

**The Australian
terrestrial carbon
budget**

V. Haverd et al.

This discussion paper is/has been under review for the journal Biogeosciences (BG).
Please refer to the corresponding final paper in BG if available.

The Australian terrestrial carbon budget

**V. Haverd¹, M. R. Raupach¹, P. R. Briggs¹, J. G. Canadell¹, S. J. Davis²,
R. M. Law³, C. P. Meyer³, G. P. Peters⁴, C. Pickett-Heaps¹, and B. Sherman⁵**

¹CSIRO Marine and Atmospheric Research, P.O. Box 3023, Canberra ACT 2601, Australia

²University of California, Dept. of Earth System Science, Irvine, CA, USA

³CSIRO Marine and Atmospheric Research, PB1, Aspendale, Victoria 3195, Australia

⁴CICERO, P.O. Box 1129 Blindern, 0318 Oslo, Norway

⁵CSIRO Land and Water, P.O. Box 1666, Canberra ACT 2600, Australia

Received: 31 July 2012 – Accepted: 17 August 2012 – Published: 12 September 2012

Correspondence to: V. Haverd (vanessa.haverd@csiro.au)

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

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Abstract

This paper reports a study of the full carbon (C-CO₂) budget of the Australian continent, focussing on 1990–2011 in the context of estimates over two centuries. The work is a contribution to the RECCAP (REgional Carbon Cycle Assessment and Processes) project, as one of numerous regional studies being synthesised in RECCAP. In constructing the budget, we estimate the following component carbon fluxes: Net Primary Production (NPP); Net Ecosystem Production (NEP); fire; Land Use Change (LUC); riverine export; dust export; harvest (wood, crop and livestock) and fossil fuel emissions (both territorial and non-territorial).

The mean NEP reveals that climate variability and rising CO₂ contributed 12 ± 29 (1σ error on mean) and 68 ± 35 Tg C yr⁻¹ respectively. However these gains were partially offset by fire and LUC (along with other minor fluxes), which caused net losses of 31 ± 5 Tg C yr⁻¹ and 18 ± 7 Tg C yr⁻¹ respectively. The resultant Net Biome Production (NBP) of 31 ± 35 Tg C yr⁻¹ offset fossil fuel emissions (95 ± 6 Tg C yr⁻¹) by 32 ± 36 %. The interannual variability (IAV) in the Australian carbon budget exceeds Australia's total carbon emissions by fossil fuel combustion and is dominated by IAV in NEP. Territorial fossil fuel emissions are significantly smaller than the rapidly growing fossil fuel exports: in 2009–2010, Australia exported 2.5 times more carbon in fossil fuels than it emitted by burning fossil fuels.

1 Introduction

Full carbon budgets for land regions are significant for several reasons: they provide insights into terrestrial carbon cycle dynamics, including processes contributing to the net trend and variability in the terrestrial carbon sink; they place anthropogenic carbon and greenhouse gas inventories in a broader context; and they indicate how anthropogenic inventories change spatially across regions and temporally in response to climate variability and changes in land use and land management. This paper reports a

BGD

9, 12259–12308, 2012

The Australian terrestrial carbon budget

V. Haverd et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



study of the full carbon budget of the Australian continent, focussing on 1990–2011 in the context of estimates over two centuries. The work is a contribution to the RECCAP (REgional Carbon Cycle Assessment and Processes) project (Canadell et al., 2011), as one of numerous regional studies being synthesised in RECCAP.

5 A carbon budget for a land region can be expressed by equating the change in territorial storage of carbon C_T per unit time t with the net flux of carbon into the land surface

$$\begin{aligned}
 -dC_T/dt &= -dC_B/dt - dC_{FF}/dt - dC_{HWP}/dt & (1) \\
 &= (F_{NPP} + F_{RH} + F_{Fire} + F_{LUC} + F_{Transport} + F_{Harvest}) + (F_{FF} + F_{FF,Export}) - dC_{HWP}/dt
 \end{aligned}$$

10 Here, C_B and C_{FF} and C_{HWP} are C stocks in the Biospheric, Fossil Fuel and Harvested Wood Products (HWP) pools respectively. Changes in other C pools (e.g. biological products other than HWP) are considered negligible. The sign convention for F is that a positive flux is directed away from the land surface. (However note also that hereon:

15 (i) positive “productivities” denoted eg NPP, NEP, NBP (in the absence of the main symbol F) are by definition uptake by the land; (ii) positive “exports” and “emissions” are by definition fluxes away from the land surface.) Flux subscripts denote contributions to the net flux from Net Primary Production (NPP), Heterotrophic Respiration (RH), Fire, Land Use Change (LUC), Transport by rivers and dust, Harvest, Fossil Fuel emissions (FF), and FF export. It is assumed that in all gaseous fluxes, C is present as C in CO_2 , and that the ultimate fate of C in the lateral fluxes (Transport, Harvest, exported FF) is C in CO_2 . (Hereafter C in CO_2 will be abbreviated as C.) Terms in Eq. (1) can also be used to construct the net land-to-atmosphere C flux:

$$F_{LAE} = F_{NPP} + F_{RH} + F_{Fire} + F_{LUC} + F_{FF} + F_{Harvest}^{Consump} - dC_{HWP}/dt \quad (2)$$

25 where LAE denotes Land Atmosphere Exchange and $F_{Harvest}^{Consump}$ is the component of the harvest flux that is consumed within the land region. The portion of the harvest that is consumed but does not decompose is accounted for by the change in stored

BGD

9, 12259–12308, 2012

The Australian terrestrial carbon budget

V. Haverd et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



HWP. The total change in atmospheric C storage attributable to loss of C from the land is given by $-dC_T/dt$ (Eq. 1), and is the sum of F_{LAE} and Non-Territorial (NT) emissions resulting from lateral fluxes (i.e. Transport fluxes, and the export of harvest and FF). As such, a bottom-up estimate of dC_T/dt formed by estimating the component fluxes provides an independent test of results from “top-down” atmospheric inversion approaches (Canadell et al., 2011).

The aim of this work is to construct a full carbon budget for the period 1990–2011 by combining estimates of the fluxes in Eq. (1). Methods for estimating the flux components are detailed in Sect. 2 and the budget is summarised in Sect. 3. Details of the component fluxes are presented in Sect. 4. In Sect. 5 atmospheric inversion results for Australia are discussed.

2 Methods and data sets

2.1 Net Primary Production, Net Ecosystem Production and Heterotrophic respiration.

We define Net Ecosystem Production as Net Primary Production (NPP) minus the heterotrophic respiration flux that would occur without the influences of fire, transport (by river and dust) and harvest, $F_{RH,-F-T-H}$. (Here subscripts $-F$, $-T$, $-H$ denote the absence of fire, harvest and transport). Section 2.2 describes the estimation of $F_{RH,-F-T-H}$, i.e. F_{RH} under a regime of fire. The effect of harvest and transport on F_{RH} is treated more simply: we assume F_{RH} is discounted by 100% of the exported flux because the C in these fluxes is removed and cannot be respired.

NPP and NEP components were derived using BIOS2 (Haverd et al., 2012), a fine-spatial-resolution (0.05°) offline modelling environment that includes a modification of the CABLE land surface scheme (Wang et al., 2011) 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 multiple

BGD

9, 12259–12308, 2012

The Australian terrestrial carbon budget

V. Haverd et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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 carbon pools (Haverd et al., 2012).

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 yr 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.

2.2 Fire

2.2.1 Gross fire emissions

Gross monthly fire emissions were extracted from the GFED3 database (van der Werf et al., 2010) for the 1997–2009 period. These emissions are determined using the algorithm of Sieler and Crutzen (1980), with burnt area determined from the MODIS burned area product from 2002 to 2009 and from AVHRR for the period 1997–2002 (Giglio et al., 2010), fuel loads calculated using the CASA terrestrial biosphere model (Randerson et al., 1997) and combustion parameters sourced from the global literature. These were compared with independent estimates derived using the 2004 National Greenhouse Gas Inventory Methodology (Australian Greenhouse Office, 2006; Meyer, 2004). This methodology also implements the algorithm of Sieler and Crutzen (1980). However the data are entirely independent of GFED. Burnt area in the tropical savanna and arid rangelands is estimated from AVHRR 1km imagery (Craig et al., 2002) while

The Australian terrestrial carbon budget

V. Haverd et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



for the forests area, fire area estimates are sourced from fire agency statistics. In all regions fuel loads and combustion parameters are sourced from field measurements. The NGGI methodology is implemented regionally, by state (administrative unit), while GFED3 is spatially explicit at 0.5 deg resolution.

2.2.2 Net fire emissions

We define net fire emissions (of CO₂-C) as the sum of contributions from clearing-fires (i.e. fires associated with conversion of forest to cropland or grassland) and non-clearing fires. Together gross emissions from these two categories of fire sum to the total gross fire emissions (detailed above and denoted by the “Fire” arrow in Fig. 1). Net emissions from clearing-fires are assumed equal to the gross emissions from these fires. In contrast, net emissions from non-clearing fires are estimated as the gross non-clearing fire emissions, minus the reduction in F_{RH} incurred by non-clearing fires (relative to a no-fire scenario). For non-clearing fires, NPP simulated using BIOS2 in the absence of fire was assumed applicable under a recurring fire regime because most Australian land scapes are resilient, with regrowth commencing after the first post-fire rainfall (Graetz, 2002).

For the purpose of estimating net fire emissions, clearing fire emissions $F_{fire,clearing}$ were specified according to DCCEE (2012) and subtracted from the gross fire emissions from GFED3 to give $F_{fire,non-clearing}$. Net fire emissions from clearing fires were assumed equal to gross fire emissions. In contrast, the net export of C from the biosphere due to non-clearing fires was evaluated as:

$$\begin{aligned}
 F_{fire,non-clearing}^{net} &= F_{fire,non-clearing} - F_{RH,-F-T-H} + F_{RH,-T-H} \\
 &= F_{fire,non-clearing} \left(1 - \frac{F_{RH,-F-T-H} - F_{RH,-T-H}}{F_{fire,non-clearing}} \right)
 \end{aligned} \tag{3}$$

Heterotrophic respiration under a recurring fire regime, (but without account for transport by rivers and dust or harvest), $F_{RH,-T-H}$, was estimated using a modification of the

BGD

9, 12259–12308, 2012

The Australian terrestrial carbon budget

V. Haverd et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



BIOS2 environment, in which (i) fire occurred at prescribed return intervals; (ii) at the time of fire, each above-ground carbon pool C_j was instantaneously depleted by $f_b \beta_j C_j$ with β_j being a set of prescribed burning efficiencies for each above-ground pool and f_b the fraction of area burned. Burning efficiencies were assigned according to values used by Barrett (2010). The fraction burned area was calculated as

$$f_b = \frac{(rNPP_t)}{\sum_j \beta_j C_j} \quad (4)$$

with r a prescribed ratio of gross fire emissions to NPP (Table 1, Sect. 3.2 below) and NPP_t the NPP accumulated since the last burn. Gross fire emissions in this simulation are thus equal to $rNPP_t$.

2.3 Land Use Change and Harvest

Land Use Change (LUC): flux estimates (F_{LUC}) were extracted from the Australian National Greenhouse Gas Inventory (DCCEE, 2011), and associated data files (UNFCCC, 2011, v.1.4). The component extracted is the one consistent with the Kyoto Protocol article 3.3 which focuses on emissions from deforestation and reforestation. Estimates of F_{LUC} are calculated using the Australian National Carbon Accounting System (NCAS), a greenhouse accounting framework for the land sector. It is based on spatially explicit ecosystem modeling that uses extensive ground-based datasets for parameterization and validation, and Landsat data time-series at 25-m resolution (Richards and Brack, 2004; Waterworth and Richards, 2008; Waterworth et al., 2007).

The LUC flux from NCAS includes emissions from converting forest to cropland and to grassland, and afforestation largely from the conversion of grasslands to forest land (i.e. plantations). The FullCAM model, used as part of NCAS, estimates emissions and removals from all pools including living biomass, dead organic matter, and soil (Richards and Evans, 2004).

BGD

9, 12259–12308, 2012

The Australian terrestrial carbon budget

V. Haverd et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The Australian terrestrial carbon budget

V. Haverd et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



5 Forests lands are defined as lands with a minimum tree cover of 20 % and trees with a minimum height of 2 m. These criteria are consistent with the reporting requirements of the UNFCCC Marrakech Accords, Montreal Process, and the Food and Agriculture Organization. For land conversion, e.g. forest to grassland, a minimum conversion area of 0.2 ha is used. Emissions from fires associated with Land Use Change are accounted for under fire emissions.

10 Harvested Products: the Australian National Carbon Accounting System (NCAS) accounts for the change in stock of harvested wood products (HWP). This stock includes wood products from forest land within Australia plus imported material minus exported material. Description of the methods and data sources are described in DCCEE (2011), and details of the wood products model and accounting framework are described in (Richards et al., 2007).

15 Production, consumption and export of C in HWP, crops and livestock feed consumption were estimated using the methodology of Peters et al. (2012), applied to Australia for this work. The livestock feed consumption data were converted to carbon content of livestock using the livestock conversion efficiency factor (for Oceania) of 3.7 % from Kraussmann et al. (2008, Table 6).

