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Recent reversal in loss of global terrestrial biomass

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Vegetation change plays a critical role in the Earth's carbon (C) budget and its associated radiative forcing in response to anthropogenic and natural climate change[1–4]. Existing global estimates of aboveground biomass carbon (ABC) based on field survey data provide brief snapshots that are mainly limited to forest ecosystems[5–8]. Here we use an entirely new remote sensing approach to derive global ABC estimates for both forest and non-forest biomes during the past two decades from satellite passive microwave observations. We estimate a global average ABC of 362 PgC over the period 1998–2002, of which 65% is in forests and 17% in savannahs. Over the period 1993–2012, an estimated −0.07 PgC yr^{-1} ABC was lost globally, mostly resulting from the loss of tropical forests (−0.26 PgC yr^{-1}) and net gains in mixed forests over boreal and temperate regions (+0.13 PgC yr^{-1}) and tropical savannahs and shrublands (+0.05 PgC yr^{-1}). Interannual ABC patterns are greatly influenced by the strong response of water-limited ecosystems to rainfall variability, particularly savannahs. From 2003 onwards, forest in Russia and China expanded and tropical deforestation declined. Increased ABC associated with wetter conditions in the savannahs of northern Australia and southern Africa reversed global ABC loss, leading to an overall gain, consistent with trends in the global carbon sink reported in recent studies[1,3,9].

Over the past two decades, the terrestrial biosphere has acted as a sink for atmospheric CO_2, removing on average approximately 2.5 petagrams of carbon per year (PgC yr^{-1}): equivalent to 25% of fossil fuel emissions[1–4]. Additional emissions from land-use change reduce the global net land sink to approximately 1.5 PgC yr^{-1}, with forests playing a dominant role[5]. Monitoring C stock changes over time can be used to determine which ecosystems and processes drive changes in C fluxes and to develop strategies for climate change mitigation. The existing global ABC estimates based on field survey data, such as the recent global synthesis by Pan *et al.*[5], provide snapshots in time and are limited to forest ecosystems only. Estimating ABC using satellite remote sensing can provide a more consistent methodology and global coverage[6]. Although offering high spatial resolution, current remote sensing products have limited temporal frequency and record length at the global scale[6–8].

Here, we derive global ABC estimates for all vegetation types for the past two decades using an entirely new approach that uses satellite-based passive microwave data rather than the optical or radar observations used previously. The intensity of natural microwave radiation from the Earth is a function of its temperature, soil moisture and the shielding effect of water in aboveground vegetation biomass, including canopy and woody components[10–12]. The biomass signal is captured in the vegetation optical depth (VOD; refs 13,14). A distinct advantage of passive microwave-derived VOD is that it remains sensitive to biomass variations at a relatively high biomass density (for example, rainforests), whereas optical-based remotely sensed vegetation products rapidly saturate[14,15]. ABC estimates can be derived for all vegetation types, not only forests, as a suitable harmonized global VOD record exists from the 1990s onwards[14].

The main disadvantage of this technique is the relatively coarse spatial resolution (>10 km), which is a consequence of the low energy of the Earth's natural microwave emissions. This means that individual plot measurements cannot be used directly to establish a relationship between VOD and ABC. Instead, we use an indirect calibration method based on spatial 'snapshot' ABC estimates from Saatchi *et al.*[6], who combined three types of satellite observations with plot-based measurements to estimate ABC in tropical regions (see Methods and Supplementary Information).

