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A new high-resolution nationwide aboveground carbon map for Brazil

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Brazil is home to the largest tracts of tropical vegetation in the world, harbouring high levels of biodiversity and carbon. Several biomass maps have been produced for Brazil, using different approaches and methods, and for different purposes. These maps have been used to estimate historic, recent, and future carbon emissions from land use change (LUC). It can be difficult to determine which map to use for what purpose. The implications of using an unsuitable map can be significant, since the maps have large differences, both in terms of total carbon storage and its spatial distribution. This paper presents comparisons of Brazil's new 'official' carbon map; that is, the map used in the third national communication to the UNFCCC in 2016, with the former official map, and four carbon maps from the scientific literature. General strengths and weaknesses of the different maps are identified, including their suitability for different types of studies. No carbon map was found suitable for studies concerned with existing land use/cover (LULC) and LUC outside of existing forests, partly because they do not represent the current LULC sufficiently well, and partly because they generally overestimate carbon values for agricultural land. A new map of aboveground carbon is presented, which was created based on data from existing maps and an up-to-date LULC map. This new map reflects current LULC, has high accuracy and resolution (50 m), and a national coverage. It can be a useful alternative for scientific studies and policy initiatives concerned with existing LULC and LUC outside of existing forests, especially at local scales when high resolution is necessary, and/or outside the Amazon biome. We identify five ongoing climate policy initiatives in Brazil that can benefit from using this map.

Key words Brazil; carbon map; GIS; aboveground biomass; land use policy; LULUCF

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Introduction

Carbon maps are essential for estimating historic, current, or future carbon emissions and sequestration associated with land use, land use change and forestry (LULUCF) – for scientific studies as well as national communication to the United Nations Framework Convention on Climate Change (UNFCCC). However, such maps are difficult to produce and the uncertainties are often large (Ometto *et al.* 2014). To accurately estimate carbon emissions and sequestration associated with LULUCF, and to support the development of relevant policy instruments, such as the REDD+ framework, it is imperative to reduce uncertainty in biomass estimations and to develop high-resolution biomass carbon maps with high accuracy (Ometto *et al.* 2014). The use of maps with poor accuracy – or maps developed for other purposes,

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regardless of accuracy – can lead to misleading results, which in turn can lead to decisions that have undesirable consequences, such as unrealised greenhouse gas (GHG) emissions reduction. In cases where several carbon maps are available – such as for Brazil – meta-analysis and synthesis of studies can also be challenging.

Brazil has the largest tracts of tropical vegetation in the world, harbouring high levels of biodiversity and carbon (Lapola *et al.* 2014). Different policy instruments can discourage land use change (LUC) that cause GHG emissions, for example, REDD+ (Gebara *et al.* 2014), and carbon pricing on LUC emissions (Englund *et al.* 2015). Deforestation has in the past decade increased in the Cerrado biome (Soares Filho *et al.* 2014), but has decreased drastically in the Amazon biome and in Brazil as a whole, mainly due to successful enforcement of new policies and legislation (Macedo *et al.* 2012; Barretto *et al.* 2013; Arima *et al.* 2014; Nepstad *et al.* 2014), and an increasing decoupling between agricultural expansion and deforestation (Lapola *et al.* 2014). However, the recent revision of the Brazilian Forest Act (Brazil 2012) – the major legal framework for conservation of natural vegetation on private land – resulted in a weaker protection of natural vegetation and less demanding requirements on restoration planting and promotion of natural regeneration on agricultural land (Silva and Ranieri 2014; Sparovek *et al.* 2015).

Several biomass maps have been produced for Brazil, using different approaches and methods, and for different purposes (Saatchi *et al.* 2007 2011; Nogueira *et al.* 2008 2015; Baccini *et al.* 2012). These maps have been used to estimate historic (Nogueira *et al.* 2015), recent (Baccini *et al.* 2012) and future (Ometto *et al.* 2014) carbon emissions from LUC. The different maps of Amazonian biomass show substantial variation in both total biomass and its spatial distribution (Aguiar *et al.* 2012; Ometto *et al.* 2014). It is not possible at this point to determine which map presents the most accurate biomass distribution, partly because the literature on the spatial pattern of forest biomass in the Amazon is very diverse, and even contains some contradictory results, and partly because available research plots do not constitute a sufficient statistical sample (Saatchi *et al.* 2015).

Brazil's former 'official' carbon map, that is, the map used for the second national communication to the UNFCCC in 2010 (henceforth referred to as O10), had three important weaknesses: (1) relatively high carbon values compared with alternative maps (Ometto *et al.* 2014), indicating overestimation of carbon values in general; (2) coarse resolution and limited spatial variability, rendering the map impractical, especially for regional and local scale studies needed to support national or regional policy and private investment decisions; and (3) high degree of patchiness, with carbon values changing significantly from one map scene to another (see Figure 1).

This paper aims to evaluate existing carbon maps for Brazil and present a new map of aboveground carbon (AGC) that has high-resolution, national coverage and that reflects current land use/cover (LULC). To this aim, the following objectives apply:

1. Compare Brazil's new 'official' carbon map, that is, the map used for the third national communication to the UNFCCC in 2016 (henceforth referred to as O16), with the former official map and alternative maps from the scientific literature.
2. Identify general strengths and weaknesses of the different maps, including their suitability for different types of studies, and their accuracy for specific LULC types.
3. Combine information from the carbon maps and a detailed LULC map, to compile a new nationwide high-resolution AGC map, reflecting current LULC.

