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Biogeosciences Discussions

Interactive comment on "The Australian terrestrial carbon budget" *by* V. Haverd et al.

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Response to reviews of "The Australian terrestrial carbon budget" by V. Haverd et al. The referee comments have been reproduced below and labelled "Comment x.y", with corresponding author responses following each comment labelled "Response x.y" where x denotes the Referee number and y the Comment number.

Anonymous Referee #1 Harverd and co-authors used a fine-spatial-resolution model (BIOS2) to estimate the full C-CO2 model for Australia. The result is comprehensive in that it includes what could be expected to be the major contributors to the carbon budget. The results and discussion are well crafted and original in places i.e. figures 6 and 7 are refreshing.I recommend this paper for publication following technical comments and suggestions on the presentation.

Comment 1.1:

General comment As I understood it, the RECAPP protocol suggests to use bottom-up measurements to estimate the regional carbon budget, in the absence of such measurements it was suggested to use a DGVM. Although it seems that some ground observations are available, this study made use of BIOS2 to estimate the carbon budget. Is BIOS2 a classic DGVM (parameterized and validated against ground observations) or is it rather a data assimilation tool (using observed LAI instead of calculating it or using soil C-inventories instead of a spin-up)? The current manuscript has only 4 lines(pages 12262-12263) on this issues. A table (or figure) showing more details is needed for the reader to assess the strengths and weaknesses of this approach. The current manuscript refers to Harverd et al 2012, this approach is acceptable to learn moreabout the details but essential information should be repeated in the manuscript under review. The same table or figure could be used to put forward that BIOS2 was used to estimate NPP and NEP but that these estimates were completed by making use of other data products and observations. The complexity of BIOS2 in terms of processes should be better described. On page 12268 climate and CO2 are put forward as the main drivers of changes in the biospheric carbon accumulation. Which processes were included in this analysis (those shown in fig 2?) and more importantly, which were not included in the analysis but could potently have an effect in Australia or regions thereof i.e. diffuse/direct light, ozone, UV-damage, nitrogen, phosphorous and sulphur cycling, land management (ploughing, grazing, extinction of large predators, ...)?

Response 1.1a:

An introduction to Section 2 now clarifies which flux components are assessed using BIOS2 and which are not: "Net Primary Production and Net Ecosystem Production were obtained using BIOS2, subject to constraint by multiple observation sets (including eddy flux data and carbon pool data), as described in Section 2.1 below. Most other components of the carbon budget were obtained independently as described in Sections 2.2-2.6, with two exceptions. First, the Heterotrophic Respiration, which is

derived primarily from BIOS2, is corrected for the influences of fire, transport (by river and dust) and harvest (Section 2.1). Second, the net fire emissions from non-clearing fires were estimated using a BIOS2 simulation with prescribed gross fire emissions (Section 2.2.2)."

Response 1.1b:

Spin-up had already been addressed in Section 2.1 of the original manuscript: "In this work we extended BIOS2 simulations back in time to 1799, to assess the effects of changing climate and atmospheric CO2 on NPP and NEP. CASA-CNP carbon pools were initialised by spinning the model 200 times over a 39 year period using NPP generated with atmospheric CO2 fixed at the pre-industrial value of 280 ppm, and 1911-1949 meteorology, corresponding to the earliest available rainfall and temperature data from the Bureau of Meteorology's Australian Water Availability Project data set (BoM AWAP) (Grant et al., 2008; Jones et al., 2009). Following spin-up, the 1799-2011 simulation was performed using actual deseasonalised atmospheric CO2 (from the Law Dome ice core prior to 1959 (MacFarling Meure et al., 2006), and from global in-situ observations from 1959 onward (Keeling et al., 2001) with repeated 1911-1949 meteorology prior to 1911 and actual meteorology thereafter."

