Earth Syst. Dynam. Discuss., 6, 865–906, 2015
www.earth-syst-dynam-discuss.net/6/865/2015/
doi:10.5194/esdd-6-865-2015

Earth System Dynamics Discussions
Open Access

Coupled Climate–Economy–Biosphere (CoCEB) model – Part 2: Deforestation control and investment in carbon capture and storage technologies

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Received: 2 March 2015 – Accepted: 31 March 2015 – Published: 20 April 2015

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Published by Copernicus Publications on behalf of the European Geosciences Union.

ESDD
6, 865–906, 2015

Coupled Climate–Economy–Biosphere (CoCEB) model – Part 2

K. B. Z. Ogutu et al.

Abstract

This study uses the global climate–economy–biosphere (CoCEB) model developed 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 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. Integrating biomass into the CoCEB and applying deforestation control as well as CCS technologies has the following results: (i) low investment in CCS contributes to reducing industrial carbon emissions and to increasing GDP, but further investment leads to a smaller reduction in emissions, as well as in the incremental GDP growth; and (ii) enhanced deforestation control contributes to a reduction in both deforestation emissions and in atmospheric carbon dioxide concentration, thus reducing the impacts of climate change and contributing to a slight appreciation of GDP growth. This effect is however very small compared to that of low-carbon technologies or CCS. We also find that the result in (i) is very sensitive to the formulation of CCS costs, while to the contrary, the results for deforestation control are less sensitive.

1 Introduction and motivation

This 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., 2015; hereafter Paper 1) presented the model structure and the coupling of economic equations and physical equations. The economic activities are rep-

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ESDD

6, 865–906, 2015

Coupled Climate–Economy–Biosphere (CoCEB) model – Part 2

K. B. Z. Ogutu et al.

resented 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 climate system evolution is modeled via an energy balance equation for the temperature T and a carbon cycle equation for the carbon dioxide (CO_2) concentration 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 the economy, and via a damage function that modifies economic activity because of climate change.

In this part, we introduce in the model a simulation of the reduction of CO_2 emissions due to carbon capture and storage (CCS) technologies and to the control of deforestation. As in Paper 1 we assume that replacement of one technology with another occurs in terms of the logistic law (Sahal, 1981), consequently we model the dynamics of reduction in carbon dioxide emission using CCS technologies by a logistic function (cf. Akaev, 2012). This is a novel approach with respect to most other integrated assessment modeling studies in the climate change mitigation literature (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.

Most of the scenario studies that aim to identify and evaluate climate change mitigation strategies (e.g. Hourcade and Shukla, 2001; Morita et al., 2001) focus on the energy sector (van Vuuren et al., 2006, p. 166). Examples of studies that focus on the energy sector are the RICE (Regional Dynamic Integrated model of Climate and the Economy) and DICE (Dynamic Integrated model of Climate and the Economy) (Nordhaus and Boyer, 2000) models, which consider emissions from deforestation as exogenous (see also, Tol, 2010, p. 97). Nevertheless, greenhouse gas (GHG) emissions from deforestation and current terrestrial uptake are significant, so including GHG mitigation in the biota sinks has to be considered within integrated assessment models (IAMs), cf. Wise et al. (2009).

ESDD
6, 865–906, 2015

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. Gullison et al., 2007; Tavoni et al., 2007; Wise et al., 2009; Bosetti et al., 2011). Again, most earlier studies have not considered the more recent mitigation options currently being discussed in the context of ambitious emission reduction, such as hydrogen and carbon capture and storage (CCS); see Edmonds et al. (2004), IEA (2004) and IPCC (2005). 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 et al., 2001; Metz and van Vuuren, 2006).

Our goal 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. Our CoCEB model is not a quantitative tool for climate change impacts: it is an exercise in simplicity and transparency. 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 analyzed the abatement share and considered 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.

We seek to show 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

ESDD
6, 865–906, 2015

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.

In the next section, we briefly revisit the CoCEB model as developed in Paper 1 for completeness. In Sect. 2, 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 caveats and avenues for future research.

