# *Final Author response to Interactive comments on* "Coupled Climate–Economy–Biosphere (CoCEB) model – Part 2: Deforestation control and investment in carbon capture and storage technologies" *by* K. B. Z. Ogutu et al.

**K. B. Z. Ogutu et al.**

okeroboto@gmail.com

We thank the Referee for his/her constructive comments and respond to him/her herewith. In the following, the referee's comments are in italics, our responses are in Roman, and the changes to be made in the manuscript are in bold. Unless otherwise stated, sections, equations, figures, page numbers, and line numbers referred to are those of the original manuscript.

1. *Presentation: Overall, the manuscript would benefit drastically from a careful round of edits. For example:*

a. *The manuscript is part 2 of a sequence and expands on the first paper. However, the first paper has also several problems that need to be addressed. This second paper seems to be in better shape than the first one. One approach may be to combine the papers and put much of the technical detail in an appendix.*

Editing and changes to Ogutu et al. (2015, hereafter Paper 1) in response to the first and second referees comments to the same paper has been done.

About the organization into 1 article with thick appendix or 2 articles, it may be ultimately an editorial decision. It is true that one could have combined Paper 1 and 2 into a single paper and put much of the technical details into an appendix. However, the results of Paper 1 require merely a simpler version of the model, while for the results of Paper 2 the inclusion of 2 extra equations is needed. Dividing the material into two allows us to keep Paper 1 self-consistent, as well as short and readable; moreover, it only increases the complexity of the model when it is needed, i.e. in Paper 2. Furthermore, we feel that the methodological aspect, i.e. the construction

of a simplified model, is one of the main points of this work, and that relegating it to an appendix would fail giving it its due importance.

b. *The use of mathematical symbols in the sentences makes for a slightly confusing reading (e.g., l. 5 p. 882). Maybe use the full name in words instead?*

We have implemented the referee's suggestion by using the full names of the Mathematical symbols when appropriate.

c. *The exposition of the model in form of equations is too terse. Maybe describe this in general words and have the equations in an appendix?*

We have tried to make the exposition of the model less terse and hopefully more understandable to the reader by offering more general word descriptions where needed without trying to sound repetitious. However, we feel that having the equations in an appendix would retard the flow of the manuscript. Moreover, we believe that the mathematical formulation should be put forward. It helps reminding the fundamental fact that the conclusions found in the paper are the result of the simplified mathematical model, and that any extension towards the real world is an interpretation.

d. *The paper suffers from a few slightly odd word choices such as "incertitude" or "resumed". Please do a careful edits to improve (at least review) the wording.*

We substituted "incertitude" with uncertainty; see also Petersen (2012), Hannart et al. (2013), Lewandowsky et al. (2014a, b), and Wesselink et al. (2015) and the references therein for an insightful uncertainty assessment. It is a more currently used term for parameter value in applied mathematics. A general review of the manuscript has been done in order to improve the wording.

Also, the following references are added in the reference list:

**Hannart, A., Ghil, M., Dufresne, J.-L., and Naveau, P.: Disconcerting learning on climate sensitivity and the uncertain future of uncertainty, Climatic Change, 119, 585–601, 2013.**

**Lewandowsky, S., Risbey, J. S., Smithson, M., Newell, B. R., and Hunter, J.: Scientific uncertainty and climate change: Part I. Uncertainty and unabated emissions, Climatic Change, 124, 21–37, 2014a.**

**Lewandowsky, S., Risbey, J. S., Smithson, M., and Newell, B. R.: Scientific uncertainty and climate change: Part II. Uncertainty and mitigation, Climatic Change, 124, 39–52, 2014b.**

**Petersen, A.: Simulating nature: a philosophical study of computer-model uncertainties and their role in climate science and policy advice, 2nd edn., CRC Press, Abingdon, 2012.**

**Wesselink, A., Challinor, A. J., Watson, J., Beven, K., Allen, I., Hanlon, H., Lopez, A., Lorenz, S., Otto, F., Morse, A., Rye, C., Saux-Picard, S., Stainforth, D., and Suckling, E.: Equipped to deal with uncertainty in climate and impacts predictions: lessons from internal peer review, Climatic Change, 132:1–14, 2015.**

*e. The paper has grammar mistakes.*

This has been rectified by carefully going through the paper.