20 For uncertainties of LUC emissions, we assumed the global value of 40 % (1σ) (Le Quere et al., 2009), while for fluxes of harvested products, we assume uncertainties of 25 % (1σ).

2.4 Riverine transport

Freshwater fluxes of dissolved organic carbon (DOC), which we assume is of terrestrial origin, are computed as the product of a representative DOC concentration and the mean annual river flow.

25 River flow is taken to be either the modelled runoff from one of several significant recent studies of surface water resources in Australia (e.g. Raupach et al., 2009; CSIRO, 2008) or, for the catchments of the Great Barrier Reef Lagoon, measured annual

discharge from the Short Term Modelling Project (Cogle, Carroll, & Sherman, 2006) and from Furnas (2003).

A database of DOC concentrations for Australian continental rivers was assembled from the literature (e.g. Bass et al., 2011). These data were used to estimate mean DOC concentrations as follows: the Australian continent is broken up into 246 distinct hydrographic basins (a.k.a. surface water management areas) (Geoscience, 2004). Where data were available for more than one river within a basin, a flow-weighted mean concentration was computed from the observations and assigned to the entire basin. This concentration was multiplied by the total basin runoff to give the DOC flux for the basin. For calculating fluxes to the ocean, the 246 basins were aggregated to areas contributing to 7 COSCAT zones (**CO**astal **S**egmentation and related **CAT**chments), based on a combination of coastal shelf morphology, coastal current patterns, and climate gradients (Meybeck et al., 2006), as shown in Fig. 13. Fluxes were calculated on a COSCAT zone basis as the product of the relevant annual runoff and a representative concentration. The representative concentration was computed as a flow-weighted average from the constituent basins. In the absence of any measured DOC data, a value was assigned using judgement to interpolate between basins with observational data and considering the local landscape and hydrologic attributes.

2.5 Dust export

Export of carbon by dust is estimated by multiplying net dust export by a fixed soil organic content (SOC) of dust, taken as $4 \pm 3\%$. This value is based on a range of 1–7% SOC observed in wind-blown sediment samples in a recent study indicating significant enrichment of carbon in Australian dusts relative to parent soils (Webb et al., 2012).

Net dust export from Australia is equal to gross dust emissions, minus wet and dry dust deposition terms. Estimates of these terms were obtained from a literature survey of eight studies (Ginoux et al., 2004; Li et al., 2008; Luo et al., 2003, 2008; Maher et al., 2010; Miller et al., 2004; Tanaka and Chiba, 2006; Werner et al., 2002; Yue et

The Australian terrestrial carbon budget

V. Haverd et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



al., 2009; Zender et al., 2003) that use global atmospheric/chemical transport models and/or climate models, specifically enabled to simulate the uplift, transport and wet/dry deposition of dust. Li et al. (2008) specifically targets regions in the Southern Hemisphere. Of the eight studies, only four provided full dust budgets. The mean ratio of net dust export to gross dust emissions for Australia obtained from these four studies was applied to the gross emissions of the remaining four studies.

2.6 Fossil fuel

Fossil fuel emissions estimates for construction of the Australian full carbon budget, were obtained from the latest available Australian National Greenhouse Gas Inventory (DCCEE, 2012). For calculation of embodied carbon emissions and comparisons with other countries, we used the dataset of the Carbon Dioxide Information and Analysis Center (CDIAC) (Andres et al., 2012; Boden et al., 2011; Marland and Rotty, 1984).

For uncertainties of FF emissions, we assumed the global value of 6% (1σ) (Andres et al., 2012).

3 The net carbon budget, 1990–2011

Table 1 summarises the net territorial Australian Carbon Budget, and it is further distilled in Figs. 1 and 2. Each component is discussed in detail in Sect. 4.

For the 1990–2011 period, the biosphere gained carbon at an average rate of $31 \pm 25 \text{ Tg C yr}^{-1}$ (1σ error on mean). As indicated in Figs. 1 and 2i, the gross loss of carbon from the biosphere is dominated by heterotrophic respiration ($2003 \pm 383 \text{ Tg C yr}^{-1}$), with smaller losses due to fire ($127 \pm 22 \text{ Tg C yr}^{-1}$), harvest ($29 \pm 7 \text{ Tg C yr}^{-1}$), Land Use Change ($18 \pm 7 \text{ Tg C yr}^{-1}$) and transport by rivers and dust ($3 \pm 1 \text{ Tg C yr}^{-1}$). However the process contributions to biospheric carbon accumulation are quite different. As shown in Fig. 2ii, the net effects of changing climate and rising CO_2 are to increase biospheric carbon by 12 ± 4 and $68 \pm 7 \text{ Tg C yr}^{-1}$ respectively,

BGD

9, 12259–12308, 2012

The Australian terrestrial carbon budget

V. Haverd et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



while fire and LUC cause net respective losses of $31 \pm 5 \text{ Tg C yr}^{-1}$ and $18 \pm 7 \text{ Tg C yr}^{-1}$ (Harvest and transport are assumed to have no net effect on biospheric carbon accumulation).

Of the total harvest, 60% is consumed in Australia and mostly contributes directly to the flux from the Australian territory to the atmosphere. A small part of the wood harvest flux contributes to the accumulation of the HWP stock at a rate of 1 Tg C yr^{-1} . The exported harvest is returned to the atmosphere as Non-Territorial emissions. Small exports of carbon by river ($2 \pm 1 \text{ Tg C yr}^{-1}$) and dust ($1 \pm 1 \text{ Tg C yr}^{-1}$) transport also contribute to Non-Territorial emissions.

During the same period, the stock of carbon in fossil fuels was depleted by $232 \pm 15 \text{ Tg C yr}^{-1}$, of which $95 \pm 6 \text{ Tg C yr}^{-1}$ was attributable to burning of fossil fuels within the Australian territory, and the remainder to export. Combining territorial fossil fuel emissions with harvest consumption and biospheric land-to-atmosphere fluxes results in a total land-to-atmosphere flux of $48 \pm 29 \text{ Tg C yr}^{-1}$, with an additional $151 \pm 17 \text{ Tg C yr}^{-1}$ contribution from Non-Territorial emissions resulting from consumption of Australian harvest and fossil fuels outside of Australia.

Components of the net flux out of the Australian biosphere and the net land-to-atmosphere flux are shown in bar-chart form in Fig. 2i and iii, along with their 1σ uncertainties and interannual variabilities (IAV). The IAV of both net fluxes is dominated by IAV in $(F_{\text{NPP}} + F_{\text{RH}})$ (136 Tg C yr^{-1}), which in turn is largely attributable to IAV in NPP (Table 1).

BGD

9, 12259–12308, 2012

The Australian terrestrial carbon budget

V. Haverd et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



4 Components of the net carbon budget

4.1 NPP and NEP

4.1.1 Spatial distribution of mean NPP

Figure 3 shows the spatial distribution of mean NPP (1990–2011) at 0.05° spatial resolution across the Australian continent, as simulated using BIOS2. Spatially and temporally variable drivers are meteorological inputs (air temperature, incoming solar radiation, precipitation), vegetation cover (total leaf area index and its partition into woody and grassy components) and soil properties (temporally invariant). The NPP is strongly weighted to the eastern, northern and southwestern margins of the continent, with the remainder of the continent having very low mean NPP.

4.1.2 Ranking the 1990–2011 period

Figure 4 shows the annual temporal variations of continental mean precipitation, NPP, and NEP, for 1911–2011. We assessed the representativeness of precipitation, NPP and NEP during 1990–2011 compared with other 22-yr periods in Fig. 4. For the purpose of regionalising results, we use the bioclimatic classification shown in Fig. 5, a simple aggregation of classes from the agro-climatic classification of Hutchinson et al. (2005, Table 2, Fig. 3), which itself is a digital reanalysis for Australia of the global scheme of Hutchinson et al. (1992). The assessment was done by (i) constructing moving average and standard deviation time series of each quantity using a 22-yr windowing period; (ii) converting each point in the time series to a percentile rank (i.e. the percentage of points in the time series that have lower values than the point in question).

Results are shown in Fig. 6, for each bioclimatic region of Fig. 5 and for the whole continent. The final point in each time series is the percentile rank for the 1990–2011 period. The x-axis represents the centre year of each 22-yr period. Several features

BGD

9, 12259–12308, 2012

The Australian terrestrial carbon budget

V. Haverd et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



emerge from Fig. 6: (i) at the decadal time-scale, NPP is strongly correlated with precipitation; (ii) variability in NEP is more noisy (occurs at shorter time scales) than variability in NPP; (iii) Mediterranean, Cool Temperate and Warm Temperate regions have experienced below-median rainfall in each 22-yr period from 1986 onwards (including 2010–2011, widely perceived as the break of a major drought from 2000–2009); (iv) in contrast, the Tropics, Savanna, Desert and the continent as a whole have experienced above-median rainfall during the same period; (v) the rankings of precipitation and NPP for the whole of Australia are very similar to those for the Desert region; (vi) continental NEP reveals additional structure not seen in the Desert, particularly a decline in the periods from 1986–1997, associated with the Tropics and Savanna regions.

Figure 7 shows the percentile rank of the 1990–2011 mean and standard deviations of precipitation, NPP and NEP, relative to every other 22-yr period since 1911. The period 1990–2011 was one of extremes in many respects: (i) precipitation in the Tropics, Savanna, Desert and the whole of Australia was exceptionally high (cumulative probability $CP > 99\%$) and variable ($CP > 90\%$); (ii) NPP and NEP were correspondingly high and highly variable in the Savanna, Desert and the whole of Australia ($CP > 85\%$), but less so in the Tropics, where variability in temperature (particularly its influence on vapour pressure deficit) strongly influences variability in NPP and NEP; (iii) the Cool Temperate region suffered from exceptionally low precipitation ($CP < 10\%$) and NEP ($CP < 3\%$), as a consequence of preceding decades of below-median NPP (Fig. 6).

4.1.3 Mean NPP 1990–2011

Mean NPP for each bioclimatic region and for the whole of Australia is shown in Fig. 8i, simulated at constant CO_2 (280 ppm, a pre-industrial concentration), and with actual (rising) CO_2 . Error bars represent 1σ 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). The Australian continental mean value (with rising CO_2 forcing) on a per unit area basis is $0.76 \text{ g m}^{-2} \text{ d}^{-1}$, equivalent to 73 % of the global

The Australian terrestrial carbon budget

V. Haverd et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



mean of $1.04 \text{ g m}^{-2} \text{ d}^{-1}$ for a global land NPP of 55 Pg C yr^{-1} (Cramer et al., 2001) and $56 \pm 14 \text{ Pg C yr}^{-1}$ (Ito, 2011). This is taking Australia as 5.5% of the global land area, and excluding Greenland and Antarctica. Rising CO_2 increases continental NPP by 13% compared with steady preindustrial forcing. Higher increases of 15–16% occur in the Tropics, Savanna and Desert (which are subject to very high temperatures and humidity deficits) and lower values of 9–10% in the Temperate and Mediterranean regions. The response of NPP to rising CO_2 is also shown in time-series form in Fig. 8i. Each time series is the difference between NPP simulated at “rising CO_2 ” and “constant CO_2 ”, relative to the “constant CO_2 ” NPP.

4.1.4 Mean NEP 1990–2011

Non-zero mean NEP (1990–2011) simulated by BIOS2, and shown in Fig. 9ii is the consequence of variable meteorological forcing (“constant CO_2 ”) and a combination of variable meteorological forcing and CO_2 forcing (“rising CO_2 ”).

Responses of NEP to CO_2 are plotted in Fig. 9ii. Interannual variations in the NPP responses (Fig. 9i) are amplified in the NEP responses because of the time delay between a change in NPP and the consequent change in RH. For clarity, the responses are replotted in Fig. 9ii (inset) as 22-yr running means, revealing distinct responses for the different regions. The largest response is in the Desert region (4.5% of NPP in 2011), and the response for Australia is 3.5% of NPP in 2011.

Figure 8ii shows that, with constant CO_2 forcing, the Tropics, Warm Temperate and Cool Temperate regions would be significant sources of CO_2 to the atmosphere because the averaging period (1990–2011) is preceded by a long period of declining NPP (Fig. 6). However, the CO_2 response is sufficiently strong that each bioclimatic region, and the whole of Australia is a net sink under a regime of no disturbance. Error bars represent the uncertainty in NEP resulting from 20% uncertainty in the partial derivative of NPP with respect to atmospheric CO_2 concentration.) The continental NEP values of $0.004 \text{ g m}^{-2} \text{ d}^{-1}$ (constant CO_2) and $0.029 \text{ g m}^{-2} \text{ d}^{-1}$ (rising CO_2) are equivalent to

BGD

9, 12259–12308, 2012

The Australian terrestrial carbon budget

V. Haverd et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



respective continental sinks 12 Tg C yr^{-1} and 80 Tg C yr^{-1} . The sink under rising CO_2 is 59 % of the mean terrestrial global sink (assuming a 1990–2011 average global sink of 2.6 Pg C yr^{-1} (Canadell et al., 2007; Pan et al., 2011), and taking the Australian land surface are as 5.5 % of the global land surface, excluding Greenland and Antarctica).

