Australian climate-carbon cycle feedback reduced by soil black carbon

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Online-only Supplementary Material

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Supplementary Methods

Sample collection

The NSA soils were collected by the Commonwealth Scientific and Industrial Research Organization (CSIRO) between 1948 and 1966. The soils represent all major soil types, climatic regions and vegetation zones in Australia (Supplementary Fig. 5). Only A horizons (organic surface layers) were analyzed for the NSA soils; multiple A horizons for the same soil profile were averaged. The QLD and DWN transect profiles comprise 0-0.1, 0.1-0.2, 0.2-0.3, 0.3-0.5 and 0.5-1.0 m depth samples, collected in 1998 and 1997 (R. Tucker, pers. comm.). The QLD transect was sampled at 8-km intervals from the townships of St. George in the south to Duaringa in the north. This transect spanned five degrees of latitude (23°-28°S), and mean annual rainfall and temperatures from 496 mm and 20° C in the south, to 311 mm and 22° C in the north (Supplementary Fig. 5). The DWN transect stretched from south of Darwin to Wauchope, and was sampled at 2-, 5-, and 10-km intervals, with the smallest interval used in the north and the largest in the south. It spans eight degrees of latitude (12–20°S), with mean annual rainfall decreasing from 1560 mm to 270 mm north to south and pronounced seasonality, but relatively constant mean annual temperature of 25°C (Supplementary Fig. 5).

Detailed modelling was done in two regions, Katherine and Daly Waters, which were both located in the DWN transect. The sites of the 13 light-textured Inceptisols (12.5% clay) have a mean annual temperature 26.5°C, and a mean annual precipitation 887 mm (Katherine; 132.4157 to 132.6302 E, -14.4979 to -14.6447 S), those of the 15 heavier-textured Inceptisols (21.0% clay) a mean annual temperature of 26.6°C, and a mean annual precipitation of 738 mm (Daly Waters; 133.1946 to 133.7299 E, -15.4924 to -18.1967 S). The elevation was between 100 and 300 m a.s.l..

Sample analyses

For quantification of the proportion of black C in QLD and DWN soils, results from the first three depths were added to give total black C stocks up to a depth of 0.3 m using bulk density measurements. These values and total SOC to a depth of 0.3 m were taken for modelling of black C and non-black C equilibrium conditions as well as response to warming. For the computation of mean residence times (MRT) of black C, black C stocks were calculated to a depth of 1 m.

The soil samples were finely ground in a puck mill before analyses. Total soil C was determined by dry combustion (LECO Corporation, St Joseph, MI, USA), and SOC calculated by correcting for carbonate C determined by Collins Calcimeter, where appropriate. The base method for black C quantification was the UV-NMR method[1]. This combined UV-NMR method captures the widest range of biomass-derived black C, and accounts for most of the charcoal-type black C in soils[2]; it typically recognizes 75-95% of fresh charcoal as black C[2]. Comparison with methods using molecular mixing models and NMR only[3] has, however, demonstrated that the UV-NMR method may in certain soils underestimate black C. It is therefore likely that UV-NMR is a conservative approach to the quantification of black C forms relevant to this study.

The soil samples were subsequently analyzed by MIR using a Fourier transform spectrometer (Bio-Rad 175C, Bio-Rad, Hercules, CA, USA). Partial least squares (PLS) analysis of the MIR spectra was used to estimate black C, the proportion of clay, and bulk density[4]. The calibration set required for the PLS analyses comprised all 0-0.1 m samples, to which the base UV-NMR method was applied, and included properties relevant for subsoils. For bulk density, the 0-0.1 m depth of all of the profiles in the QLD and DWN sets were independently measured gravimetrically and included in the calibration set for the PLS analyses of all other samples. Gravel (>2 mm) contents were determined as a fraction of weight of total soil sampled for each horizon. Bulk density of gravel was calculated from the weight of the sample and its volume by water displacement.

Data used for simulations

Average vegetation input data were modelled for the period from 1891 to 2004, using the AussieGRASS SRC3 model[5]. AussieGRASS is a daily time step simulation model of pasture systems in Australia, and is a spatial implementation of the GRASP model[6].