Response 1.1c:

We have added additional detail to Section 2.1 about BIOS2, the modelling framework used to evaluate NPP, NEP and RH: "NPP and NEP components were derived using BIOS2 (Haverd et al., 2012), constrained by multiple observation types, and forced using remotely-sensed vegetation cover. BIOS2 is a fine-spatial-resolution (0.05o) offline modelling environment built on capability developed for the Australian Water Availability Project (King et al., 2009; Raupach. et al., 2009). It includes a modification of the CABLE land surface scheme (Wang et al., 2011b) incorporating the SLI soil model (Haverd and Cuntz, 2010) and the CASA-CNP biogeochemical model (Wang et al., 2010). BIOS2 parameters are constrained and predictions are evaluated using mul-

tiple observation sets from across the Australian continent, including streamflow from 416 gauged catchments, eddy flux data (CO2 and H2O) from 12 OzFlux sites, litterfall data, and data on soil, litter and biomass carbon pools (Haverd et al., 2012b). CABLE consists of five components (Wang et al., 2011a): (1) the radiation module describes direct and diffuse radiation transfer and absorption by sunlit and shaded leaves; (2) the canopy micrometeorology module describes the surface roughness length, zero-plane displacement height, and aerodynamic conductance from the reference height to the air within canopy or to the soil surface; (3) the canopy module includes the coupled energy balance, transpiration, stomatal conductance and photosynthesis of sunlit and shaded leaves; (4) the soil module describes heat and water fluxes within soil and snow at their respective surfaces; and (5) the ecosystem carbon module accounts for the respiration of stem, root and soil organic carbon decomposition. In BIOS2, the default CABLE v1.4 soil and carbon modules were replaced respectively by the SLI soil model (Haverd and Cuntz, 2010) and the CASA-CNP biogeochemical model (Wang et al., 2010). Modifications to CABLE, SLI and CASA-CNP for use in BIOS2 are detailed in (Haverd et al., 2012a)."

Response 1.1d:

We have added the following paragraph in Section 2.1 to address missing processes: "Nitrogen and phosphorous cycles in CASA-CNP were disabled and land management was not considered explicitly. However BIOS2 is driven by remotely-sensed vegetation cover and parameters and uncertainties were estimated using multiple observation types spanning the entire bioclimatic space, including managed lands. These two factors mitigate against the exclusion of potentially important processes. Moreover, model structural errors incurred by process omission are incorporated in the model-observation residuals, which are propagated through to uncertainties in model predictions (Haverd et al., 2012a)."

Comment 1.2: Add a paragraph/section describing which information went into the error bars. IAV is clear but it is not clear whether the error on the mean is a real uncer-

tainty (model, parameter, driver uncertainty) or mainly reflects spatial heterogeneity.

Response 1.2:

In Section 4.1.3 we had already written:

“Error bars represent 1s uncertainties due to uncertainties in model parameters and forcing. The parameter uncertainty component represents the constraint on NPP predictions provided by multiple observation sets in the parameter estimation process (Haverd et al. 2012).”

We have modified the text in Section 4.1.4 to read:

“Error bars represent the 1s uncertainties in NEP resulting from 20% uncertainty in the partial derivative of NPP with respect to atmospheric CO2 concentration, combined in quadrature with uncertainties due to uncertainties in model parameters and forcing.”

We have also added the following text to Section 2.1 and clarified the sources of uncertainties in each of the other Methods subsections:

“Uncertainty in BIOS2 predictions (all uncertainties hereafter expressed as 1s), due to parameter uncertainty and uncertainty in forcing data were estimated separately and combined in quadrature to give total uncertainty, as described by Haverd et al. (2012). To obtain uncertainties in model predictions associated with parameter uncertainties in a parameter set p, the parameter covariance matrix C was projected onto the variance in the prediction Z... is the vector of sensitivities of a prediction Z to the elements of p. Uncertainties in model predictions associated with forcing uncertainties were estimated as the absolute change in prediction associated with perturbations to forcing inputs. NEP uncertainty estimates also include the uncertainty due to an assumed 20% uncertainty in the partial derivative of NPP with respect to atmospheric CO2 concentration”

In Section 2.2 we have added:

“Uncertainty (1s) in continental gross fire emissions was estimated as the difference between the NGGI and GFED3, each averaged over the period (1997-2009) for which both products exist.”

Comment 1.3:

Suggestions - Providing some basic statistics on Australia may be useful to many readers i.e. surface area of Australia (the conversion is given in Table 1 but not the absolute numbers), surface areas of the different biomes/land covers, productivity of the different biomes/land covers etc. Rather than having one field for ’Biosphere’ in table 1, I suggest to distinguish some relevant biomes or land cover types i.e. forest, savannah, cropland, grassland, desert, etc. –

Response 1.3:

We have included a new Table, now Table 5, which gives spatial extent, mean annual temperature and Precip for each bioclimatic region in what is now Figure 3 (since the introduction of the bioclimatic regions has been moved to the top of Section 4). We have not distinguished biomes in the C-budget summary table, because it currently contains the appropriate aggregated fluxes required for the higher level (global) RECCAP synthesis. Regional details of coupled carbon and water fluxes are presented elsewhere (in the BIOS2 modelling paper) (Haverd et al. 2012)

Table 5: Spatial extent, mean annual temperature and precipitation of the bioclimatic regions shown in Figure 1.

