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Geographic Bias of Field Observations of Soil Carbon Stocks with Tropical Land-Use Changes Precludes Spatial Extrapolation

Classification: BIOLOGICAL SCIENCES, Sustainability Science

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Abstract

Accurately quantifying changes in soil carbon (C) stocks with land-use change is important for estimating the anthropogenic fluxes of greenhouse gases to the atmosphere and for implementing policies such as REDD that provide financial incentives to reduce carbon dioxide fluxes from deforestation and land degradation. Despite hundreds of field studies and at least a dozen literature reviews, there is still considerable disagreement on the direction and magnitude of changes in soil carbon stocks with land-use change. We conducted a meta-analysis of studies that quantified changes in soil C stocks with land use in the tropics. Conversion from one land use to another caused significant increases or decreases in soil C stocks for 8 of the 14 transitions examined. For the three land-use transitions with sufficient observations, both the direction and magnitude of the change in soil C pools depended strongly on biophysical factors of mean annual precipitation and dominant soil clay mineralogy. When we compared the distribution of biophysical conditions of the field observations to the area-weighted distribution of those factors in the tropics as a whole or the tropical lands that have undergone conversion, we found that field observations are highly unrepresentative of most tropical landscapes. Because of this geographic bias we strongly caution against extrapolating average values of land-cover change effects on soil C stocks such as those generated through meta-analysis and literature reviews to regions that differ in biophysical conditions.

Introduction

Organic carbon stored in the world's soils is the largest terrestrial pool of carbon, and is at least three times larger than the pool of atmospheric carbon dioxide (1-3). It has long been recognized that land-cover change and management can alter the amount of organic carbon stored in the soil (4, 5), and this in turn affects both soil fertility and atmospheric carbon dioxide (CO_2) concentrations. While the contributions of land-cover change to anthropogenic CO_2 atmospheric emissions have recently been revised downward (6), the estimated current annual contribution of 1.2 Pg or about 12-15% of total anthropogenic fluxes is still significant. The terrestrial CO_2 flux includes emissions from both biomass and soils (7, 8). Continued improvements in remote sensing allow for ever-better estimates of both the areal extent of different land uses and aboveground biomass stocks (9) . In contrast, remote sensing is currently not a reliable option for measuring stocks of soil C. Despite hundreds of field studies and dozens of literature reviews, our understanding of the patterns and processes that determine responses of soil C stocks to land-cover change remains problematic. Indeed, the IPCC 2006 Guidelines for National Greenhouse Gas Inventories states, "the current knowledge remains inconclusive on both the magnitude and direction of C stock changes in mineral forest soils associated with forest type, management and other disturbances, and cannot support broad generalizations" (10).

We conducted a meta-analysis of field studies of land-use change effects on total soil organic carbon stocks to determine whether general patterns exist and if including biophysical factors reduces unexplained variation in observed responses. We focused on the tropics, as these latitudes account for the bulk of the current CO_2 emissions from land-cover change (11). We considered precipitation and clay mineralogy as the most important biophysical drivers, as precipitation strongly influences soil C stocks and residence time (1) and, within a precipitation regime, clay mineralogy is often the most important factor explaining differences in soil C stocks in tropical regions (12, 13). Here we show that mean annual precipitation and clay mineralogy affect the direction and magnitude of changes in soil C stocks with different land-cover changes. However, the distribution of field studies does not match the distribution of biophysical factors on an areal basis, and is highly skewed towards high precipitation regions with allophanic clay mineralogy. Historically, land-conversion activities in the tropics have focused on high activity clay soils in lower precipitation regions. Thus, we strongly caution against extrapolating average values of land-cover change effects on soil C stocks such as those generated through meta-analysis and literature reviews to regions that differ in biophysical conditions.

Results

Patterns of land-cover change effects. Our search of the literature yielded 837 observations from 80 studies that met our criteria for inclusion in the database. Across all sampling depths, precipitation classes, and clay mineralogy classes, 8 out of 14 land-use changes had significant effects on soil C stocks (Figure 1). The conversion of forests to shifting cultivation or permanent crops reduced soil C stocks by an average of 15.4% or 18.5%, respectively. Interestingly, both the conversions of forests to pastures and pastures to secondary forests, which were the two best represented land-cover transitions in the database, increased soil C stocks (Figure 1). The establishment of perennial tree plantations on lands that were previously grazed or cropped increased soil C stocks, while the conversion of unmanaged forests, grasslands, or savannas to plantations had no effect.