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 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:

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

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

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ESDD

6, 865–906, 2015

Coupled Climate–Economy–Biosphere (CoCEB) model – Part 2

K. B. Z. Ogutu et al.

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

$$\frac{dC}{dt} = \beta_2 E_Y - \mu_o(C-\hat{C}), \quad (1d)$$

$$\frac{dE_Y}{dt} = [g_\sigma + g_Y + n]E_Y, \quad (1e)$$

with:

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

$$g_\sigma = \frac{1}{\sigma}\frac{d\sigma}{dt}, \quad \text{(Growth of carbon intensity, } \sigma) \quad (3)$$

$$\sigma = f_c\left[1 - \frac{r\exp(\psi t)}{1 + r(\exp(\psi t)-1)}\right]\left[c_{-\infty} + \frac{a_c}{1 + r\exp(-\psi t)}\right], \quad \text{(Carbon intensity)} \quad (4)$$

$$\psi = \psi_0\{1/[1-\alpha_\tau\tau_b(1-f)]\}, \quad \text{(Energy intensity parameter)} \quad (5)$$

$$g_Y = \alpha g_K + (1-\alpha)g_H + \frac{1}{D}\frac{dD}{dT}\frac{dT}{dt}, \quad \text{(Growth rate of per capita output, } Y) \quad (6)$$

$$g_K = \frac{1}{K}\frac{dK}{dt}, \quad \text{(Growth rate of per capita physical capital, } K) \quad (6)$$

$$g_H = \frac{1}{H}\frac{dH}{dt}. \quad \text{(Growth rate of per capita human capital, } H)$$

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

$$\frac{dL}{dt} = nL\{1-\exp[-(L/L(1990))]\}, \quad \text{(Human population)} \quad (7)$$

$$\frac{dn}{dt} = \left(\frac{1}{1-\delta_n} - 1\right)n. \quad \text{(Human population growth rate)} \quad (8)$$

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

ESDD
6, 865–906, 2015

Coupled Climate–Economy–Biosphere (CoCEB) model – Part 2

K. B. Z. Ogutu et al.

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

2.1.1 Inclusion of CCS in the industrial CO_2 emissions equation

In Paper 1, the formulation of industrial CO_2 emissions used the Kaya–Bauer identity (Kaya, 1990; Bauer, 2005), in which the CCS growth term g_{ccs} was 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:

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

In order to express the term g_{ccs}, we assume the leakage of captured carbon to be zero and use Akaev's (2012) formula to define the reduction of emissions by the CCS as a fraction κ_{ccs}:

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

In this equation, $\varpi = \varpi_0\{1-[1/(1+\alpha_\varpi \tau_b f)]\}$, with ϖ_0 and α_ϖ constant, and the parameter f represents the share of investment in CCS; the investment in low-carbon technologies is $1-f$ and appears in the energy intensity parameter ψ in Eq. (5). Taking the natural logarithms and differentiating both sides of Eq. (10), we get the growth rate of κ_{ccs} as

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

Cost of CCS

There is uncertainty regarding the costs of carbon capture, transportation and storage (Morita et al., 2000, 2001; IPCC, 2005, p. 354; Al-Juaied and Whitmore, 2009; Kalkuhl

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |
ESDD
6, 865–906, 2015
Coupled Climate–Economy–Biosphere (CoCEB) model – Part 2
K. B. Z. Ogutu et al.

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 $(\mathrm{t\,C})^{-1}$ by the year 2100 (IEA, 2004; Johnson and Keith, 2004; McFarland et al., 2004; Wise and Dooley, 2004; IPCC, 2005; van Vuuren et al., 2006, p. 271, Table F.1; Al-Juaied and Whitmore, 2009; Bosetti, 2010, p. 344; Metz, 2010, p. 141; Al-Fattah et al., 2011, p. 296; Middleton and Brandt, 2013; Stephenson, 2013, p. 132; IPCC, 2014; 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 $\mathrm{Gt\,C\,yr^{-1}}$ (IPCC, 2005; Bosetti, 2010, p. 344; 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 $\mathrm{Gt\,C\,yr^{-1}}$ with a possibility of growing to 0.1364–0.409 $\mathrm{Gt\,C\,yr^{-1}}$ by 2050; also see, Uyterlinde et al. (2006).