The typical proportion burned for the studied regions is 85-90% since the late Holocene, with fires occurring every other year[7,8]. In the modelled scenarios the proportions used were 60, 70, 80 and 90%. The optimisation for the proportion of black C formed during each burn was repeated with values ranging from 1.0 to 2.5 and 4.0%. Average recoveries of black C for open tropical fires and savannah burns lie between 0.1 and 4.8% of the C consumed[9]. For Australia, Graetz and Skjemstad[10] found a median production rate of 4.0%, and for the modelled sites 1.0 to 8.0% with an average of 2.5%. In all cases it was assumed that the belowground C input from grass vegetation was not altered as a result of burning. The input of C to soil used in RothC was adjusted to reflect the disappearance of the aboveground portion of the vegetation by fire and ranged from 0.40 to 0.94 Mg C ha^{-1}. Average C input values for the global savannah biome have been calculated as 0.48 Mg C ha^{-1} (ref. 11). Mean monthly air temperature, rainfall and open-pan evaporation data were obtained as an average for 1968 to 2003 from Australia's National Carbon Accounting System (FullCAM Vers.3.10, Australian Greenhouse Office, Canberra). The annual decomposition rate for the resistant plant material (RPM) pool was set to 0.15 $years^{-1}$, as previously determined for Australian soils by Skjemstad et al.[12].

Establishing equilibrium conditions for soil C requires some degree of certainty that the C balance was similar over long periods of time, exceeding the records that are available and were used in the above calculations. Ocean surface temperatures in pre-industrial times were similar in the region 3000 years ago and did not show the depression of the little ice age typical for the northern hemisphere[13]. Rainfall and fire occurrence remained stable over the past 5000 years in Northern Australia, as evidenced by a 23,000-year pollen record in Northern Queensland[14]. Very long charcoal and vegetation records from Lynch's crater in Northern Queensland show variations over the course of the past 45,000 years, but no clear increase or decrease[15]. The beginning of human settlement in Northern Australia which coincides with a pronounced increase in fire frequency started 45,000-55,000 years ago[16] and therefore predates the period relevant to our investigation. Human influence on the environment and fire frequency remained relatively unchanged in the areas for which detailed modelling was conducted[8,10]. We therefore assume that conditions that are most important to the C balance used in our study were reasonably stable to obtain equilibrium conditions.

To represent future temperature change, the mean monthly temperature was increased by an equal fraction for each year to give total temperature changes of 1, 3 and 5°C over 100 years, reflecting current global projections[17]. For the light-textured Inceptisols (Katherine region), the coupled climate-carbon cycle runs of Jones et al.[18] and Cox et al.[19] found changes in mean annual temperature of 5.6°C over the next 100 years.

Temperature sensitivity

The heterogeneity of SOC[18] not only means that different soil C pools have different turnover times, but most likely also their temperature sensitivity differs[20]. In simulation models, the temperature sensitivity is generally included by means of a Q_{10} value, which represents the increase in the decomposition rate due to a 10°C rise in temperature. The effect of soil warming on the Q_{10} of black C is not well quantified, but it could be larger than for other soil C pools due to its greater chemical recalcitrance[20,21,22], even though some studies report equal temperature sensitivity of stable C fractions[23] presumably including black C. Therefore, we tested the sensitivity of our results to an increase in the Q_{10} value of black C mineralization which was calculated external to RothC. Even with a compared to experimental evidence[22,23] unrealistically high doubling of the Q_{10} only of black C decomposition, our simulations with and without black C still differed by 10%. In the event that black C does not react with greater mineralization at all, or has a greater MRT than calculated under the current scenario, this difference would increase to 22%. Due to the high stability of black C, a significant overestimation of the emissions as a response to warming even occurs under greater temperature sensitivity of black C than labile C.

Supplementary References

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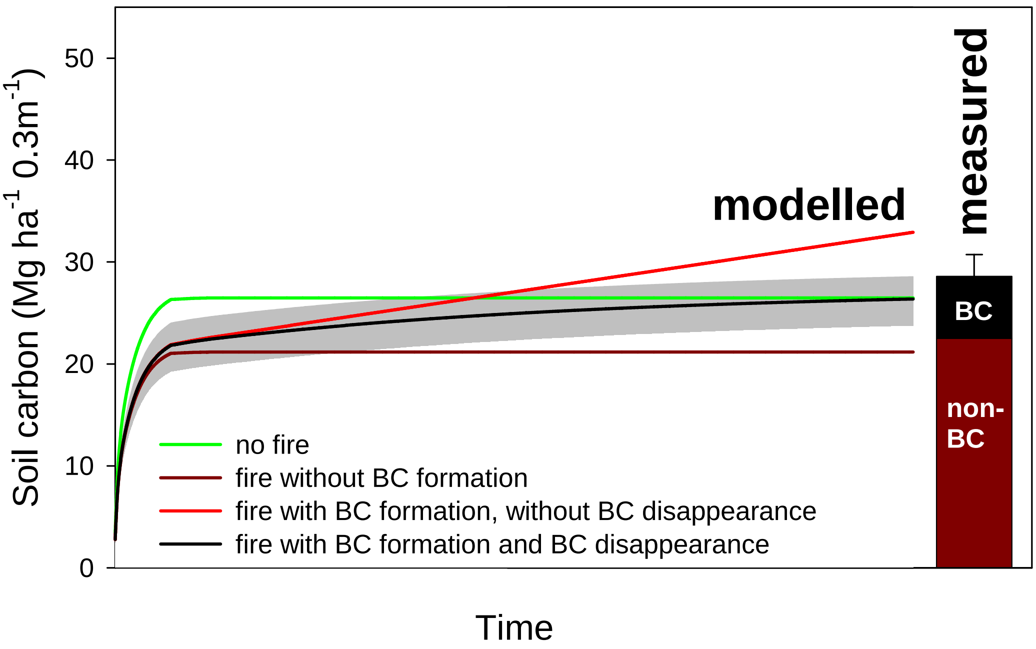
Supplementary Table 1. Mean residence time of black C assuming different proportions of vegetation burnt and of black C formed from burnt vegetation (burning every second year; fitted to black C stocks at 0-1 m) (means, N=13 and 15 for light- and heavy-textured Inceptisols at Katherine and Daly Waters, respectively).