Area [106 km2] Fractional area [%] Mean annual T (1975-2011) [oC] Mean annual precip (1975-2011) [mm y-1] Tropics 0.39 5.07 26.4 1345 Savanna 1.62 21.31 24.2 704 Warm Temperate 0.32 4.27 17.2 808 Cool Temperate 0.34 4.47 12.4 881 Mediterranean 0.55 7.22 16.8 420 Desert 4.39 57.66 21.8 296

Comment 1.4:

The fields in Table 3 (i.e. the COSCAT region numbers) are not very useful. The

information in Table 3 could be plotted (as a bar graphs?) on Figure 13. This would reduce the number of display items.

Response 1.4:

We have retained the COSCAT region numbers in this table as they are essential for associating the DOC fluxes with the regions in Figure 13.

Comment 1.5:

- Consider drawing the boundaries of Fig. 5 on Fig. 4. This would increase the information content of Fig.4 and Fig.5 and reduce the number of display items. - Fig 10 adds little to the topic of the manuscript i.e. the Australian carbon budget. The text is sufficient. This would reduce the number of display items.

Response 1.5:

We have modified Figure 3 (now Figure 4) according to this suggestion, but retained Figure 5 (now Figure 3) for clarity. We have included the following text in Section 4.1: "Solid lines in Figure 4 indicate the boundaries of the bioclimatic regions (Figure 5) and emphasise the strong climate-dependence of NPP."

Comment 1.6:

- Figure 11 nicely shows how the fire season moves from the W to the East. However, most of the figure is white. May be a zoom over Northern Australia would make for a better figure.

Response 1.6:

We choose to retain the entire continental maps as there is significant fire activity across the continent.

Comment 1.7:

- Check the manuscript for (trivial) acronymsi.e. NT and WA appear to be provinces

of Australia but this was not made explicit. SH is introduced but only used a couple of times (write in full as it is much easier to read and won't make the manuscript substantially longer). Same with the wind directions mespecially when combined with province codes i.e. page 12274 line 11 '...the arid interior to NW WA is ...'.

Response 1.7:

We have replaced these acronymns as suggested.

Referee #2: Joshua B. Fisher

Comment 2.1:

This study presents the ambitious accounting of the Australian terrestrial carbon budget for contribution to the RECCAP project. It is a difficult undertaking in its necessary allinclusiveness, but at the same time no new measurements were expectedâĂŤonly a careful analysis of the reported values in the literature was needed.

Response 2.1:

The RECCAP is entirely open to new datasets and assessments. In this study we used the best possible model estimates of NPP and NEP for Australia, constrained by multiple data types, including observations from 12 eddy flux towers. Other key components were derived by careful synthesis of existing data.

Comment 2.2:

Indeed, the authors present the compilation of a large number of datasets; however, the analysis and presentation were problematic. There were two serious problems with the carbon budget: first, it is imperative that the authors address uncertainty much more rigorously (or at all, really) than was done for the carbon budget to be meaningful;

Response 2.2:

We agree that uncertainty is very important, which is why every component in the key

Table 1 “Components of the Australian Carbon Budget” already had an estimate of the IAV and the uncertainty on the mean (1 sigma). See also Response 1.5.

Comment 2.3:

and, second, the mixing of time periods, though the focus was on 1990-2011, is highly confusing and may be a flaw in the analysis.

Response 2.3:

This is not a flaw in the analysis. Unless there is a strong trend in a flux over the budget period, the error in the budget. incurred by averaging over necessarily different periods is small. We have taken care (see text below) of the only strongly trending fluxes which do not cover the full budget period, namely the fossil fuel xes. We have clarified our choice of time periods at the beginning of Section 3 , where the budget is presented:

“The budget period for each flux component is specified as “1990-2011”, and is defined as starting at the beginning of 1990 or whenever data become available thereafter, and ending at the end of 2011, or whenever data cease being available before then. Estimates of NPP, NEP and fossil fuel emissions span the entire budget period. Of the remaining fluxes, it is mostly assumed that the average flux over the available years applies to the entire budget period. The exceptions are the fossil fuel emissions and exports. Emissions were extrapolated to the end of 2011 from the available 1990-2010 data, while fossil fuel exports for 1990-2011 were derived from the value in 2009-2010 using the assumption of a fixed growth rate.”