Keeping in mind this range of emissions reduction and of prices, we calibrated the parameter α_ϖ in that affects ϖ in Eq. (10) above, in order to obtain similar values. For $\alpha_\varpi = 46.1$, the scenario (see Sect. 3.3 below) corresponding to the abatement share $\tau_\mathrm{b} = 0.075$ and with $f = 1.0$, gives aggregate carbon emissions reduction from baseline of 0.4 $\mathrm{Gt\,C\,yr^{-1}}$ by 2050 and 0.17 $\mathrm{Gt\,C\,yr^{-1}}$ by 2100. This emissions reduction comes at an approximate aggregate cost of USD 124 $(\mathrm{t\,C})^{-1}$ by 2050 and USD 558 $(\mathrm{t\,C})^{-1}$ by 2100. The cost is computed as $fG_\mathrm{E}L = f\tau_\mathrm{b}\tau YL$, 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. (5) above. These costs lie within the range of the CCS costs in the literature, as given above. Given the large incertitude in this range of costs, we conduct in Sect. 4.1 below a sensitivity study to changes in the α_ϖ value.

2.1.2 Inclusion of a biosphere module: CO_2-biomass interactions

Uzawa (1991, 2003) extended 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

ESDD
6, 865–906, 2015

K. B. Z. Ogutu et al.

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) proposed 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:

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

$$\frac{\mathrm{d}C}{\mathrm{d}t} = \beta_2[E_Y+E_B]-\mu_\mathrm{o}(C-\hat{C})-\gamma_\mathrm{b}B(C-\hat{C}), \tag{13}$$

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 is industrial emissions as in Eq. (1e), and $\hat{C}$ the pre-industrial 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 (1990) as a population growth model.

ESDD
6, 865–906, 2015

Carbon flux from deforestation and deforestation control

This section follows the work of Eriksson (2013) who investigated the role of the forest in an IAM of the climate and the economy. 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:

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

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 prescribed carbon emissions from deforestation to decrease in time according to:

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

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, 2013; see also FAO, 2010). The carbon intensity parameter, in this case, represents the average amount of carbon per volume of growing forest biomass. The total biomass deforestation in Gt C at any time period is then given by

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

ESDD
6, 865–906, 2015

K. B. Z. Ogutu et al.

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 $0 \leq R_\mathrm{d} < 1$, 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. (1e) 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, 2013):

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

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

$$R_\mathrm{e} = (E_{B0} \exp(-\delta_\mathrm{b} t)) R_\mathrm{d}. \quad (18)$$

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

$$\frac{\mathrm{d}\overline{V}}{\mathrm{d}t} = \int_t \overline{V}_\mathrm{mc}(s)\mathrm{d}s. \quad (19)$$

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

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ESDD

6, 865–906, 2015

Coupled Climate–Economy–Biosphere (CoCEB) model – Part 2

K. B. Z. Ogutu et al.

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 capital stock 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 capital stock increases with deforestation. The accumulated investment in land is here assumed to be implicit in the total capital stock and does not affect the development of the total capital stock 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 capital stock. The per capita cost of avoiding deforestation is thus $V = \overline{V}/L$.

Through a meta-analysis of published works, Phan et al. (2014) estimated the cost of carbon emissions reduction due to deforestation control to range from 0.11 to USD 246 $(\mathrm{t\,C})^{-1}$ with a mean of USD 19 $(\mathrm{t\,C})^{-1}$. Actually, Kindermann et al. (2008) used 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 found that a 10 % deforestation control could be feasible within the context of current financial flows.

Following the latter result, we take $R_\mathrm{d} = 0.1$ 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-carbon technologies and with $\tau_\mathrm{b} = 0.075$, the value of $R_\mathrm{d} = 0.1$ gives an approximate aggregate cost of deforestation emissions reduced of USD 164 $(\mathrm{t\,C})^{-1}$ by 2100. We notice that the CoCEB total cost for $R_\mathrm{d} = 0.1$ is within the range of deforestation control costs given by Phan et al. (2014).