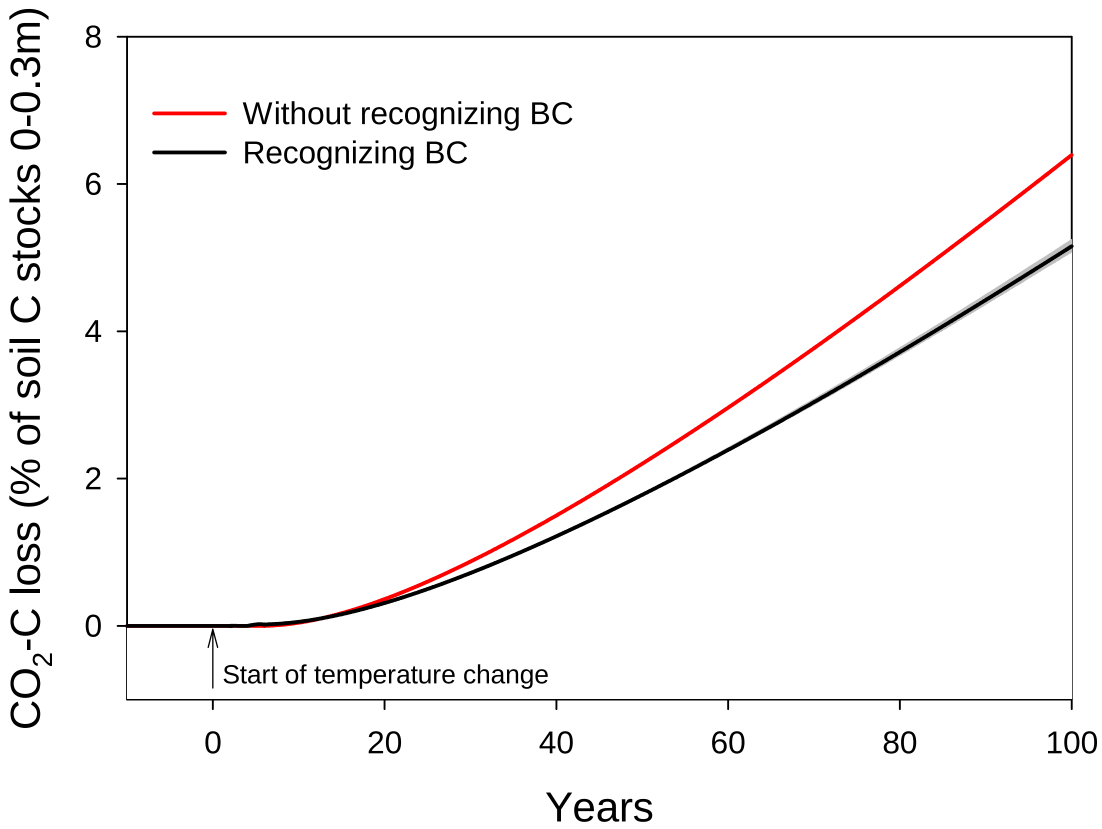
	Mean residence time (years)		
	Black C formation (% of C in burned vegetation)		
	1	2.5	4
Vegetation burnt (% of total vegetation)	Light-textured Inceptisols at Katherine (MAP[1] 887 mm; MAT[2] 27°C; clay 13%)		
60	4292	1715	1074
70	3674	1471	921
80	3212	1300	806
90	2856	1145	718
	Heavy-textured Inceptisols at Daly Waters (MAP 738 mm; MAT 27°C; clay 21%)		
60	9259	3506	2163
70	7704	2984	1855
80	6631	2603	1623
90	5841	2310	1444