5 However the combined effects of fire and LUC (Fig. 2ii) reduce the continental biospheric sink to 31 Tg C yr^{-1} or 23 % of the global mean sink per unit area.

4.1.5 Interannual variability

As seen in the time series of Fig. 4, interannual variability (IAV) of continental NPP and NEP is strongly associated with IAV in rainfall. For the 1990–2011 period, IAV (1σ) of NPP, relative to mean NPP is 9% for the continent, with high values of 14–15 % in the Savanna, Warm Temperate, Mediterranean and Desert regions, and lower values of 8 % in the Tropics and Cool Temperate regions. The IAV of NEP is similar in absolute magnitude to that of NPP, with a continental value of 8 %, relative to mean NPP.

4.2 Fire

4.2.1 Gross fire emissions

Figure 10i compares gross annual fire emissions derived using the GFED and NGGI methodologies. Each point represents an annual state (administrative unit) flux from one of three vegetation classes. The two estimates generally agree well, particularly for the Forest and arid rangelands where the NGGI estimates are 20 % lower and 9 % higher respectively than the GFED estimates. The comparison of the Savanna Woodland estimates is slightly more complex. In this region, the Queensland fuel loads were prescribed by State experts while for NT and WA, they were based on field measurements. It is now clear that the Queensland estimates were biased towards heavily grazed regions of Western Queensland where the fuel loads are low in comparison to Cape York Peninsula where most fires occur. Excluding the Queensland data, NGGI

The Australian terrestrial carbon budget

V. Haverd et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



estimates for Tropical Savanna Woodland are on average 13% lower than GFED estimates. Annual continental fire emissions (Fig. 10ii) also agree very well, with a mean bias of 15% of GFED with respect to NGGI.

Figure 11 shows the spatial distribution of GFED fire emissions by month. Cool Temperate fires occur in the Austral summer months (December–March). In contrast, intense fires ($> 10 \text{ Tg C month}^{-1}$) in the Tropics occur May–November, corresponding to the tropical dry season, with late season fires (September–October) being more intense. There is a migration of fire from West to East across the top end, corresponding to a time lag in the onset of the dry season. During the dry season, the air flows to the NW from the arid rangelands in central Australia to the Timor Sea and the fetch across the arid interior to NW WA is particularly long. Hence this region becomes fire prone very early in the season, in contrast to the NE (Cape York, Qld) where winds are E to SE, sometimes off the ocean and therefore more humid. The seasonality of fire in the rangelands is more variable than in the tropics; in the south fires occur more frequently in the summer, in the north, the seasonality of monsoons is the main driver.

Figure 12 shows time series of the GFED3 annual gross fire emissions by region. The Tropics are a persistently high source of gross fire emissions, while the Savanna fire emissions are similarly high, but show higher IAV because fuel loads are more variable. The fire events in the Desert coincide with years of high NPP associated with large rainfall events; the extreme fire years of 2000 and 2001 followed several extremely wet years in central Australia between 1997 and 1999.

The Cool Temperate region, usually a small source of fire emissions, produced large emissions in the severe bushfire seasons of 2003 and 2006 during a period of extended drought (seen above in Fig. 6).

In Table 2, we list the mean fraction of NPP burned by region, its variability (1σ), and maximum value. On average, biomass burning represents 6% of continental NPP, slightly less than the IAV (1σ) of continental NPP (9%, Sect. 3.1.4) or continental NEP (8%, Sect. 3.1.4). At 2% of NPP, the IAV (1σ) of gross fire emissions is small compared to that of NPP or NEP.

The Australian terrestrial carbon budget

V. Haverd et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



4.2.2 Net fire emissions

Annual gross fire emissions from non-clearing fires were adjusted using Eq. (3) to obtain net annual emissions from these fires. The correction factor in Eq. (3) was approximated as $\left(1 - \frac{F_{RH,-F-T-H} - F_{RH,-T-H}}{rNPP_t}\right)$ using consistent estimates of $F_{RH,-F-T-H}$, $F_{RH,-T-H}$ and $rNPP_t$, aggregated spatially over bioclimatic regions and over the 1990–2011 period. The ratio r in Eq. (3) was specified using the mean ratio of gross fire emissions to mean NPP (Table 2) and the fire return interval was specified as 3 yr (Tropics and Savanna); 50 yr (Warm Temperate and Cool Temperate) and 20 yr (Mediterranean and Desert).

Results for each region and for the Australian continent are listed in Table 2. Net emissions are typically less than 5 % of gross emissions, indicating that, over the averaging period of interest (1990–2011), the C lost due to burning fuel is approximately matched by the additional heterotrophic respiration that occurs in the absence of fire. Significant exceptions are the Warm and Cool Temperate regions, where net fire emissions account for about 60 % of gross fire emissions. The reason for this large fraction is that, owing to the long fire return interval (50 yr), the biosphere does not recover to its pre-fire state within the averaging period (22 yr). Net fire emissions in the Tropics and Savanna are slightly negative. This does not mean that fire is increasing the uptake of biospheric carbon in the long term. On the contrary, in the absence of fire more carbon is sequestered in the soil in the absence of fire over hundreds of years preceding the 1990–2011 period. Because of this and because 1990–2011 occurs after an extended decline in NPP (Fig. 7), more C is temporarily being released as RH during 1990–2011 in the simulations with no fire than in the simulations with fire.

The net fire emissions in Table 2 do not account for clearing fires. Graetz (2002) estimated this to be $18 \pm 10 \text{ Pg C yr}^{-1}$ (IAV, 1σ) which is precisely equal to the current estimate of $18 \pm 5 \text{ Pg C yr}^{-1}$ for 1990–2010 (DCCEE, 2012). Gross emissions from these fires are converted entirely to net emissions (Graetz, 2002).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



4.3 Land Use Change and Harvest

Net cumulative emissions from Land Use Change were 359 Tg C during the 1990–2009 period with mean annual emissions of 21.4 Tg C for the 1990s and 14.4 Tg C for the 2000s.

5 This cumulative net flux over 20 yr was the result of two major land use changes. First, the conversion of forest to grassland (12.9 Mha; 359 Tg C) and forest to cropland (4.4 Mha; 47 Tg C) (Fig. 11). This dominant flux remained quite stable on average throughout the period after an initial decline of 51 % during the period 1990–1995. The flux also takes into account the dynamics of regrowth and re-clearing of forest land
10 which takes place particularly in the Northeast of Australia.

Second, the expansion of new forest largely resulting from the conversion of grasslands to forest which creates a CO₂ sink (1.1 Mha; –47.9 Tg C) (Fig. 11). This flux was largely driven by the increase of plantations which grew from about 1 Mha in 2003 to 1.8 Mha in 2006, largely attributable to the expansion of hardwood plantations, mainly Eucalyptus (Montreal Process Implementation Group for Australia 2008).
15

Carbon fluxes for non-CO₂ greenhouse gases are negligible for this type of land conversions and not part of the accounting of this paper.

The change in stock of harvested wood products ΔC_{HWP} accounts for a small carbon sink in the context of other major fluxes reported for the Australian terrestrial carbon budget. ΔC_{HWP} was estimated at 1.4 Tg C in 1990, declining to 1.2 Tg C in 2009 (DC-CEE, 2011). We use an annual average across the period 1990–2009 of 1.3 Tg C yr⁻¹.
20

Production, consumption and export of in HWP, crops and livestock are given in Table 1 for the year 2004, as estimated by Peters et al. (2012), and extracted for Australia for this work. Of these harvest types, crops dominate production (19 Tg C yr⁻¹), with smaller productions of HWP (6.4 Tg C yr⁻¹) and livestock (3.1 Tg C yr⁻¹). In 2004 there was a net import of HWP (6 % of production), while 45 % of crop production and 63 % of livestock production were exported.
25

BGD

9, 12259–12308, 2012

The Australian terrestrial carbon budget

V. Haverd et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



4.4 Riverine transport

The estimated DOC flux has been computed for each COSCAT zone receiving water from Australia (Table 3). There is a trend for DOC concentrations to increase towards the south of the continent relative to the wet tropical regions to the north (Fig. 13). This may reflect longer transit times for rainfall to reach the coast thereby allowing more time for leaching of organic matter. The total DOC flux across the Australian coastline is estimated to be $2.3 \pm 1 \text{ Tg C yr}^{-1}$. This number is a preliminary estimate and could be refined as more DOC concentrations data become available (presently available for only 33 of the total 246 basins).

Runoff estimates for Australia differ by roughly $\pm 5\%$ (not shown) suggesting a relatively small error in flux estimates is attributable to uncertainty in runoff. Far greater uncertainty can be attributed by the relatively large range of measured values for any given river. This variability must stem in part from the timing of flow events relative to field sampling. Field sampling on a weekly or less frequent basis may miss a significant proportion of the total DOC flux. Bass et al. (2011) suggest that insufficient temporal resolution of DOC measurements can lead to underestimating the flux by a factor of two or more.

There are several significant complications which are not accounted for in the above approach. First, there is no distinction between the DOC flux in the significant portion of runoff that does not reach the sea and that which does. This is probably important: for example, of an estimated 27 041 GL yr^{-1} of gauged runoff within the Murray-Darling basin, just 4733 GL reaches the ocean (CSIRO, 2008). Second, there is a chance that the typical DOC concentrations reported (and used here) have missed the initial surge of leaching and remineralisation which is likely to occur within the first few days of rainfall or flooding after an extended dry period (Glazebrook and Robertson, 1999; Hladysz et al., 2011). Third, remineralisation of DOC as water moves downstream along a river is not accounted for, and is probably important because the fraction of total organic carbon present as DOC can be highly variable (e.g. Vink et al., 2005).

BGD

9, 12259–12308, 2012

The Australian terrestrial carbon budget

V. Haverd et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



4.5 Dust transport

Australia is the largest source of atmospheric dust and subsequent dust deposition (outside Australia) within the Southern Hemisphere (SH) (Tanaka and Chiba, 2006). This is primarily due to the arid climate across much of Australia (rainfall $< 1 \text{ mm d}^{-1}$) and consequently low soil moisture and sparse vegetation coverage. Wind erosion is the primary means of dust uplift, although human activities also contribute (Boon et al., 1998). Australian emissions account for 59 % of total SH emissions, 34 % of the dust burden of the Southern Ocean (Li et al., 2008) and significantly influence atmospheric dust loading within the SH (Luo et al., 2003). However, Australian emissions only contribute $\sim 5 \%$ to global emissions ($\sim 1000\text{--}2000 \text{ Tgyr}^{-1}$, Tanaka and Chiba, 2006), since major Northern Hemisphere (NH) source regions (e.g. northern Africa and Asia) produce substantially larger emissions. The lack of significant influence of NH dust emissions within the SH is due to the short atmospheric lifetime of dust.

Dust emissions peak from October–February and the major source regions within Australia are the Great Artesian Basin in Central Australia and the Murray Darling Basin (Li et al., 2008; Maher et al., 2010). Dust emission and export are also characterized by short-lived sporadic, intense events, sometimes resulting in short-lived, offshore ocean fertilization due to high iron content (Luo et al., 2008). The major pathways of dust export are to the SE of the continent and to a lesser extent, the NW (Maher et al., 2010).

Both total emission estimates and the fraction of dust exported from Australia vary considerably (Table 4). Of the 8 emission estimates provided in Table 3, only four are accompanied by a full budget, leading to a mean estimate of 27 % of dust emissions being exported out of Australia. Applying this estimate of 27 % to the remaining 4 emission estimates provides a set of 8 estimates of the total mass of dust exported from Australia annually. The mean annual estimate of dust export from Australia is $26 \pm 33 (1\sigma) \text{ Tgyr}^{-1}$. The remaining dust is deposited elsewhere on the Australian

BGD

9, 12259–12308, 2012

The Australian terrestrial carbon budget

V. Haverd et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



continent, primarily through dry deposition (Yue et al., 2009; Tanaka and Chiba, 2006; Luo et al., 2003), although the proportion of dry vs. wet deposition varies significantly.

Assuming a dust carbon content of $4 \pm 3\%$ (Sect. 2.5 above) and a 100 % uncertainty estimate on net dust export leads to an estimate of $1 \pm 1 \text{ Tg C yr}^{-1}$.

5 4.6 Fossil fuel emissions

Carbon and GHG accounts are conventionally referenced to territorial regions, and account for emissions from within the region to the atmosphere. On this basis, Australia's total greenhouse gas (GHG) emissions in 2009–2010, excluding net CO₂ emissions from Land Use, Land Use Change and Forestry (LULUCF), were $148 \text{ Tg C eq yr}^{-1}$, or $543 \text{ Tg CO}_2 \text{ eq yr}^{-1}$ in the units conventionally used in greenhouse accounting (DC-CEE, 2012). These CO₂-equivalent emissions include all Kyoto GHGs (CO₂, CH₄, N₂O, HFCs, PFCs, SF₆). Of these emissions, CO₂ makes by far the largest contribution at 110 Tg C yr^{-1} , due almost entirely to emissions from fossil fuel combustion. The 1990–2011 average fossil fuel emission was $94.5 \text{ Tg C yr}^{-1}$. Thus, Australia's fossil fuel emissions are both the largest single contribution to its total GHG emissions (about 74 %), and also a major term in its full carbon budget (Eq. 1).