Global C stocks

We estimate total global ABC at 362 PgC with a 90% confidence interval (CI_{90}) of 310–422 PgC circa 2000 (that is, 1998–2002; Fig. 1a). ABC values per region and biome and annual ABC change rate are very close to values reported in other studies when the same categorization, definitions and assumptions are applied[5–7] (see Supplementary Information for details). Our ABC estimates for boreal forests (CI_{90} = 37–66 PgC) and temperate forests (CI_{90} = 24–39 PgC) circa 2000 overlap with inventory-based estimates (44 and 36.4 PgC, respectively) by Pan and colleagues[5]. For tropical forests, our ABC estimates are comparable to Pan *et al.*[5] (205 versus our 195; CI_{90} = 180–208 PgC circa 2000), Saatchi *et al.*[6] (173–212 versus our 211; CI_{90} = 194–226 PgC for 10% tree cover threshold circa 2000) and Baccini *et al.*[7] (159 versus our 157; CI_{90} = 146–166 PgC circa 2007/8). For the savannahs and shrublands of the pan-tropics (excluding Australia), Baccini *et al.*[7] reported 51 PgC ABC circa 2007/8, which is similar to our estimate of 49 (CI_{90} = 42–56) PgC (see Supplementary Information).

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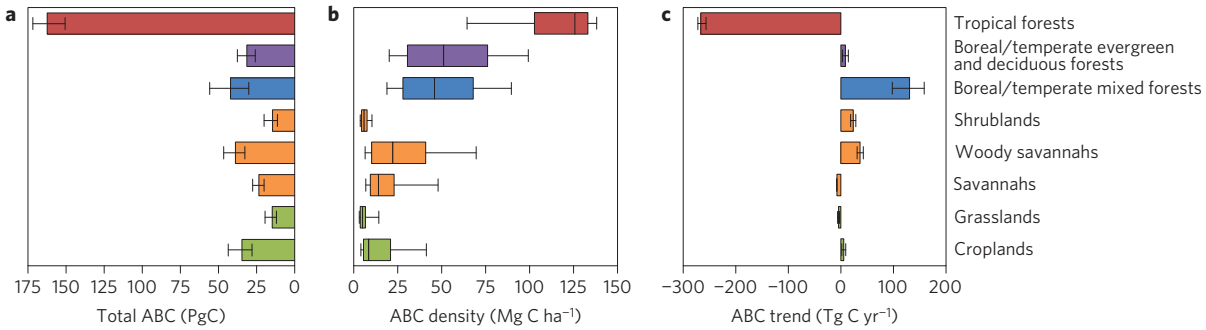

Figure 1 | Aboveground biomass carbon stores and density by biome. a, Total ABC in eight biomes circa 2000 (mean estimate; error bars indicate the 90% confidence interval). 'Tropical forests' include those in Southeast Asia, Africa and the Americas (that is, South America, Caribbean countries and Mexico); remaining forests are considered as 'boreal/temperate'. 'Shrublands' includes both open and closed shrublands; 'Croplands' includes both 'croplands' and 'cropland/natural vegetation mosaic' based on the MODIS IGBP land-cover map for 2001 (ref. 16). **b**, ABC density per unit area circa 2000. The bottom, middle and top band of the box represent the 25th, 50th (median) and 75th percentile, respectively, and the ends of the whiskers represent the 5th and 95th percentile for all corresponding grid cells. **c**, Annual trends in total biome ABC for 1993–2012 (mean estimate; error bars indicate the 90% confidence interval). The classification relates to year 2001 and grouping of different biomes to the same colour is mainly based on woody vegetation canopy cover, that is, 10–60% for shrublands, savannahs and woody savannahs and less than 10% for grasslands. Croplands with harvest and thus considerable variation in woody components are grouped with grasslands.

Applying the MODIS Collection 5 International Geosphere Biosphere Programme (IGBP) land-cover classification product (MCD12C1; ref. 16) of 2001, tropical forests contain 162 (CI_{90} = 151–172) PgC or 44% of global ABC, whereas the remaining forests contain 73 (CI_{90} = 56–93) PgC or 21%. Savannahs (including woody savannahs) make up another 62 (CI_{90} = 53–74) PgC or 17%, whereas shrublands (15, CI_{90} = 11–20 PgC), grasslands (15, CI_{90} = 12–19 PgC) and croplands (35, CI_{90} = 28–44 PgC, including vegetation mosaics) together account for the remaining 18%. We emphasize that our relatively coarse 0.25° resolution data represent biome-integrated values rather than values for component land-cover units. For example, at 0.25° resolution a considerable part of cropland ABC may be contained in forests, woodlots and individual trees present within the agricultural landscape. Also, because dynamic land-cover maps were not available before 2000, changes in area between land-cover types during this period are not explicitly accounted for.