[1] Mean annual precipitation

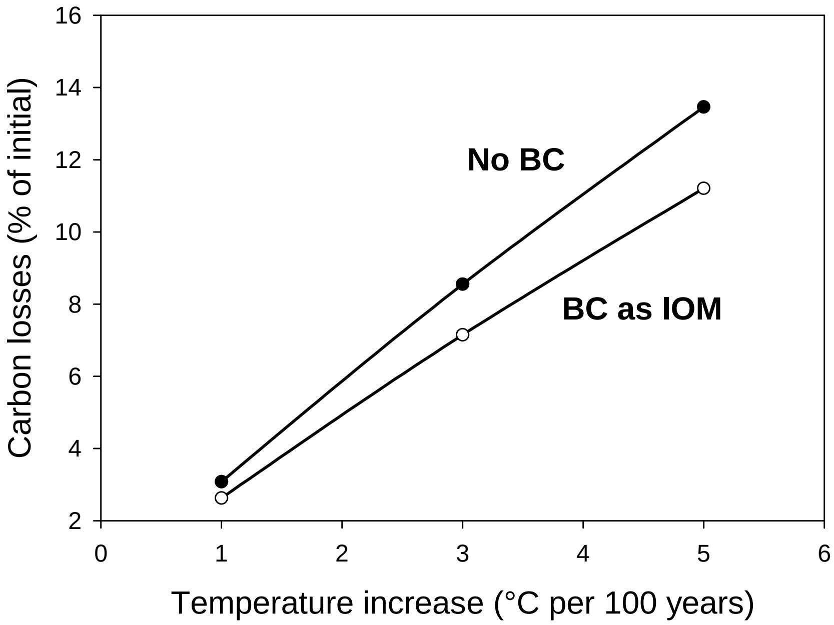
[2] Mean annual temperature



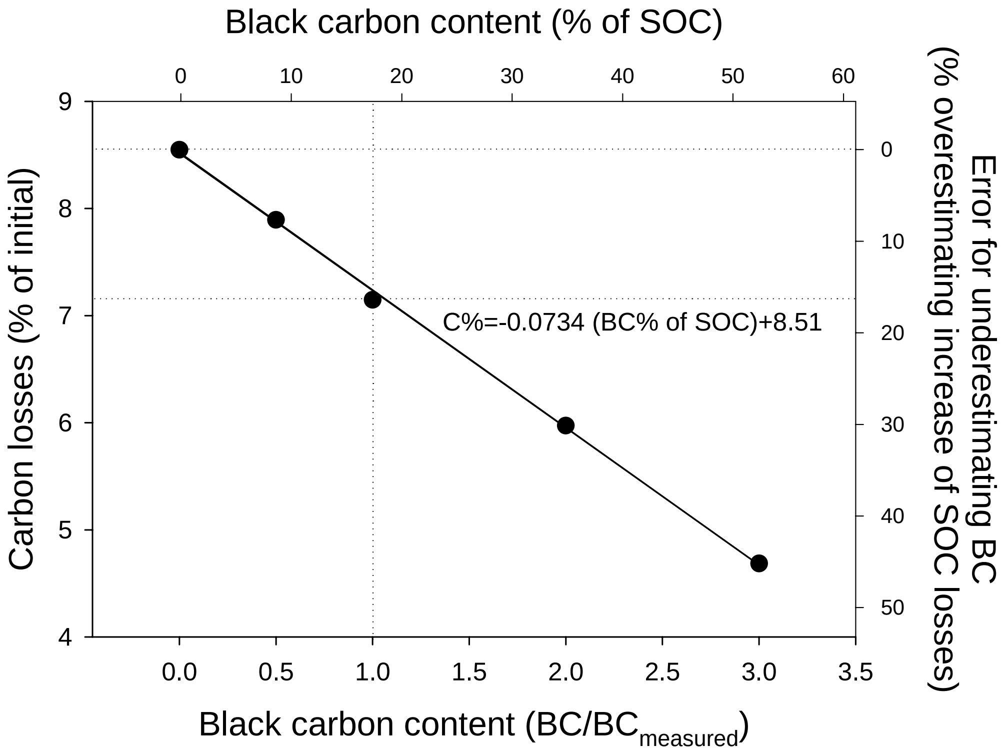
Supplementary Figure 1. Convergence of model equilibrium conditions (lines) to measured soil stocks (bars). Average of 15 heavy-textured Inceptisols (Daly Waters region, DWN). Total measured SOC (0-0.3 m) is the sum of non-BC and BC (mean and standard error). Errors for model equilibrium conditions (grey-shaded area) were calculated using a range from 90% burnt every 1.5 years to 70% every 3 years (for clarity only shown for fire with BC formation and BC disappearance).



