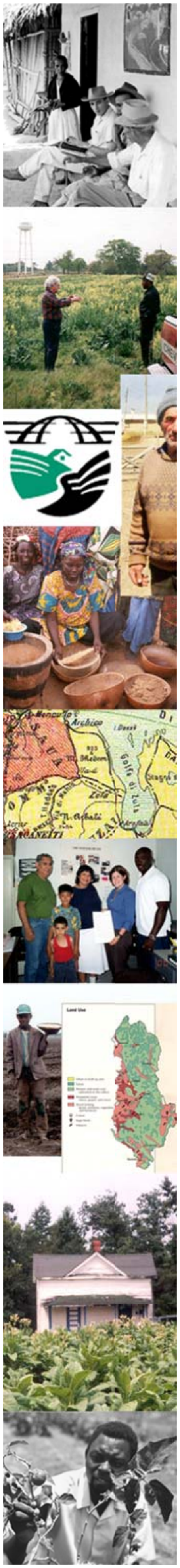

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Land Tenure Center

SOIL CARBON AND LAND-USE CHANGE IN THE TROPICS:

AN UPDATED META-ANALYSIS

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Soil carbon and land-use change in the tropics:

An updated meta-analysis

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Soil carbon, tropics, land-use change, carbon sequestration, meta-analysis

Abstract

Soil carbon stocks are a vital component of ecosystem services, particularly in the tropics. Recent attention has focused effects of land-use change in the tropics on soil carbon stocks to better understand how human activities have influenced the release of carbon from soils. We conducted an updated meta-analysis of data from 144 studies that measured soil carbon under different land uses across the tropics. Mean soil carbon stocks vary between dry (55 MgC/ha, <1000 mm MAP), moist (67 MgC/ha, 1000-2500 mm MAP), and wet (85 MgC/ha, >2500 mm MAP) climates with wet climates having the highest mean stocks for each land use. Overall, grasslands (60±4 MgC/ha) and cultivated sites (59±4 MgC/ha) have statistically significant lower soil carbon stocks than pastures (68±4 MgC/ha), which do not differ significantly from unconverted forests (80±3 MgC/ha) and secondary forests (84±2 MgC/ha). Using a regression tree analysis, we show that soil type and climate are the most influential factors in determining the fate of soil carbon during conversion from one land use to another. Hence, understanding a site's environment is crucial for predicting the loss or gain of soil carbon.

Our soil carbon meta-analysis revealed a number of challenges for comparing soil carbon stocks across studies. These include comparing soil carbon concentrations when differences in bulk density are unknown, variation in sampling depths and replication, and incomplete knowledge of site land use history. Addressing these challenges will enhance our understanding of rates of soil carbon sequestration and factors contributing to the fate of soil carbon.

Introduction

Researchers have come to recognize the importance of understanding soil carbon stocks and tropical land-use change. The release of soil carbon due to land use change is a major source of greenhouse gases contributing to global climate change (Houghton 2003; 2007). Globally, the long-term flux of carbon from changes in land use (1850-2000) released 156 Pg of carbon to the atmosphere, with approximately 60% of it coming from the tropics (Houghton 2003; 2007). Until recently, focus on the release of carbon due to changes in land use has emphasized the role of aboveground vegetation (Marín-Spiotta et al. 2008). This is primarily because it is easier to measure carbon in visible trees than in stocks belowground. However, globally, soils store up to three times more carbon than aboveground vegetation, and are thus vital to understanding the implications of tropical land-use change.

Meta-analyses provide valuable insights as they synthesize information on carbon stocks and land-use change. Past meta-analyses compared changes in soil carbon stocks in different regions with different land uses, including the conversion from agriculture to forest re-establishment and grassland (Post and Kwon 2000), conversion of forest to agriculture (Murty et al. 2002), and a variety of land-use changes between forest, pasture, cropland, and plantation (Guo and Gifford 2002). Some of the major findings from these studies are the conversion of forests to cropland results in a loss of 30-50% of soil carbon (Murty et al. 2002; Guo and Gifford 2002). The conversion of forest to pasture results in no significant loss of soil carbon (Murty et al. 2002), and in some cases soil carbon stocks tend to increase in areas of high precipitation (Guo and Gifford 2002). And, when forests re-establish following agricultural use, there is an overall increase in soil carbon in tropical and subtropical sites (Post and Kwon 2000). Since the publication of these meta-analyses, however, studies focused on reporting soil carbon have increased (Figure 1). In addition, our methods of measuring soil carbon have become more advanced. Thus, it is necessary for these meta-analyses to be updated, accounting for recent technological advances and an abundance of recent publications that report soil carbon stocks under changing land uses.

