A baseline for soil carbon monitoring in Amazonia

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Abstract
Amazonian forests are important reservoirs of carbon both below and above ground. The status of such C reservoirs is changing, forests are becoming more productive and the net gain in vegetation structures is likely to enter the soil in short term. Nevertheless, the Amazon forest is predicted to suffer from periodic droughts in the near future. This has the potential to convert current C sinks to sources. An Amazonian baseline for detecting soil C changes is now being implemented to allow temporal monitoring of soils. Here we evaluate the feasibility of such an endeavour based on soil C variability in 67 one-hectare plots across Amazonia. We estimated the minimum detectible change (MDC) of background C after a standardized sampling effort as a selection tool for site inclusion into the baseline. Most sites allow precise monitoring of soil C changes with a relatively small number of samples. We estimate that only a 20% change in current background soil C concentrations are needed to allow detection of soil C changes in most of our sites. At an increasing soil C stock of 0.33 Mg C ha^{-1} yr^{-1} in Amazonia, this should allow accurate appraisal of soil C changes on decadal timescales.

Introduction
In the past few decades, Amazonian forests have been observed to be experiencing increasing rates of forest productivity and biomass turnover (Phillips *et al.* 1998; 2004; 2009; Baker *et al.* 2004). Such increment in forest productivity translates into increasing above ground forest biomass at an average rate of 1.22 ± 0.43 Mg/ha/yr (Baker *et al.* 2004). Much of this net increase in vegetation biomass is likely to enter the soils as necromass, thus potentially increasing soil carbon (C) stocks. Nevertheless, Amazonian forests are also subject of a changing environment and likely to become hotter and drier in the near future. Most climate change scenarios predict that severe droughts may become more frequent in the 21st century, particularly for southern Amazonia (i.e. Cox *et al.* 2008), with potential to revert both the net sink for atmosphere CO_2 and the capacity of soils to store C (Phillips *et al.* 2009). Although, it is possible that drought-associated increments in solar radiation could be associated with increasing rates of tropical forest productivity (Huete *et al.* 2006; Saleska *et al.* 2007), a recent study by Phillips *et al.* (2009) showed that severe droughts can reverse the last decades trend to increase biomass, converting forested Amazonia to a net source of C to the atmosphere. Therefore soil C storage is likely to be currently changing in Amazonia, and further dramatic changes in response to climate change might be expected in the near future. As changes in soil C stocks are dynamic and expected to occur at different rates across Amazonia, a network of permanent plots for soil C studies we perceived as needed to act as a definitive baseline for future comparisons. The RAINFOR network, with more than 130 permanent forest plots scattered across Amazonia, provides the needed infrastructure for such a baseline soil carbon network. These plots are inventoried each 4-5 years for above ground biomass and vegetation dynamics (Malhi *et al.* 2002), as well as being inventoried for soil chemical and physical properties (Quesada *et al.* 2009). In its next phase, the RAINFOR project is implementing the first basin wide, Pan Amazonian baseline for soil C monitoring. This paper outlines our goals and preliminary results acquired to date, evaluating the importance of local soil variability in influencing our ability to detect soil C changes in Amazonia.

Method
Study sites
The RAINFOR network has now more than 130 one hectare forest plots scattered across Amazonia. These sites include only pristine forests encompassing a large variety of vegetation forms and soil types common to Amazonia. In this paper we included soil C stocks for 67 sites, in six different South American countries, while another 38 are being processed at the laboratory. Our final goal is to perform soil C inventories in 130 sites, from which 60 will be sampled at high intensity to form a baseline for soil C in Amazonia.

Soil sampling
Two different sampling strategies are being used. At every site a relatively low intensity sampling is carried out for inventory purposes, usually collecting 5 soil cores plus one soil pit per hectare. At each sampling point, soil is retained in the following depths: 0-0.05, 0.05-0.10, 0.10-0.20, 0.20-0.30, 0.30-0.50, 0.50-1.00, 1.00-1.50 and 1.50-2.00 m using an undisturbed soil sampler (Eijkelkamp Agrisearch Equipment BV, Giesbeek, The Netherlands). For soil pits down to 2.0 m depth, soil and three bulk density samples are collected per sampling depth (as for the soil cores).
Once these samples had been analysed for soil C concentration, a subset of 60 study sites was selected to integrate the soil C monitoring baseline. This selection is based primarily on soil C variability, geographical distribution and logistical aspects of each site such as accessibility, site facilities, sampling costs, and level of protection for these areas.
For the baseline, a fixed number of 50 soil cores are being sampled per hectare plot, at the same depth interval as per soil cores (0 – 2.0 m), using a mechanised auger system.
As each forest plot shows specific conditions, the sampling strategy varies from one plot to another. Sites with a higher degree of spatial variability are sampled using random stratified sampling techniques while forests having high degree of homogeneity are sampled using systematic random sampling. No matter the sampling design, sample points are recorded in an X and Y diagram to allow future measurements to be made as closer as possible to the same sampling point used to estimate the baseline.