Australia's emissions have also grown rapidly from 1990 to 2009–2010, the last period for which finalised data are available. Excluding LULUCF, fossil-fuel CO₂ emissions have grown by 50 % (76 to 114 Tg C yr^{-1} from 1990 to 2009–2010) and total GHG emissions by 30 % (114 to $148 \text{ Tg C eq yr}^{-1}$). Including LULUCF, the growth in total GHG emissions has been much smaller (4 % over 20 yr) because the baseline year, 1990, was a year of very high LULUCF emissions (DCCEE, 2012) followed by step reductions over the following five years. This will allow Australia to formally meet its Kyoto commitment of an 8 % increase in emissions from 1990 to 2008–2012. However, the underlying emissions growth from fossil fuels is much higher.

The above figures for CO₂ emissions for fossil fuels reflect territorial emissions from fossil-fuel combustion within Australia's borders. An even larger contribution comes

BGD

9, 12259–12308, 2012

The Australian terrestrial carbon budget

V. Haverd et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



from export of mined fossil fuels, mainly coal and gas. Australia is the world's largest coal exporter, responsible for about 5 % of total world coal production. Australia's total black (thermal and metallurgical) coal production in 2009–2010 was 356 Mt (about 270 Tg C, assuming a carbon content of 75 %), of which 300 Mt coal (225 Tg C) was exported, with the major export destinations being Japan, Korea, Taiwan, India and China (ABARES, 2011). Coal exports are growing rapidly ($\sim 3\% \text{ yr}^{-1}$ over 2005–2010, and faster since then). Additional brown coal (lignite) production is around 30 % of black coal production in carbon terms, but is not exported. Gas production for Australia in 2009–2010 was 1954 PJ (petajoules) or about 24 Tg C, of which about 16 Tg C were exported. In liquid fuels (including liquefied petroleum gas, LPG) Australia is a net importer at about 19 GL yr^{-1} or 15 Tg C yr^{-1} (2009–2010 data; ABARES, 2011). Across all fossil fuels (solid, liquid, gas), Australia's net exports were close to 241 Tg C (2009–2010), with black coal being the largest flow by far. This is about twice the territorial CO_2 emissions from Australia by fossil fuel combustion. This estimate of FF exports, combined with the 2004 estimate of 135 Tg C yr^{-1} (Davis et al., 2011), and the assumption of a fixed growth rate leads to an estimate of 137 Tg C yr^{-1} for the mean FF export over the 1990–2011 period. Major destination countries included Japan, Korea, Taiwan, India and China (Fig. 15, upper). Australia also imported and burned fossil fuels extracted in other regions, mostly oil from the Middle East and Vietnam (Davis et al., 2011).

5 Embodied carbon flows

International trade in goods and services also embody CO_2 emissions. For example, emissions produced during the manufacture of goods for export may be attributed to the country where the goods are consumed. In this way, goods and services consumed in Australia in 2004 were associated with 361 Mt CO_2 , with net exports of 16 Mt CO_2 mostly destined for the EU, Japan and the US (Fig. 15, lower). Of exported emissions, the vast majority (83 %) were embodied in intermediate goods for input to further

BGD

9, 12259–12308, 2012

The Australian terrestrial carbon budget

V. Haverd et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



manufacturing processes elsewhere. Among the exported emissions embodied in final goods, 46 % were associated with just four industry sectors: air transport, machinery, beef, and motor vehicles/parts. Emissions embodied in imports were similarly concentrated in four sectors: machinery, electronic equipment, motor vehicles/parts, and unclassified transport.

Australian territorial emissions have grown steadily since 1990 (Sect. 4.6). However, the Australian economy is heavily dependent on mining and energy-intensive manufacturing (e.g. aluminium), much of which is exported. When allocating the emissions in Australia required to produce exported products, 25 % (20 Tg C) of Australia's carbon emissions in 1990 were from the production of exported products and this almost doubled in size in 2008 to 41 % of the domestic emissions (39 Tg C) (Peters et al., 2011, Fig. 1). In terms of imports, in 1990 10 Tg C, representing 13 % of Australia's domestic emissions, were emitted in other countries to produce imports into Australia and this more than doubled to 24 Tg C (25 %) by 2008 (Peters et al., 2011, Fig. 1). Thus, Australia is a net exporter of carbon emissions to the rest of the world, increasing 50 % from a net export of 10 Tg C (13 % domestic emissions) in 1990 to a net export of 15 Tg C (16 %) in 2008. Consequently, after adjusting for the net trade in embodied carbon emissions (Peters, 2008), consumption-based emissions in Australia are lower than the territorial emissions with the gap increasing over time.

Consumption-based (embodied) carbon emissions and the flows of carbon in traded fossil fuels are not included in territorial or production-based national carbon budgets. However, these flows help to understand the drivers of changes in national emission profiles over time and how they relate to the global total fossil fuel emissions (Peters et al., 2008; Davis and Caldeira, 2010).

6 Analysis of global inversions

Fourteen sets of estimated fluxes are available from a range of global inversions (Peylin et al., 2012, RECCAP). Coarse resolution inversions (such as the TransCom cases),

BGD

9, 12259–12308, 2012

The Australian terrestrial carbon budget

V. Haverd et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The Australian terrestrial carbon budget

V. Haverd et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



solve for Australia as a single region combined with New Zealand. Other inversions solve for sub-regions of Australia, or at model grid-scale. However the major limitation of all these inversions is the atmospheric CO₂ data for the Australian region. Typically the inversions include flask records at Cape Grim (144.7° E, 40.7° S) and Cape Ferguson (147.1° E, 19.3° S). However these are taken under baseline conditions, which are designed to avoid sampling air that has recently crossed the Australian continent. Some inversions also use aircraft measurements taken on Japan-Sydney flights but these are from around 10 km altitude. Thus none of the global inversions considered here includes atmospheric CO₂ measurements that are representative of air that has had recent contact with the Australian continent. Consequently the estimated fluxes are highly dependent on prior information included in the inversion, typically fluxes from a biosphere model simulation such as CASA (Randerson et al., 1997).

The inversions were run for different time periods with fossil emissions taken as well known (though not prescribed identically for different inversions). Decadal mean ($F_{LAE} - F_{FF}$) for Australia ranges from -0.26 to 0.31 Pg C yr⁻¹ with most variation being across models and a smaller variation being across the years used to make the decadal mean. Some inversions show decadal mean fluxes that become more negative over time. The inversions with higher fossil emissions do not show correspondingly lower net biosphere fluxes. It is apparent that global inversions driven by baseline CO₂ observations provide no meaningful constraint on Australian fluxes.

7 Summary

Key findings emerging from the construction of the full Australian carbon budget (1990–2011) are listed below:

- Climate variability and rising CO₂ contributed 12 ± 29 and 68 ± 35 Tg C yr⁻¹ to biospheric C accumulation. The relative contributions of these forcings varied across bioclimatic regions. One extreme was the Desert region, where CO₂ fertilisation reinforced the positive impact on NEP of extremely high rainfall in 1990–2011,

The Australian terrestrial carbon budget

V. Haverd et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



preceded by several decades of increasing rainfall. The other extreme was the Cool Temperate Region where CO₂ fertilisation was only just sufficient to offset the negative impact of decades of drought on NEP. The response of NPP to rising CO₂ varies regionally, being higher for regions where GPP is strongly influenced by high humidity deficit.

- ii. Net ecosystem productivity is partially offset by fire and LUC, which cause net losses of $31 \pm 5 \text{ Tg C yr}^{-1}$ and $18 \pm 7 \text{ Tg C yr}^{-1}$ from the biosphere. The resultant NBP of $31 \pm 35 \text{ Tg C yr}^{-1}$ offsets fossil fuel emissions ($95 \pm 6 \text{ Tg C yr}^{-1}$) by $32 \pm 36 \%$.
- iii. Gross fire emissions account for 6 % of continental NPP, approximately the same as the 1σ interannual variability in NPP. However net fire emissions, largely associated with clearing fires account for only 1 % of NPP.
- iii. Lateral transport of C as DOC in rivers accounts for 0.1 % of NPP, while net export of C by dust is smaller at 0.05%. Bth transport terms have large uncertainties of $\sim 100 \%$.
- iv. Land use change emissions (the net effect of deforestation and reafforestation) is a similar magnitude to net fire emissions, accounting for 1 % of NPP.
- v. Australia exported 1.4 times as much fossil-fuel carbon as it consumed in territorial emissions (1990–2010). However this ratio is growing rapidly, with 2009–2010 exports being 2.5 times larger than territorial emissions from fossil fuels.
- vi. The interannual variability in NEP and hence NBP exceeds Australia's total carbon emissions by fossil fuel consumption, and indeed its total anthropogenic GHG emissions accounted under extant territorial GHG inventories.
- vii. Global atmospheric inversion studies do not meaningfully constrain the Australian terrestrial carbon budget.

References

- ABARES (Australian Bureau of Agricultural and Resource Economics and Sciences): Energy in Australia 2011, Commonwealth of Australia, Canberra, 2011.
- Andres, R. J., Boden, T. A., Bréon, F.-M., Ciais, P., Davis, S., Erickson, D., Gregg, J. S., Jacobson, A., Marland, G., Miller, J., Oda, T., Olivier, J. G. J., Raupach, M. R., Rayner, P., and Treanton, K.: A synthesis of carbon dioxide emissions from fossil-fuel combustion, *Biogeosciences*, 9, 1845–1871, doi:10.5194/bg-9-1845-2012, 2012.
- Australian Greenhouse Office: National greenhouse gas inventory 2004, Australian Government Department of the Environment and Heritage, 2006.
- Barrett, D. J.: Timescales and Dynamics of Carbon in Australia's Savannas, in: *Ecosystem Function in Savannas: Measurement and Modeling at Landscape to Global Scales*, edited by: Hill, M. J. and Hanan, N. P., CRC Press, 347–366, 2010.
- Bass, A. M., Bird, M. I., Liddell, M. J., and Nelson, P. N.: Fluvial dynamics of dissolved and particulate organic carbon during periodic discharge events in a steep tropical rainforest catchment, *Limnol. Oceanogr.*, 56, 2282–2292, 2011.
- Boden, T. A., Marland, G., and Andres, R. J.: Global, regional and national fossil-fuel CO₂ emissions. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy, Oak Ridge, TN, USA, doi:10.3334/CDIAC/00001, 2011.
- Boon, K. F., Kiefert, L., and McTainsh, G. H.: Organic matter content of rural dusts in Australia, *Atmos. Environ.*, 32, 2817–2823, 1998.
- Canadell, J. G., Le Quere, C., Raupach, M. R., Field, C. B., Buitenhuis, E. T., Ciais, P., Conway, T. J., Gillett, N. P., Houghton, R. A., and Marland, G.: Contributions to accelerating atmospheric CO₂ growth from economic activity, carbon intensity, and efficiency of natural sinks, *P. Natl. Acad. Sci. USA*, 104, 18866–18870, 2007.
- Canadell, J. G., Ciais, P., Gurney, K., Le Quere, C., Piao, S., Raupach, M. R., and Sabine, C. L.: An international effort to quantify regional carbon fluxes, *EOS*, 92, 81–82, 2011.
- Craig, R., Heath, B., Raisbeck-Brown, N., Steber, M., Marsden, J., and Smith, R.: The distribution, extent and seasonality of large fires in Australia, April 1998–March 2000, as mapped from NOAA-AVHRR imagery, in: *Australian fire regimes: contemporary patterns (April 1998–March 2000) and changes since European settlement*, Department of the Environment and Heritage, Canberra, 2002.

BGD

9, 12259–12308, 2012

The Australian terrestrial carbon budget

V. Haverd et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The Australian terrestrial carbon budget

V. Haverd et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



CSIRO: Water availability in the Murray-Darling Basin: a report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project, CSIRO, Canberra, Australia, 2008.

Davis, S. J. and Caldeira, K.: Consumption-based accounting of CO₂ emissions, P. Natl. Acad. Sci. USA, 107, 5687–5692, 2010.

Davis, S. J., Peters, G. P., and Caldeira, K.: The supply chain of CO₂ emissions, P. Natl. Acad. Sci. USA, 108, 18554–18559, 2011.

DCCEE: Australia's national greenhouse accounts: quarterly update of Australia's National Greenhouse Gas Inventory (December Quarter 2011), Department of Climate Change and Energy Efficiency, Australian Government, Canberra, 2012.

Geoscience: Australian Surface Water Management Areas (ASWMA) 2000: Product User Guide, 3rd Edition, Geoscience Australia, Canberra, 2004.

Giglio, L., Randerson, J. T., van der Werf, G. R., Kasibhatla, P. S., Collatz, G. J., Morton, D. C., and DeFries, R. S.: Assessing variability and long-term trends in burned area by merging multiple satellite fire products, Biogeosciences, 7, 1171–1186, doi:10.5194/bg-7-1171-2010, 2010.