Materials and Methods

Data

We conducted a meta-analysis of 144 studies that reported carbon stocks under different land uses in the tropics. We restricted our analysis to include only those studies which had study sites within 23° latitude (Figure 2). We included studies that were published since the publication of previous meta-analyses and studies that were excluded from previous meta-analyses. We did include a handful of studies that were included in previous meta-analyses since we discovered this after we ran our statistical analyses. However, this small group of studies is consistently included in soil carbon meta-analyses since they represent foundational work in the field, and thus we kept them in ours (Veldkamp 1994; van Dam et al. 1997; Neill et al. 1997; Desjardins et al. 1994; Trumbore 1995; Bashkin and Binkley 1998; Brown and Lugo 1990). Our meta-analysis resulted in 898 distinct data points of carbon stocks under different land uses, including forest, secondary forest, pasture, plantation, grassland, and cultivated land.

In some instances, data on bulk density was missing. For these studies, we calculated bulk density (BD) using the Adams (1973) equation, which has also been used in previous meta-analyses (Post & Kwon 2000):

$$BD = 100 / (\%OM / 0.244) + ((100 - \%OM) / MBD)$$

where OM is organic matter and MBD is mineral bulk density. We used the commonly accepted value of 1.64 for MBD (Mann 1986; Post & Kwon 2000).

Studies that report soil carbon stocks vary in their research objectives, so there is not a standard depth by which soil carbon is measured and reported. Therefore, we had to standardize our results to a common depth so that we could compare results across different land uses, climates, and soil types. We standardized all data to a 30cm depth since the majority of studies reported soil carbon stocks for this depth. We standardized soil carbon stocks based on life zone (dry climate = < 1000 mm MAP; moist climate = 1000-2500 mm MAP; wet climate = > 2500 mm MAP). For studies that reported soil carbon for multiple depths, we chose the depth nearest to 30cm. If there were multiple depths equally distant to 30cm we chose the depth that was less than 30cm. For instance, if a study reported soil carbon for 20cm depth and 40cm, we chose 20cm and standardized that number to 30cm. Thus, each of the 898 study sites within the 144 studies was represented by a single soil carbon stock.

We eliminated extreme outliers from three of our studies, including Campos et al. (2007), Van Noordwijk et al. (1997), and Nepstad et al. (1994). These studies had 10 of the total 898 study sites, which we eliminated from our statistical analysis. The outliers were either high-elevation Histosols or studies that only reported soil carbon down to 1cm. In the case of studies that reported soil carbon in the top 1cm, when we used a multiplier to standardize these to 30cm the results were extremely high. In both cases, when we standardized the data to 30cm depth, these study sites showed order of magnitudes more soil carbon than any of the other studies (Figure 3).

Meta-Analysis

We analyzed our final data set in JMP 8.0 (means comparison) and R (regression tree). First, we calculated mean soil carbon stocks for each land use: forest, secondary forest, pasture, plantation, grassland, and cultivated land. We did a Tukey-Kramer means comparison test on the logtransformed data to determine which mean soil carbon stocks under different land uses were statistically significant. And, although our 144 studies are in the tropics, there are very different climate regimes within the tropics. We did an additional means comparison for specific climate regimes (dry climate = < 1000 mm/y; moist climate = 1000-2500 mm/y; wet climate = > 2500 mm/y).

Previous studies compare soil carbon stocks without regard to the number of years that the land has been under specific land uses (Milne et al. 2007; Guo and Gifford 2002). Therefore, we calculated annual mean rates of change for different land-use transitions. We went through the 144 studies and gathered data on the number of years each land use had been there, before and after land-use change. We also used the published studies to identify the logical land-use changes that were taking place. For instance, we do not want to use the data to look at transitions from agriculture to primary forest because this transition does not intuitively make sense. We identified the primary land uses that the authors were investigating and aggregated all of the same types of transitions (i.e. forest to pasture, agriculture to secondary forest, etc.) to calculate the annual mean rate of change for each logical land-use transition.