Materials and methods

Carbon maps

In the third Brazilian national communication to the UNFCCC (MCTI 2016), a new carbon map was presented (O16). As in the carbon map for the second national communication (O10), carbon stored in vegetation classes in each Brazilian biome was estimated from values of living belowground and aboveground biomass, and dead organic matter (deadwood and litter). The new carbon map for the Amazon biome is – as the previous map – based on forest inventory plots from the RADAMBRASIL project (MME 1987), in which forest biomass in the Amazon was mapped at a 1:1000.000 scale based on tree measurements conducted between 1971 and 1986 in 0.5–1 ha randomly distributed plots. These data were combined with maps of vegetation classes from the Brazilian Institute of Geography and Statistics (IGBE 2004). There are however notable methodological differences in the development of the two maps: different RADAMBRASIL data used (O16 is based on 1668 RADAMBRASIL plots, compared with 1710 for O10); different allometric equations to estimate biomass, and different biomass to carbon conversion factors; deadwood biomass was added for O16, in addition to aboveground and belowground biomass and litter; O10 was created by combining the individual RADAMBRASIL volumes (the total project was divided into 34 volumes, each covering a specific part of the total project area). In each volume, average carbon values were calculated

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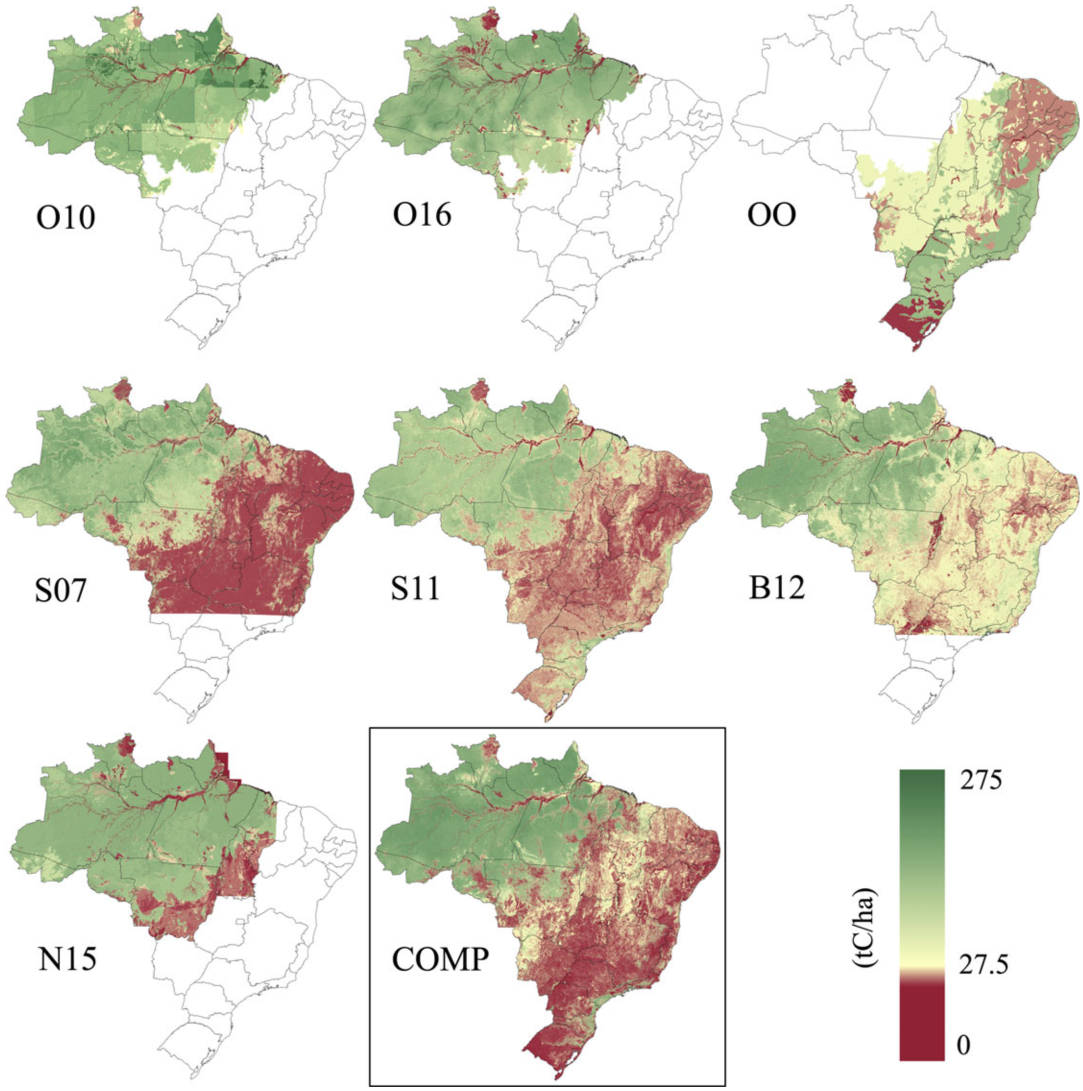

Figure 1 The AGC distribution and extent for all maps included in this paper, including the new nationwide aboveground C map (COMP)

for each type of vegetation within the area. Since these values differed between volumes, O10 got highly 'patchy'. O16 was instead created by combining a basal area interpolated surface with mean biomass values of the biome's predominant vegetation classes. This resolved the 'patchiness' of O10, as seen in Figure 1. Outside of the Amazon biome (OO), carbon values for most vegetation classes were updated for the third communication to the UNFCCC, based on a literature review. In absolute terms, however, there are only small differences between OO in the second and third communication. More methodological information about OO and O16 is available in Brazil's third national communication to the UNFCCC (MCTI 2016).