2. *The manuscript would benefit from a more careful discussion of the prior relevant studies. For example, what about Keith, D. W., M. Ha-Duong, and J. K. Stolaroff (2006), Climate strategy with CO2 capture from the air, Climatic Change, 74(1-3), 17-45, doi:10.1007/s10584-005-9026-x. Other papers also analyze the effects of leakage. This paper assumes this to be zero (p. 872).*

In the revision, the following paragraph is added in Section 2.1.1 (p. 872):

**Carbon capture and storage (CCS) provides a tentative solution for continued use of fossil fuels, until the technology to transition to more sustainable energy sources is developed (Herzog, 2001). Like in most of the literature on CCS technologies which addresses the problem of capturing $CO_2$ released during fuel combustion, we 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 (see, e.g., Eliasson et al., 1999; Willams et al., 2001; Akaev, 2012, 2015; Creamer and Gao, 2015, and references therein); see also Keith et al. (2006; and references therein), as well as Pielke Jr. (2009), 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 Kuckshinrichs and Hake (2015) for an integrated technology study discussing and assessing the technical, economic, environmental, and social perspectives of CCS technologies.**

Now, leakage associated with CCS is assumed to be zero in the current paper for simplicity purposes, without, we hope, endangering the possibility of understanding the qualitative mechanisms of the coupled-system processes and of evaluating their possible consequences. Our assumption is supported by Ha-Duong and Keith (2003) who assessed the global implications of leakage on CCS activity and undertook a sensitivity results with the Dynamics of Inertia and Adaptability Model (DIAM), which is a model based on marginal cost functions of mitigation and damage. They found out that CCS being a long term mitigation option requires sufficiently low leakage rates (Bauer, 2005, p. 293). Furthermore, according to the Model of Investment and Technological Development (MIND) Version 1.1's results, the leakage rate becomes a sensitive parameter, if the alternative climate change mitigation options, like investment in low-carbon technologies, are limited or exhibit a bad performance (Bauer, 2005, p. 293).

We clarify this by rephrasing the second paragraph in page 872 as:

**In order to express the term $g_{ccs}$, and for simplicity purposes, we assume the leakage of captured carbon to be zero (see also, Ha-Duong and Keith, 2003; Bauer, 2005,**

**pp. 97 and 241 and the references therein) and use Akaev's (2012, 2015) formula to define the reduction of emissions by the CCS as a fraction $\kappa_{ccs}$ :**

Also, the following references are added in the reference list:

**Akaev, A.: Stabilization of Earth's Climate in the 21st Century by the Stabilization of Per Capita Consumption, in: The Oxford Handbook of the Macroeconomics of Global Warming, edited by: Bernard, L. and Semmler, W., Oxford University Press, New York, NY, USA, pp. 499–554, 2015.**

**Ha-Duong, M. and Keith, D. W.: Carbon storage: The economic efficiency of storing in leaky reservoirs, Clean. Technol. Envir., 5, 181–189, 2003.**

**Herzog, H. J.: What future for carbon capture and sequestration?, Environ. Sci. Technol., 35, 148A–153A, 2001.**

**Keith, D. W., Ha-Duong, M., and Stolaroff, J. K.: Climate strategy with $CO_2$ capture from the air, Climatic Change, 74, 17–45, 2006.**

**Pielke Jr., R. A.: An idealized assessment of the economics of air capture of carbon dioxide in mitigation policy, Environ. Sci. Policy, 16, 216–225, 2009.**

**Eliasson, B., Riemer, P. W. F., Wokaun, A. (Eds.): Greenhouse gas control technologies: Proceedings of the 4th international conference, Pergamon, Interlaken, Switzerland, 1999.**

**Willams, D., Durie, B., McMullan, P., Paulson, C., and Smith, A. (Eds.): Greenhouse gas control technologies: Proceedings of the 5th international conference on greenhouse gas control technologies, CSIRO Publishing, Collingwood, Australia, 2001.**

3. *Overall, the main results as discussed in the current manuscript seem not very surprising. Given that both papers focus a lot on model development, the question is whether ESD is the appropriate venue.*

This comment makes us think that the importance of our results is not made clear enough. We do believe that the results are not trivial, for they put in doubt that (i) an increased investment in CCS would go hand in hand with an increased reduction in $CO_2$ emissions, and (ii) a reduction of deforestation would be as effective as investment in low-carbon or CCS technologies for reducing climate damage. These two assumption are shown to be very complex to address and also very dependent on the uncertainties about their costs. We have tried to make these concepts clearer in the text.

As for the choice of the journal, we suppose the editor will have to give his/her opinion as well. But we think that the important methodological part of the paper, that involves "hard" mathematical modeling applied to an interdisciplinary case, is particularly suited for ESD.

4. *Does the model represent the potential reduction in CCS costs in the future? If not, how would this change the conclusions*?