Finally, previous studies calculated means rates of change for land use transitions (Post and Kwon 2000) and found a tendency for rates of carbon accumulation to increase from temperate regions to sub-tropical regions. They inferred from this that major factors determining the rate of accumulation are rates of organic matter inputs which increase with temperature and moisture. Based on this idea, we did a univariate regression tree analysis in R to determine which factors predicted the fate of soil carbon. A regression tree analysis explains variation of a single response variable (soil carbon) by one or more explanatory variables (De’ath and Fabricius 2000; De’ath 2002). Our explanatory variables were land-use type, soil type, climate (based on precipitation), and number of years under a specific land use. The tree structure partitions the data set into mutually exclusive groups, each of which has similar values of the response variable. The tree is grown by repeated binary splitting of the data (De'ath 2002).

Results

We found that secondary forests have statistically significant higher soil carbon stocks compared to all other land uses except forests (Figure 4). Grasslands and cultivated sites have statistically significant lower soil carbon stocks than pastures, which do not differ significantly from unconverted forests and secondary forests.

Mean soil carbon stocks vary between dry (55 MgC/ha, <1000 mm MAP), moist (67 MgC/ha, 1000-2500 mm MAP), and wet (85 MgC/ha, >2500 mm MAP) climates with wet climates having the highest mean stocks for each land use.

Mean rates of change in soil carbon stocks varied with different land use transitions (Figure 5). Land-use change from forest to cultivation show the greatest mean annual decrease in soil carbon stocks (5 MgC/ha/year). In contrast, changes in land use from cultivation to secondary forest and from pasture to plantation show the greatest mean annual increase in soil carbon stocks (2.6 MgC/ha/year and 3 MgC/ha/year, respectively).

In our regression tree analysis, soil type and climate are the most influential factors in determining the fate of soil carbon during conversion from one land use to another. The primary predictor for the fate of soil carbon is soil type (Figure 6). Following this, the second most important predictor for the fate of soil carbon is precipitation. These variables and their interactions explain 46.6% of the variability in soil carbon. According to our regression tree, land use type is not a significant predictor of the fate of soil carbon.

Discussion

Our results for mean soil carbon stocks are somewhat consistent with previous meta-analyses (Post and Kwon 2000; Murty et al. 2002; Guo and Gifford 2002). Forests and secondary forests have a statistically significant difference in mean soil carbon stocks than cultivated land. We can gather from this that the conversion of forest or secondary forest to cultivated land results in a significant loss of soil carbon overall and annually (Figure 4 and Figure 5).

In previous meta-analyses, and individual soil carbon stock studies, the conversion of forest to pasture is one of the least understood land-use changes. In some instances there have been recognized increases in soil carbon following the conversion of forest to pasture (Neill 1997; Guo and Gifford 2002), and in some cases there have been recognized decreases (Lopez-Ulloa 2005; Trumbore 1995). However, we show that there is not a statistically significant difference between soil carbon stocks in forest compared to pasture (Figure 4). This is because many tropical pasture grasses have deep roots, which contribute to below ground carbon pools. And, pasture grasses continuously maintain a cover of vegetation on the soil, and the high productivity and turnover rates add organic matter to the soil, especially below ground.

Although our results show that there are statistically significant differences between soil carbon stocks under some land uses, our regression tree analysis shows that land use type is not a significant predictor of soil carbon stocks (Figure 6). This is not entirely surprising since many studies in recent years have emphasized the need for a better understanding of the physical properties and processes involved stabilizing soil carbon stocks (Lopez-Ulloa 2005; Post and Kwon 2000; Milne 2007). Soil type and climate play a large role in those physical processes since they directly control factors such as soil aggregation and the physical protection of soil carbon and indirectly control factors such as organic matter inputs and decomposability.

It is possible that the coarse resolution of our study (categorizing land use as forest, secondary forest, grassland, cultivated land, or pasture) was not enough to highlight distinctions among study sites. For instance, we only had one category for cultivated land, and thus, cultivated land could have meant rice paddies or maize. We also did not distinguish among management regimes. Although these are potential reasons why land use type does not come up as an important predictor for the fate of soil carbon, our method of categorizing was the only feasible way to approach this meta-analysis since it is on a global scale. Numerous studies have documented the importance of factors such as management regimes, but it is necessary to highlight patterns present at a global scale.

