang Phan et al. (2014). A variation of −99 % gives a total cost of USD 0.9 $(\mathrm{tC})^{-1}$ and that of +47 % gives a total cost of USD 246 $(\mathrm{tC})^{-1}$. Even using these two extreme values, no significant effect is observed on the integration of the CoCEB model. The results in both cases only differ from Table 6 in the third decimal place.

5 Conclusions and way forward

5.1 Summary

In this paper we describe the completion of the CoCEB model by the addition of the biomass equation and the related exchanges of CO_2. This allows analyzing the effect of carbon capture and storage technologies and of deforestation control in the coupled climate–economy–biosphere model. As in Paper 1, we assume the hypothesis that the current global warming is caused largely by anthropogenic increase in the CO_2 concentration in the Earth's atmosphere. We also assume that all nations participate in carbon emissions mitigation activities. But as of now, there are no effective international agreements to limit the emissions of CO_2 and other GHGs (Nordhaus, 2013, p. 11; Tomlinson, 2015, p. 1; Kowarsch, 2016; Van der Gaast, 2017). In fact, while stabilization of CO_2 would require a 60–80 % reduction in current global anthropogenic CO_2 emissions, they instead have been increasing, further increasing the required emission restrictions (Crutzen, 2016). There also has been growing doubts, and enormous political and public debate, regarding the practicality of significant carbon emission reductions to be achieved in practice due to technical, economic, social, or political barriers (Miller, 2013; Klimenko et al., 2016; Reiner, 2016; Van der Gaast, 2017).

This extended version of the CoCEB model is used here to investigate the relationship between the long-term effects of using CCS and deforestation control, and the long-term growth rate of the economy under threat from climate change–related damages. The abatement share and investment in low- and zero-carbon technologies was considered in Paper 1. The framework developed allows one to investigate policy sensitivity to the choice of key parameters. We analyze in particular the effect of the parameters setting the costs of the different means of climate change mitigation: in the present work, the parameter values tested span the range of cost values found in the mitigation literature.

This study indicates that an increased investment in CCS will not suffice to reduce CO_2 emissions, and that a reduction of deforestation would be as effective as investment in low- and zero-carbon or CCS technologies for reducing climate damage. This paper also demonstrates that with an eye toward global efforts to mitigation climate change, the $\tau_b = 0.145$ scenario provides an optimistic note: it indicates that a combined investment in low-carbon and CCS technologies, as well as deforestation control guarantees a deviation from pre-industrial SAT that is substantially less than 2 °C on the entire transition path from now to 2100. In accordance with Canadell and Schulze (2014), Clarke et al. (2014), Nature Editorial (2014), Kalkuhl et al. (2015) and Rao et al. (2016), this mitigation regime illustrates that potential pathways to climate stabilization require the deployment of a broad portfolio of solutions to increase energy efficiency, replace fossil fuel use and remove GHGs.

We find that per capita GDP growth on the paths with nonzero abatement share lies below growth on the Business as Usual (BAU) path for the earlier time period, approximately for 1990 to 2060, while GDP growth in the BAU scenario slows down and falls below the level on the other paths, i.e. the paths cross and mitigation strategies pay off in the longer run; see also Admiraal et al. (2016, Fig. 4). One thing is highly likely, if the world continues on its present course, i.e., business-as-usual, then disaster is imminent: the costs of reducing emissions enough to limit global warming to 2 °C may be high but doing so will provide certain obvious benefits that will clearly outweigh the costs (Fulton, 2016; Obama, 2017; Van den Bergh, 2017). This kind of future already provide an impetus to act, otherwise, deferring the decision to act forecloses options for creating a better future, for avoiding a collision course with the natural world, which supports us all; see also Nordhaus (2013, p. 11) and Raufer et al. (2017).

5.2 Discussion

In the climate modeling literature, the role of a full hierarchy of models, from the simplest to the most detailed ones, is well understood (e.g., Schneider and Dickinson, 1974; Ghil, 2001, 2016, and references therein). There is an even greater need for such a model hierarchy to deal with the higher-complexity problems at the interface of the physical climate sciences and of socio-economic policy.