Comment 2.4:

Further, there seemed to be heavy reliance on a single model for ecosystem CO2 fluxes, which, as the authors state, dominate IAV. Given that this study should be incorporating all relevant data, there was noticeable lack of incorporation eddy flux measurements as well as other models.

Response 2.4:

The justification for using a single model is that it contains information from multiple Australian data sets, such that the uncertainties are significantly smaller than the variation across multiple global model estimates. Eddy flux data were used in the model data fusion process. BIOS2 results are effectively an upscaling of Flux data using a sophisticated process-based model, with constraints by multiple other data types including observations of carbon stocks and water fluxes. This is clarified in the introduction to Section 2: “Net Primary Production and Net Ecosystem Production were obtained using BIOS2, subject to constraint by multiple observation sets (including eddy flux data and carbon pool data), as described in Section 2.1 below. We choose to use BIOS2 in preference to multiple estimates of NPP and NEP from ecosystem models participating in the carbon cycle model intercomparison project (TRENDY) (Sitch et al., 2012, submitted) (http://dgvm.ceh.ac.uk/node/9). The reason for this is that these global models exhibit variability in Australian contintental NPP estimates (2.2 PgCy-1 (range) and 0.8 PgCy-1 (1s)), which is much higher than the uncertainty (0.2 PgCy-1 (1s)) in the regionally-constrained BIOS2 estimates.”

Comment 2.5:

The overall writing is succinct and clear, which is important because the study is very long. The presentation of results is unfocused, however, oftentimes seemingly there just because data or model output were available, not because results contributed meaningfully to the analysis or budget.

Response 2.5:

This is not the case. Every data set included contributes directly to the estimation of the fluxes specified in the carbon budget (Equation (1)).

Comment 2.6:

In the end, the paper presents itself more as a collection of different datasets than a quality summary and analysis.

Response 2.6:

We recognised the need for a “quality summary”, which is why the results are presented clearly in the form of the Table 1 “Components of the Australian Budget” and Figure1 “Summary of the Australian territorial carbon budget” We also recognised the need for “quality analysis” , which is why we assess and discuss each component of the budget in turn in Section 4.

Comment 2.7:

Abstract - “in the context of estimates over two centuries” does not make sense, and should probably be deleted.

Response 2.7:

We choose to retain this phrase because NBP is the result of long-term changes in carbon stores and cannot be estimated for recent decades without consideration of the impacts of previous climate and CO2 forcing.

Comment 2.8:

- Include a sentence that outlines the basic methods used in the study (and don’t forget the uncertainty estimation too).

Response 2.8:

We have included the (necessarily short) following text, in which the uncertainty estimation is implicit in the phrase “are constrained by multiple observation types.” “Major biospheric fluxes were derived using BIOS2 (Haverd et al., 2012b), a fine-spatial-resolution (0.05o) offline modelling environment in which predictions of CABLE (Wang et al. 2011), a sophisticated land surface model with carbon-cycle, are constrained by multiple observation types.”

Comment 2.9:

It would be good to have a statement on what the biggest source(s) of uncertainty were and why.

Response 2.9:

We have modified the statement of NBP to: “The resultant Net Biome Production (NBP) is 31 $\pm$ 35 TgC y-1, in which the largest contributions to uncertainty are NEP, Fire and LUC.”

Comment 2.10:

Introduction - Say why 1990-2011 was selected. Compare with the time period for the other RECCAP studies (i.e., are the regional studies comparable?)

Response 2.10:

The analysis period is intentionally slightly longer than the prescribed RECCAP period (1990-2010), in order to capture the record-breaking wet years of 2010-2011. This small extension is expected to introduce a negligible inconsistency into the global RECCAP synthesis.

Comment 2.11:

Methods- NPP, NEP: needs uncertainty estimation.

Response 2.11:

See Response 1.5.

