Carbon biophysical parameters applied to the Brazilian Cerrado

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Focusing on the biophysical aspect of carbon sequestration, this document outlines how the carbon sequestration/storage parameters were derived.[1] For the modeling approach, please refer to the carbon valuation documentation provided on The Nature Conservancy (TNC) website provided above.

Biophysical parameters[2]

Different approaches exist for quantifying the amount of carbon sequestered by vegetation for different land cover/land use (LULC) types. For example, the InVEST Terrestrial Carbon Storage and Sequestration model estimates the net carbon amounts in a pixel of a specific LULC type as the sum of the carbon in four pools: aboveground biomass, belowground biomass, soil, and dead organic matter (InVEST v2.5.6).[3] A fifth pool can be added for harvested wood products such as firewood or charcoal. The amounts of carbon in each pool are determined through estimates of the amount of carbon in each of the LULC classes. Bateman et al (2013) quantified changes in the above- and belowground biomass and soil organic carbon stocks across Great Britain, using national-level estimates from the European Soil Database of the carbon stored in peat and non-peat lands. They calculated a spatially homogeneous estimate for the carbon stocks in aboveground forest biomass, using previous estimates from the literature. In order to reflect differences in the management practices and nutrient cycling, they applied a unique adjustment factor for each LULC/soil combination. Still other studies focus only on the carbon sequestration by aboveground biomass as changes in the belowground biomass may be too difficult to estimate reliably at a larger spatial scale, and may be small relative to changes in the aboveground biomass (Naidoo & Ricketts, 2006; Naidoo et al, 2009).

All of the studies above assume full steady state carbon stock levels in the biomass, which remains constant within LULC types; they do not model growth and are therefore not appropriate for transitional assessments. A few studies have attempted to model changes in carbon stocks as

[1] Here we use carbon storage and sequestration interchangeably to refer to the ecosystem services associated with removing carbon from the atmosphere.
[2] In our analyses we focus exclusively on carbon sequestration and do not consider other greenhouse gas emissions (e.g. NO_x), which may be affected by land conversion and transitions away from livestock grazing.
[3] The carbon pools are defined as: Aboveground biomass pertains to the carbon stored in *living* plant foliage and branches; belowground biomass is the carbon stored in underground *living* roots of plants; soil carbon is the organic component of the soil; the dead organic matter includes the carbon in litter and lying/standing dead wood. Values of the carbon in each pool are required. The InVEST manual is available here: http://ncp-dev.stanford.edu/~dataportal/invest-releases/documentation/current_release/carbonstorage.html#carbon-3-0-beta. Accessed on Oct 14, 2013.

a function of time using different growth functions (e.g. Cacho et al, 2003; Silver et al, 2000). While these models account for the transitional dynamics of forest systems, they require multiple growth parameters that vary significantly depending on tree species and ecosystems. These parameters necessitate on-the-ground measurements and are commonly not known for many systems without fieldwork.[4]

For our analysis, we focus on above- and belowground biomass and soil carbon. We excluded the carbon stored in dead organic matter and harvested wood products because 1) these are small relative to the other three pools (above- and belowground biomass and soil) and 2) secondary data on the amount of carbon in these pools are not readily available. We assume full steady state carbon stock levels and do not model transitional carbon stocks. While previous studies have attempted to quantify the amount of carbon stored in biomass per unit area as a function of tree diameter (DBH), tree height and number of stems (see Torres & Lovett, 2012), we used secondary data from previous studies for the carbon sequestration of each LULC type within our study area (Table 1). In this way, we circumvent the need to select the most appropriate allometric equation for which to model biomass based on tree characteristics and the need to rescale the estimate at the stand level (see Torres & Lovett, 2012 for a review of the approaches and difficulties associated with selecting the appropriate function form and scale parameters).

While previous studies have suggested that soil organic carbon processes likely operate at much longer time scales than those for the aboveground biomass, and that there is often a lack of consistent field measurements of changes in the soil organic carbon in the Cerrado biome (Batlle-Bayer et al, 2010), we include soil organic carbon as it plays an important role for carbon sequestration in the region (Batlle-Bayer et al, 2010). We rely on previous studies that have estimated that soils contain between 37.9 and 81.9 tC/ha depending on the type of native Cerrado vegetation (Batlle-Bayer et al, 2010).[5] Because of the size of this carbon pool compared to the above- and belowground biomass, ignoring soil carbon would bias our results. For example, because of the wide ranges for carbon in the above- and belowground biomass for the Cerrado vegetation types, in some instances sugarcane may appear more beneficial in terms of carbon sequestration relative to the natural vegetation (Table 1). Such a result would seem counterintuitive and be inaccurate biophysically over the long-term.

We do not attempt to model transitional dynamics for human-modified cover types and assume mature crops accordingly. Even though sugarcane gets harvested at the end of the growing season, a new ratoon is assumed to be identical in terms of its carbon sequestration capabilities. For this reason, we treat the carbon stored by sugarcane as constant (see Bateman et al (2013) for a similar justification). We treat other row crops within our study area (e.g., rice, cassava, corn, sorghum and soybeans) separately from sugarcane.