Ginoux, P., Prospero, J. M., Torres, O., and Chin, M.: Long-term simulation of global dust distribution with the GOCART model: correlation with North Atlantic Oscillation, Environ. Modell. Softw., 19, 113–128, 2004.

Glazebrook, H. S. and Robertson, A. I.: The effect of flooding and flood timing on leaf litter breakdown rates and nutrient dynamics in a river red gum (*Eucalyptus camaldulensis*) forest, Aust. J. Ecol., 24, 625–635, 1999.

Graetz, R. D.: The net carbon dioxide flux from biomass burning on the Australian continent, CSIRO Division of Atmospheric Research, 2002.

Grant, I., Jones, D., Wang, W., Fawcett, R., and Barratt, D.: Meteorological and remotely sensed datasets for hydrological modelling: A contribution to the Australian Water Availability Project., Catchment-scale Hydrological Modelling & Data Assimilation (CAHMDA-3) International Workshop on Hydrological Prediction: Modelling, Observation and Data Assimilation, Melbourne, 2008.

Haverd, V. and Cuntz, M.: Soil-Litter-Iso: A one-dimensional model for coupled transport of heat, water and stable isotopes in soil with a litter layer and root extraction, J. Hydrol., 388, 438–455, 2010.

The Australian terrestrial carbon budget

V. Haverd et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Haverd, V., Raupach, M. R., Briggs, P. R., Canadell, J. G., Isaac, P., Pickett-Heaps, C., Roxburgh, S. R., van Gorsel, E., Viscarra Rossel, V. A., and Wang, Z.: Multiple observation types reduce uncertainty in Australia's terrestrial carbon and water cycles, *Biogeosciences Discuss.*, in press, 2012.
- 5 Hladyz, S., Watkins, S. C., Whitworth, K. L., and Baldwin, D. S.: Flows and hypoxic blackwater events in managed ephemeral river channels, *J. Hydrol.*, 401, 117–125, 2011.
- Hutchinson, M. F., Nix, H. A., and McMahon, J. P.: Climate constraints on cropping systems, in: *Field Crop Systems*, edited by: Pearson, C. J., Elsevier, Amsterdam, 37–58, 1992.
- Hutchinson, M. F., McIntyre, S., Hobbs, R. J., Stein, J. L., Garnett, S., and Kinloch, J.: Integrating
10 a global agro-climatic classification with bioregional boundaries in Australia, *Global Ecol. Biogeogr.*, 14, 197–212, 2005.
- Ito, A.: A historical meta-analysis of global terrestrial net primary productivity: are estimates converging?, *Global Change Biol.*, 17, 3161–3175, 2011.
- Jones, D. A., Wang, W., and Fawcett, R.: High-quality spatial climate data-sets for Australia,
15 *Aust. Meteorol. Oceanogr. J.*, 58, 233–248, 2009.
- Keeling, C. D., Piper, S. C., Bacastow, R. B., Wahlen, M., Whorf, T. P., Heimann, M., and Meijer, H. A.: Exchanges of atmospheric CO₂ and 13CO₂ with the terrestrial biosphere and oceans from 1978 to 2000, I. Global aspects, Scripps Institution of Oceanography, San Diego, 2001.
- Krausmann, F., Erb, K. H., Gingrich, S., Lauk, C., and Haberl, H.: Global patterns of socioeco-
20 nomic biomass flows in the year 2000: A comprehensive assessment of supply, consumption and constraints, *Ecol. Econ.*, 65, 471–487, 2008.
- Le Quere, C., Raupach, M. R., Canadell, J. G., Marland, G., Bopp, L., Ciais, P., Conway, T. J., Doney, S. C., Feely, R. A., Foster, P., Friedlingstein, P., Gurney, K. R., Houghton, R. A., House, J. I., Huntingford, C., Levy, P. E., Lomas, M. R., Majkut, J., Metz, N., Ometto, J.,
25 Peters, G. P., Prentice, I.C., Randerson, J. T., Running, S. W., Sarmiento, J. L., Schuster, U., Sitch, S., Takahashi, T., Viovy, N., van der Werf, G. R., and Woodward, F. I.: Trends in the sources and sinks of carbon dioxide, *Nat. Geosci.*, 2, 831–836, doi:10.1038/NGEO689, 2009.
- Li, F., Ginoux, P., and Ramaswamy, V.: Distribution, transport, and deposition of mineral dust in the Southern Ocean and Antarctica: Contribution of major sources, *J. Geophys. Res.-Atmos.*, 113, D10207, doi:10.1029/2007JD009190, 2008.
- 30

The Australian terrestrial carbon budget

V. Haverd et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Luo, C., Mahowald, N. M., and del Corral, J.: Sensitivity study of meteorological parameters on mineral aerosol mobilization, transport, and distribution, *J. Geophys. Res.-Atmos.*, 108, 4447, doi:10.1029/2003JD003483, 2003.

Luo, C., Mahowald, N., Bond, T., Chuang, P.Y., Artaxo, P., Siefert, R., Chen, Y., and Schauer, J.: Combustion iron distribution and deposition, *Global Biogeochem. Cy.*, 22, GB1012, doi:10.1029/2007GB002964, 2008.

MacFarling Meure, C. M., Etheridge, D., Trudinger, C., Steele, P., Langenfelds, R., van Ommen, T., Smith, A., and Elkins, J.: Law Dome CO₂, CH₄ and N₂O ice core records extended to 2000 years BP, *Geophys. Res. Lett.*, 33, L14810, doi:10.1029/2006GL026152, 2006.

Maher, B. A., Prospero, J. M., Mackie, D., Gaiero, D., Hesse, P. P., and Balkanski, Y.: Global connections between aeolian dust, climate and ocean biogeochemistry at the present day and at the last glacial maximum, *Earth-Sci. Rev.*, 99, 61–97, 2010.

Marland, G. and Rotty, R. M.: Carbon dioxide emissions from fossil fuels: A procedure for estimation and results for 1950–82, *Tellus B*, 36, 232–261, 1984.

Meybeck, M., Durr, H. H., and Vorosmarty, C. J.: Global coastal segmentation and its river catchment contributors: A new look at land-ocean linkage, *Global Biogeochem. Cy.*, 20, GB1S90, doi:10.1029/2005GB002540 2006.

Meyer, C. P.: Establishing a consistent time-series of greenhouse gas emission estimates from Savanna burning in Australia, Report to the Australian Greenhouse Office by CSIRO Atmospheric Research, Aspendale, Australia, 2004.

Miller, R. L., Tegen, I., and Perlwitz, J.: Surface radiative forcing by soil dust aerosols and the hydrologic cycle, *J. Geophys. Res.-Atmos.*, 109, D04203, doi:10.1029/2003JD004085 2004.

Pan, Y.D., Birdsey, R.A., Fang, J.Y., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O. L., Shvidenko, A., Lewis, S. L., Canadell, J. G., Ciais, P., Jackson, R. B., Pacala, S. W., McGuire, A. D., Piao, S. L., Rautiainen, A., Sitch, S., and Hayes, D.: A Large and Persistent Carbon Sink in the World's Forests, *Science*, 333, 988–993, 2011.

Peters, G. P.: From production-based to consumption-based national emission inventories, *Ecol. Econ.*, 65, 13–23, 2008.

Peters, G. P., Minx, J. C., Weber, C. L., and Edenhofer, O.: Growth in emission transfers via international trade from 1990 to 2008, *P. Natl. Acad. Sci, USA*, 108, 8903–8908, 2011.

Peters, G. P., Davis, S. J., and Andrew, R.: A synthesis of carbon in international trade, *Biogeo-sciences*, 9, 3247–3276, doi:10.5194/bg-9-3247-2012, 2012.

The Australian terrestrial carbon budget

V. Haverd et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Peylin, P., Gurney, K. R., Law, R. M., Chevallier, F., Jacobson, A., Niwa, Y., Patra, P., Rayner, P. J., Rödenbeck, C., Peters, W., and Yamada, K.: Global Atmospheric Carbon Budget: results from an ensemble of atmospheric CO₂ inversions, RECCAP special issue, in preparation, 2012.

5 Randerson, J. T., Thompson, M. V., Conway, T. J., Fung, I. Y., and Field, C. B.: The contribution of terrestrial sources and sinks to trends in the seasonal cycle of atmospheric carbon dioxide, *Global Biogeochem. Cy.*, 11, 535–560, 1997.

Richards, G. P. and Brack, C. L.: A continental biomass stock and stock exchange estimation approach for Australia, *Austral. For.*, 67, 284–288, 2004.

10 Richards, G. P., Borough, C., Evans, D., Reddin, A., Ximenes, F., and Gardner, D.: Developing a carbon stocks and flows model for Australian wood products, *Austral. For.*, 70, 108–119, 2007.

Seiler, W. and Crutzen, P. J.: Estimates of gross and net fluxes of carbon between the biosphere and the atmosphere from biomass burning, *Climatic Change*, 2, 207–247, 1980.

15 Tanaka, T. Y. and Chiba, M.: A numerical study of the contributions of dust source regions to the global dust budget, *Global Planet. Change*, 52, 88–104, 2006.

van der Werf, G. R., Randerson, J. T., Giglio, L., Collatz, G. J., Mu, M., Kasibhatla, P. S., Morton, D. C., DeFries, R. S., Jin, Y., and van Leeuwen, T. T.: Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009), *Atmos. Chem. Phys.*, 10, 11707–11735, doi:10.5194/acp-10-11707-2010, 2010.

20 Vink, S., Bormans, M., Ford, P. W., and Grigg, N. J.: Quantifying ecosystem metabolism in the middle reaches of Murrumbidgee River during irrigation flow releases, *Mar. Freshwater Res.*, 56, 227–241, 2005.

25 Wang, Y. P., Law, R. M., and Pak, B.: A global model of carbon, nitrogen and phosphorus cycles for the terrestrial biosphere, *Biogeosciences*, 7, 2261–2282, doi:10.5194/bg-7-2261-2010, 2010.

30 Wang, Y. P., Kowalczyk, E., Leuning, R., Abramowitz, G., Raupach, M. R., Pak, B., van Gorsel, E., and Luhr, A.: Diagnosing errors in a land surface model (CABLE) in the time and frequency domains, *J. Geophys. Res.-Biogeo.*, 116, G01034, doi:10.1029/2010JG001385 2011.

Waterworth, R. M. and Richards, G. P.: Implementing Australian forest management practices into a full carbon accounting model, *Forest Ecol. Manag.*, 255, 2434–2443, 2008.

The Australian terrestrial carbon budget

V. Haverd et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Waterworth, R. M., Richards, G. P., Brack, C. L., and Evans, D. M. W.: A generalised hybrid process-empirical model for predicting plantation forest growth, *Forest Ecol. Manag.*, 238, 231–243, 2007.

Webb, N. P., Chappell, A., Strong, C. L., Marx, S. K., and McTainsh, G. H.: The significance of carbon-enriched dust for global carbon accounting, *Global Change Biol.*, doi:10.1111/j.1365-2486.2012.02780.x, 2012.

Werner, M., Tegen, I., Harrison, S. P., Kohfeld, K. E., Prentice, I. C., Balkanski, Y., Rodhe, H., and Roelandt, C.: Seasonal and interannual variability of the mineral dust cycle under present and glacial climate conditions, *J. Geophys. Res.-Atmos.*, 107, 4744, doi:10.1029/2002JD002365, 2002.

Yue, X., Wang, H. J., Wang, Z. F., and Fan, K.: Simulation of dust aerosol radiative feedback using the Global Transport Model of Dust: 1. Dust cycle and validation, *J. Geophys. Res.-Atmos.*, 114, D10202, doi:10.1029/2008JD010995, 2009.

Zender, C. S., Bian, H. S., and Newman, D.: Mineral Dust Entrainment and Deposition (DEAD) model: Description and 1990s dust climatology, *J. Geophys. Res.-Atmos.*, 108, 4416, doi:10.1029/2002JD002775, 2003.

Table 1. Components of the Australian Carbon Budget.