ESDD
6, 865–906, 2015

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

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

Given the large incertitude 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 Eqs. (1b), (1c), (9), (12), (13), and (20). The equations are grouped for the reader's convenience below:

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

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

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

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

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

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

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

ESDD
6, 865–906, 2015

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 clean 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, $\tau_b =$ 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 $R_d = 0$, 0.1, 0.5, 1.0, and 1.2, times four values of $\tau_b = 0$, 0.075, 0.11, 0.145, with $f = 0$.

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

ESDD
6, 865–906, 2015

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 $Gt\,C\,yr^{-1}$ by year 2100. This is an increase of approximately 4.7 from the 29.3 $Gt\,C\,yr^{-1}$ 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 %.

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 surface air temperature (SAT) and consequently damages. Atmospheric CO_2 decreases from 1842 to 1729 Gt C, i.e. about 113 Gt C by 2100, which implies a sequesteration of approximately 1 $Gt\,C\,yr^{-1}$ between 1990 and 2100.

The model's behavior in response to inclusion of biomass agrees with Mackey et al.'s (2013) claims that the capacity of terrestrial ecosystems to store carbon is finite and that the current sequestration potential primarily reflects depletion due to past land-use. 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 $\tau_b = 0$ in this column, the same results are obviously obtained for all values of f.

On the other hand, when $f = 0$, i.e for the first row of Table 4, all the abatement share goes into investment in low-carbon technologies as in Paper 1; varying the value of τ_b

ESDD
6, 865–906, 2015

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 $\tau_b = 0.075$, 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-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 baseline 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 ($\tau_b = 0.11$ 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 baseline 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 $\tau_b = 0.11$ (Fig. 1b) and 0.145 (Fig. 1c), this effect is am-

ESDD
6, 865–906, 2015

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◂◂ | ▸▸
◂ | ▸
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

plified, i.e. the emissions decrease at the beginning and then increase even more by 2100.

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 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 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 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 Moonry (1996); see also Polglase et al. (2013).

The reduction in atmospheric CO_2 due to biomass photosynthesis contributes to a decrease in SAT and consequent damages. These actually increase the GDP growth slightly. The improvements due to R_d are nevertheless small compared to the effect of low-carbon technologies or CCS. It has to be said, however, that besides reducing carbon emissions, reduced deforestation also delivers other benefits, such as biodiversity conservation and watershed and soil quality protection (Sedjo et al., 1995; Chomitz and Kumari, 1998; Ebeling and Yasué, 2008; Stickler et al., 2009; World Bank, 2011; Strassburg et al., 2012; Eriksson, 2013). The latter benefits are not accounted for in the present version of our CoCEB model. In fact, little attention has been paid so far in the literature to the presence of these co-benefits of deforestation control when calculating its cost (Phan et al., 2014, Table 1).

ESDD
6, 865–906, 2015

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 are obtained by combining the various mitigation measures discussed. This was found in Table 4 and Fig. 1, where we noted that 100 % investment in CCS or low-carbon technologies is slightly less efficient than the combined investment in both technologies.

For illustration purposes, we chose 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 $\tau_b = 0$, 0.075, 0.11 and 0.145. From the table, the scenario corresponding to $\tau_b = 0$ attains total emissions of 34.2 Gt C yr^{-1} by 2100. This leads to an atmospheric CO_2 concentration of 1727 Gt C, 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 IPCC results for their RCP8.5 scenario (Rao and Riahi, 2006; Riahi et al., 2007; IPCC, 2013).

For the scenarios corresponding to $\tau_b = 0.075$, 0.11 and 0.145, the results obtained are slightly better than those in Table 4 when $f = 0$ or 1. We also note that, for $\tau_b = 0.075$ and 0.11, the CO_2 emissions per year, as well as the CO_2 concentrations and SAT deviations from pre-industrial level in year 2100, agree fairly well with those of RCP6.0 and RCP4.5 respectively (Fujino et al., 2006; Smith and Wigley, 2006; Clerke et al., 2007; Hijioka et al., 2008; Wise et al., 2009; IPCC, 2013).