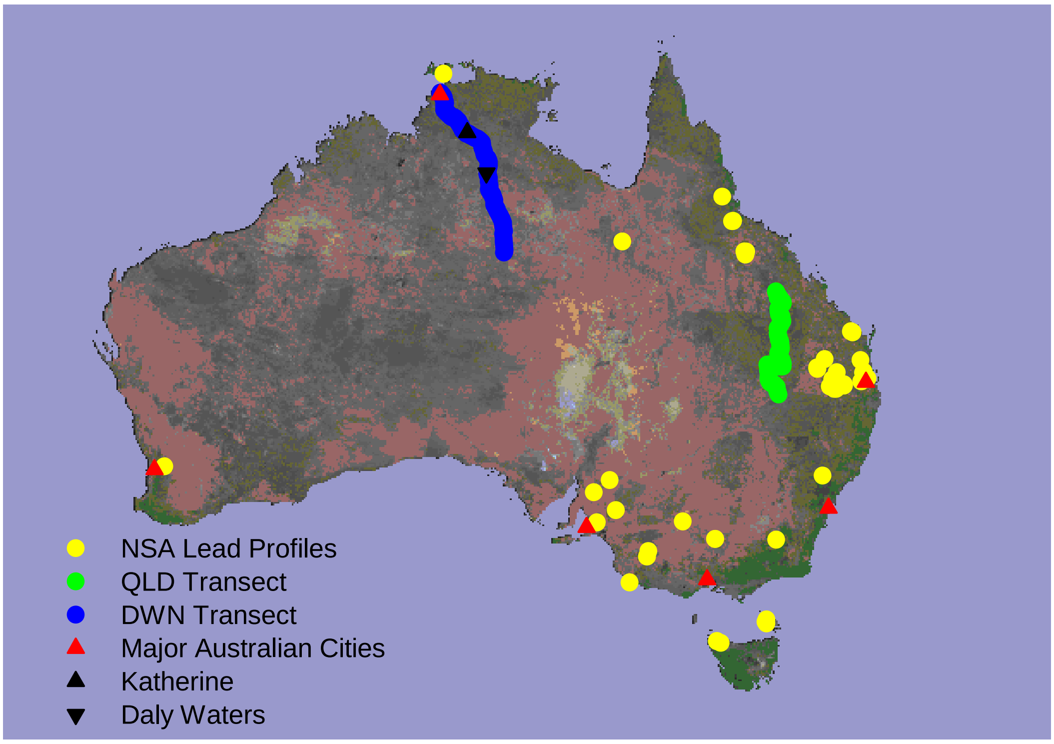
Supplementary Figure 2. Effect of ignoring BC as IOM on SOC losses by mineralization in response to warming by 3°C over 100 years. Response to different warming shown in Supplementary Fig. 3. Average of 15 heavy-textured Inceptisols (Daly Waters region, DWN). Grey-shaded area shows responses with mean residence times of black C ranging from 1444 to 9259 years around the most likely scenario of 2603 years (corresponding to measured 80% biomass burnt and 2.5% black C formation every second year; Supplementary Table 1).



Supplementary Figure 3. Relationship between temperature increase and the fraction of SOC lost over 100 years. Data shown for two scenarios: a, BC is not considered. b, BC and a temperature effect on BC decomposition is considered (using Q_{10} from RothC). (regression assuming a linear relationship: No-BC, y = 2.5954x + 0.5758; BC as IOM, y = 2.1452x + 0.5569).



Supplementary Figure 4. Carbon losses and overestimation of C losses from soil for a warming of 3°C over 100 years when black C is ignored. Data shown as a function of black C (BC) contents of soils (% of SOC) and relative to the investigated soil from Katherine ($BC/BC_{measured}$ at Katherine). A greater error (right y axis) due to underestimation of black C in soils decreases actual C losses (left y axis).



Supplementary Figure 5. Locations of soil profiles. Samples obtained from the Australian National Soil Archive (NSA), the Queensland (QLD) and Darwin (DWN) transects overlain on a Landsat image of Australia (CSIRO Land and Water). The Darwin transect captures most of the variability in landforms, vegetation and soils in Central and Western Australia. The Queensland transect captures most of the variability in Eastern Australia.