Soil Analysis
All samples are air dried and have roots, detritus, small rocks and particles over 2 mm removed. Soils are then milled to less than 50 µm and have their moisture correction factor and rock volume determined. Samples are then analysed using an automated elemental analyser (Pella 1990) model Vario Max CN (Elementar Instruments, Germany).
All analysis included in this study were made with 0 - 30 cm data only which is the soil layer more susceptible for changes. However, Fig. 1 shows soil C stocks to the depth of 2 m, to provide better representation of spatial variability of soil C stocks in Amazonia.

Results and discussion
Figure 1 show soil C stocks to 2 m depth derived from field data collected by the RAINFOR project (Quesada *et al.* 2009). Based on such soil C inventories, we calculated the minimum soil C change needed to allow detection with 0.95 power (2-sample t test, based in a sampling effort of 50 cores per ha, Figure 2a). Calculations were also done at power = 0.99 and usually differences between power 0.99 and 0.95 were below 1%, the exception being the sites with minimum detectible change (MDC) > 0.40 at power = 0.95. Differences in these specific sites ranged from 13 to 41%.

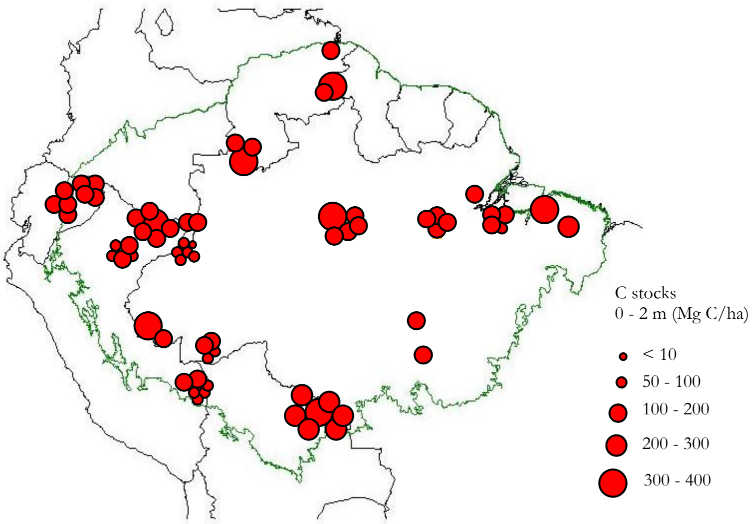

Figure 1. Soil C stocks for 67 sites across Amazonia

Most of our sites had low coefficient of variation for soil C which resulted in a generally low minimum detectible change at power = 0.95. About 45% of our sites had MDC below 0.25 of background C, and 67% were below 0.40. As there is an abundance of sites with low soil C variability in Amazonia, sites above 0.40 MDC, obtained with 50 cores per plot, can be discarded from baseline studies as there would be little gain in

increase the number of cores per plot. For example, doubling the sampling effort to 100 cores would change MDC of 0.45, 0.59 and 0.71 (at 0.95 power, 50 cores per plot) to 0.32, 0.41 and 0.50 respectively - still above the median MDC for all sites in this study (all sites median = 0.28).
We considered that MDC of 0.40 (at 0.95 power) would be the top limit for site inclusion into the baseline. This minimum change is low compared to results from Zhou *et al.* (2006), which reported an approximate 64% increase in background soil C in a 24 years interval in old-growth forests in China. Soil C concentrations changed from 14 mg g^{-1} to 24 mg g^{-1} during this interval at an average rate of increase *ca.* 0.4 mg g^{-1} yr^{-1}.

As for Amazonia, increasing rates of tree mortality and net biomass gain suggest that current soil C stocks should be now increasing. In addition to increments in net biomass gain, carbon inputs to the soil through higher rates of tree mortality should be increasing at about 0.03 Mg C ha^{-1} yr^{-1} (Phillips *et al.* 2004), and assuming this to be a more or less ongoing increase in soil C inputs (dM_i/dt) then the actual rate of increase is the soil carbon pool should be $\tau \circ dM_i/dt$ with a reasonable value for tropical forest soil τ as 10 years (Lloyd 1999). The rate of increase for soil C should thus be of order 0.3 Mg C ha^{-1} yr^{-1}.