The CCS costs reduction in the future is prescribed in the model by the CCS abatement efficiency parameter. The study takes this parameter to be constant over time. However, as clearly shown in the sensitivity analysis Section 4.1, different choices of the value of the parameter give very different results. This is actually one of the main messages of this paper.

5. *Are there not simpler ways to represent CCS due to afforestation than shown in equations 11 and 12? What are the dynamics of this system?*

Equation 12 is the most standard equation for the balance of biomass. Equation 11 translates the hypotheses found in the literature on the pricing and technological evolution of CCS. There might be simpler ways to model these, but in a way using these two equations, we take a conservative stand: we haven't invented anything, just put into our model equations the ideas found in the literature. The whole paper deals precisely with the dynamics of the system.

6. *What does the capital stock (p. 877) refer to?*

To remove any ambiguity, we replace "capital stock" with "**physical capital**"

7. *The analysis (attribution) on page 880 (page 6 onwards) is interesting, but too terse to follow easily and also not backed up by evidence. Can this be explained and analyzed better (e.g., through sensitivity studies)?*

We have revised the analysis in order for it to be less terse and to be backed up by evidence. The sensitivity analysis is contained in section 4. Expanding the sensitivity analysis is certainly a sensible suggestion. We plan to use Monte-Carlo Analysis where various parameters are varied simultaneously. This however is a large enough work that would result in another paper entirely.

8. *The manuscript discusses how "current sequestration potential primarily reflects depletion due to past land-use". How does the model at hand handle this?*

It is true that the discussion in the paragraph of line 14 is rather speculative. In order to avoid confusion, we moved part of it to the discussion section, and modified the paragraph as follows:

**The model 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.**

9. *The reference to "IPCC, 2013" is not precise enough. Which chapter? Should the reader look at all "1535" (p. 893) pages?*

To remove the impreciseness, we rephrase the reference as: **(IPCC, 2013, p. 23, Table SPM.2 and p. 27, Table SPM.3)**.

10. *The conclusions need to be rephrased to make clear that these statements are about the model (i.e., a highly stylized and simplified approximation), not the real world.*

Done.

11. *What is the evidence behind the claim of: "Delaying action may mean that high temperatures and low growth are approached on a path that becomes irreversible" (p. 888).*

We modify the text as follows:

**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, and references therein; Richardson et al., 2011, p. 163; Rydge and Bassi, 2014). To enable human society avoid such a situation, the IPCC reports (IPCC, 1996; 2007; 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, p. 88; DDPP, 2015).**

Also, the following references are added in the reference list:

**Bahn, O., Edwards, N., Knutti, R., and Stocker, T.: Energy policies avoiding a tipping point in the climate system, Energ. Policy, 39, 334–348, 2011.**

**Deep Decarbonization Pathways Project (DDPP): Pathways to deep decarbonization 2015 report, Sustainable Development Solutions Network (SDSN) - Institute for Sustainable Development and International Relations (IDDRI), 2015.**

**IPCC: Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific Technical Analyses, in: Contribution of Working Group II to the Second**

**Assessment Report of the IPCC, edited by: Watson, R. T., Zinyowera, M. C., and Moss, R. H., Cambridge University Press, 1996.**

**IPCC: Climate Change 2007: Mitigation of Climate Change, Contribution of Working Group III to the Fourth Assessment Report of the IPCC, edited by: Metz, B., Davidson, O. R., Bosch, P. R., Dave, R., and Meyer, L. A., Cambridge University Press, 863 pp., 2007.**

**IPCC: Climate Change 2014 – Mitigation of Climate Change, Contribution of Working Group III to the Fifth Assessment Report of the IPCC, Cambridge University Press, Cambridge, UK, 2014.**

**Lenton, T. M., Held, H., Kriegler, E., Hall, J. W., Lucht, W., Rahmstorf, S., and Schellnhuber, H.-J.: Tipping elements in the Earth's climate system, P. Natl. Acad. Sci. USA, 105, 1786–1793, 2008.**

**Moser, E., Prskawetz, A., and Tragler, G.: Environmental Regulations, Abatement and Economic Growth, in: in: Green Growth and Sustainable Development, edited by: Crespo Cuaresma, J. and Palokangas, T., Dynamic Modeling and Econometrics in Economics and Finance 14, Springer Verlag, Berlin Heidelberg, pp. 87–111, 2013.**

**Richardson, K., Steffen, W., Liverman, D., Barker, T., Jotzo, F., Kammen, D. M., Leemans, R., Lenton, T. M., Munasinghe, M., Osman-Elasha, B., Schellnhuber, H. J., Stern, N., Vogel, C., and Wæver, O.: Climate Change: Global Risks, Challenges and Decisions, Cambridge University Press, New York, USA, 2011.**