The CoCEB model lies toward the highly idealized end of such a hierarchy: it cannot, nor does it claim to, represent the details of the real world. Despite, or rather because of, its simplicity, the strength of this formulation lies in it allowing us to illustrate some policy-relevant observations about the climate change mitigation challenge. Simple models do not allow one to provide a quantitative description of the fully coupled dynamics of the real climate–economy–biosphere system; on the other hand, though, the study of such models provides insights and makes it possible to understand the qualitative mechanisms of the coupled-system processes and to evaluate their possible consequences.

More than just a simple model, CoCEB is a formal framework in which it is possible to represent in a simple way several components of the coupled system and their interactions. In this paper, we show as an example how to insert the effects of CCS and deforestation control. Several choices are possible in modeling these effects.

In this paper, formulations taken from the literature are integrated into the CoCEB framework. Doing so allows us to treat low- and zero-carbon technologies, CCS and deforestation control consistently, and to translate the range of uncertainties on their relative cost into long-term effects on the climatic and economic system. The CoCEB framework also allows us to evaluate the sensitivity of the results on the cost parameters.

Given the recent scientific evidence on global warming and its consequences, as documented in the numerous IPCC reports, the importance of climate change mitigation policies represents by now a consensus that is widely accepted by the climate community. Lack of climate change mitigation measures would yield a situation where the risk of confronting policy-relevant climatic shifts in the climate system can no longer be avoided in the future (see e.g., Lenton et al., 2008; Bahn et al., 2011; Rydge and Bassi, 2014; Gaucherel and Moron, 2016; Obama, 2017). To enable humanity avoid such a situation, the IPCC reports (IPCC, 1996; 2007a; 2014) suggest a significant number of policy measures to prevent further emission of GHGs and a further rise of global temperature (see also, Moser et al., 2013; DDPP, 2015).

As measures leading toward a low- and zero-carbon economy, the IPCC Fourth Assessment Report emphasizes the role of technology policies to achieve lower CO_2 stabilization levels (IPCC, 2007b, pp. 149–153, 218–219; see also DDPP, 2015; Rozenberg et al., 2015), a greater need for more efficient research and development efforts, and higher investment in new technologies over the next few decades, as emphasized further in IPCC (2012, Ch. 11, p. 878). The most recent assessment reports suggest government initiatives for funding or subsidizing alternative energy sources, including solar energy, ocean power, windmills, biomass, and nuclear fusion (see, e.g., IPCC, 2012, Ch. 8, p. 612). However, for technology to be truly beneficial it must be “appropriate” and fit within the requisite economic, social, cultural and environmental factors of the place of its application (Nilsson et al., 2016).

Forestry policies, particularly reduced deforestation, also emerge as additional low-cost measures for the reduction of carbon emissions. Reduced deforestation would cut carbon emissions and increased afforestation would sequester CO_2 from the atmosphere. As noted earlier, besides reducing carbon emissions as well as contributing to carbon sequestration, reduced deforestation can also provide a range of other sociocultural, economic, and environmental benefits (Canadell and Raupach, 2008). It is advisable that future research focuses on the presence of the co-benefits of avoided deforestation, which could not be done in the present study nor in the existing mitigation literature, although steps in this direction are being taken (see e.g., Ebi and Kovats, 2007; Liang et al., 2016; Rao et al, 2016; Crawford-Brown, 2017).

In the present study and in Paper 1, we consider technological abatement activities, as well as deforestation control to reduce the sources and enhance the sinks of GHGs, thereby lessening the radiative forcing that leads to temperature rise and economic impacts. Our results indicate that a pure CCS policy or a pure low- and zero-carbon technologies policy carry their own specific risks of being less efficient in combating climate change, a sentiment echoed by Riahi et al. (2004), Uyterlinde et al. (2006), Akashi et al. (2014), Kalkuhl et al. (2015), among others.

Through our CoCEB framework, we demonstrate that best results — in terms of comparatively increased per capita GDP growth accompanied with decreased CO_2 emissions — are obtained by combining the various mitigation measures discussed in this study, i.e., high investment in low- and zero-carbon technologies and low investment in CCS technologies, as well as inclusion of deforestation control. While we show that certain results are robust to very substantial variations in parameter values, uncertainties do remain; see also Guivarch and Hallegatte (2013) and Wesselink et al. (2015). Further research is, therefore, necessary, to reduce these uncertainties in the cost of the CCS technologies and of deforestation control.