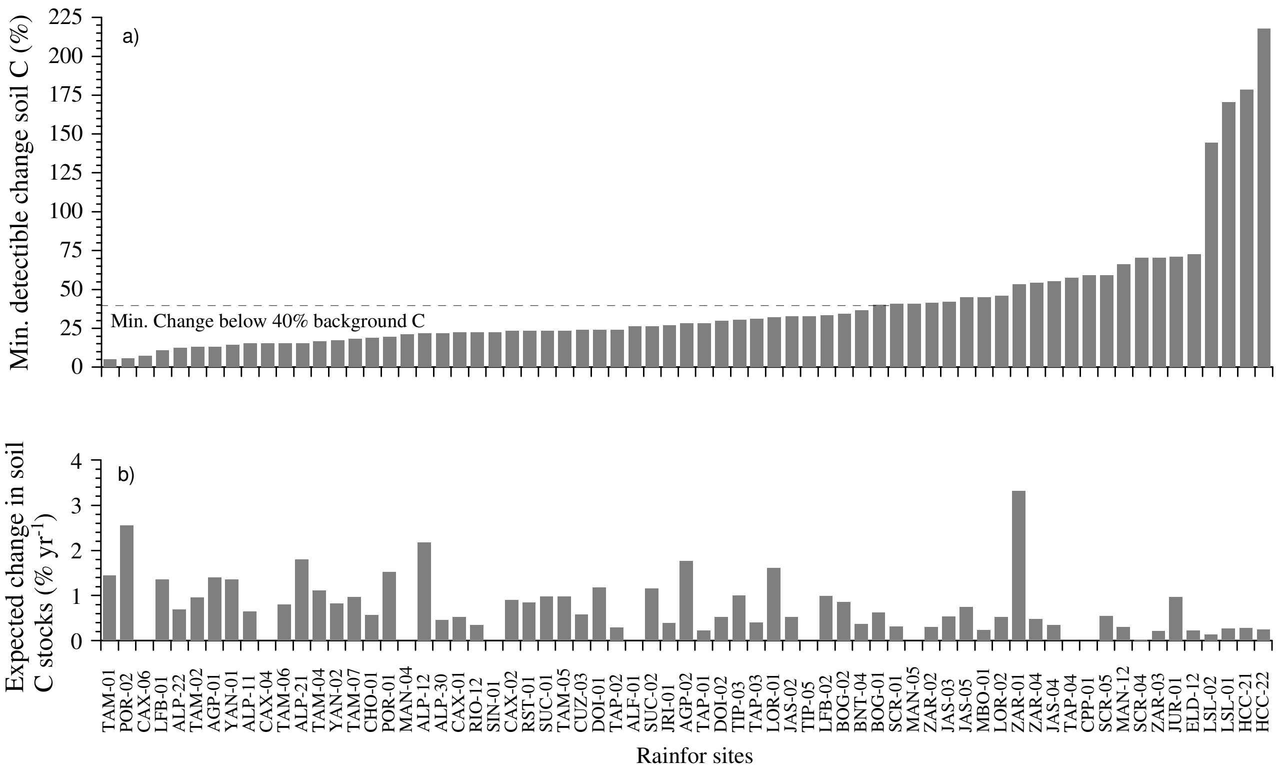

Figure 2. a) Minimum detectible changes in soil C at 0.95 power, based on 2-sample t test, 50 soil cores per hectare. b) Expected rate of change in soil C stocks, for each site in this study. Missing sites in 2b are due to lack of tree mortality rates to date.

The relative increase for soil C for our sites in Amazonia as a result of a stimulation of inputs from above increasing rates of above ground mortality was therefore calculated to be 0.008 of current soil C stocks per year (ranging from 0.0002 to 0.03 of background C stocks, Figure 2b), this disregarding any organic matter input from other vegetation structures except tree boles. Although organic matter input estimations made only with boles involves a time lag for necromass decomposition (which would probably decrease the average rate suggested here in the short term), our calculation ignores the production of lighter vegetation structures such as leaves and twigs which may also be having their productivity and turnover increased. This suggests that higher changes in soil C are likely to occur, possibly close to the values reported by Zhou *et al.* (2006), and imply in the possibility of detecting changes in background soil C in about 20 – 30 years with anticipated increases over 30 years averaging around 0.25 our estimate of current soil stocks . Also, not all sites with MDC 0.4 will be included in the baseline as there are other constraints for such intensive field sampling. A total of 29 sites from this study were selected to form the baseline, and other plots are being currently analysed. It resulted in an even lower MDC level for the baseline, averaging only 0.20 MDC at 0.95 power (0.23 at power 0.99).

Conclusion

Despite difficulties in working on such large and logistically difficult area, Amazonia stands out as an adequate site for soil C monitoring. Most sites allow precise monitoring of soil C changes with a relatively short number of samples. Estimated changes in soil C for the future and low soil C variability are likely to make monitoring of changes feasible in relatively short term (20 or 30 years).

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