Figure 2 plots the per capita GDP growth curves with time for the $f = 0$ and $R_d = 0$ scenario (Fig. 2a) and for $f = 0.3$ and $R_d = 0.1$ 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,

ESDD
6, 865–906, 2015

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-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 conducted 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 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 baseline 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 α_ω is equivalent to USD 615 $(\mathrm{t\,C})^{-1}$ by 2100, while the high value is equivalent to USD 548 $(\mathrm{t\,C})^{-1}$; these values agree quite well with

ESDD
6, 865–906, 2015

those given in the literature. 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 $\alpha_{\varpi} = 46.1$ (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 $(\mathrm{t\,C})^{-1}$, the $f = 1.0$ case gives more or less the same emissions reduction and GDP growth as $f = 0$.

Comparing the efficiency of CCS and low-carbon technologies, which depend on their cost estimation, we note that given the uncertainties, low-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.

4.2 Robustness to changes in the deforestation control cost parameters

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

We now vary simultaneously the R_d cost parameters from the standard values so as to span the range of costs given by Phan et al. (2014). A variation of −99 % gives a total cost of USD 0.9 $(\mathrm{t\,C})^{-1}$ and that of +47 % gives a total cost of USD 246 $(\mathrm{t\,C})^{-1}$. 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.

ESDD
6, 865–906, 2015

5 Conclusions and way forward

5.1 Summary

In this paper we described 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 assumed 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 assumed that all nations participate in carbon emissions mitigation activities. But as of 2013, there were no effective international agreements to limit the emissions of CO_2 and other GHGs (Nordhaus, 2013, p. 11).

This extended version of the CoCEB model has been 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-carbon technologies was considered in Paper 1. The framework developed allows one to investigate policy sensitivity to the choice of key parameters. We analyzed 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 spanned the range of cost values found in the mitigation literature.

We have shown that: (i) low investment in CCS contributed to a reduction in industrial carbon emissions and to an increase in GDP growth, but a further investment leads to a decrease in the reduction of 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 (iii) the results in (i) remain very sensitive to the formulation of CCS costs. Conversely, the results for deforestation control were found to be less sensitive to the formulation of its cost. A large range of assumptions on these costs is found in

ESDD
6, 865–906, 2015

the literature and the flexibility of the CoCEB model permitted us to span this range and to check the sensitivity of its results.

We found 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.

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, and references therein). There is an even greater need for such a hierarchy to deal with the higher-complexity problems at the interface of the physico-chemical 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, but its simplicity is also a strength. 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 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 showed 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 have been integrated into the CoCEB framework. Doing so allowed us to treat low-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 allowed 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. Delaying action may mean that high temperatures and low growth are approached on a path that becomes irreversible. To prevent human society's engaging on such a path, the IPCC reports (IPCC, 1995, 2007a, 2014) propose a significant number of policy measures to prevent further emission of GHGs and a further rise of global temperature.

As measures leading toward a low-carbon economy, the IPCC Fourth Assessment Report emphasizes the role of technology policies to achieve lower CO_2 stabilization levels (IPCC, 2007b, 149–153, 218–219), 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 recommend government initiatives for funding or subsidizing alternative energy sources, including solar energy, ocean power, windmills, biomass, and nuclear fusion.

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, reduced deforestation can also deliver other benefits – such as biodiversity conservation and watershed and soil quality protection. 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.

In the present study and in Paper 1, we considered 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

ESDD
6, 865–906, 2015

economic impacts. Our results indicate that a pure CCS policy or a pure low-carbon technologies policy carry their own specific risks of being less efficient in combating climate change, a sentiment echoed by Riahi et al. (2004a, b), Uyterlinde et al. (2006), Akashi et al. (2014), Kalkuhl et al. (2015), among others.

Through our CoCEB framework, we have demonstrated that best results are obtained by combining the various mitigation measures discussed in this study, i.e. high investment in low-carbon technologies and low investment in CCS technologies, as well as inclusion of deforestation control. While we have also shown that certain results are robust to very substantial variations in parameter values, uncertainties do remain. Further research is, therefore, necessary, to reduce these uncertainties in the cost of the CCS technologies and of deforestation control.

Recent academic work has argued for a greater urgency to implement effective climate policies to combat climate change. Yet, to the best of our knowledge, no study has sufficiently explored the possibility of bringing together all the three mitigation measures under one coherent framework – including their impact on economic growth – as suggested here.