		Flux (away from land surface) (Tg C yr ⁻¹) ^a	IAV (1σ) (1σ)	error on mean (1σ)	averaging period
Biosphere (no fire, no transport, no harvest, no LUC)	GPP	-4110	345	740	1990–2011
	RA	1900	154	342	1990–2011
	NPP	-2210	195	398	
	RH _{F-T-H} (no fire, no transport, no harvest)	2130	66	383	
	NEP = NPP – RH _{F-T-H}	-80	136	7	
Fire	Fire (non-clearing)	99	30	19	
	Fire (clearing)	28	5	4	1990–2010
	Total fire	127.0	30	22	1997–2009
	RH _{T-H} (Corrected for fire)	2034	66	342	
	Net Fire = F _{Fire} + RH _{T-H} – RH _{F-T-H}	31	30	6	
Transport	Riverine	2.3	–	1	
	Dust	1	–	1	
	Total Transport	3	–	1	
Harvest (wood, livestock, crops)	HWP gross	6.1	–	1.5	2004
	HWP consumption	6.4	–	2	2004
	HWP export	-0.3	–	2	2004
	Livestock gross	3.1	–	0.8	2004
	Livestock consumption	2.0	–	0.5	2004
	Livestock export	1.1	–	0.3	2004
	Crop gross	19.6	–	5	2004
	Crop consumption	8.9	–	2	2004
	Crop export	10.7	–	3	2004
	Harvest gross	29	–	7	
	Harvest export	12	–	3	
	Harvest consumption	17	–	4	
Heterotrophic Respiration	RH (corrected for fire, harvest, transport)	2002	66	383	
Land Use Change	LUC	18	–	7	1990–2009
Fossil fuels	FF (territorial)	95	–	6	1990–2010
	FF (export)	137	–	14	1990–2011
Net Fluxes	NBP	-31	139	35	
	Land-Atm-Exchange	48	139	29	
^b Changes in Stock	$\Delta C_{FF}/dt$	-232	–	15	
	$\Delta C_{Non-Territorial}/dt$	151	–	17	
	$\Delta C_{Biosphere}/dt$	31	139	35	
	$\Delta C_{Territorial}/dt$	-200	139	38	
	$\Delta C_{HWP}/dt$	1	–	–	
	$\Delta C_{Atmosphere}/dt$	199	139	38	

^a Multiply by 0.126 to convert to g m⁻² yr⁻¹.

^b Sign convention: positive change in stock is an increase in stock.

BGD

9, 12259–12308, 2012

The Australian terrestrial carbon budget

V. Haverd et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The Australian terrestrial carbon budget

V. Haverd et al.

Table 2. Ratio of annual Gross Fire Emissions and annual Net Fire Emissions to mean NPP (1990–2011): mean ratio; IAV of ratio and maximum ratio for the 1997–2009 period.

	Gross Fire Emissions/mean NPP			Net fire emissions/mean NPP		
	mean	IAV (1σ)	max	mean	IAV (1σ)	max
Tropics	0.18	0.04	0.24	-0.015	0.003	0.001
Savanna	0.09	0.03	0.15	-0.002	0.0006	0.000
Warm Temp	0.01	0.01	0.05	0.008	0.008	0.030
Cool Temp	0.03	0.04	0.14	0.016	0.022	0.075
Mediterr	0.006	0.003	0.01	1.8×10^{-5}	8×10^{-6}	3×10^{-5}
Desert	0.03	0.02	0.07	0.004	0.002	0.0089
Australia	0.06	0.02	0.08	0.0014	0.003	0.0074

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The Australian terrestrial carbon budget

V. Haverd et al.

Table 3. Mean annual runoff draining into Australian COSCAT regions (Fig. 12), mean DOC concentrations computed from observed concentration data (*italics* denotes assumed DOC concentration used to compute DOC fluxes), and DOC fluxes computed using each of the 3 runoff estimates. Fluxes were calculated using the maximum concentration observed in region 1411.

COSCAT region	Number of basins	AWAP runoff (GL yr ⁻¹)	mean DOC (mg l ⁻¹)	DOC flux (Gg C yr ⁻¹)
n/a interior	31	4830	12	58
1403	62	76 273	6.3	481
1410	37	40 157	5	201
1411	95	79 600	3–13.4	1067
1412	18	3869	12.8	50
1413	13	2077	13.0	27
1414	14	18 284	5	91
1415	55	128 840	2.6	335
Total	325	353 931		2309

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The Australian terrestrial carbon budget

V. Haverd et al.

Table 4. Australian continental dust: annual emission, deposition, export and emission as % global emission.

Ref.	Emission (Tgyr ⁻¹)	Total Depos. (Tgyr ⁻¹)	Export (Tgyr ⁻¹)	% exported	Dry depos. (Tgyr ⁻¹)	Wet depos. (Tgyr ⁻¹)	% global emission
Tanaka and Chiba (2006)	106	106	0	0.0	65	41	5.7
Luo et al. (2003)	132	129	3	2.3	70	59	8.0
Miller et al. (2004)	148	46	102	68.9	44	2	15.0
Yue et al. (2009)	73	46	27	37.0	38	8	
Zender et al. (2003)*	37	27	10	27.0			2.5
Ginoux et al. (2004)*	61	45	16	27.0			2.9
Li et al. (2008)*	120	88	32	27.0			5.2
Werner et al. (2002)*	52	38	14	27.0			4.9
Mean	91	65	26	27.0			6.3
SD	41	37	33	30			4.2

* Full dust budget not published. Export and total deposition calculated assuming Export accounts for 27% of Emission.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The Australian terrestrial carbon budget

V. Haverd et al.

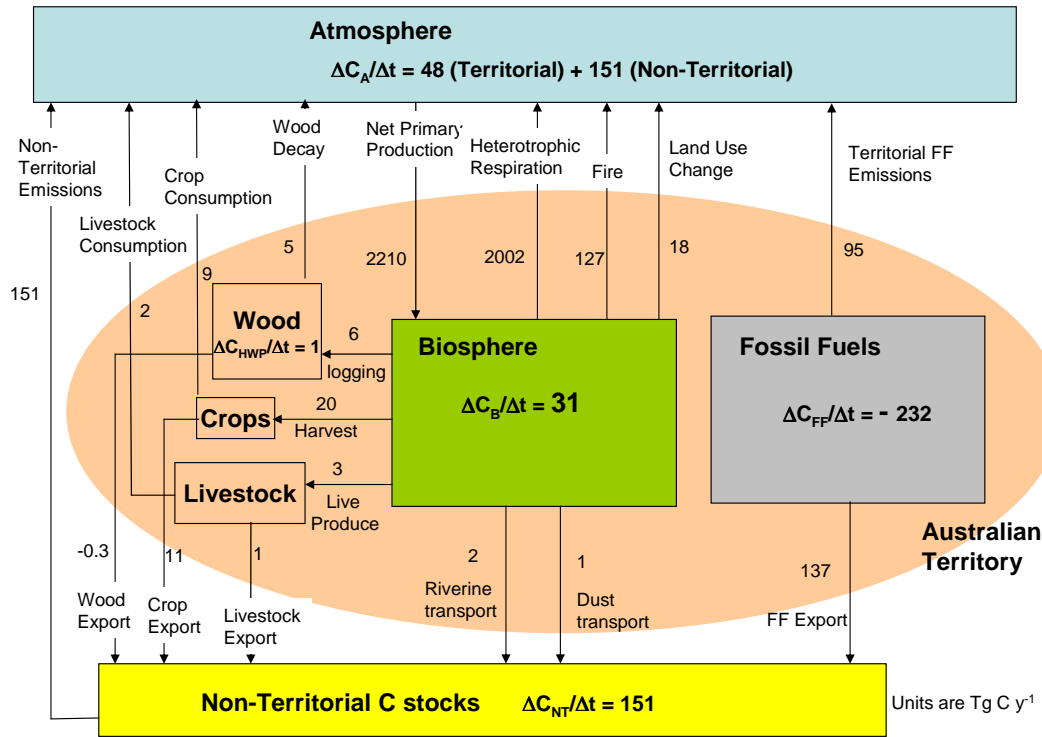


Fig. 1. Summary of the Australian territorial carbon budget, 1990–2011.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



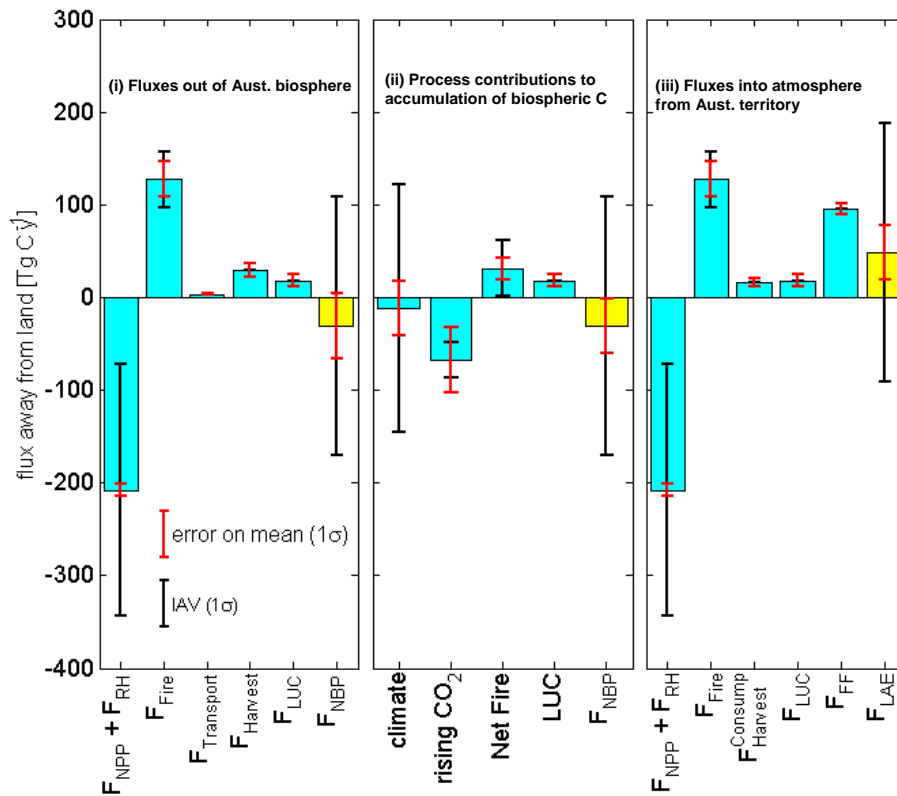


Fig. 2. (i) Net flux of carbon out of the Australian biosphere (F_{NBP} , yellow) as the sum of components (blue); (ii) net flux of carbon out of the Australian biosphere (F_{NBP} , yellow) as the sum of process contributions (blue) due to variable climate, rising CO_2 , net effect of fire (mainly clearing fires) and LUC; (iii) net flux of carbon from the Australian territory to the atmosphere (F_{LAE} , yellow), as the sum of components (blue). Error bars represent errors on the mean (1σ , red) and interannual variability (1σ , black).

The Australian terrestrial carbon budget

V. Haverd et al.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



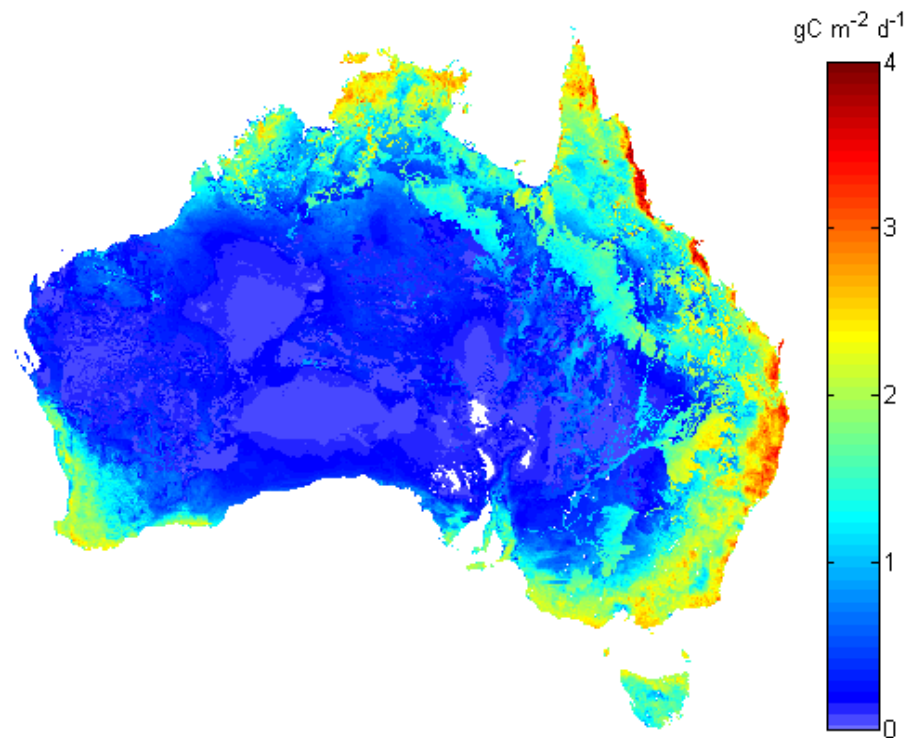


Fig. 3. Mean NPP (1990–2011).

