Biogeosciences

Discussions

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Interactive comment on "Transient Dynamics of Terrestrial Carbon Storage: Mathematical foundation and Numeric Examples" *by* Yiqi Luo et al.

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Dear M. Freilich, maraf@mit.edu:

We greatly appreciate your comments on our manuscript. We have carefully studied your comments and revised the manuscript accordingly. Please note the line numbers and pages numbers in this letter are all refereed in the revised manuscript.

Hope you will find our revision and responses satisfactory.

Yiqi Luo On behalf of all the authors

Below we list our point-to-point responses to your comments:

[Comment] Luo et al provide an excellent mathematical framework for studying the dynamics of the carbon cycle in terrestrial ecosystems. The focus on transient dynamics makes clear which aspects of carbon storage and sequestration are most important to consider in order to understand the functioning of forests are carbon reservoirs. The reduction of the models to a 3D parameter space is seemingly very useful for a mechanistic understanding of the effects of global change on terrestrial carbon storage.

[Response] We greatly appreciate your positive comments.

[Comment] The modeling assumptions could use further clarification. In particular, the assumption that short-term disturbances can be well represented by the matrix equation (assumption 5) and the assertion that this assumption is unlikely to affect the results need further support. Disturbances may be very important for the carbon cycling of terrestrial systems and can affect ecosystem dynamics and carbon cycling for decades, in addition to causing C fluxes that greatly exceed those from annual cycles.

[Response] We agree. Disturbances can substantially affect ecosystem carbon cycling

[Comment] Presumably, disturbance events could be incorporated in the time varying factors u(t) and _(t). However, there are a number of well-developed non-linear models for pest outbreaks that might violate the assumption that transfer between pools can be represented by a linear model (assumption 1) if outbreaks were to be incorporated into these factors.

[Response] We appreciate for your point that there are many non-linear models for pest outbreaks. Pest outbreaks affect tree mortality, which usually is in proportion to the severity of pest outbreaks. Tree mortality can be non-linearly responding to pest outbreaks as decomposition of soil organic carbon to temperature. Such non-linear responses still do not affect fundamental properties of the carbon cycle as discussed in Assumption 4 on response functions.

[Comment] While one aspect of pest outbreaks is a reduction in GPP or NPP, which may be sufficiently represented by u(t), even a linear approximation of the rapid change in the transfer of biomass between classes cannot be represented by this model without making the matrix A of transfer coefficients also time-dependent. One way this may be overcome is by setting limits on the timescale of applicability of this mathematical framework, so as to assume that transfer coefficients are not changing. Further, abiotic disturbances such as fire or disturbances that remove carbon from the ecosystem completely such as harvesting would be outside the scope of this model.

[Response] Matrix A can be time-dependent. Equation 1 does not explicitly include abiotic disturbances in influencing carbon cycle. Weng et al. (2012) developed a disturbance regime model that explicitly incorporates disturbances into equation 1 for their influences of terrestrial carbon cycle. This paper focuses on understanding of fundamental properties of equation 1.

To clarify this point, we have revised the second half of the paragraph on Assumption 4 as:

"Those disturbance influences can be represented in terrestrial C cycle models through changes in parameter values, environmental scalars, and/or discrete C transfers among pools of eq. 1 (Luo and Weng 2011). While eq. 1 does not explicitly incorporate disturbances for their influences on land C cycle, Weng et al. (2012) developed a disturbance regime model that combines eq. 1 with frequency distributions of disturnace severity and intervals to quantify net biome exchanges."

[Comment] The authors show that X'(t) in this model is the net ecosystem production (NEP), but non-biotic transformation from organic and inorganic carbon is not included in NEP, nor is transfer between ecosystems. This may just require a clarification of terminology in order to include fire, other abiotic oxidation, and harvesting in the _(t) term of the model.

[Response] Yes, you are very sharp to point out the omission of this analysis. We did

not explicitly include disturbances in the analysis but state that disturbances do not alter fundamental properties of the system. As explained above, Weng et al. (2012) developed a model that explicitly combines disturbances with equation 1 to quantify net biome production on lines 503-506.

[Comment] Finally, it may be useful to clarify on what scale the results apply. Based on the assumptions about linear decay smoothing small scale fluctuations and the neglect of lateral C fluxes, it seems important to point out that this is model applies only at the ecosystem scale. The parameters are calibrated based on one grid cell of the TECO model; would the same procedure be expected to scale up to larger spatial scales?

[Response] Thanks for your comment. Equation 1 has been also applied to several global models, such as National Center for Atmosphere Research (NCAR) Community Land Model (CLM) and LPJ-GUESS. See a published paper by Ahlström et al. (2015) for the application of equation to the global model LPJ-GUESS. Fundamentally equation 1 fully represents carbon balance equations in matrix form for almost all the land carbon cycle models. Equation 1 does not do any more smoothing of small-scale fluctuations than do the original models. The paragraph on page 27 about physical emulators explains it.

Yes, equation 1 does not apply to the models with lateral fluxes.

[Comment] In the conclusion, the authors state that this model is consistent with complex dynamics including tipping points, which they say are "caused by multiple environmental forcing variables interacting with relatively simple internal processes over different temporal and spatial scales." Tipping point behavior crucially depends on non-linear dynamics and so seems inconsistent with this model. However, a clarification that this method can evaluate the transient dynamics in a given state but does not reproduce more complex behavior may be more accurate.

[Response] You are right that the eq. 1 does not cause some of the complex dynamics such as tipping points. Tipping points occur in carbon cycle mainly due to complex be-

haviors in external forcings. Luo and Weng (2011) and Luo et al. (2015) have explained this phenomenon in detail. While this paper could not explain this in detail again, we revised the manuscript by pointing readers to those papers for detailed discussion as on pages 29-30:

"The two components of land C storage dynamics represent interactions of external forces (via changes in the capacity) and internal capability of the land C cycle (via changes in the C storage potential) to generate complex phenomena of C cycle dynamics, such as fluctuations, directional changes, and tipping points, in the terrestrial ecosystems. From a system perspective, these complex phenomena could not be generated by relatively simple internal processes but are mostly caused by multiple environmental forcing variables interacting with internal processes over different temporal and spatial scales as explained by Luo and Weng (2011) and Luo et al. (2015). Note that while those internal processes can be mathematically represented with a relatively simple formula, their ecological and biological underpinnings can be very complex."

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