Effects of biophysical drivers. Even though many of the patterns of land-cover change effects are statistically significant, there is still unexplained variance that may be reduced by including biophysical variables such as precipitation and dominant clay mineralogy in the analyses. We grouped observations into four precipitation regimes and three classes of clay minerals that may affect soil C dynamics - allophanic soils dominated by non-crystalline clay minerals that may stabilize soil C, highly-weathered soils dominated by low activity clay with low surface area and cation exchange capacity (CEC), and young- to moderately-weathered soils dominated by high activity clay with high surface area and CEC. Three additional meta-analyses were conducted for observations from depths including 0-30 cm for the land-cover change transitions with sufficient data to examine whether soil C dynamics depended on biophysical variables: the conversions of forest to pasture, pasture to secondary forest, and forest to crop (Table 1). These analyses show that the effects of land-use change on soil C stocks depend upon both precipitation regime and soil clay mineralogy, and that the interactions between these two drivers are significant (Table 1). For example, on allophanic soils, conversion of forest to pasture reduced soil C stocks, but only in high precipitation (>3500mm mean annual precipitation) regions. In contrast, forest to pasture conversion increased soil C stocks on soils with low activity clay receiving from 1501 to 2500mm of precipitation annually, but had no effect in regions receiving > 2500 mm. Secondary forest regeneration on abandoned pastures increased soil C stocks from 19.0% to 32.6% on soils with low activity clay, but had smaller or no effects on other soil types. Last, conversion of forest to crops caused large losses of soil C stocks under diverse precipitation conditions on soils with allophane and high activity clay, but no effect on soils with low activity clay receiving from 1501 to 2500mm annual precipitation. Regardless of the exact magnitude of increase or decrease in soil C stock under each combination of clay mineralogy class and precipitation regime, the most salient result from this analysis is that the effects of land-use change on soil C stocks vary as a function of biophysical drivers. These strong patterns suggest that extrapolating average stock change factors (e.g. Figure 1) to unmeasured sites across the tropics would be warranted *only if* the distribution of field observations corresponds to the biophysical conditions in the landscape.

Geographic bias in the field observation dataset. There is strong evidence that the distribution of field studies is not representative of the distribution of biophysical variables in tropical regions that affect the magnitude and direction of change in soil C stocks following land-cover change (Figure 2 a and b; Chi-square = 11,789, d.f. =11, P<0.0001). While the global areal distribution of biophysical factors in the tropics is skewed towards lower precipitation areas (500-1500mm mean annual precipitation) with high activity clay soils (Figure 2b), the distribution of field observations is skewed towards regions with higher precipitation and allophanic clay mineralogy (Figure 2 a). It is possible that land-conversion activities are biased towards regions with certain combinations of biophysical factors, and therefore field studies merely reflect the non-random nature of land conversion. However, when we compared the distribution of field observations to the distribution of biophysical factors in tropical lands that have experienced > 50% conversion over the past century or longer, the patterns are even more striking (Figure 2c). Historically over 75% of tropical land-use activities have occurred primarily in drier regions (500-1500 mm mean annual precipitation) with high activity clay soils, allowing us to reject the hypothesis that the distribution of biophysical factors represented in the field observations reflects the typical conditions on managed lands in the tropics (Chi-square = 12,262, d.f. =11, P<0.0001).

Discussion

Biophysical drivers of land-use related soil C changes. There is growing recognition that unless biophysical drivers are explicitly considered, we will not be able to estimate the consequences of land-use changes on soil C stocks (14) or predict the effects of management decisions such as biochar amendment to increase carbon sequestration (15). Precipitation strongly influences plant production, fluxes of soil C pools, and ultimately total soil C stocks and residence time (1). The control of clay mineralogy on total soil C stocks, residence time, and susceptibility of the soil C pool to land-use change (16, 17) is through mechanisms such as differential chemical complexation, aggregation, or physical protection (18). Large-scale quantifications of soil C stocks in tropical regions show that within a precipitation regime, clay mineralogy is often the single largest factor explaining differences in soil C stocks within the landscape or with land-use change (12, 13). These findings are not new and date back to the work of Jenny (1941) (19). What is new is that we are able to illustrate these effects (and their interactions) in this pan-tropical database (in contrast to local- and regional-based studies) of the relationship between land-use change and soil C stocks.