ABC changes in space and time

A map of ABC trends over the period 1993–2012 (Fig. 2) reflects spatial changes in the underlying VOD data, which were attributed to their main natural and anthropogenic drivers in a previous study[17]. Prominent features of these trends include ABC changes due to widespread tropical forest clearing in several countries (for example, Brazil and Indonesia); rainfall variability in water-limited ecosystems (for example, savannahs and shrublands) causing an ABC increase in southern Africa and northern Australia; regrowth on abandoned farm land in former communist countries in boreal and temperate regions; and pest attacks and wildfires in the boreal forests of northeast Russia and Canada and the temperate forests of the USA.

Harris *et al.*[8] reported a gross carbon stock loss from tropical deforestation of 0.81 (CI_{90} = 0.57–1.22) PgC yr^{-1} between 2000 and 2005. We derive a comparable value of 0.99 (CI_{90} = 0.91–1.05) PgC yr^{-1} and a very similar spatial pattern (Fig. 2). We calculate a net mean annual ABC change of −0.26 PgC yr^{-1} for the period 1993–2012 for areas that were tropical forests circa 2000 (Figs 1c and 3b), which is the net effect of considerable deforestation and a slight C increase over the intact tropical forests (Fig. 2). The ABC declines were −0.16, −0.09 and less than −0.01 PgC yr^{-1} over the Americas, Southeast Asia and Africa respectively (Fig. 3c). The steepest ABC decline is observed during 2002–2005 over the Americas, most likely caused

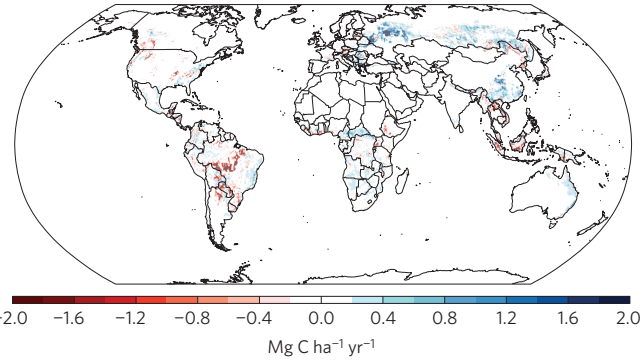

Figure 2 | Mean annual change in aboveground biomass carbon between 1993 and 2012.

by intensive biomass burning associated with deforestation[18]. The loss of ABC from tropical deforestation during 2003–2012 (−0.21 PgC yr^{-1}) is largely compensated by increasing ABC in boreal and temperate mixed forests (+0.18 PgC yr^{-1}) (Fig. 3b), particularly in Russia (+0.10 PgC yr^{-1}) owing to regrowth on abandoned state farmland[19] and in China (+0.07 PgC yr^{-1}) resulting from afforestation programmes[20] (see Supplementary Fig. 8). In addition, ABC in water-limited ecosystems fluctuates considerably during 1993–2012, with an overall increasing trend. These dynamics can be mainly attributed to corresponding rainfall patterns in southern Africa and northern Australia (Fig. 3d), which in turn can be partially attributed to El Niño Southern Oscillation (ENSO) conditions[21,22]. This includes an ABC increase during the 1990s that culminated during the 2000 La Niña, followed by a rapid decline associated in part with two El Niño events during the following five years. ABC recovered towards the end of the period in response to the beginning of very wet La Niña conditions[23]. In addition to these interannual dynamics, the continued increase of atmospheric CO_2 concentrations may well contribute to the positive long-term trend in ABC (ref. 24).