Recent academic works argue for a greater urgency to implement effective climate policies to combat climate change. Yet, to the best of our knowledge, no study sufficiently explores the possibility of bringing together all the three mitigation measures under one coherent framework — including their impact on economic growth — as we suggest here.

Another essential issue that has not been sufficiently addressed so far is how to reconcile and couple the IPCC's RCPs, the Shared Socio-economic Pathways (SSPs) — being developed in the framework of more detailed IAMs by the impacts, adaptation, and vulnerability (IAV) communities — and the Shared Climate Policy Assumptions (SPAs) being formulated to provide new insights into the implications of alternative policy designs for climate action; see Rozenberg et al. (2014), Kriegler et al. (2016, and references therein) and Riahi et al. (2017, and references therein). Actually, the complex and interdisciplinary nature of the climate change problem has creates a need for a holistic and consistent theoretical-empirical framework that can support research across multiple domains — including geo-political, socio-economic, technological, and environmental — to explore the tangible, real-world actualities of how such processes play out today and into the future (Steffen, 2012; Barron and McJeon, 2015). This framework is particularly relevant in the context of real world resource management and regulation problems in coevolving nature-society-economy systems where the implications for policy-making of the complexity and diversity of human attitudes, beliefs, knowledge and behavior are little known; see also Clark (2010, Chap. 5), Beckenbach and Kahlenborn (2016), Nilsson et al. (2016) and Schlüter et al. (2017). Furthermore we contend that the framework can be valuable globally in helping to frame the debate on climate mitigation from the viewpoint of the Earth as shared, multiuse and finite. We hope this study serves as an illustrative pointer in this direction.

The CoCEB model can be extended in several directions for scholarly-practitioner collaboration particularly germane to discussion (UNFCCC, 2015) of limiting warming to well below 2 °C. The next most interesting item on the research agenda is to let the biomass colonization rate and human population growth depend on the availability and quality of water, and to investigate how this will affect model feedbacks. Doing so will require a simple treatment of the water cycle.

The influence of energy, solar cycles, and economic cycles on the social-economic sphere is an exciting and flourishing area of research: it involves scientists from a breadth of disciplines, uses measurements from a wide range of observational campaigns and addresses an issue of significant policy and environmental concern. Therefore, as one of our next research agendas, we will analyze the energy production and consumption dynamics role, as well as the effect of economic cycles and solar cycles on the global climate change (see Ogutu et al., 2017a).

Furthermore, the CoCEB model can be regionalized, while maintaining its essential simplicity. For example, one might want to establish separate energy balance modules for the tropical and extratropical areas, and extend a similar separation to the economic module.

Finally, current IAMs disregard endogenous variability and represent both climate and the economy as a succession of equilibrium states with no endogenous dynamics. This shortcoming can be overcome by introducing business cycles into the economic module (e.g., Chiarella et al., 2005; Akaev, 2007; Hallegatte et al., 2008; Grasselli and Huu, 2015) and by taking them into account in considering the impact of natural, climate-related, as well as purely economic shocks (Hallegatte and Ghil, 2008; Groth et al., 2016). It is quite possible that the results of such extensions might affect our conclusions with respect to our refined ability of perceiving the hidden connections and feedbacks between complex subsystems. This outcome — which is by no means the final word as new findings are modifying the conventional wisdom all the time — will lead to an informed choice of more definitive and robust abatement measures, as discussed in Sect. 3 in this study and the sections 3 and "Appendix A" in Paper 1.

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Table 1. **List of new variables with respect to Paper 1, parameters and their values.**