Besides the official maps, several other maps have been produced by scientists – for different purposes and using different methods. In this article, O16 is compared with O10 and four alternative maps that fulfil three selection criteria: (1) they are original, that is, they are not a product of other maps; (2) they cover at least the entire Amazon biome, and (3) they consider geoexplicit attributes, for example, vegetation type, when estimating carbon content in vegetation. The first criterion excludes, for example, the integrated pan-tropical biomass map by Avitabile *et al*. (2016) (combining S11 and B12), the second excludes local assessments (e.g. Barrett *et al*. 2009) that would be impractical to include, compare and combine, and the third excludes, for example, the plot-based AGB map

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by Mitchard *et al*. (2014) that was produced using interpolation (two-dimensional kriging). The following four maps were selected:

- S07: an Amazon-wide map of AGB with 1000 m resolution, based on remote sensing data, environmental variables, and ground measurements, produced by Saatchi *et al.* (2007).
- S11: a global AGB map with 1000 m resolution, based on remote sensing data, environmental variables, and ground measurements, produced by Saatchi *et al.* (2011).
- B12: a pan-tropical AGB map with 500 m resolution, based on remote sensing data, environmental variables, and ground measurements, produced by Baccini *et al.* (2012).
- N15: a 'premodern' (prior to major increases in disturbance beginning in the 1970s) AGB map for the legal Amazon with the scale 1:250,000, based on vegetation maps and mean biomass values from the literature. Produced by Nogueira *et al.* (2015).

For full information about methods used to produce the different maps, we refer to the respective references in the above list. A methodological summary (including main differences between the remote sensing maps) is available in Ometto *et al*. (2014). A description of how the carbon maps were prepared for analysis is provided in Table 1.

Table 1 Description of how the original carbon maps were prepared for analysis in this paper

Dataset	*Preparation for analysis*
O16	Raster resampled and snapped, i.e. cells resized and aligned, to match B12[a] Values converted to integer for enhanced accuracy in statistical calculations
O10	Feature dataset rasterised and snapped to match B12 Values converted to integer
OO[b]	Calculated using the methodology described in the national communication to the UNFCCC, i.e. by linking vegetation types to carbon values Rasterised and snapped to match B12
S07	Reclassified to the average values of the aboveground biomass (AGB) ranges that the dataset classes represent, multiplied with 0.5 to convert AGB values into AGC[c] Clipped using a polygon of Brazil Resampled and snapped to match B12 Values converted to integer
S11	Values multiplied with 0.5 to convert AGB values into AGC[c] Resampled and snapped to match B12 Values converted to integer
B12	Values multiplied with 0.5 to convert AGB values into AGC[c]
N15	Feature dataset rasterised using the field representing AGC ('CARB_ABOVE'), and snapped to match B12. Values converted to integer

[a] The carbon map having the highest resolution.
[b] Official carbon map outside of the Amazon biome.
[c] From Chave *et al*. (2005), as previously applied for B12 (Baccini *et al.* 2012).

Land use/cover map

A recently produced 50 m LULC database compilation by Sparovek *et al*. (2015) was used for assessing how the carbon maps match the current LULC, and for constructing the new C map. This LULC map was produced using satellite-based land-cover datasets from various projects, for example, TerraClass (Almeida *et al*. 2016), PROBIO (MMA 2011), CANASAT (Rudorff *et al*. 2010), global map of forest cover change (Hansen *et al*. 2013), and datasets from local high-resolution mapping (see supplementary information to Sparovek *et al*. (2015) for further information).

Spatial and statistical comparisons between C maps

The following spatial and statistical comparisons were made between the different C maps. ESRI ArcGIS standard tools used for calculations are specified within quotation marks.

Median aboveground carbon content was calculated for cells classified as natural vegetation, pasture, and cropland, respectively (Table 3). Calculations were made using 'cell statistics as table', with O16 as mask to ensure a consistent processing extent. To indicate how the different C maps in general reflect current LULC, median values for pastures and cropland were compared with IPCC default values (IPCC 2006).

Histograms of the total area of natural vegetation, pasture and cropland, respectively, within specified intervals of C values, were produced for each C map (Figure 4). Calculations were made using a 'zonal histogram'.

Total AGC stock for natural vegetation in the Amazon biome was calculated for all maps (Table 3). Calculations were made using 'cell statistics as table'.

To identify differences in spatial distribution of AGC, C values in all maps were compared on a cell-by-cell basis. Each cell in each map was assigned a number (0–5) reflecting its carbon value in relation to the other maps (i.e. 0 = carbon value lower than in all other maps; 5 = carbon value higher than in all other maps).

Construction of a new nationwide C map

The comparisons between the C maps (as presented in the 'Results and discussion' section) confirmed that it is not possible to determine which map is most accurate, mainly due to the absence of sufficient validation data (Saatchi *et al.* 2015). However, they did yield indications that certain C maps show more accurate C values for certain kinds of land. These indications (points 1–3 below) were used as a basis for compiling a new C map intended to represent the current LULC well, with high accuracy and resolution (50 m), and a national coverage:

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Table 2 Data sources and methods used to compile the new carbon map, for each land use class in the LULC map

Aggregated land use class	*Land use class (code)*	*Data sources*	*Method*
Natural vegetation	Regeneration from pasture (4)	S07, S11, B12	Average
	Non-forest (8)	S07, S11, B12	Average
	Forest (15)	OO, O16, S07, S11, B12, N15	Average
	Secondary vegetation (16)	S07, S11, B12	Average
	Forest under cloud (17)	OO, O16, S07, S11, B12, N15	Average
	Cerrado (18)	OO, O16, S07, S11, B12, N15	Average
	Floodplain/sandbank (20)	OO, O16, S07, S11, B12, N15	Average
	Grassland (51)	OO, S11[a]	(1) calculate pixel average (2) downscale all pixel values so that the total average becomes 3.1 tC ha^{-1}[b]
Water	Water (14)	None	Set to zero
Urban	Three urban classes (10, 11, 12)	None	Set to zero
Pasture	Five pasture classes (1, 2, 3, 13, 50)	S07, S11, B12	(1) calculate pixel average (2) downscale all pixel values so that the total average becomes 3.1 tC ha^{-1}[b]
Cropland	Six agricultural classes (5, 19, 22, 23, 24, 25)	S07, S11, B12	(1) calculate pixel average (2) downscale all pixel values so that the total average becomes 4.7 tC ha^{-1}[c]
Other	Cloud (9)	OO, O16, S07, S11, B12, N15	Average

[a] None of the other maps cover any cells classified as grassland in the LULC map.
[b] IPCC default value for tropical grassland.
[c] IPCC default value for tropical cropland.