There are numerous difficulties that come with creating data sets that successfully highlight soil carbon stock patterns present at a global scale. These include comparing soil carbon concentrations when differences in bulk density are unknown, variation in sampling depths and replication, and incomplete knowledge of site land use history. Previous meta-analyses have attempted to partially address some of these issues. Our study successfully addresses all of these issues by calculating bulk density for sites where it is unknown, standardizing soil carbon stock measurements, and calculating annual mean rates of change for land-use changes. We recommend that future meta-analyses take similar steps to address these issues. In doing so, we enhance our understanding of rates of soil carbon sequestration and factors contributing to the fate of soil carbon.

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Figure 1: Trend in the number of soil carbon stock studies from 1990-2010

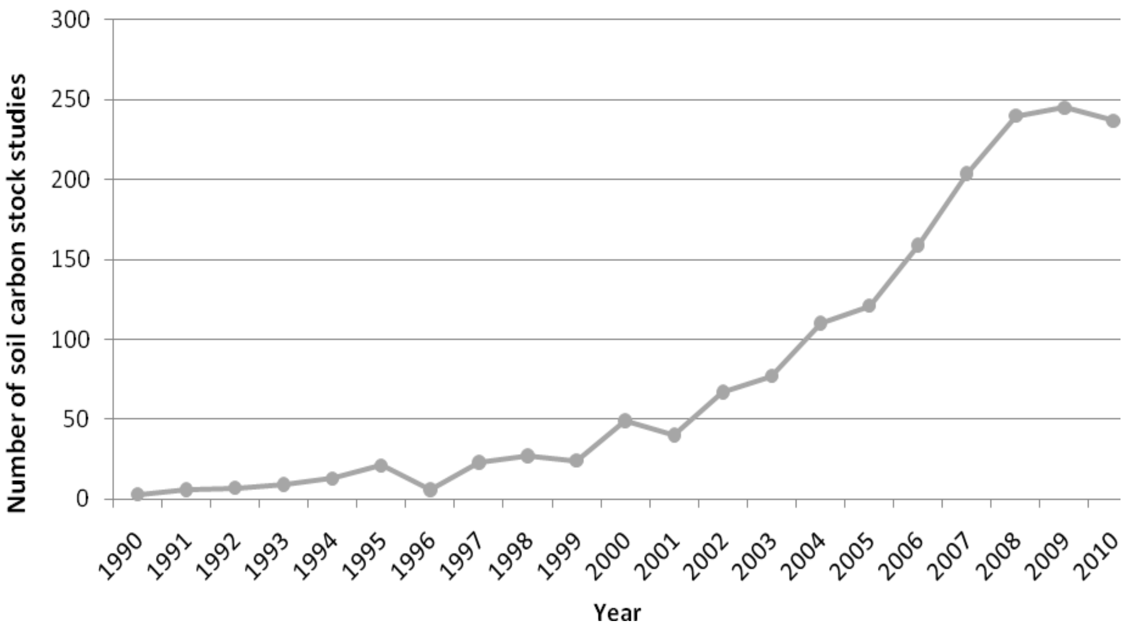

Figure 1: Study sites for the 144 studies we used in our meta-analysis

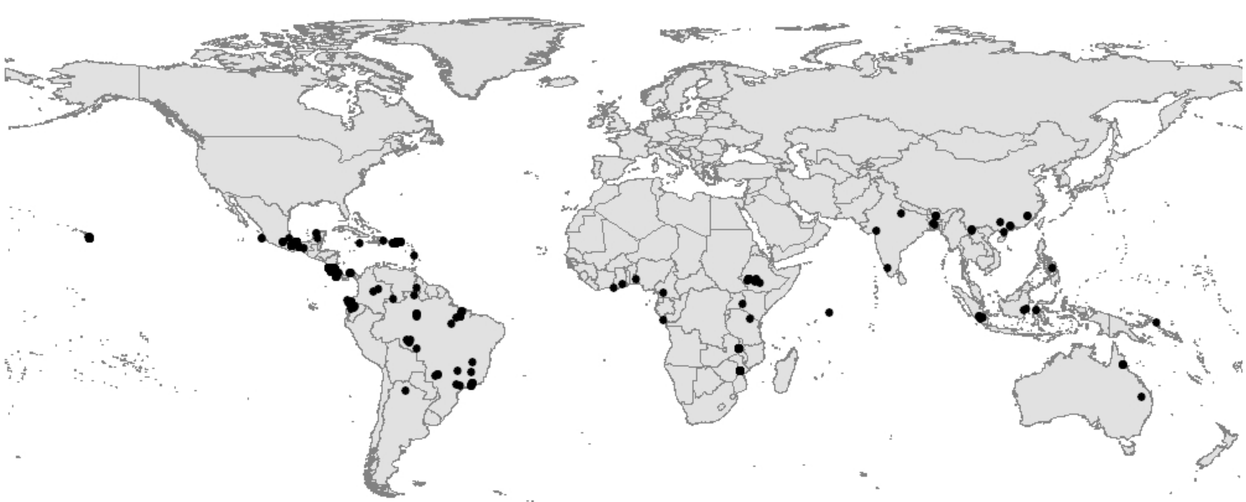

Figure 2: Outliers for soil carbon stock data set. Points represent outliers excluded from our study, and the bars represent mean soil carbon stocks when outliers are excluded

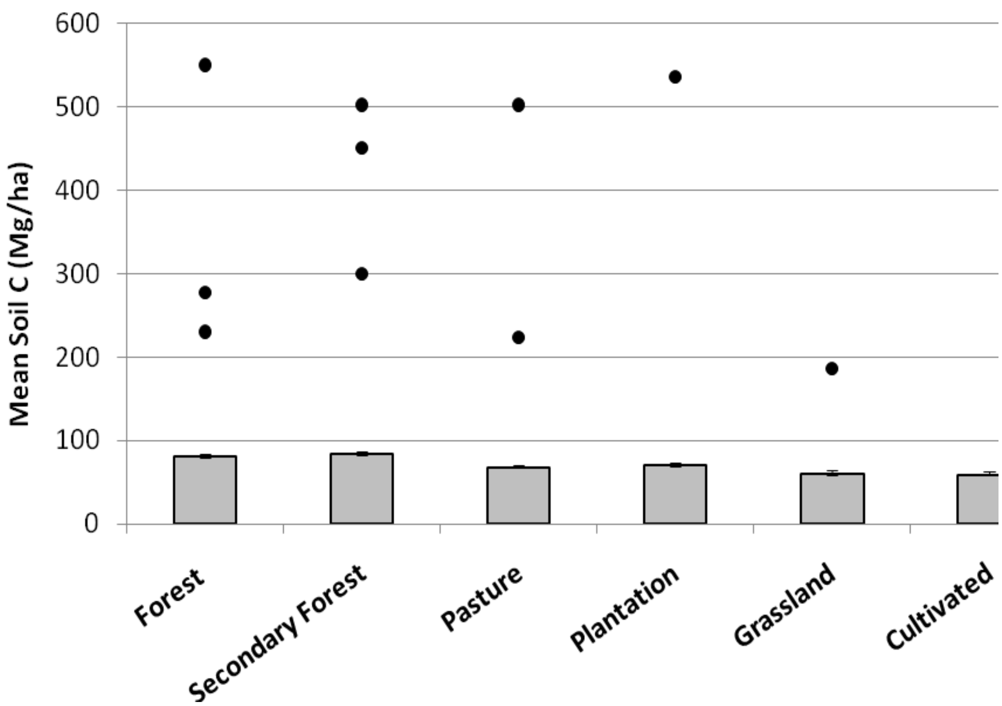

Figure 3: Mean soil carbon stocks for each land use. Letters above each bar indicate statistical significance