Symbol	Meaning	Value	Units	Source
Independent variable				
B	Biomass		GtC	
Initial (1990) values for independent variables				
B_0		500	GtC	Van Wassenhove (2000)
Parameters and other symbols				
CCS				
κ_{ccs}	CCS technologies		Ratio	Akaev (2015)
g_{ccs}	Growth rate of κ_{ccs}			
ω_0	CCS parameter	0.01		Akaev (2015)
α_ω	CCS abatement efficiency	46.1		
f	Share of investment in CCS		% yr^{-1}	
Biosphere module (biomass)				
Λ_b	Biomass carrying capacity		GtC	Eriksson (2015)
Λ_{b0}	1990 biomass carrying capacity	900	GtC	Van Wassenhove (2000)
E_{B0}	1990 deforestation emissions	1.128	GtC yr^{-1}	Nordhaus and Boyer (2000)
γ_b	Fertilization parameter	0.0000053	$(GtC)^{-1}$	Van Wassenhove (2000)
g_b	1990 biomass intrinsic growth rate	4	% yr^{-1}	Van Wassenhove (2000)
δ_b	Rate of decline of deforestation emissions	0.01		Nordhaus and Boyer (2000)
θ_{for}	Carbon intensity in global forest biomass	0.5147	GtC	Eriksson (2015)
R_d	Deforestation control rate	0.1		Kindermann et al. (2008)
π_1; π_2; π_3; π_4; π_5	Deforestation control cost parameters	14.46;0.26; 1.022; 0.03; 20		Eriksson (2015)

Table 2. **The scenarios studied herein.**

Scenario	Control
Run with biomass, no CCS and no deforestation control (new BAU)	$\tau_b = 0$; $f = 0$; $B \neq 0$; $R_d = 0$
12 Runs with investment in CCS	$f = 0, 0.3, 0.6, 1.0$; $\tau_b = 0.075, 0.11, 0.145$; $R_d = 0$
20 Runs with deforestation control	$R_d = 0, 0.1, 0.5, 1.0, 1.2$; $\tau_b = 0, 0.075, 0.11, 0.145$; $f = 0$

Table 3. **Variable values for year 2100 for the model with no biomass ($B = 0$) and no CCS (f = 0), i.e. BAU of Paper 1, and with no deforestation control but $B \neq 0$ (new BAU run).**

Scenario	Emissions $E_Y + E_B$ (GtC yr^{-1})	CO_2 $C/\hat{C}$	Biomass B (GtC)	Deviation from pre-industrial $T - \hat{T}$ (°C)	Damages (% Y)	GDP growth g_Y (% yr^{-1})
$\tau_b = 0$; $B = 0$; $R_d = 0$ (BAU of Paper1)	29.3	3.1	–	5.20	26.9	1.07
$\tau_b = 0$; $B \neq 0$; $R_d = 0$ (BAU of Paper 2)	34.0	2.9	810	4.93	24.5	1.42

Table 4. Variable values for year 2100 with deforestation emissions in parentheses, for the runs with investment in CCS scenario.

f	τ_b	0	0.075	0.11	0.145
0	$E_Y + E_B$	34.0 (0.4)	13.3 (0.4)	6.7 (0.4)	3.0 (0.4)
	$T - \hat{T}$	4.93	3.12	2.37	1.78
	g_Y	1.42	2.30	2.32	2.08
0.3	$E_Y + E_B$	34.0 (0.4)	12.7 (0.4)	6.8 (0.4)	3.4 (0.4)
	$T - \hat{T}$	4.93	2.99	2.30	1.78
	g_Y	1.42	2.39	2.35	2.08
0.6	$E_Y + E_B$	34.0 (0.4)	13.7 (0.4)	8.1 (0.4)	4.6 (0.4)
	$T - \hat{T}$	4.93	3.02	2.40	1.91
	g_Y	1.42	2.36	2.29	2.02
1.0	$E_Y + E_B$	34.0 (0.4)	15.5 (0.4)	10.3 (0.4)	6.6 (0.4)
	$T - \hat{T}$	4.93	3.12	2.55	2.09
	g_Y	1.42	2.27	2.19	1.94

Table 5. Variable values for year 2100, with deforestation emissions in parenthesis, for runs with inclusion of deforestation control scenario.