**Rydge, J. and Bassi, S.: Global cooperation and understanding to accelerate climate action, in: The Global Development of Policy Regimes to Combat Climate Change, edited by: Stern, N. H., Bowen, A., and Whalley, J., The Tricontinental Series on Global Economic Issues, Volume 4, World Scientific Publishing Co. Pte. Ltd., Singapore, pp. 1−22, 2014.**

*12. Do the IPCC reports really "propose" and/or "recommend" (p. 888)?*

Yes, “a broad range of mitigation policy measures are suggested, which especially emphasizes the role of technology policies and the increasing need for more research and development efforts” (Moser et al., 2013, p. 88).

Nevertheless, to be more consistent we replace “propose” and “recommend” with “**suggest**”. We also add the references: **(see also, Moser et al., 2013, p. 88)** at the end of line 10, page 888 and **(see e.g., IPCC, 2012, Ch. 8, p. 612)** at the end of line 18, page 888.

The following reference is also added in the reference list:

**IPCC: Renewable Energy Sources And Climate Change Mitigation, A Special report of the IPCC, edited by: Edenhofer, O., Madruga, R. P., Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S., Zwickel, T., Eickemeier, P., Hansen, G., Schlömer, S., and von Stechow, C., Cambridge University Press, 1089 pp., 2012.**

*13. How is “best” defined (p. 889)?*

To make things clearer, we modify the sentence as:

Through our CoCEB framework, we have demonstrated that best results**, in terms of comparatively increased per capita GDP growth accompanied with decreased GHG emissions,** 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.

*14. Please add parameter names and units to the tables as needed.*

Done.

*15. The figures are of poor quality (e.g. rasterized).*

We followed ESD's recommendations on the type of figures to upload, both for Paper 1 and the current paper. However, if the editors feel that the figures need to be upgraded, we can do that.

16. *The effects on GDP growth (figure 2) are quite large. Please discuss and also show the integral.*

Figure 2 of the current paper is discussed in Section 3.5. We suspect the referee might be referring to figure 2 of Paper 1 which is also discussed in Section 4.1 of the same paper.

We finally would like to add the following in the acknowledgements: **It is a pleasure to thank Prof. Hermann Held and an anonymous reviewer for thoughtful and constructive comments to an earlier version of this manuscript. The CoCEB model code is available from the authors upon request.**

Once more, we would like to thank the referee for his/her thoughtful and critical reviews which have been extremely helpful at refining the manuscript. We are greatly appreciative of the effort that went into it and hope that our answers are satisfying. If there are still things unclear or incomplete, we are happy to receive further comments.

## References

Akaev, A.: Stabilization of Earth's Climate in the 21st Century by the Stabilization of Per Capita Consumption, in: The Oxford Handbook of the Macroeconomics of Global Warming, edited by: Bernard, L. and Semmler, W., Oxford University Press, New York, NY, USA, pp. 499–554, 2015.

Bahn, O., Edwards, N., Knutti, R., and Stocker, T.: Energy policies avoiding a tipping point in the climate system, Energ. Policy, 39, 334–348, 2011.

Bauer, N.: Carbon capturing and sequestration – an option to buy time, PhD Thesis, Faculty of Economics and Social Sciences, University Potsdam, Potsdam, 2005.

Deep Decarbonization Pathways Project (DDPP): Pathways to deep decarbonization 2015 report, Sustainable Development Solutions Network (SDSN) - Institute for Sustainable Development and International Relations (IDDRI), 2015.

Eliasson, B., Riemer, P. W. F., and Wokaun, A. (Eds.): Greenhouse gas control technologies: Proceedings of the 4th international conference, Pergamon, Interlaken, Switzerland, 1999.

Ha-Duong, M. and Keith, D. W.: Carbon storage: The economic efficiency of storing in leaky reservoirs, Clean. Technol. Envir., 5, 181–189, 2003.

Hannart, A., Ghil, M., Dufresne, J.-L., and Naveau, P.: Disconcerting learning on climate sensitivity and the uncertain future of uncertainty, Climatic Change, 119, 585–601, 2013.

Herzog, H. J.: What future for carbon capture and sequestration?, Environ. Sci. Technol., 35, 148A–153A, 2001.

IPCC: Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific Technical Analyses, in: Contribution of Working Group II to the Second Assessment Report of the IPCC, edited by: Watson, R. T., Zinyowera, M. C., and Moss, R. H., Cambridge University Press, 1996.