Using this knowledge in predicting land-use change effects on soil C stocks is both promising and challenging. It is promising that stratification along biophysical drivers indeed reduces variance in the dataset (Table 1). The strong patterns suggest that extrapolating average stock change factors (e.g. Fig. 1) to unmeasured sites across the tropics would result in large errors of unknown direction and magnitude. Stratification would strongly reduce this error. The challenge is however that the present database is insufficient for this approach. Even with our simple stratification of twelve biophysical strata (4 annual precipitation classes x 3 clay mineralogy classes) only three land-cover change transitions can be included.

Caveats of datasets. The database of our meta-analysis was selected using rigorous criteria. This prevented errors related to bulk density estimates instead of measurements (20, 21) and errors related to unclear reference land uses (22). Although the database is to our knowledge larger than any other used for meta-analysis or reviews for the tropics, we acknowledge the many limitations of our datasets. First, the paucity of field observations did not allow us to evaluate temporal trends in soil C dynamics with land-use change. Thus, our analysis assumes that soil C stocks have reached equilibrium values under current land uses. Undoubtedly other factors also affect the direction and magnitude of changes in soil C stocks including site preparation, fertilization, and species effects. We did not however stratify according to these factors as their effect is less studied and no georeferenced databases of these factors exist that might be used to improve predictions of soil C stock changes following land-use change.

Second, even for the three land-cover change transitions which data enabled us to examine whether soil C dynamics depended on biophysical variables, many of the categories did not have enough observations whereas one category (i.e. forest to pasture conversion on soils with low activity clay in the 1501-2500 mm annual precipitation class, Table 1) was over-represented. This illustrates that no systematic effort has been made to sample under-represented land-use changes or regions. On the contrary, the non-random character of our database strongly suggests sampling and geographic bias (see also below).

Third, the majority of field observations are sampled at inconsistent depths that are typically only above 30 cm. Thus, we cannot draw reliable conclusions about land-use effects deeper in the soil profile.

Fourth, the coarse spatial resolution of the global maps of precipitation, soil type, and land cover likely masks important spatial heterogeneity (23). For example, due to their high native fertility, we would expect that agricultural activities would be preferentially located on allophanic soils. However, the global soil map only considers the dominant soil types. Consequently, soils dominated by allophanes (Andosols) appear in very few of the 1° by 1° grid cells we sampled (and none in the >3500 mm precipitation category), even though Andosols cover about 98 million hectares worldwide, or an estimated 1.0% of the total tropical area (23). This mismatch in spatial scales helps in part to reconcile our finding that 9% of field observations were located on high precipitation, allophanic soils, while the global map contained no grid cells with this combination of precipitation and clay mineralogy composition. Nevertheless, we believe that our main conclusions are robust to these limitations.

Causes and consequences of geographic and sampling bias. One of the strongest conclusions from our analyses is geographic bias in the field observations of land-use change effects relative to biophysical drivers (Figure 2). What this means is that we have concentrated our scientific research on regions of the landscape that are highly unrepresentative of the tropics as a whole, and are particularly unrepresentative of the tropical lands that have undergone conversion to other land covers. A likely cause of this bias is that published scientific research in tropical countries is disproportionately conducted in countries and locations of large, internationally funded field stations (e.g. Costa Rica and Panama) (24). Not only are certain combinations of biophysical variables under-sampled as our data show (e.g. regions with precipitation <1500mm and high activity clays), but also the intellectual and scientific infrastructure for conducting research in certain geographical regions (e.g. Africa) remains under-developed, which should be a cause for global concern (24).

A consequence of unrepresentative sampling is that it precludes us from extrapolating field observations to the continental or global scales that are relevant for global biogeochemistry and policy. For example, in our analyses we obtained the curious result that both forest to pasture and pasture to secondary forest conversions increased soil C contents (Figure 1). One biological explanation for this is that productive pastures are unlikely to be abandoned, which biases the pasture to secondary forest conversion field studies toward low-productivity pastures that likely lost soil C when they initially were converted from forest. A second explanation is unequal sampling across the biophysical driving variables. 62% of the data that estimate the mean effect of forest to pasture conversion came from low activity clay soils with precipitation between 1501-2500mm, which was the only combination of biophysical factors that yielded increases in soil C stocks for this land-use conversion (Table 2). In contrast, soil C stocks increased when secondary forests grew on abandoned pastures in 4 out of 8 classes of biophysical variables. In summary, the mean estimated stock change factors are highly dependent on the number of observations from each class of biophysical variables, and the data we have do not allow us to discriminate between the biological and the sampling bias explanation for this result.