R_d	τ_b	0	0.075	0.11	0.145
0	$E_Y + E_B$	34.0 (0.4)	13.3 (0.4)	6.7(0.4)	3.0 (0.4)
	$C/\hat{C}$	2.90	1.94	1.64	1.44
	$T - \hat{T}$	4.93	3.12	2.37	1.78
	g_Y	1.42	2.30	2.32	2.08
0.1	$E_Y + E_B$	34.2 (0.3)	13.3 (0.3)	6.7 (0.3)	2.9 (0.3)
	$C/\hat{C}$	2.90	1.93	1.63	1.43
	$T - \hat{T}$	4.93	3.11	2.36	1.76
	g_Y	1.42	2.31	2.33	2.09
0.5	$E_Y + E_B$	34.7 (0.2)	13.4 (0.2)	6.6 (0.2)	2.8 (0.2)
	$C/\hat{C}$	2.88	1.92	1.62	1.42
	$T - \hat{T}$	4.91	3.08	2.31	1.71
	g_Y	1.45	2.34	2.35	2.10
1.0	$E_Y + E_B$	35.3 (0)	13.5(0)	6.6 (0)	2.7 (0)
	$C/\hat{C}$	2.87	1.90	1.60	1.40
	$T - \hat{T}$	4.88	3.03	2.25	1.64
	g_Y	1.48	2.37	2.38	2.12
1.2	$E_Y + E_B$	35.6 (-0.1)	13.6 (-0.1)	6.6 (-0.1)	2.6 (-0.1)
	$C/\hat{C}$	2.86	1.89	1.59	1.39
	$T - \hat{T}$	4.87	3.01	2.23	1.61
	g_Y	1.49	2.39	2.39	2.13

Table 6. Target values of key variables for our policy scenarios at year 2100, with $f = 0.3$ and $R_d = 0.1$.

Abatement share τ_b	Emissions $E_Y + E_B$ (GtC yr^{-1})	CO_2 $C/\hat{C}$	Biomass B (GtC)	Deviation from pre-industrial $T - \hat{T}$ (°C)	Damages (% Y)	GDP growth g_Y (% yr^{-1})
0	34.2	2.9	829	4.9	24.4	1.42
0.075	12.8	1.9	782	3.0	8.7	2.40
0.11	6.8	1.6	769	2.3	4.8	2.36
0.145	3.4	1.4	761	1.8	2.6	2.08

Table 7. Effect of varying α_ω on CoCEB model results by year 2100; $B \neq 0$, $R_d = 0$, $\tau_b = 0.075$, and all other parameter values as in Table 1.

Share of investment in CCS f	Reduction of emissions (E_Y) from BAU (GtC yr^{-1})	CCS abatement cost [USD (tC)$^{-1}$]	Per capita GDP growth g_Y (% yr^{-1})
0	0.19– (0.19) –0.19	0– (0) –0	2.30– (2.30) –2.30
0.3	0.20– (0.19) –0.17	147– (149) –153	2.46– (2.39) –2.22
0.6	0.19– (0.19) –0.16	306– (311) –330	2.42– (2.36) –2.14
1.0	0.17– (0.17) –0.14	548– (558) –615	2.32– (2.27) –2.02