Comment 2.12:

- How was OzFlux integrated into the NPP/NEP estimates? It would seem odd to ignore these valuable data, and rely only on a single model.

Response: 2.12:

We have not ignored these data. See Response 2.4.

Comment 2.13:

- Fire: needs uncertainty estimation. There are known biases with these datasets that were not mentioned or accounted for.

Response 2.13:

We have checked for and quantified the bias error as far as possible by comparing two largely independent estimates of continental fire emissions. This was discussed already in detail in the first paragraph Section 4.2.1, in which biome-specific biases are quantified and continental fire emissions from GFED are found to be biased high by 17% compared to the regional NGGI product.

Comment 2.14:

- LUC: what's the spatial resolution? Clarify if this is the LUC from 2011 minus 1990.

Response 2.14:

The data period (1990-2008) has been repeated in Section 2.3. The spatial resolution of 25 m had already been quoted in this section.

Include some discussion as to why the assumed uncertainties are valid or representative.

Comment 2.15:

- DOC: uncertainty estimation.

Response 2.15:

We have added the following text to Section 2.15:

"In the absence of uncertainty estimates, we assign a relative uncertainty of 50% on this component of the C budget. This crude estimate has negligible impact on the uncertainty of NBP because the C flux associated with riverine transport is very small (Section 4.4)."

Comment 2.16:

- Dust: Representativeness of studies used for Australia as a whole? Response 2.16:

We have only been able to extract results from global studies, which include Australia as part of their spatial domain.

Comment 2.17:

- Fossil fuel: Include some discussion as to why the assumed uncertainties are valid or representative.

Response 2.17:

We have extended our comment on the uncertainty of FF emissions in Section 2.6: "For uncertainties of FF emissions, we assumed the global value of 6% (1s) (Andres et al. 2012). We take this as applicable to Australia, because although fossil fuel consumption is known relatively accurately, there uncertainties in the carbon content of fossil fuels."

Comment 2.18:

Net C budget- Mixing and matching of different time periods, as shown in Table 1. This shouldn't add up correctly. Discuss why various non-1990-2011 numbers were not extrapolated to the full time period.

Response 2.18:

See Response 2.3 which contains associated additional text addressing this point.

Comment 2.19:

Why do Figs. 4, 6, 9 go beyond the 1990-2011 period? This is out of the context set up by the authors.

Response 2.19:

This time-domain was chosen because NBP is the result of long-term changes in carbon stores (the Australian biospheric turnover time is $\sim$ 70 y) and cannot be estimated for recent decades without consideration of the impacts of previous climate and CO2 forcing.

Comment 2.20:

- Having a (sub-) figure on Precip is maybe a bit out of scope of the Carbon budget focused paper. Maybe the intention is how the Carbon budget might change with changing Precip? Seems like it was included just because the data were available, not because it contributed to the argument, which is the construction of a carbon budget. Correlation of Precip to NPP is not interesting, as the NPP is model-driven from that precip forcing.

Response 2.20:

Variability in precip forcing does not necessarily correlate with NPP. . .it depends how water-limited the NPP is. We have modified the text at the beginning of Section 4.1.2 to read:

"It is important to assess the 1990-2011 period in the context of longer term variability. Figure 5 shows the annual temporal variations of continental mean precipitation, NPP, and NEP, for 1911-2011. Precipitation is included because it is the single largest driver of variability in the Australian carbon cycle."

Comment 2.21:

- Fig. 3: how does this map compare to satellite observations of NDVI? Are the spatial patterns consistent? Speaking of which, perhaps more remote sensing data could have been used in this study, especially given the narrow modern time window focus, which is good for remote sensing.

Response 2.21:

We have used remotely-sensed LAI (derived from AVHRR FAPAR) to drive BIOS2. While an estimate of GPP could be derived using remote-sensing information alone, we choose to use a model-data-fusion approach in which additional constraints (namely knowledge of physical processes as encapsulated by CABLE, and other data sets), together with remotely-sensed LAI, enable a more accurate assessment. While the budget period is relatively short, NEP cannot be derived for this period from remote-sensing. As stated in Response 2.19, NBP is the result of long-term changes in carbon stores (the Australian biospheric turnover time is $\sim$ 70 y) and cannot be estimated for recent decades without consideration of the impacts of previous climate and CO2 forcing.

Interactive comment on Biogeosciences Discuss., 9, 12259, 2012.