Table 3 Median AGC content in cells classified as natural vegetation, pasture, and cropland, respectively, and total AGC stock in natural vegetation in the Amazon biome, for the different carbon maps

	Median C value (t AGC/ha)						*Total C stock (Gt AGC)*
Carbon map[a]	*Natural vegetation*	*Std*[b]	*Pasture*	*Std*	*Cropland*	*Std*	*Natural vegetation*
O16	143	41	133	36	108	34	48.1
O10	156	43	147	36	140	33	54.6
S07	113	48	19	51	19	42	40.2
S11	118	36	37	44	31	39	40.0
B12	140	41	42	23	32	24	45.9
N15	147	40	140	30	128	30	48.3
COMP	132	33	6	4.8	10	7.3	43.9

[a] Maps are coded with one letter representing the first letter in the main author's family name (exception: O = 'official'), and two digits representing the publication year.
[b] Std = standard deviation.

1. All six maps can be considered accurate for natural vegetation that is largely untouched and has high C content.
2. Maps based on remote sensing data, that is, S07, S11 and B12, are better than the maps based on vegetation maps at distinguishing between land with (currently) low and high carbon content. They are therefore preferred for representing natural vegetation that has been degraded and/or fully/partly converted to agriculture or other anthropogenic uses.
3. Despite being preferred for managed land, the remote sensing maps generally overestimate carbon values for agricultural land. This has previously been shown and explained by Englund *et al.* (2015), who proposed how to correct for this by downscaling C values in cells classified as cropland, pasture and grassland so that the median values match corresponding IPCC default values.

Table 2 presents how the above information was used to compile the new C map (denoted 'COMP' in Table 3 and Figures 1 and 3–5). In summary, for most land cover types an average of different biomass maps was used, taking into consideration the advantages and disadvantages of each map for each vegetation type, as discussed above (and in 'Results and discussion'). For

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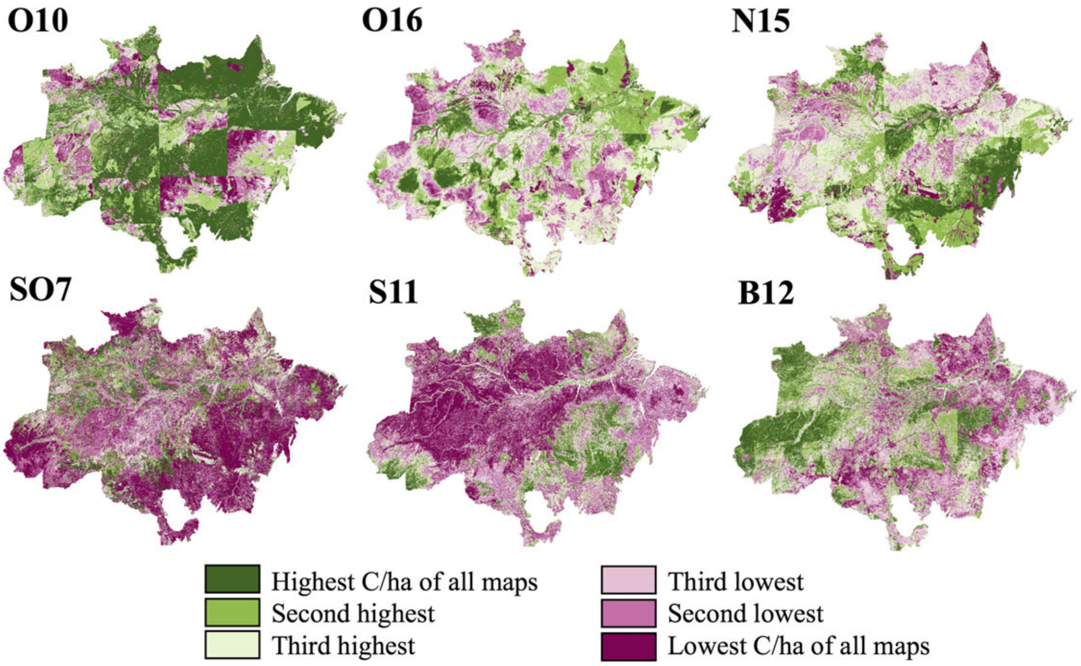

Figure 2 Illustration of where the different maps have high/low carbon values relative to the other maps

some land cover types the average value was also downscaled. The cell size was set to match the LULC map, 50 m.

Spatial indication of reliability

To spatially indicate the reliability of the new C map, the coefficient of variation of input values was calculated for each individual cell. This was done by dividing the cell-specific standard deviation of input values with the cell-specific mean value of input values (using 'cell statistics'). Note that input values differ between cells according to their LULC class (as described in Table 2). Note also that values prior to downscaling (on managed land) was used.

Comparison with reference data

An attempt was made to evaluate the new COMP map using an independent reference dataset of ground-based biomass estimates. For this purpose, the Pearson correlation coefficient was calculated for each input map and the resulting COMP map using the reference dataset from Avitabile *et al*. (2016).