Limitations and caveats

Soil types

The amount of carbon sequestered by each LULC class should depend on the soil type. Estimates of the soil organic carbon by soil type for each of the LULC categories in our study region, however, are not available. The literature reports a strong correlation between Cerrado biome

[4] These parameters are also not available for many of vegetation types in our study area.
[5] "tC/ha" stands for metric ton of carbon per hectare.

and latosols and ultisols (Batlle-Bayer et al, 2010); for this reason and because of the lack of additional data on carbon sequestration by soil *and* LULC type, the values in Table 1 for the natural vegetation are provided for latosols (oxisols), which are also dominant in our study area. For Eucalyptus, the current soil organic carbon ranges in Table 1 aggregates the values for the different soil types: Stape et al (2004) report values of 18-35 tC/ha for quartzipsamment, 32-44 tC/ha for latosols (oxisols) and 27-66tC/ha for ultisols (argisols). While data for the soil carbon for Eucalyptus for the remaining two soil types in our study area, cambisols (inceptisols) and gleissols (entisols), are not available, these soil types cover only a small portion of our study area (for a map of the soil types within our study area, please refer to the geospatial data documentation provided on TNC's website above). The estimates for sugarcane, other row crops and pasture also pertain to oxisols.

Management practices

Carbon is stored in plant biomass as well as in the soil. If living trees are harvested, the fate of the timber products determines the amount of carbon release: carbon can be stored for years in wood products, but released into the atmosphere as CO_2 within a few years if the wood is turned into paper or pulp.[6] In our analyses we account for only the amount of carbon storage by different land cover (vegetation) types without considering management practices like timber harvesting or grazing. We do not account for emissions due to differential management practices on fields (e.g., tillage) as well as the production of ethanol from sugarcane.

Edge effects

We ignore temporal considerations and threats of habitat loss from natural and anthropogenic factors and treat carbon storage as permanent under the assumption that natural vegetation licensed under the Forest Code benefits from protection status in perpetuity.[7] We also exclude any potential effects of disturbance (including edge effects) on carbon cycling as well as the distribution and amount of sequestered carbon (Nascimento & Laurance, 2004; Gower, 2003; Galdos et al, 2009).

Livestock

Even though livestock has often been identified as a significant factor driving carbon emissions, we exclude it from the carbon calculations (both grazing and the emissions from enteric fermentation and manure).[8] Thus, we are likely to overestimate the carbon sequestration in pastures. We do not consider livestock impacts because we do not have a clear prediction of how the livestock numbers for our study area may change with the shifts in agricultural practices. The displacement of livestock to areas outside our study region, which could occur in under the different land use planning scenarios, would not constitute a reduction in emissions.

Leakage

"Leakage", the displacement of deforestation in areas outside our study region, is also not modeled because of the lack of data. Previous studies that have examined the impacts of soybean

[6] Previous studies have suggested accounting for the number of years carbon needs to be stored in biomass, in order for the reduction in emissions to be considered a permanent one (e.g. Cacho et al, 2003).

[7] Specifically, we expect that if pasture were to be replaced with sugar cane fields that these fields would be put into production for at least the next 20 years. Similarly, if reforestation were to occur under compliance with Brazil's Forest Code, then this re-vegetation would be protected legally in perpetuity.

[8] For example, see Bateman et al (2013) for estimates of carbon emissions per head.

expansion in the state of Mato Gross (Brazil) between 2001 and 2010 found reduced deforestation, but no evidence of leakage within Mato Grosso or in the neighboring states (Macedo et al., 2012).[9] Other authors find that leakage is more likely at smaller scales (e.g., Murray et al, 2004).

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[9] See Murray et al (2004) for different models and empirical evidence of leakage from forest projects.

Tables

Table 1. Carbon sequestration by different land cover types based on estimates from the literature (in tC/ha).[10] We used a conversion factor of 0.5 to translate biomass into carbon (*sensu* Brown & Lugo, 1984; Naidoo et al., 2009). The majority of the soil organic carbon (SOC) estimates pertain to the topsoil layer (0-20 cm in depth). We chose this range for consistency purposes, as SOC estimates for some LULC were not available at greater depths. We use the measurements to the cerradao to proxy for carbon in the semi-deciduous and gallery forests.