Recommendations. We believe that a relatively simple set of criteria could significantly improve estimates of average soil C stock change factors following land use conversion. First, we recommend that clear reference land use and change trajectories should be sampled under comparable biophysical conditions, and sampling should be based on defined depths with measured soil bulk density and not based on soil horizons. These have been recurring recommendations from literature in the past few decades, but are still commonly neglected, given the number of studies that we had to exclude from our database due to this missing critical information. Second, field studies should focus on areas that are under-represented in the present database (i.e. drier part of the tropics (500-1500 mm annual precipitation) on soils dominated by high activity clay) in order to amend the present geographic bias. Third, the present dataset does not include current, important land-cover changes, i.e. conversion of tropical peatland and savanna to agro-biofuel production (25, 26), and detailed quantification of soil C stock changes is missing for these areas. Finally, we should abandon the idea that we can extrapolate average values of land-cover change effects on soil C stocks unless the distribution of field observations corresponds to the distribution of biophysical conditions in the tropics.

Methods

Literature Review and Meta-analysis

Published studies located between 28°35'N and 28°15'S latitude were identified from previous meta-analyses and reviews (27-31) or from searching online scientific databases. The majority of the studies were conducted between 23°N and 23°S latitudes and only a few are considered subtropical. Most of the studies quantified land-cover change effects by comparing plots on different land uses, assuming that soil C stocks were identical prior to land-cover change (i.e. chronosequence and space-for-time substitution designs). The final database consisted of studies that: 1) reported soil C stocks or information that allowed us to calculate it (carbon percentages, measured bulk density, and sampling depth) and excluded studies lacking bulk density or that estimated it from soil function formulas, 2) included clear, logical reference sites that represented the immediate, previous land cover, and 3) included data on climate and soils. Observations were assigned to one of the following land-cover transitions: forest to pasture, forest to plantation (i.e. perennial trees), forest to crop, pasture to secondary forest, pasture to plantation, crop to plantation, crop to secondary forest, crop to pasture, savanna to crop, savanna to pasture, or savanna to plantation. We also included two types of shifting-cultivation studies: those that compared shifting cultivation to primary forest (referred to as SC: forest to crop), and those that compared cropped fields to fallow forest (SC: crop to fallow). Observations were assigned one of three clay mineralogy classes (low activity clay, high activity clay, and allophanic mineralogy) that we inferred from reported soil classification, cation exchange capacity (CEC), geological substrate, or a combination of these criteria. In general, soils dominated by low activity clay have CEC of <24 $cmol_c\ kg^{-1}$ clay or <4 $cmol_c\ kg^{-1}$ soil, e.g. Acrisols, Ferralsols and Nitisols; soils dominated by high activity clay have CEC of >24 $cmol_c\ kg^{-1}$ clay, e.g. Alisols, Cambisols, Fluvisols and Luvisols; soils dominated by allophane are typically developed on volcanic ash, e.g. Andosols (32). Because many studies reported more than one observation, the final database consisted of 837 observations from 80 different studies, across all soil depths.

The percent difference in C stock between plots representing managed and initial conditions, expressed relative to the initial soil C stock (i.e. (Xc-Xr)/Xr)*100)), was used as the metric of change in soil C (with Xc representing soil C stock in the current land use, and Xr the reference land use). Following other authors (27, 28), we used non-parametric re-sampling methods to generate bootstrapped approximate 95% confidence intervals (CI) from 10,000 randomizations in META-WIN (33), and response effects were not weighted by sample size. Observed effect sizes were considered statistically different from zero if the 95% CI did not include zero, and land-cover transitions or other categorical grouping factors were considered different from one another if their 95% CI did not overlap. For land-use transitions with sufficient observations, we assessed how precipitation class and clay activity class affected the responses of soil C pools to land-use change using identical statistical methods for depths including 0-30 cm in the profile.