Results and discussion

Comparison of carbon maps

There is a substantial variation between the different C maps, both in total aboveground carbon (Table 3) and its spatial distribution (Figures 1 and 2). O16 shows a lower total AGC stock than O10, that is, values are more similar to those in the alternative maps (S07, S11, B12, N15). While O10 has relatively higher values in most parts of the Amazon biome, O16 has relatively high carbon values in the northeast and scattered areas throughout the Amazon, primarily in the southwest, and relatively low carbon values in the southeast and most of the northwest. S07 and S11 have relatively low values overall, although S07 has relatively high values in parts of the northwest and S11 has relatively high values in limited parts of the southeast, southwest and north. B12 shows relatively high values in the west and in central parts of the State of Pará, and relatively low values in the northeast and south. Finally, N15 has relatively high values in the southeast and centre, and relatively low values in most parts of the west and northeast.

There are large variations in how the maps match the land use/cover (LULC) (Figures 3 and 4, Table 3). Agricultural land has in general significantly lower carbon content than natural vegetation. However, in O10, O16 and N15, large areas of agricultural land have carbon contents up to about 150 tC ha^{-1} (Figure 4, cf. Table 3). All maps show much higher median carbon values than IPCC default values for tropical grasslands (pastures) and cropland (3.1 and 4.7 tC ha^{-1}, respectively). For N15 this is logical since it was made to show 'premodern' vegetation (before the 1970s), and much of this vegetation has since degraded and/or been converted to agriculture. For O10 and O16, the deviation is due to the use of vegetation maps that include information about the *type* of vegetation but not its *status*, that is, whether it is intact or has been degraded or converted since the vegetation map was created.

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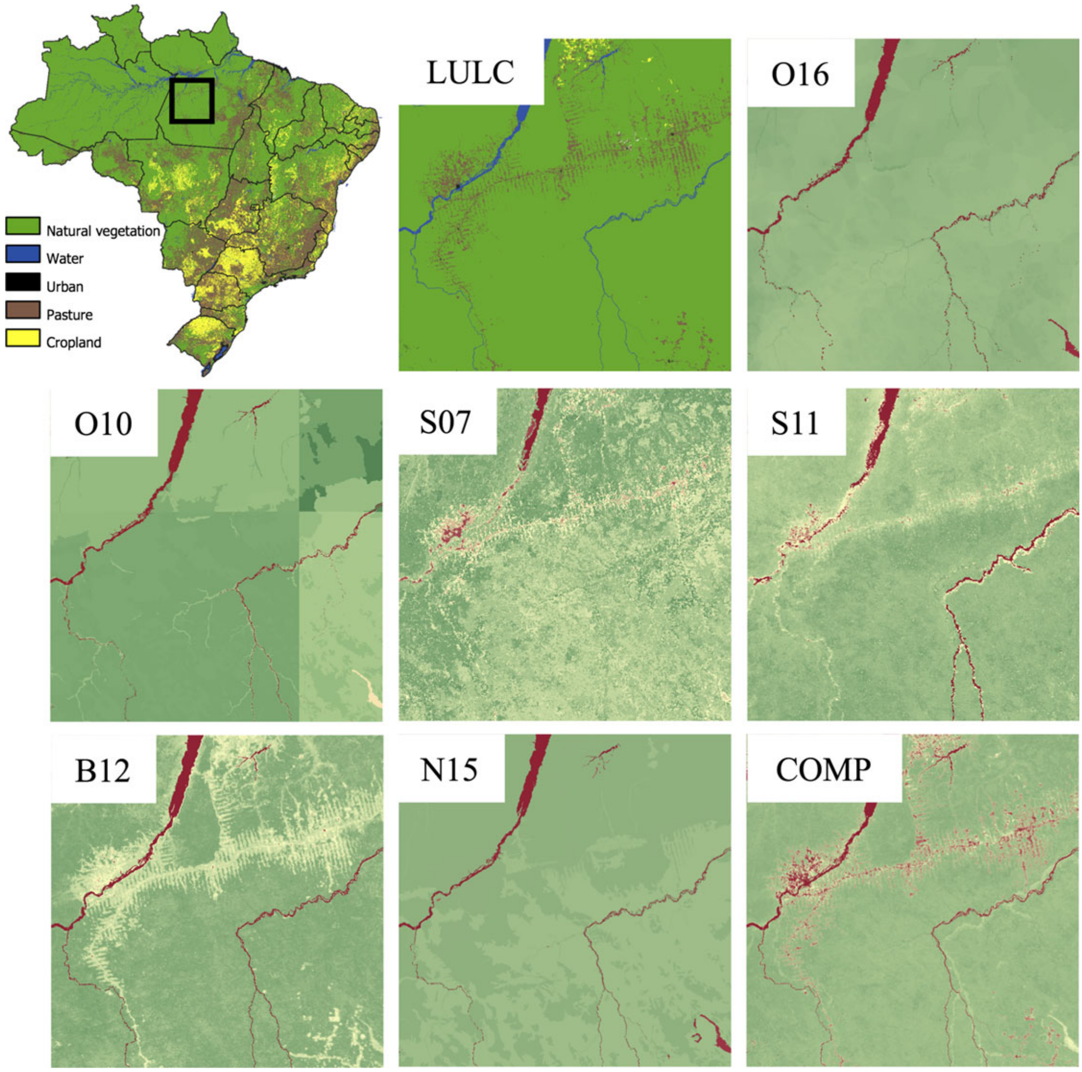

Figure 3 LULC and carbon values (legend identical as in Figures 1, 5) for the different carbon maps in an example region south of Santarém in eastern Pará

On the one hand, this facilitates estimations of carbon emissions from historic LUC, which cannot be done with maps based on more recent remote sensing data. On the other hand, it grossly overestimates the current carbon stocks, meaning that these maps must be corrected for current LULC in order to be useful in studies of current or future land use and LUC outside of existing forests. Maps that are based on remote sensing data, that is, S07, S11 and B12, match the current LULC better, but still seem to overestimate carbon values for agricultural land (Table 3, Figure 4). For B12, primarily due to the main objective of quantifying carbon in forests. Empirical measurements and appropriate methods for quantifying carbon in areas with low carbon content were for this reason lacking (Englund *et al.* 2015). The same can be assumed for S11 and S07. However, it is clear that the remote sensing maps in general can distinguish between land with low and high carbon content (Figures 3 and 4). For S11 and B12, this can probably be explained primarily by the use of LIDAR data that estimate vegetation height. This means that – even though S07, S11 and B12 match the current LULC much better than O16 and N15 – the remote sensing maps also need to be corrected to be useful in studies of current or future LULC outside of existing forests.