The interannual ABC patterns of these water-limited ecosystems play an important role in the terrestrial ABC dynamics. Globally, year-to-year ABC changes for savannahs and shrublands combined varied from −1.2 PgC (2001/2002) to +1.5 PgC (2008/2009), whereas total global ABC changes varied from −2.5 PgC (2001/2002) to +2.2 PgC (2008/2009). The declining linear

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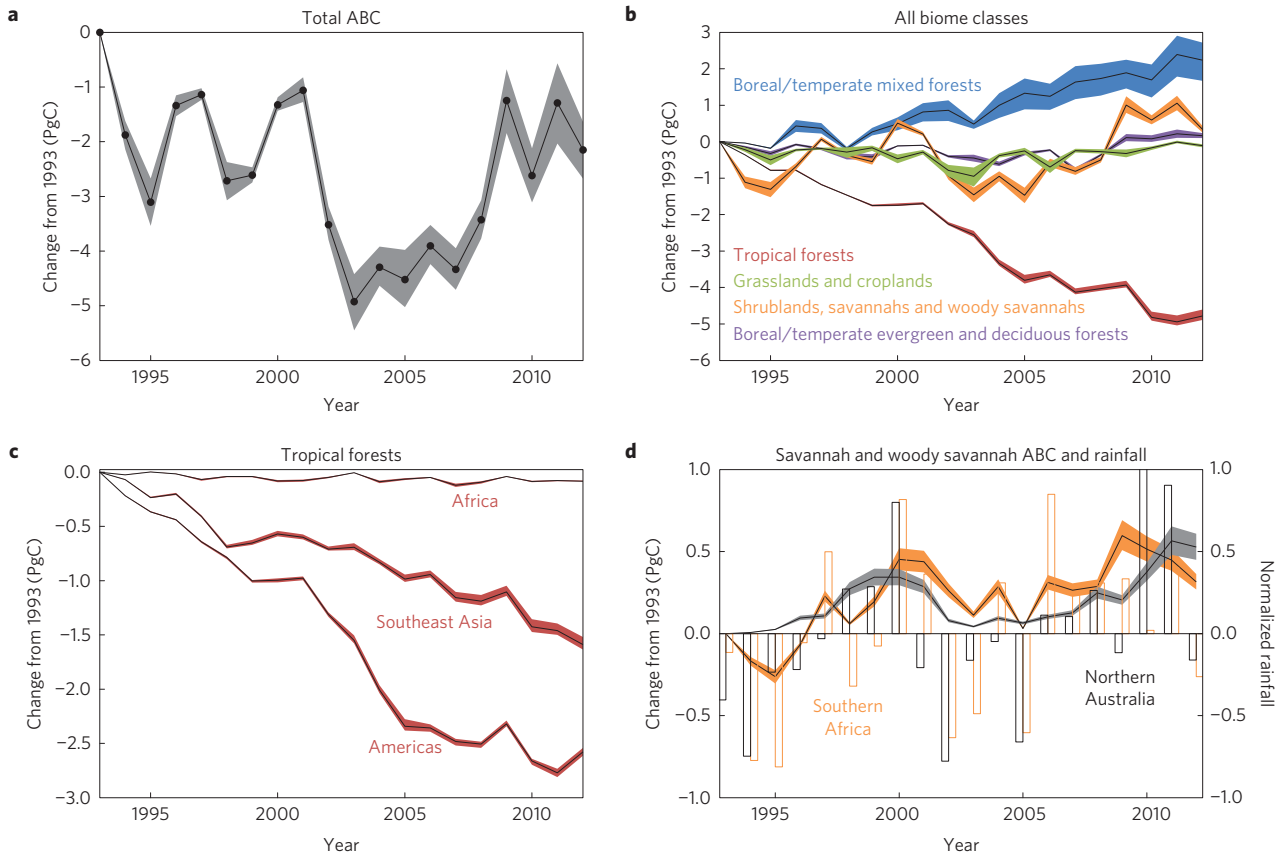

Figure 3 | Interannual variations in aboveground biomass carbon (ABC) storage. a, Time series of annual total ABC for all ecosystems, expressed as the difference from 1993 values. **b**, Time series of annual total ABC in five biome groups (merged as per colour codes in Fig. 1), with a classification based on MODIS IGBP 2001 (ref. 16). **c**, Time series of annual tropical forest ABC over the Americas, Southeast Asia and Africa. Southeast Asia here includes Asian countries as well as Papua New Guinea (see Supplementary Fig. 3b). **d**, Time series of the annual total ABC and normalized rainfall for the savannahs and woody savannahs of southern Africa and northern Australia. Coefficients of determination (r^2) between ABC and rainfall are 0.53 and 0.65 for southern Africa and northern Australia, respectively. The solid line represents the mean value and the shadow represents the CI_{90} range.