Geographic Analysis

We tabulated the distribution of average precipitation conditions and soil clay mineralogy from global databases as follows. A global map of the 1961-1990 annual mean precipitation was derived from the Climate Research Unit dataset at 1.0° by 1.0° resolution (34) and classified into four categories: 500-1500, 1501-2500, 2501-3500, and >3501mm annual precipitation. All oceans, extra-tropical land (defining tropical lands as those occurring between 24° N and 24° S latitude), and tropical lands with mean annual precipitation <499 mm (e.g. the Sahara Desert) were omitted from the analysis. We used the 1.0° by 1.0° resolution FAO global soil map to generate a map of soil clay mineralogy (http://data.giss.nasa.gov/landuse/soilunit.html). To accomplish this, we reclassified the map units into the same three clay activity classes used for the literature studies—low activity clay, high activity clay, and allophanic mineralogy. This gridded, classified map was overlaid onto the precipitation map, and the numbers of grid cells in each combination of precipitation and clay mineralogy (12 classes total) were tabulated (N=2857 grid cells).

The distribution of field observations that included information on both precipitation and soil order (N=837) was compared to the actual area-weighted distribution of annual precipitation and soil clay mineralogical conditions in the tropics using a Chi-square test. At the coarse-scale resolution of global datasets, there are no tropical grid cells in the category of allophanic mineralogy and annual precipitation >3501mm, even though 9.0% of the field observations come from lands with these conditions. To accommodate the fact that this precipitation /clay mineralogy class had an expectation of 0, we assigned it a pseudo-expectation of one and decreased the expected number of field observations in the 500 to 1500 mm precipitation/high activity clay class from 276 to 275. Chi-square tests are considered robust only when all of the expected counts are >5, which was not the case for three of the twelve precipitation/clay mineralogy categories we analyzed. Nevertheless, the extremely large Chi-square statistic of 11,789 (d.f. =11) was highly significant (P<0.0001) and gives us assurance that the distributions of field observations and actual precipitation and clay mineralogy conditions are indeed distinct.

To control for the possibility that the distribution of field observations reflects the conditions of lands that have undergone conversion, we used a time series of global maps of grazing lands and croplands (the Global Cropland and Pasture Data from 1700-2007) (35) to create a map of all grid cells in the tropics that have undergone at least 50% conversion in the last century (including all lands in pasture or cropland prior to 1900). We used this land-conversion map as a mask and retabulated the distribution of annual precipitation/clay mineralogy classes for the 981 grid cells that had undergone >50% conversion (roughly 34% of all tropical lands with annual precipitation >500 mm). We compared the distributions of field observations to converted conditions using the Chi-square test described above.

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Figure Legends

Figure 1 Average percentage change in total soil carbon stocks for different land-use changes in the tropical region with 95% confidence intervals obtained by randomization. Land-use transitions appear beside means and the number of observations for each mean is in parentheses. SC refers to shifting cultivation.

Figure 2 Numbers of observations or grid cells grouped into 12 biophysical classes defined by annual precipitation and soil clay mineralogy. a) field observations of soil C changes (N=837), b) pan-tropical distribution of 1° x 1° grid cells (N=2,857), c) tropical grid cells that have experienced >50% conversion to other land uses (N=981). Grey bars are low activity clay, open bars are high activity clay, and black bars are allophanic clays.

Table Legends

Table 1. Mean values of land-cover change effects on soil carbon contents (including 0-30 cm sampling depths), grouped by clay mineralogy and annual precipitation classes. Significant transitions, inferred as approximate 95% bootstrapped confidence intervals that do not contain 0, are in bold. Only data from clay mineralogy and precipitation classes that had at least 3 observations were included in the analyses.

Table 1.

Clay mineralogy class	Annual precipitation class	Mean Percent Change (Lower and Upper CI)		N
		forest to pasture conversion		
Allophane	1501 to 2500	7.3	(-33.82, 55.2)	3
	2501 to 3500	-2.7	(-16.3, 14.1)	7
	>3501	**-15.8**	**(-24.4, -7.3)**	5
High activity	<1500	16.4	(-1.8, 37.7)	6
	1501 to 2500	**-10.2**	**(-21.4, -0.5)**	7
Low activity	1501 to 2500	**26.4**	**(20.8, 32.2)**	79
	2501 to 3500	1.1	(-14.4, 18.1)	9
	>3501	14.1	(-0.7, 29.7)	12
		pasture to secondary forest conversion		
Allophane	2501 to 3500	4.0	(-5.5, 17.8)	9
High activity	<1500	**16.5**	**(8.3, 24.1)**	4
	1501 to 2500	10.8	(-0.6, 21.9)	15
	2501 to 3500	-5.0	(-18.3, 6.9)	8
Low activity	1501 to 2500	**19.0**	**(1.3, 34.9)**	11
	2501 to 3500	**23.6**	**(4.8, 43.4)**	6
	>3501	**32.6**	**(25.9, 39.2)**	4
		forest to crop		
Allophane	<1500	**-36.9**	**(-46.4, -26.1)**	5
	2501-350	**-41.8**	**(-50.4, -33.4)**	7
High activity	1501 to 2500	**-30.8**	**(-39.9, -22.7)**	16
Low activity	1501 to 2500	-10.4	(-24.4, 6.8)	12