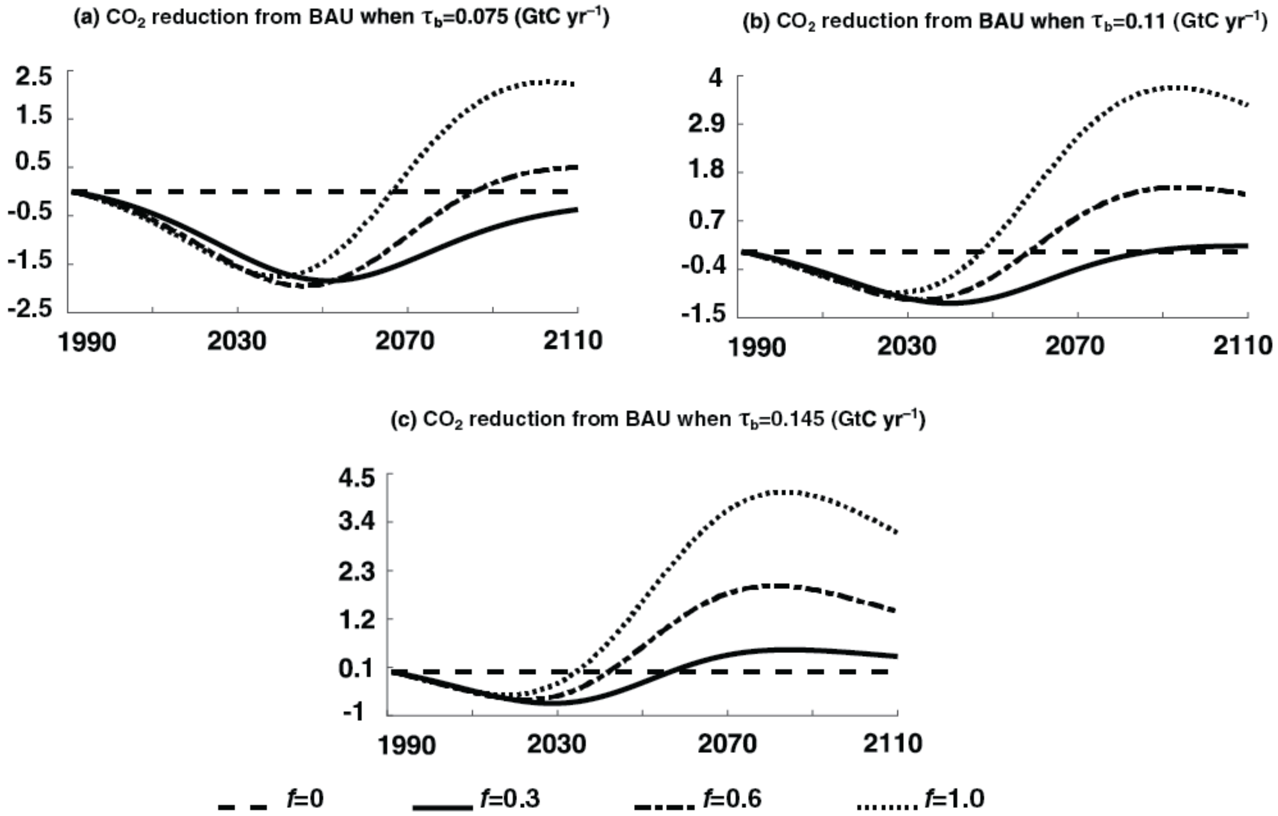

Figure 1. **Evolution in time of reduction in CO_2 emissions from BAU, for $B \neq 0$ and $R_d = 0$, and for f values that range from 0 (0 % investment in CCS) to 1.0 (100 % investment in CCS). (a) τ_b = 0.075, (b) τ_b =0.11, and (c) τ_b = 0.145; see legend for curves, with f = 0 – dashed, f = 0.3 – solid, f = 0.6 – dash-dotted, and f = 1.0 – dotted.**

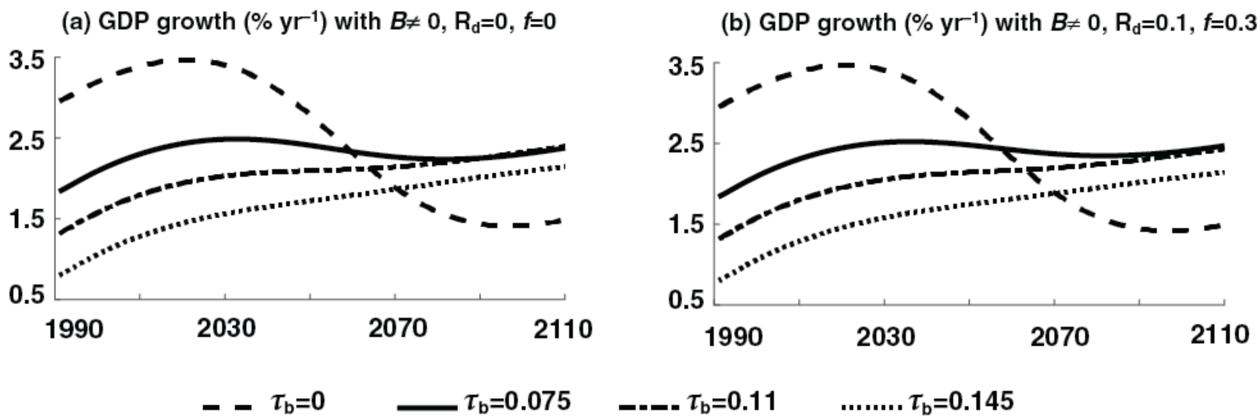

Figure 2. **GDP growth over time, with biomass module ($B \neq 0$), as a function of abatement share values τ_b between 0.0 (no abatement) and 0.145. (a) $R_d = 0$ and $f = 0$; and (b) $R_d = 0.1$ and $f = 0.3$; see legend for curve identification.**