BGD

9, 12259–12308, 2012

The Australian terrestrial carbon budget

V. Haverd et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The Australian terrestrial carbon budget

V. Haverd et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper

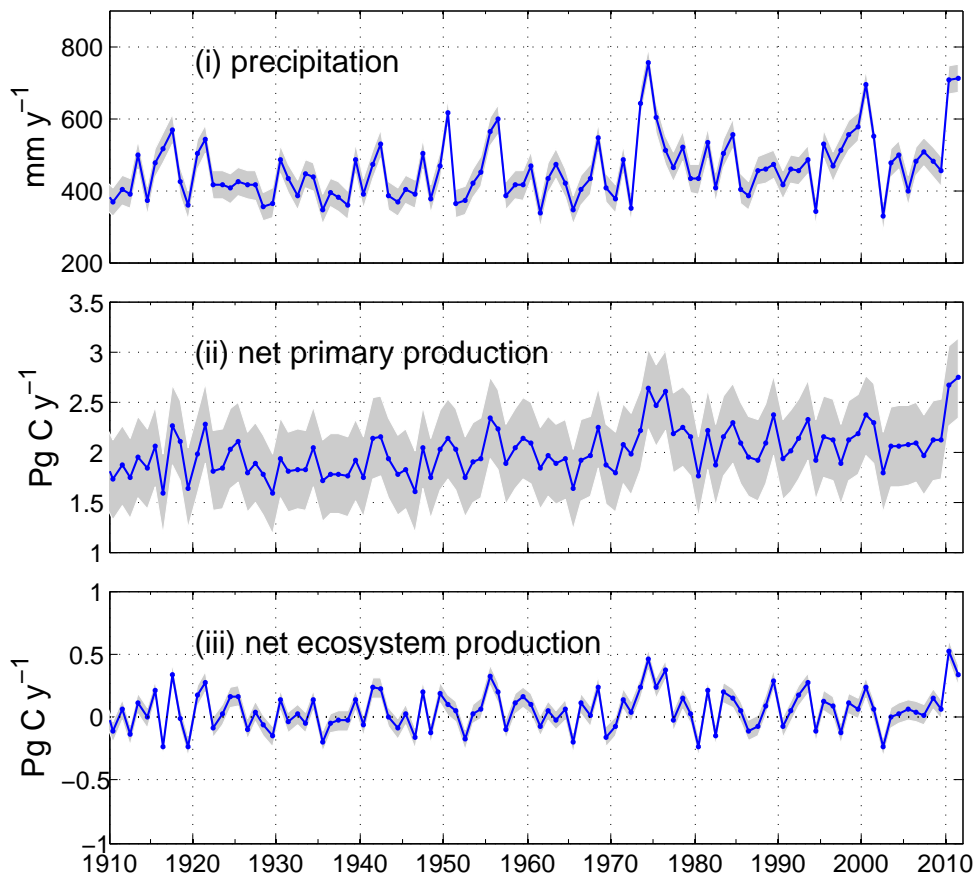
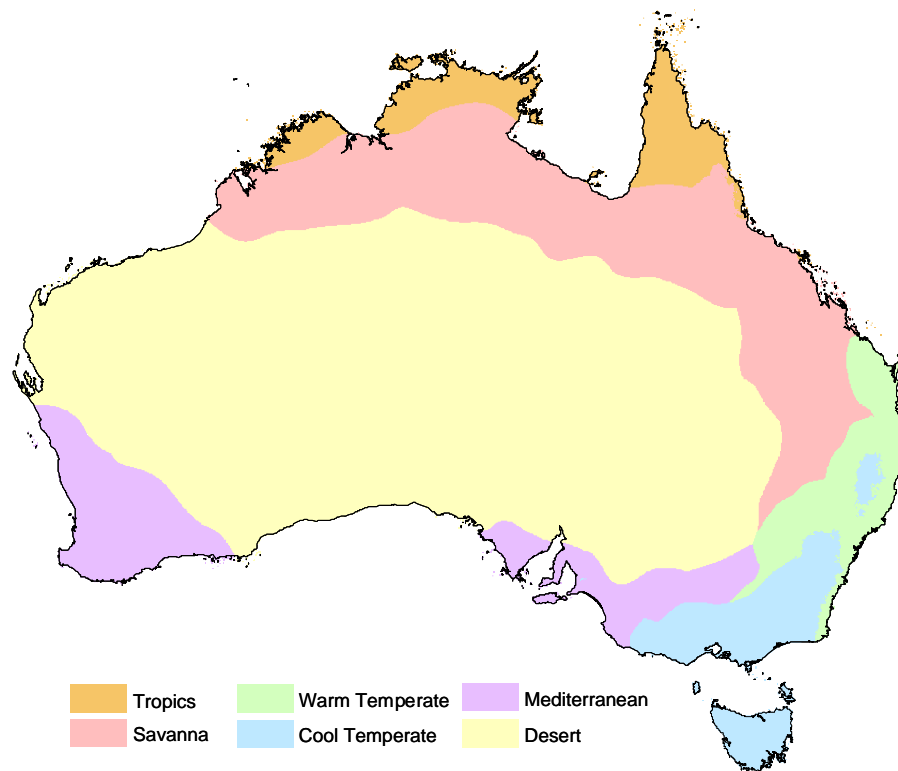


Fig. 4. Annual time-series of Australian continental (i) precipitation; (ii) NPP and (iii) NEP (NPP – RH in the absence of fire and harvest). Shading represents 1σ uncertainties on the mean, and includes contributions from parameter uncertainties and forcing uncertainties, as evaluated in Haverd et al. (2012).

**The Australian
terrestrial carbon
budget**

V. Haverd et al.

**Fig. 5.** Bioclimatic classification for use in regionalisation of results.[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

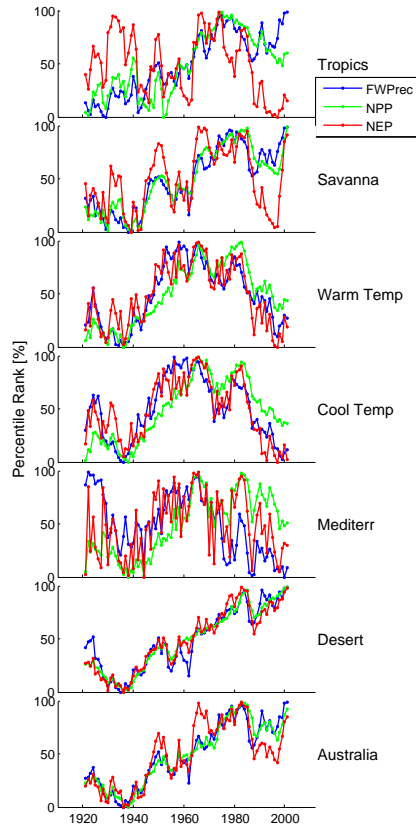


Fig. 6. Percentile rank time series of 22-yr averaged precipitation, NPP and NEP. Each point is the percentile rank of the variable (precipitation, NPP or NEP), averaged over a 22-yr window, centered at the time on the x-axis. A point having a percentile rank of 100% means that all other points in the time series have lower values.

The Australian terrestrial carbon budget

V. Haverd et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The Australian terrestrial carbon budget

V. Haverd et al.

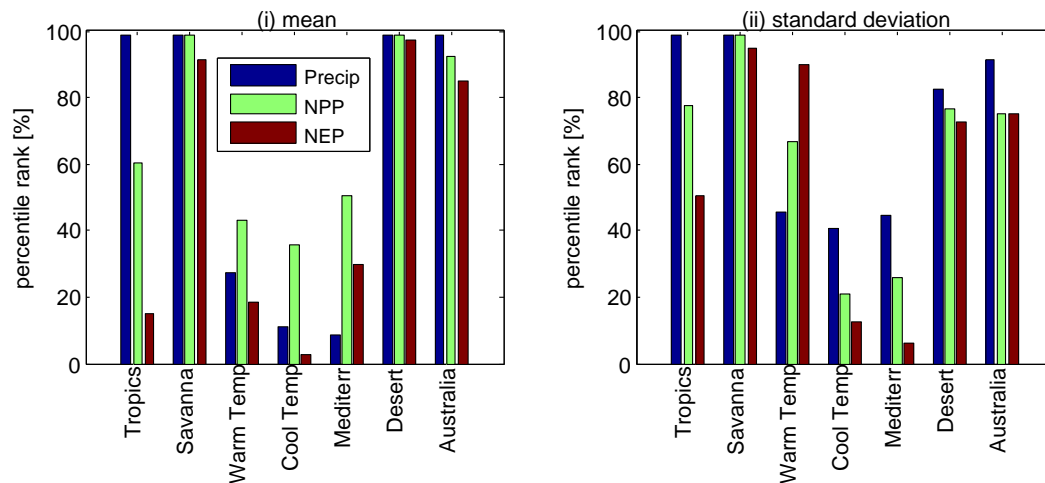


Fig. 7. Percentile ranks of the 1990–2011 (i) mean and (ii) standard deviation of precipitation, NPP and NEP, relative to all other 22-yr periods starting in successive years from 1911.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The Australian terrestrial carbon budget

V. Haverd et al.

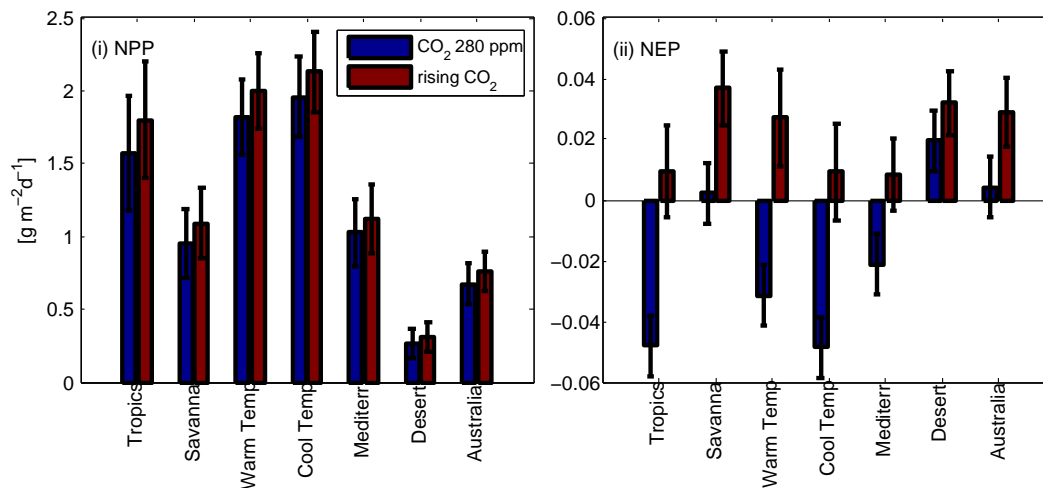


Fig. 8. (i) BIOS2 estimates of 1990–2011 mean NPP under pre-industrial CO₂ and increasing CO₂ forcing. (ii) BIOS2 estimates of 1990–2011 mean NEP under pre-industrial CO₂ and rising CO₂. Error bars represent 1σ uncertainties on the mean, and include contributions from parameter uncertainties and forcing uncertainties, as evaluated in (Haverd et al., 2012).

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[◀](#)
[▶](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)

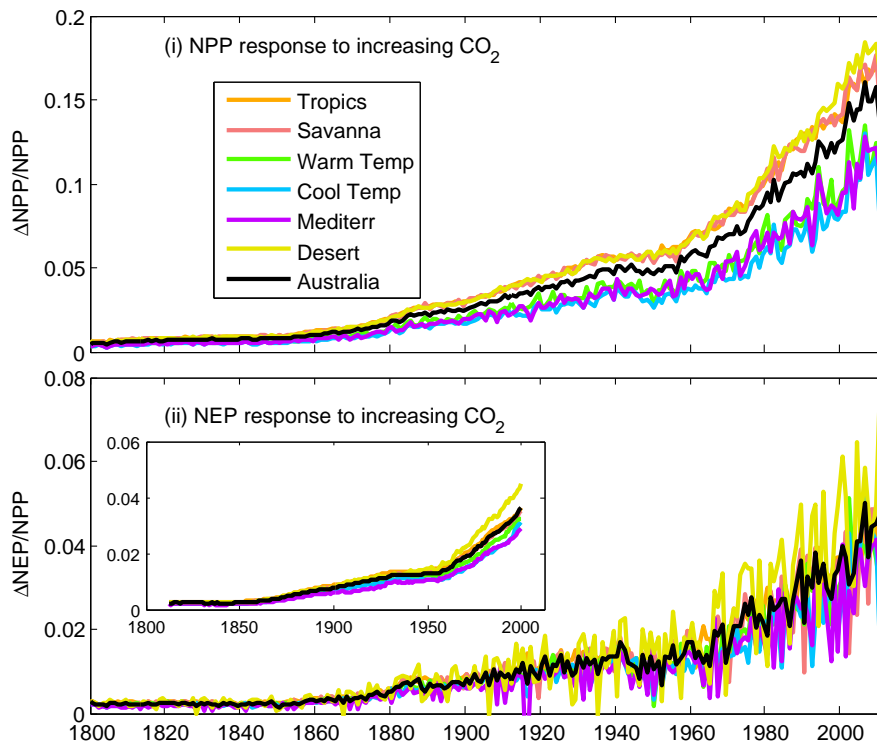



Fig. 9. (i) Response of NPP to increasing CO_2 , calculated as the difference between NPP simulated with rising CO_2 and pre-industrial CO_2 (280 ppm), relative to NPP simulated with pre-industrial CO_2 ; **(ii)** response of NEP to increasing CO_2 , calculated as the difference between NEP simulated with rising CO_2 and pre-industrial CO_2 , relative to NPP simulated with pre-industrial CO_2 .