trend in global total ABC of 0.07 PgC yr^{-1} for 1993–2012 is not statistically significant ($p > 0.05$), and includes a rapid reduction from 2000 to 2003 followed by a more gradual recovery (Fig. 3a).

Aboveground biomass in the global C budget

Global carbon budget analyses[1,3,25] and CO_2 atmospheric inversion studies[9] suggest a terrestrial net carbon sink (measured as the net exchange between the atmosphere and all lands) of approximately 1.4 ± 0.4 PgC yr^{-1}. Using biome-specific ratios of aboveground and total biomass carbon (ABC/TBC; ref. 26) and ratios between TBC and total carbon stock (see Supplementary Table 3 in Pan *et al.*[5]), combined with the MODIS IGBP dynamic land-cover maps for 2003–2012, we estimated trends in mean forest ABC and total forest carbon of +0.10 and +1.19 PgC yr^{-1}, respectively, for this period (Table 1). Global total forest area was similar for 2003 and 2012, but there was a reduction in tropical forests and an increase in boreal and temperate forests. The very different carbon structure of tropical and boreal forests plays a crucial role in increasing the global total forest carbon stock: tropical forests store 44% of total carbon in aboveground biomass but boreal forests only 15%, with the remainder contained in living roots, litter and soil organic carbon[5]. Total biomass carbon in non-forest biomes increased by +0.63 PgC yr^{-1} (Table 1), with an unknown change in non-living carbon. Combined, these numbers suggest a net terrestrial sink of at least +1.82 PgC yr^{-1} for 2003–2012, still consistent with that estimated from the global carbon budget[1,3,9]. The main uncertainty in the rate of increase is associated with the slow and passive carbon pools of soil organic matter, which are expected to take longer to respond than short-term biomass variations.

Our findings based on an assessment of all lands reveal that non-forests also contribute to the global land sink, contrary to previous analysis where the land sink has been largely attributed to forests in Pan and colleagues[5]. The additional sinks are still consistent with mass conservation of the global carbon because of the level of uncertainties reported here and in Pan *et al.*[5], particularly for the large and highly uncertain flux from forest regrowth in the tropics. Our findings also show that savannahs and shrublands in southern Africa and northern Australia are becoming an increasingly important component of interannual variability in the carbon cycle, consistent with recent studies based on terrestrial biosphere model, atmospheric CO_2 inversion and field experiments[27,28].

The ABC estimates presented here provided new insights into the global carbon cycle. Importantly, our data cover all biomes, albeit at a coarse spatial resolution, which makes them most appropriate for global and continental analyses. We show that ABC has increased in several regions world-wide, but the long-term trend is dominated by tropical deforestation. Globally, water-limited ecosystems are a net biomass sink for atmospheric CO_2, but one that is very sensitive to rainfall variations and ENSO (ref. 29). Our results are consistent with current knowledge of the role of terrestrial C sinks in the global carbon budget, and the considerable contribution of non-living carbon components (Table 1) suggests an important role for litter, root and soil carbon in creating the sink. The future

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Table 1 | Linear trends in ABC (aboveground biomass carbon), TBC (above- and belowground biomass carbon combined) and total carbon stock for various biome classes during 2003–2012.