Another essential issue that has not been sufficiently addressed so far is how to reconcile and couple the IPCC's Representative Concentration Pathways (RCPs) and the Shared Socio-economic Pathways (SSPs) being developed in the framework of more detailed integrated assessment models (IAMs) by the impacts, adaptation, and vulnerability communities; see Ebi et al. (2014); Kriegler et al. (2014); O'Neill et al. (2014); Rozenberg et al. (2014); Vuuren et al. (2014). We hope this study will serve as an illustrative pointer in this direction.

The CoCEB model can be extended in several directions. 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.

Furthermore, the CoCEB model can be regionalized, while maintaining its essential simplicity. For example, one might want to establish separate energy balance modules

ESDD
6, 865–906, 2015

for the tropical and extratropical areas, and extend a similar separation to the economic module.

Finally, even though there are several truly coupled IAMs (e.g. Nordhaus and Boyer, 1998; Ambrosi et al., 2003; Stern, 2007), these IAMs disregard variability and represent both climate and the economy as a succession of equilibrium states without endogenous dynamics. This can be overcome by introducing business cycles into the economic module (e.g. Akaev, 2007; Hallegatte et al., 2008) and by taking them into account in considering the impact of both natural, climate-related and purely economic shocks (Hallegatte and Ghil, 2008; Groth et al., 2014).

Acknowledgements. This work was supported by Dedan Kimathi University of Technology (DeKUT) and the Embassy of France in Kenya, whose views it does not claim to represent.

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K. B. Z. Ogutu et al.

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ESDD
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K. B. Z. Ogutu et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀◀ | ▶▶
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

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

Symbol	Meaning	Value	Units	Source
Independent variable				
B	Biomass		Gt C	
Initial (1990) values for independent variables				
B_0		500	Gt C	van Wassenhove (2000)
Parameters and other symbols CCS				
κ_{ccs}	CCS technologies		Ratio	Akaev (2012)
g_{ccs}	Growth rate of κ_{ccs}			
ω_0		0.01		Akaev (2012)
α_ω		46.1		
f	Share of investment in CCS		$\%\,yr^{-1}$	
Biosphere module (biomass)				
Λ_b	Biomass carrying capacity		Gt C	Eriksson (2013)
Λ_{b0}	1990 biomass carrying capacity	900	Gt C	van Wassenhove (2000)
E_{B0}	1990 deforestation emissions	1.128	$Gt\,C\,yr^{-1}$	Nordhaus and Boyer (2000)
γ_b	Fertilization parameter	0.0000053	$(Gt\,C)^{-1}$	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	Gt C	Eriksson (2013)
R_d	Deforestation control rate	0.1		Kindermann et al. (2008)
$\pi_1;\pi_2;\pi_3;\pi_4;\pi_5$	Deforestation control cost parameters	14.46; 0.26; 1.022; 0.03; 20		Eriksson (2013)

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ESDD
6, 865–906, 2015

Coupled Climate–Economy–Biosphere (CoCEB) model – Part 2

K. B. Z. Ogutu et al.

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	$R_d = 0, 0.1, 0.5, 1.0, 1.2$; $\tau_b = 0, 0.075, 0.11, 0.145$; $f = 0$

ESDD
6, 865–906, 2015

Coupled Climate–Economy–Biosphere (CoCEB) model – Part 2

K. B. Z. Ogutu et al.

ESDD
6, 865–906, 2015

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 $E_Y + E_B$ ($\mathrm{Gt\,C\,yr^{-1}}$)	CO_2 $C/\hat{C}$	Biomass B (Gt C)	Deviation from pre-industrial $T - \hat{T}$ (°C)	Damages (% GDP)	GDP growth g_Y ($\%\,\mathrm{yr^{-1}}$)
$\tau_b = 0$; $B = 0$; $R_d = 0$ (BAU of Paper 1)	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