Comparing carbon maps outside the Amazon biome

It is more difficult to compare carbon maps for the other biomes in Brazil. N15 covers the socio-geographic region

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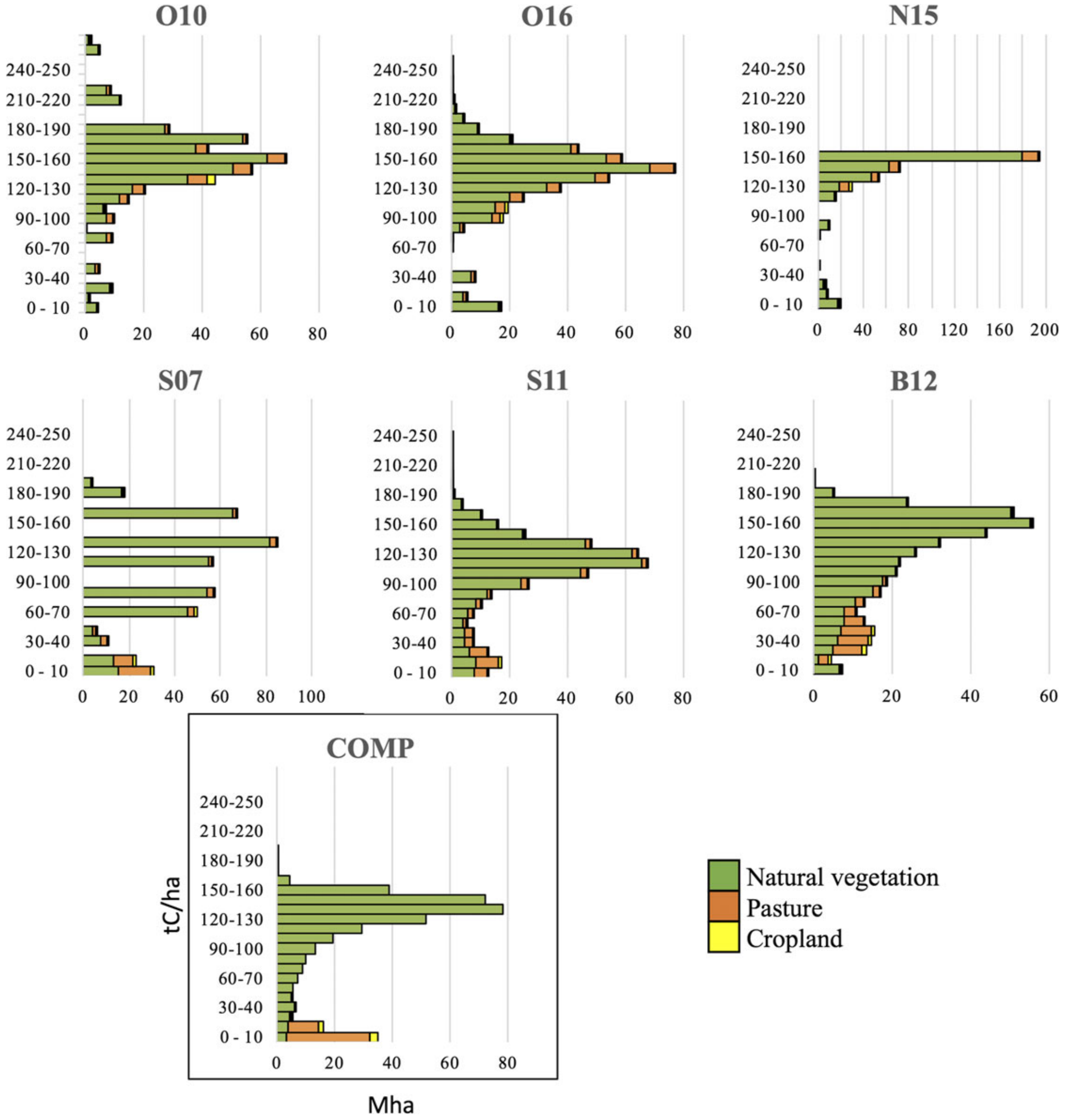

Figure 4 Histograms showing the total land area with different AGC levels in the Amazon biome for natural vegetation, pasture and cropland, respectively, for the different carbon maps. Note that the scale of the horizontal axis varies, but the vertical gridlines represent identical intervals

Legal Amazon, S07 extends as far south as covering most of the State of Minas Gerais, and B12 extends further south covering most of the State of São Paulo. Only the official carbon maps (O10 and O16, in combination with OO) and S11 cover the entire country (Figure 1). The official maps, however, only use biomass data from the literature in areas outside the Amazon (i.e. no biomass data from the RADAMBRASIL project). Furthermore, calibration plots in Brazil for S11 and B12 are all located in the Amazon biome, probably causing a reduced accuracy in other biomes. It can therefore be assumed that carbon values are overall less accurate outside of the Amazon biome. It is logical that the focus is on the Amazon biome, but carbon-rich vegetation exists in other biomes as well, such as Cerrado and the Atlantic rainforest. A lack of reliable carbon maps may affect the quality of scientific studies, and thus the information on which policy decisions are based.