The Australian terrestrial carbon budget

V. Haverd et al.

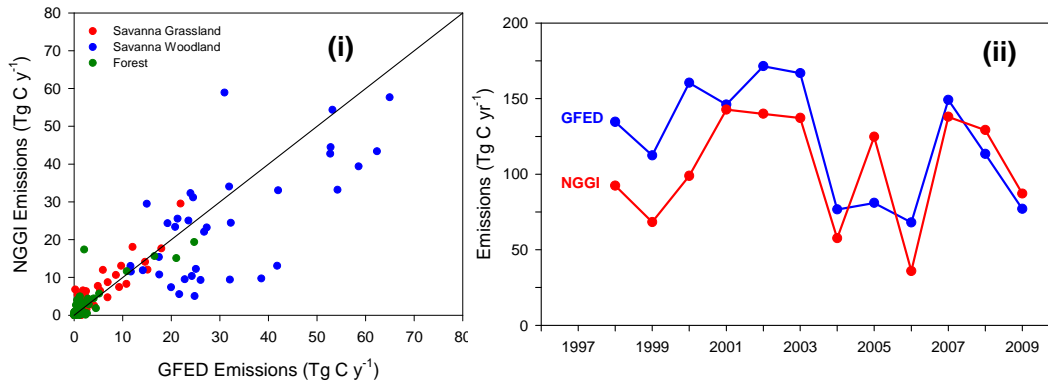


Fig. 10. Comparison of GFED3 and NGGI CO₂-C Gross Fire Emissions estimates. **(i)** Annual fluxes per state per vegetation class; **(ii)** total annual Australian continental fire emissions 1997–2009.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The Australian terrestrial carbon budget

V. Haverd et al.

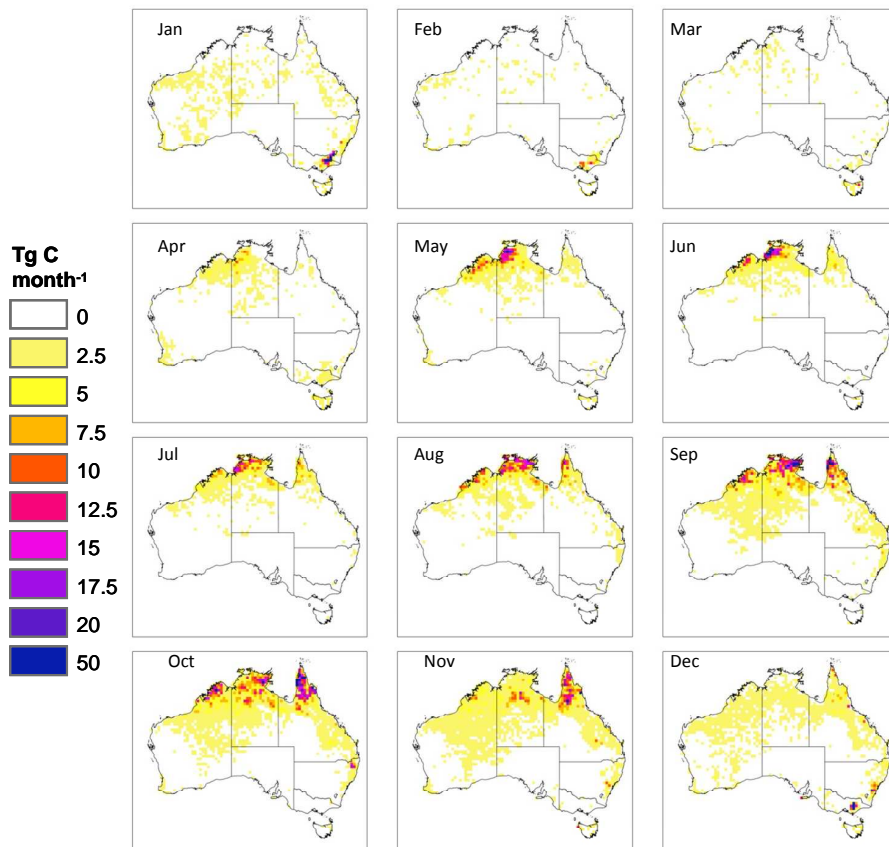


Fig. 11. Ensemble average GFED CO₂-C Gross Fire Emissions (1997–2009) by month.

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

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The Australian terrestrial carbon budget

V. Haverd et al.

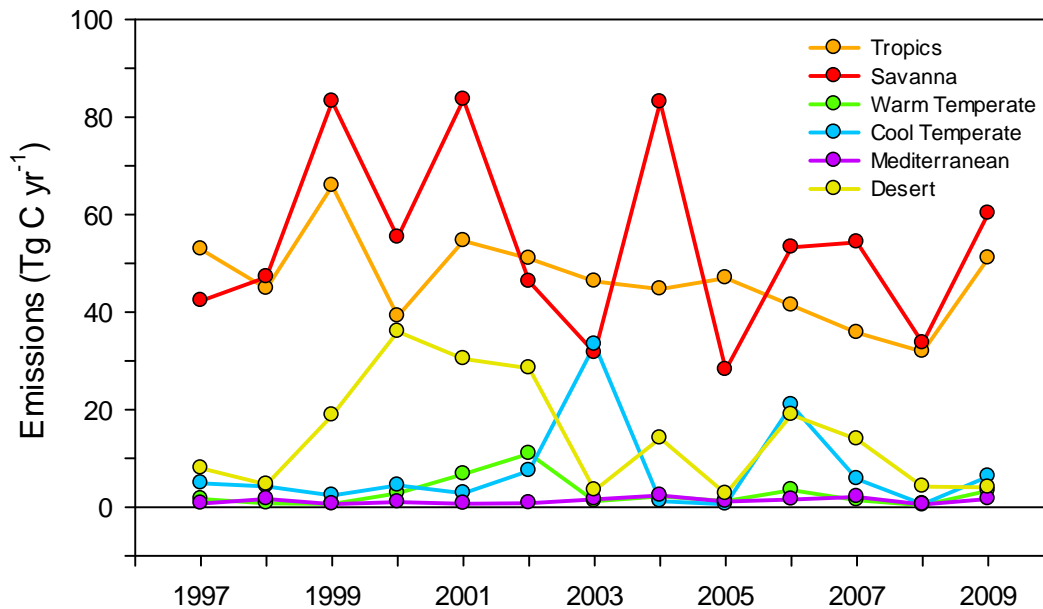


Fig. 12. Annual time series of GFED CO₂-C Gross Fire Emissions by bioclimatic region.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The Australian terrestrial carbon budget

V. Haverd et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

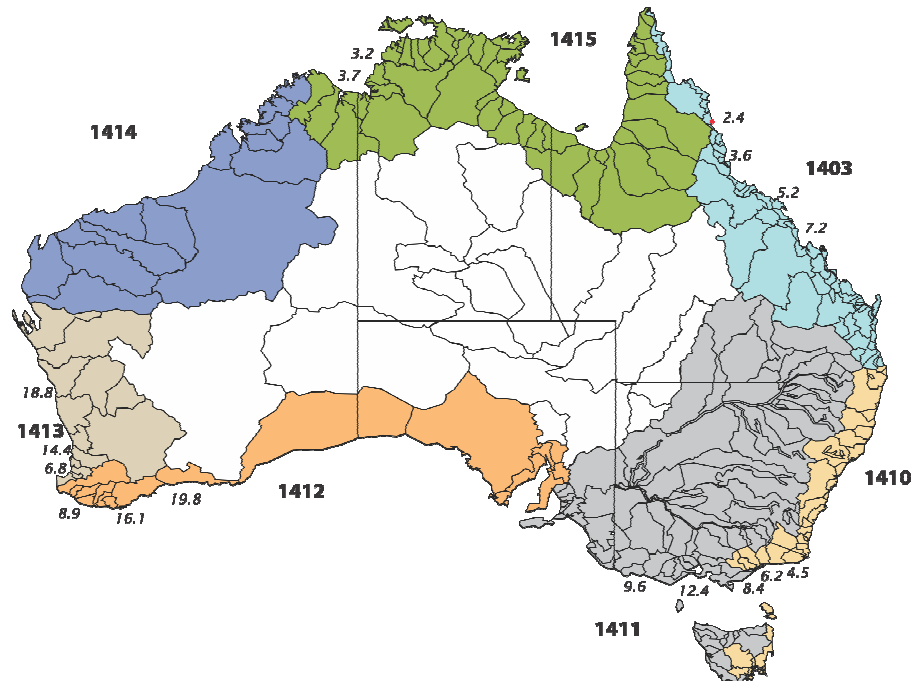


Fig. 13. Australian water catchments grouped by COSCAT zones (fill colours). Bold text denotes COSCAT zones. Italicised text denotes representative DOC concentrations (mg l^{-1}) from measurements taken in adjacent catchment rivers. COSCAT zones are based on a combination of coastal shelf morphology, coastal current patterns, and climate gradients (Meybeck, Durr, & Vorosmarty, 2006).

The Australian terrestrial carbon budget

V. Haverd et al.

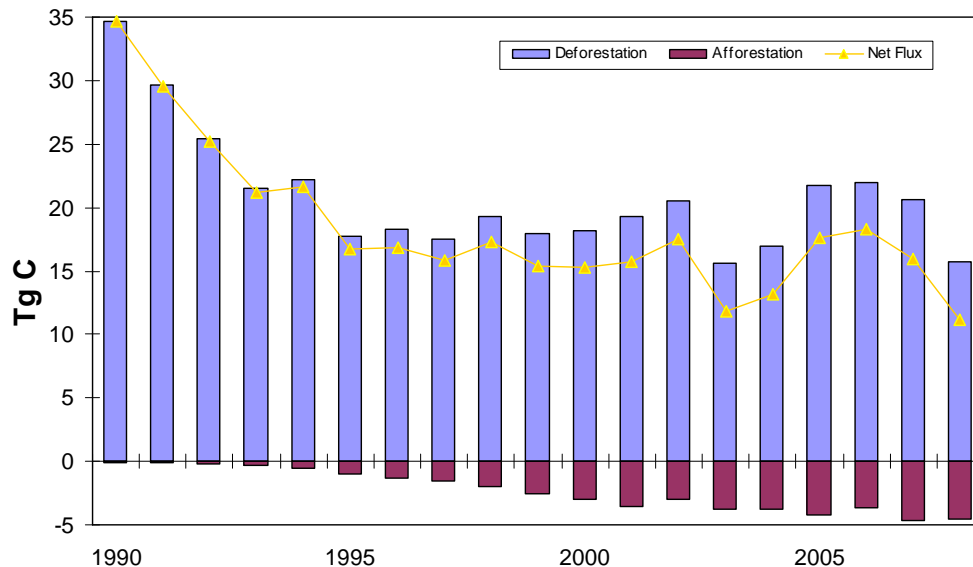


Fig. 14. Annual CO₂-C fluxes from Land Use Change (Tg C).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The Australian terrestrial carbon budget

V. Haverd et al.

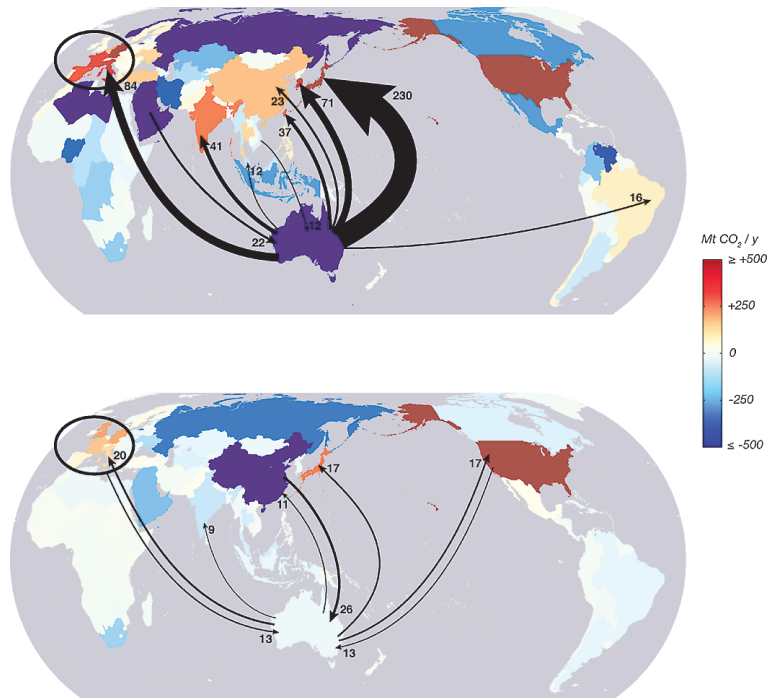


Fig. 15. Millions of tons (Mt) of CO₂ embodied in trade in 2004. The upper panel shows regional differences between extraction and production emissions (i.e. the net effect of emissions from traded fossil fuels) and the lower panel shows regional differences between production and consumption emissions (i.e. the net effect of emissions embodied in goods and services). Net exporting countries are shown in blue and net importing countries in red. Arrows in each panel depict the fluxes of emissions (Mt CO₂ yr⁻¹) to and from Australia greater than 9 Mt CO₂ yr⁻¹. Fluxes to and from Europe are aggregated to include all 27 member states of the European Union.