ESDD
6, 865–906, 2015

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

ESDD
6, 865–906, 2015

Coupled Climate–Economy–Biosphere (CoCEB) model – Part 2

K. B. Z. Ogutu et al.

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

τ_b	Emissions $E_Y + E_B$ ($\mathrm{Gt\,C\,yr^{-1}}$)	CO_2 $C/\hat{C}$	Biomass B (Gt C)	Deviation from pre-industrial $T - \hat{T}$ (°C)	Damages (% GDP)	GDP growth g_Y ($\%\,\mathrm{yr^{-1}}$)
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

ESDD
6, 865–906, 2015

Table 7. Effect of varying α_{ϖ} 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.

f	Reduction of emissions (E_Y) from baseline ($GtC\,yr^{-1}$)	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

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ESDD

6, 865–906, 2015

Coupled Climate–Economy–Biosphere (CoCEB) model – Part 2

K. B. Z. Ogutu et al.

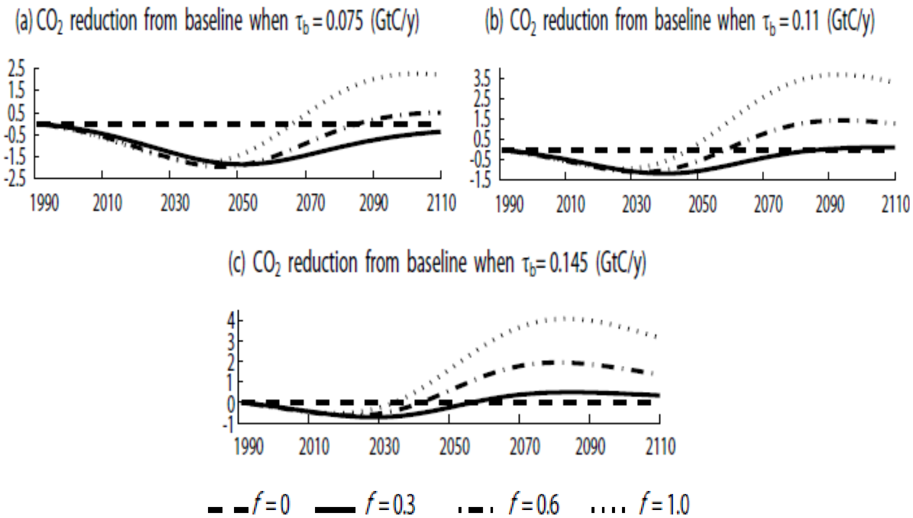

Figure 1. Evolution in time of reduction in CO_2 emissions from baseline, for $B \neq 0$ and $R_d = 0$, and for f values that range from 0 (0 % investment in CCS) to 1.0 (100 % investment in CCS). **(a)** $\tau_b = 0.075$, **(b)** $\tau_b = 0.11$, and **(c)** $\tau_b = 0.145$; see legend for curves,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

ESDD
6, 865–906, 2015

Coupled Climate–Economy–Biosphere (CoCEB) model – Part 2

K. B. Z. Ogutu et al.

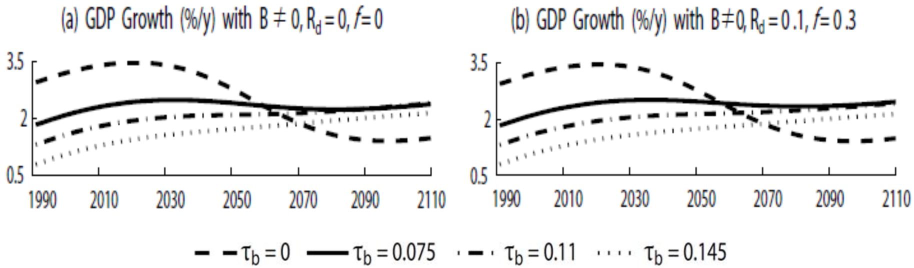

Figure 2. GDP growth over time, with biomass module ($B \neq 0$), as a function of abatement share values τ_b between 0.0 (no abatement) and 0.145. **(a)** $R_d = 0$ and $f = 0$; and **(b)** $R_d = 0.1$ and $f = 0.3$; see legend for curve identification.

ESDD
6, 865–906, 2015

Coupled Climate–Economy–Biosphere (CoCEB) model – Part 2

K. B. Z. Ogutu et al.