How to use the different carbon maps

When selecting an existing C map, it is important to understand strengths and weaknesses of different maps. O16 is a clear improvement on O10 (which is now obsolete) and may be a good option for studies on

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carbon emissions associated with historic LUC. Another option is N15, which is based on the same data as O16 but processed differently. Maps that are based on remote sensing are less useful for this purpose since they reflect the LULC at the time of remote sensing data collection, which may be more recent than the LUC of interest. One advantage of using the official map (O16) is that results can be more relevant to policy-makers and in line with the UNFCCC communication. For studies of current or future conditions, S07, S11 and B12 should be more useful than O16 and N15 – at least in their original form – since they represent the current LULC better, including areas where natural vegetation has been degraded and/or partly converted to agriculture or other uses. However, they still overestimate carbon values where the carbon content is low.

Thus, all maps can be useful where land has high carbon values while no map in its original form is suitable where land has low carbon values. Therefore, it may not be a matter of choosing one specific map for studying current or future conditions, but rather a matter of combining maps and adjusting them to represent the current LULC sufficiently well, as demonstrated below (Figure 5).

Introducing a new nationwide aboveground carbon map

A new high-resolution (50 m) AGC map with national coverage was compiled from available carbon maps and a detailed LULC map. This map (denoted 'COMP' in Table 3 and in Figures 1 and 3–5) has a total AGC stock of 43.9 Gt C for natural vegetation in the Amazon biome, which is higher than S07 and S11, but lower than B12, N15 and O16 (Table 3). It reflects the current LULC well, and does not generally overestimate carbon values for agricultural land (Figures 3 and 4) (the COMP map is available for download at https://doi.org/10.5879/ecds/2017-09-12.1/1).

The reliability of the new map (i.e. the consistency of the maps used to compile it) is indicated to be higher in the north-west and the south, and lower in the central and eastern parts (Figure 5, right). The comparison with reference data showed a higher correlation for the COMP map ($r = 0.59$) than for any of the input maps ($0.28 \leq r \leq 0.56$).

The COMP map can be a useful alternative for scientific studies and policy initiatives concerned with existing land use and LUC outside of existing forests, especially when high resolution is necessary, and/or outside the Amazon biome. For example, it may be an alternative for (1) implementing local (farm-level) policies and actions relevant for Brazilian Nationally Determined Contributions (NDCs) – for example, PLANVEG, the 12 Mha forest restoration initiative, and Plano ABC (Low Carbon Agriculture), reduction of carbon emissions by pasture restoration and other technological improvements; (2) implementing offsetting rules for native vegetation toward areas with higher carbon content, currently under implementation at the State level for the new Forest Act; (3) supporting the Amazonian land titling initiative 'Terra Legal' in deciding whether or not to assign private titles to 89

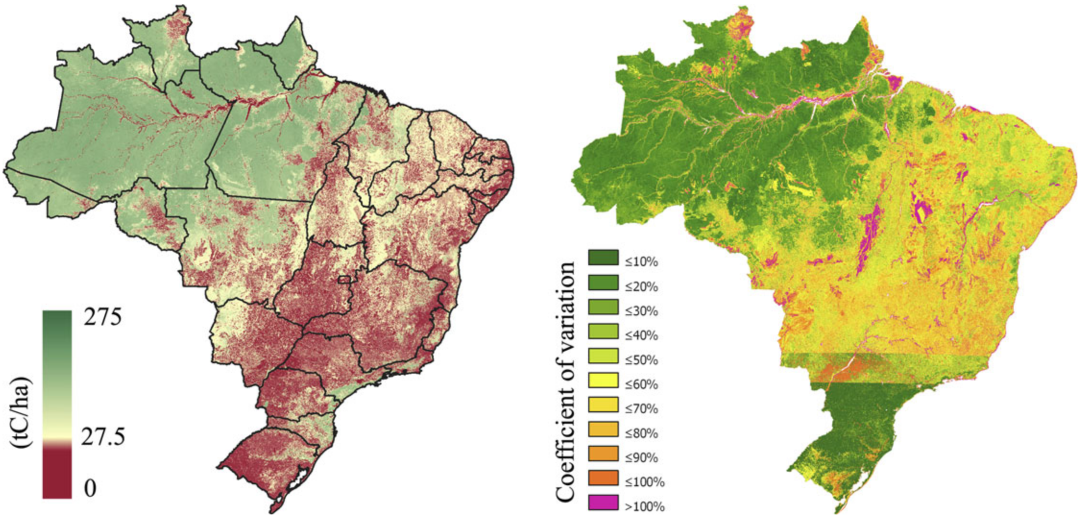

Figure 5 Left: 'COMP', the new national AGC map with 50 m resolution, compiled from a combination of existing carbon maps and corrected for current LULC. Note that the maximum carbon value in the map is 200, but 275 was used as the maximum value for the stretched colour band in order to make the colours in the map exactly comparable to the maps in Figure 3. Right: cell-specific coefficient of variance (CoV) as an indicator of reliability: low CoV (green) indicates higher reliability and high CoV (purple, via yellow) indicates lower reliability

Mha of Amazonian public land (Sparovek *et al.* 2015); (4) allowing the deforestation monitoring systems in the Amazon (PRODES) to assign carbon values on small-scale deforestation plots; and (5) providing the Brazilian licensing framework for legal deforestation with initial carbon emissions at farm scale, to be verified with more precise local assessments. In addition to these practical applications, this new map may be useful in studies connecting local scales to larger scales and perspectives on LUC-related issues, for example, climate change, biodiversity loss, water scarcity and food security.

Methodological comments and implications

AGC was used for all comparisons, but what the different maps include in AGC is not entirely clear. For example, N15 includes litter and deadwood in AGC, while O16 specifies such carbon pools as additional to AGC. Due to lack of information on what is included as AGC in all maps, it was not possible to adjust the maps so that their AGC values were perfectly comparable. Therefore, we used the available maps with no modifications besides what is specified in Table 1.