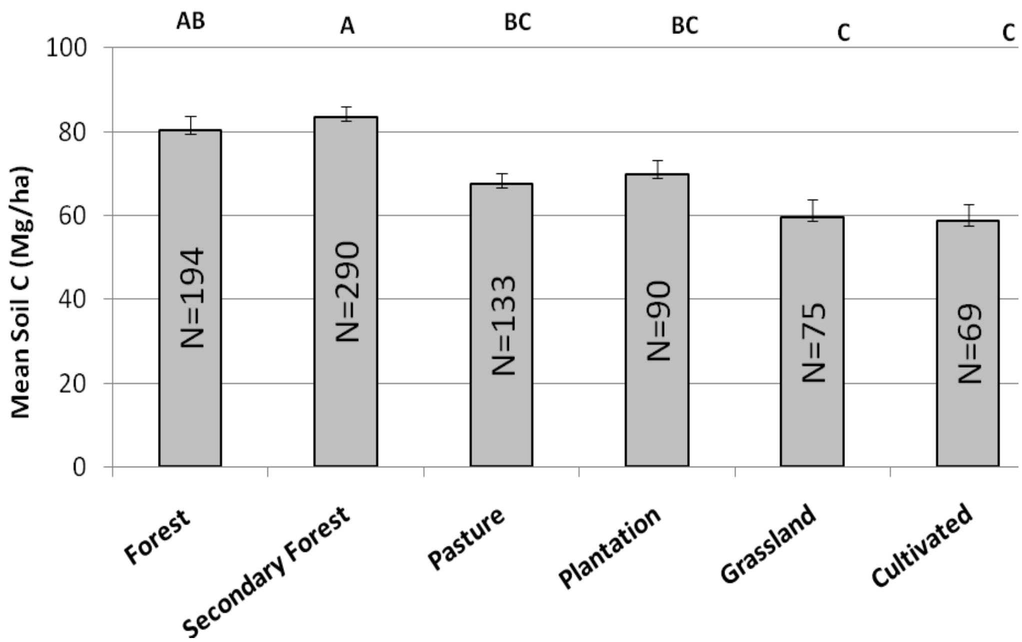

Figure 4: Annual mean rates of change in soil carbon stocks for land-use changes

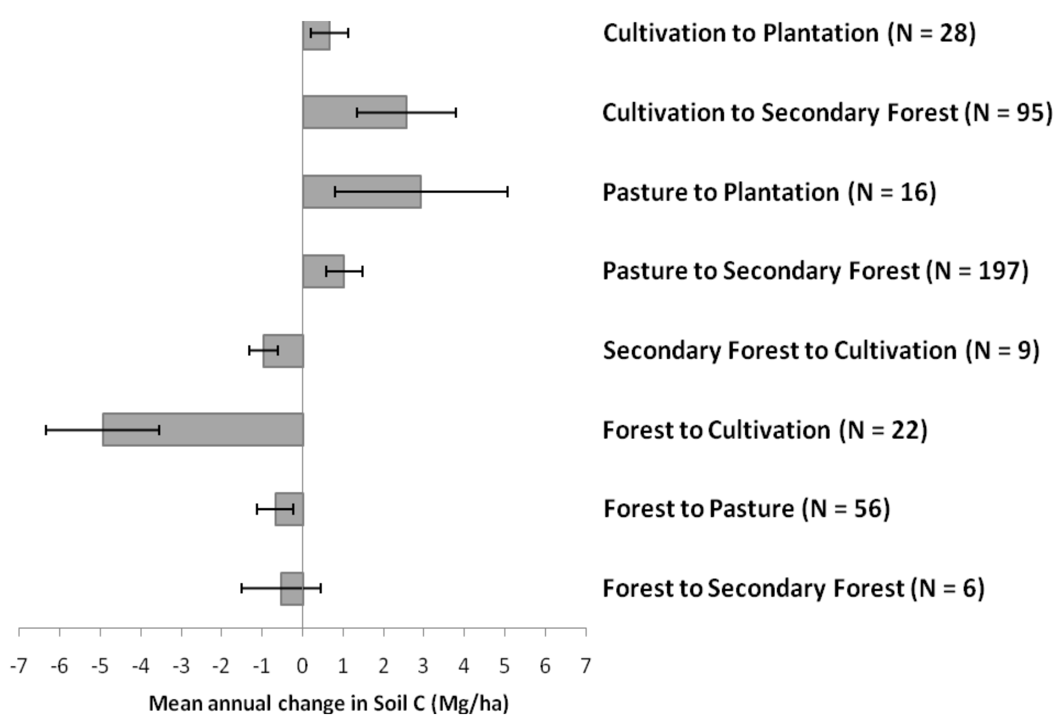

Figure 5: Regression tree showing the primary predictors of soil carbon stocks in the tropics.