	2003–2012				
	ABC trend (PgC yr^{-1})	TBC/ABC ratio	TBC trend (PgC yr^{-1})	Total C*/TBC ratio	Total C trend (PgC yr^{-1})
Boreal forests	+0.16[a]	1.24	+0.20[a]	5.18	+1.04[a]
Temperate forests	+0.17[b]	1.24	+0.21[b]	3.19	+0.67[b]
Tropical forests	−0.23[c]	1.26	−0.29[c]	1.80	−0.52[c]
Forest†	+0.10[a]		+0.12[a]		+1.19[a]
Shrublands	+0.08[b]	2.78	+0.21[b]	-	>+0.21[b]
Woody savannahs	+0.11[b]	1.82	+0.20[b]	-	>+0.20[b]
Savannahs	+0.08[b]	2.38	+0.20[b]	-	>+0.20[b]
Grasslands	−0.002[b]	3.45	−0.01[c]	-	<−0.01[c]
Croplands	+0.02[c]	1.25	+0.03[b]	-	>+0.03[b]
Non-forest‡	+0.29[b]		+0.63[b]		>+0.63[b]
Total	+0.39[a]		+0.75[b]		>+1.82[a]

The classification takes into account the land-cover dynamics during 2003–2012. a, b and c represents the uncertainty (that is, ratio between half range of CI_{90} and mean value) >25%, 10–25% and <10%, respectively. *Total C includes TBC and non-living carbon in dead wood, litter and soil organic matter for a soil depth of 1 m (see Supplementary Table 3 in Pan *et al.*[5]). †A grid cell is considered as 'forest' if it is classified as 'forest' in any year during 2003–2012 according to the MODIS IGBP land-cover maps. Thus, the ABC trend reflects the net influence of forest changes (that is, deforestation, afforestation and reforestation combined). ‡The ratios between total carbon and total living carbon for non-forest land-cover types are unknown.

of the terrestrial carbon sink may be particularly sensitive to the evolution of tropical deforestation rates, the fate of Eurasia's former croplands, afforestation in China, and rainfall in sub-humid tropical savannahs.

Methods

The ABC estimates were based on harmonized VOD data for 1993 onwards derived from a series of passive microwave satellite sensors[14], including Special Sensor Microwave Imager (SSM/I), Advanced Microwave Scanning Radiometer for Earth Observation System (AMSR-E), FengYun-3B Microwave Radiometer Imager (MWRI) and Windsat. VOD values affected by the presence of inland water bodies were corrected by considering nearby grid cells with the same landscape type. Values missing owing to frost conditions were estimated using two alternative assumptions about ABC decreases in winter. An empirical relationship was established to convert VOD to ABC by calibrating against the aboveground biomass map for tropical regions from Saatchi *et al.*[6] to predict the mean and 90% confidence interval (CI_{90}; see Section 2.1 in Supplementary Information). We combined these with the two frost corrections to produce six ABC estimates and report the mean and the CI_{90} range of the resulting analyses. Global estimates of ABC stocks and changes were compared to ABC values estimated from Pan *et al.*[5], Baccini *et al.*[7] and Harris *et al.*[8]; taking care to match the reported biome area, measurement period, and definition of countries and regions. Pan *et al.*[5] reported TBC only, but we could infer ABC from the description of methods. A global land-cover map based on the MODIS Collection 5 IGBP classification product (MCD12C1; ref. 16) was re-sampled to 0.25° by dominant land use to calculate ABC per biome. The Global Precipitation Climatology Centre (GPCC) precipitation data for 1993–2012 were used in interpretation[30]. To estimate the TBC from our ABC values, we applied the conversion factors used by Pan *et al.*[5] for different forests and used literature values for non-forest vegetation[26]. Further details are provided in the Supplementary Information. The aboveground biomass carbon (ABC) data set derived and used in this study over the period 1993–2012 can be accessed at http://www.wenfo.org/wald/global-biomass and http://hydrology.unsw.edu.au/downloads/data/global-biomass

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Author contributions

All authors contributed to the development of the paper. Y.Y.L. and A.I.J.M.v.D. designed the study. R.A.M.d.J., Y.Y.L. and G.W. prepared the VOD data set. Y.Y.L. conducted the analysis and wrote the Supplementary Information. A.I.J.M.v.D. and J.G.C. summarized the results and wrote the first draft of the paper, with subsequent addition and improvement by all authors.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to Y.Y.L.

Competing financial interests

The authors declare no competing financial interests.

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