The approach used for managed land – that is, to downscale carbon values in individual cells so that the total average value equals IPCC default values – will not introduce any bias if all cells have equally overestimated carbon values and if the relative difference between cells reflects reality. The advantage of this approach is that the spatial variability is maintained while the average values are set at a predefined and realistic level. The disadvantage is that the validity of the assumption can be disputed, since the methodologies behind these maps are not optimised for low-carbon land cover (spatial variability is not very useful if it does not reflect reality). However, since the remote sensing maps S11 and B12 use vegetation height LIDAR data to estimate carbon stock, the relative differences between cells should be largely accurate.

The reference dataset used to calculate correlation coefficient (Avitabile *et al*. 2016) was independent from all input maps. But as the dataset does not constitute a sufficient statistical sample, the results can only be considered indicative. As pointed out by Saatchi *et al.* (2015), there is no sufficient statistical sample of biomass measurements available for Brazil, even if all known datasets are combined. There are also other challenges when comparing carbon maps with ground estimates (as well as using ground estimates to produce carbon maps) such as uncertainties associated with the use of different allometric estimates of biomass (each with an error of 10–20%); coordinates of sample plots (e.g. the coordinates of biomass samples in the Mitchard *et al*. (2014) dataset have an uncertainty of 10–50 km); and temporal variations that can be significant, even within datasets (can biomass estimates from the 1980s be considered representative of current conditions?) (Saatchi *et al*. 2015).

Using the average of multiple maps with no further modification (as done for natural vegetation) means assuming that all maps are equally (in)accurate. Any given map may be more accurate for individual cells and it is consequently not certain that the approach enhances the accuracy for all cells. However, in the absence of sufficient validation data, it is difficult to determine which map is most accurate overall – or even in a representative set of the cells. Further, even if there was an analytical way of determining which map is most accurate overall, all maps are likely less accurate than other maps for some areas. Using average values should smoothen out major discrepancies and provide acceptably accurate carbon values for all cells.

The resolution for the COMP map was set to 50 m to match the LULC map. To set output resolution based on the finest input data is normal practice in GIS analysis, since it preserves the quality of all input datasets. It also results in the most accurate match possible with the current land use, which was considered an important feature for the output map. Furthermore, it smoothens shifts in C values, which in maps with coarse resolution can be unrealistically large from one cell to another. However, it should be noted that the use of higher output resolution than most input datasets may give readers who are unfamiliar with GIS analysis an impression of an overall higher precision and accuracy than what is achieved in reality.

To use the coefficient of variation as an indicator for the reliability of the new map can be disputed, since there is no guarantee that high agreement means high reliability. However, the input maps are produced using different methods and input data, and present highly differing biomass distributions. Systematic bias is therefore unlikely. High agreement between input maps in certain areas should therefore indicate that the C values in the output map are more reliable than in other areas where the input variability is large.

In cells classified as agricultural land or grassland, the coefficient of variation was calculated prior to downscaling. This implicitly assumes that the uncertainty is determined solely by the number of maps; and the variation between them. Therefore, it does not capture any potentially additional uncertainty introduced by the method of downscaling values for managed land.

It can be argued that the integrated pan-tropical biomass map by Avitabile *et al*. (2016), which is based on S11 and B12, should have been included here in addition to – or instead of – the maps on which it is based. By comparison, this map has a total AGC stock of 42.8 Gt C for natural vegetation in the Amazon biome, which is more similar to COMP (43.9 Gt) than any of the input

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maps (see Table 3). On agricultural land – similar to the remote sensing maps – it shows significantly lower (albeit overestimated) carbon values for pastures (median 32 tC ha^{-1}) and cropland (25 tC ha^{-1}) than for natural vegetation (median 120, cf. 132 for COMP).

Conclusions

When selecting an existing C map, it is important to understand which map to use and what limitations it has. The new official C map (O16) is a clear improvement compared with the former C map (O10), which is now obsolete. However, it does not match the current LULC sufficiently well to be useful for studies concerned with current land use and LUC outside of existing forests. N15 is based on the same data as O16 and is therefore also impracticable for such studies. Unaltered, these maps are best for studies concerned with historic land use changes or existing forests. The remote sensing maps match the current LULC much better, although still not sufficiently well to be useful in all studies. They can identify land with low C values, but they tend to overestimate the C values at the lower end, that is, on agricultural land. They should be better than N15 and O16 in estimating C values for degraded forests, since N15 and O16 are only based on the type of vegetation and not its current status. The remote sensing maps are also impractical in studies concerned with historic LUC, since the remote sensing data are too recent.

The new 50 m national C map presented in this article (Figure 5) can provide a useful alternative for scientific studies and policy initiatives concerned with existing land use and LUC outside of existing forests, especially when a high resolution is necessary, and/or outside the Amazon biome.

Most countries do not have the same abundance of C maps as Brazil. In these countries, the global remote sensing maps (S11 and B12) can be important as a basis for creating national maps to be used, for example, for national reporting to the UNFCCC. It is important though that such maps are thoroughly evaluated using, for instance, ground truthing.

New initiatives and technology based on remote sensing can enhance the mapping of biomass and carbon in vegetation, in Brazil and elsewhere. For example, the BIOMASS mission to be launched in 2021 by the European Space Agency will employ a P-band-frequency radar system to generate a high-resolution global map of forest biomass (200 m), forest height (200 m) and deforestation detection (50 m) every six months (Le Toan *et al.* 2011). Similarly, NASA's GEDI (Global Ecosystem Dynamics Investigation) mission, planned to commence in 2019, will estimate AGB globally at a resolution of 500 m (Dubayah *et al.* 2014). In parallel, scientists continuously demonstrate novel applications of remotely sensed data, providing additional methods for estimating biomass in vegetation (Liu *et al.* 2013; Konings *et al.* 2016).

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