IPCC: Climate Change 2007: Mitigation of Climate Change, Contribution of Working Group III to the Fourth Assessment Report of the IPCC, edited by: Metz, B., Davidson, O. R., Bosch, P. R., Dave, R., and Meyer, L. A., Cambridge University Press, 863 pp., 2007.

IPCC: Renewable Energy Sources And Climate Change Mitigation, A Special report of the IPCC, edited by: Edenhofer, O., Madruga, R. P., Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S., Zwickel, T., Eickemeier, P., Hansen, G., Schlömer, S., and von Stechow, C., Cambridge University Press, 1089 pp., 2012.

IPCC: Climate Change 2013: the Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the IPCC, edited by: Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, 1535 pp., 2013.

IPCC: Climate Change 2014 – Mitigation of Climate Change, Contribution of Working Group III to the Fifth Assessment Report of the IPCC, Cambridge University Press, Cambridge, UK, 2014.

Keith, D. W., Ha-Duong, M., and Stolaroff, J. K.: Climate strategy with $CO_2$ capture from the air, Climatic Change, 74, 17–45, 2006.

Kuckshinrichs, W. and Hake, J-F.: Carbon Capture, Storage and Use: Technical, Economic, Environmental and Societal Perspectives, Springer International Publishing, Switzerland, 2015.

Lenton, T. M., Held, H., Kriegler, E., Hall, J. W., Lucht, W., Rahmstorf, S., Schellnhuber, H.-J.: Tipping elements in the Earth's climate system, P. Natl. Acad. Sci. USA, 105, 1786–1793, 2008.

Lewandowsky, S., Risbey, J. S., Smithson, M., Newell, B. R., and Hunter, J.: Scientific uncertainty and climate change: Part I. Uncertainty and unabated emissions, Climatic Change, 124, 21–37, 2014a.

Lewandowsky, S., Risbey, J. S., Smithson, M., and Newell, B. R.: Scientific uncertainty and climate change: Part II. Uncertainty and mitigation, Climatic Change, 124, 39–52, 2014b.

Mackey, B., Prentice, I. C., Steffen, W., and House, J.: Untangling the confusion around land carbon science and climate change mitigation policy, Nat. Clim. Chang., 3, 552–557, 2013.

Moser, E., Prskawetz, A., and Tragler, G.: Environmental Regulations, Abatement and Economic Growth, in: in: Green Growth and Sustainable Development, edited by: Crespo Cuaresma, J. and

Ogutu, K. B. Z., D'Andrea, F., Ghil, M., Nyandwi, C., Manene, M. M., and Muthama, J. N.: Coupled Climate–Economy–Biosphere (CoCEB) model – Part 1: Abatement share and investment in low-carbon technologies, Earth Syst. Dynam. Discuss., 6, 819–863, 2015.

Palokangas, T., Dynamic Modeling and Econometrics in Economics and Finance 14, Springer Verlag, Berlin, Heidelberg, pp. 87–111, 2013.

Petersen, A.: Simulating nature: a philosophical study of computer-model uncertainties and their role in climate science and policy advice, 2nd edn., CRC Press, Abingdon, 2012.

Pielke Jr., R. A.: An idealized assessment of the economics of air capture of carbon dioxide in mitigation policy, Environ. Sci. Policy, 16, 216 – 225, 2009.

Richardson, K., Steffen, W., Liverman, D., Barker, T., Jotzo, F., Kammen, D. M., Leemans, R., Lenton, T. M., Munasinghe, M., Osman-Elasha, B., Schellnhuber, H. J., Stern, N., Vogel, C., and Wæver, O.: Climate Change: Global Risks, Challenges and Decisions, Cambridge University Press, New York, USA, 2011.

Rydge, J. and Bassi, S.: Global cooperation and understanding to accelerate climate action, in: The Global Development of Policy Regimes to Combat Climate Change, edited by: Stern, N. H., Bowen, A., and Whalley, J., The Tricontinental Series on Global Economic Issues, Volume 4, World Scientific Publishing Co. Pte. Ltd., Singapore, pp. 1−22, 2014.

Wesselink, A., Challinor, A. J., Watson, J., Beven, K., Allen, I., Hanlon, H., Lopez, A., Lorenz, S., Otto, F., Morse, A., Rye, C., Saux-Picard, S., Stainforth, D., and Suckling, E.: Equipped to deal with uncertainty in climate and impacts predictions: lessons from internal peer review, Climatic Change, 132:1–14, 2015.

Willams, D., Durie, B., McMullan, P., Paulson, C., and Smith, A. (Eds.): Greenhouse gas control technologies: Proceedings of the 5th international conference on greenhouse gas control technologies, CSIRO Publishing, Collingwood, Australia, 2001.