Landcover/landuse	**Aboveground biomass (tC/ha) (1)**	**Belowground biomass (tC/ha) (2)**	**SOC[11] (tC/ha) (3)**	**Source[12]**
Natural landcover				
Cerrado (aggregate)	6.28-29	22.38-23.3	37.9-81.9	
Campo cerrado	6.28-19.53	23.3	44.5-81.9	(1) Bustamante & Ferreira, 2011 (2) Bustamante & Ferraira, 2011 (3) Batlle-Bayer et al, 2010
Cerrado sensu stricto	10.45-29.00	22.38	37.9-60.8	(1) Bustamante & Ferreira, 2011 (2) Paiva & Faria (2007) cited in Morais et al, 2013 (3) Batlle-Bayer et al, 2010
Cerradao	14.95-35.95	26.45	36.74-78.64	(1)Bustamante & Ferreira, 2011 (2) Bustamante & Ferreira, 2011 (3) Morais et al, 2013
Wetlands	25.92-81.41	16.13	234-276	(1) Morison et al, 2000[13] (2) Schroeder & Winjum, 1995[14] (3) Campos et al, 2012; Meirelles et al, 2006[15]; Shroeder & Winjum, 1995
Gallery forests	32.84	17.7-34	34-165[16]	(1) Delitti & Burger, 2000; (2) Houghton et al, 2001 (3)Delitti & Burger, 2000; Lardy

[10] Morais et al (2013) and Stape et al (2010) present allometric equations to convert tree measurements into carbon.
[11] The cerrado values refer to 20cm below ground. Previous studies have indicated that the soil carbon sequestered by the cerrado may reach 190-230tC/ha for depths up to 2 meters (Batlle-Bayer et al, 2010). However, the values for carbon stored at more than 20 cm below ground was available for only some of the cerrado types. Thus, the table presents conservative estimates for the cerrado. The values for Eucalyptus were measured up to 60cm in depth.
[12] The numbers refer to the columns. E.g. (1) lists the source for Column 1.
[13] Focusing on the Amazon, the study estimates the total stem biomass of *Echinochloa polystachya*, a type of wetland grass.
[14] The belowground biomass was estimated by dividing the total belowground carbon for wetlands by the total wetland area for Brazil.
[15] Campos et al (2012) report 552 tons of organic matter per hectare of peatland in Minas Gerais. We used 0.5 to convert to tons of carbon. Meirelles et al (2006) report values for flooded grasslands around Brasilia.
[16] The lower measurement pertains to 10cm of depth (Delitti & Burger, 2000). The upper bounds were measured up to 100 cm in depth (Delitti & Burger, 2000; Lardy et al, 2002).

				et al, 2002
Agriculture				
Sugarcane	14.9-17.3	14.27-14.44	27.86-37.66	(1) Our estimate[17] (2) Evensen et al (1997)[18] (3) Galdos et al (2009)[19]
Eucalyptus plantation	53.5-70.5[20]	11-14.5	18-66	(1) Stape et al, 2008 (2) Stape et al, 2004[21] (3) Stape et al, 2004[22]
Pastures	7.6	1.1	15-37.3	(1) Fujisaka et al, 1998[23] (2) Fujisaka et al, 1998 (3) Fujisaka et al, 1998[24] Silva et al, 2004[25]
Other row crops (trees)	8.73-61	4.3-12.9	22-35	(1) Hutchinson et al, 2007[26] (2) Schroth et al, 2002 Amazonia (3) Hutchinson et al, 2007; Bernardi et al, 2007
Other row crops (herbaceous)[27]	0.28-9.25	0.04-1.39	34.6-59	(1) Reijnders & Huijbregts, 2008[28]; Bolinger et al, 2006[29] (2) Salvagiotti et al, 2008[30] (3) Batlle-Bayer et al, 2010[31]

[17] We used the predicted sugarcane yield of 86-100 tons/ha for our study area. Previous studies report that only one third of the biomass is converted to ethanol (Buckleridge, 2012), with carbon taking up 52% of the mass.
[18] Study performed in Hawaii. All other estimates reported in the table are from Brazil.
[19] These refer to the soil carbon up to 20 cm in depth. The lower bound value is for burnt fields, whereas the upper bound-for unburnt sugarcane at 8 years of age.
[20] Measured at age 5 (mature growth).
[21] We converted the reported biomass for coarse roots using a conversion factor of 0.5.
[22] Measured at 0-60cm depth
[23] See Bolinger et al (2006) for estimates of the biomass for different types of pasture grasses
[24] The SOC values refer to the 0-20cm layer. For 0-40cm, the article reports a value of 19.6 tC/ha.
[25] The article reports different values depending on the type of grasses growing in the pastures. The data are for 0-20 cm depth on oxisols.
[26] These are for agroforestry systems. Hutchenson et al (2007) report values of 8.73-12.5 tC/ha for coffee (mean 11) and 27-61 tC/ha (mean 47) for peach palms in Brazil.
[27] The dominant herbaceous crops for our study area are soybeans, sorghum, rice, cassava and corn (IBGE 2013)
[28] Values for soybeans. The authors report an average difference of 16.7 tC/ha of aboveground carbon between cerrado and farm vegetation.
[29] The values from Bolinger et al (2006) refer to sorghum (*Sorghum bicolor*)
[30] Our calculations based on the article reporting that for well-irrigated soybean crops globally, the belowground biomass is about 15% of the aboveground biomass.
[31] Note that these refer to soil depths of 0-20 cm. The values vary according to soil type and management type (tillage vs. no tillage: no tillage tends to result in higher soil carbon compared to conventional tillage practices). Refer to Table 5 in the original article for more details

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