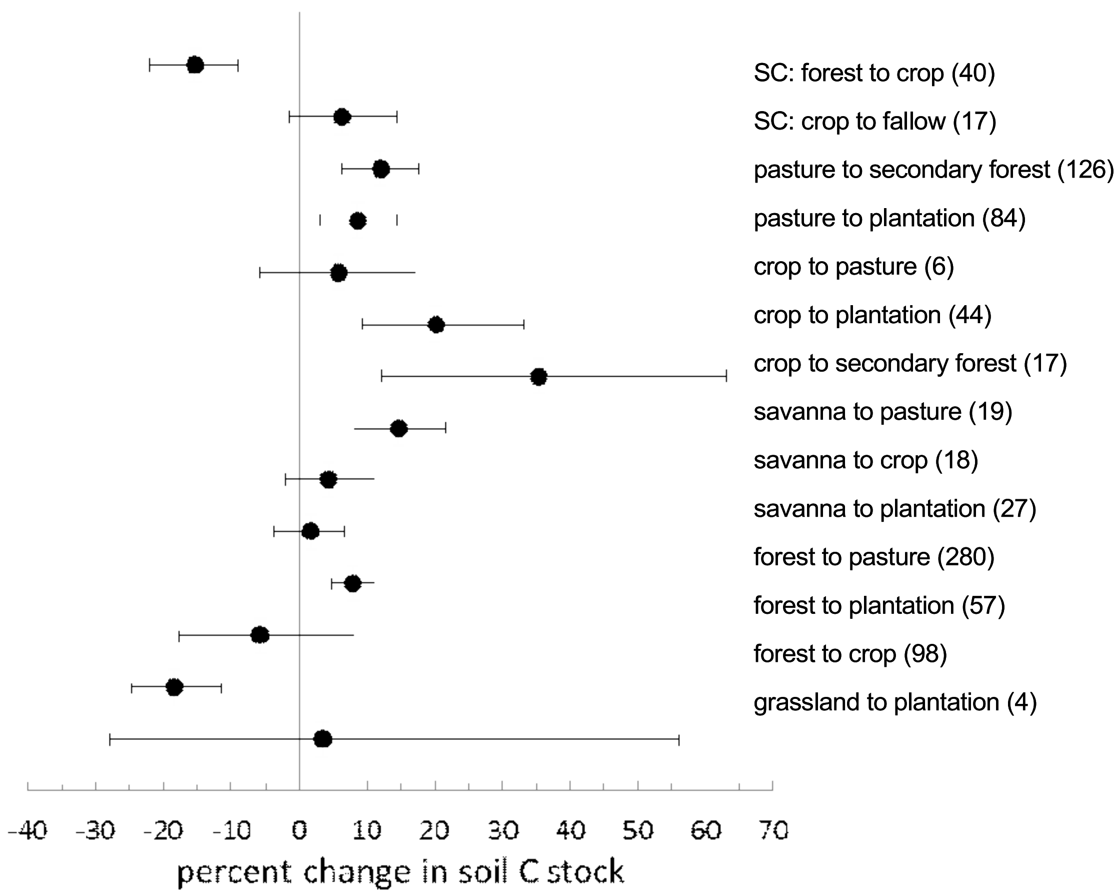
SC: forest to crop (40)
SC: crop to fallow (17)
pasture to secondary forest (126)
pasture to plantation (84)
crop to pasture (6)
crop to plantation (44)
crop to secondary forest (17)
savanna to pasture (19)
savanna to crop (18)
savanna to plantation (27)
forest to pasture (280)
forest to plantation (57)
forest to crop (98)
grassland to plantation (4)
-40 -30 -20 -10 0 10 20 30 40 50 60 70
percent change in soil C stock

Fig. 1

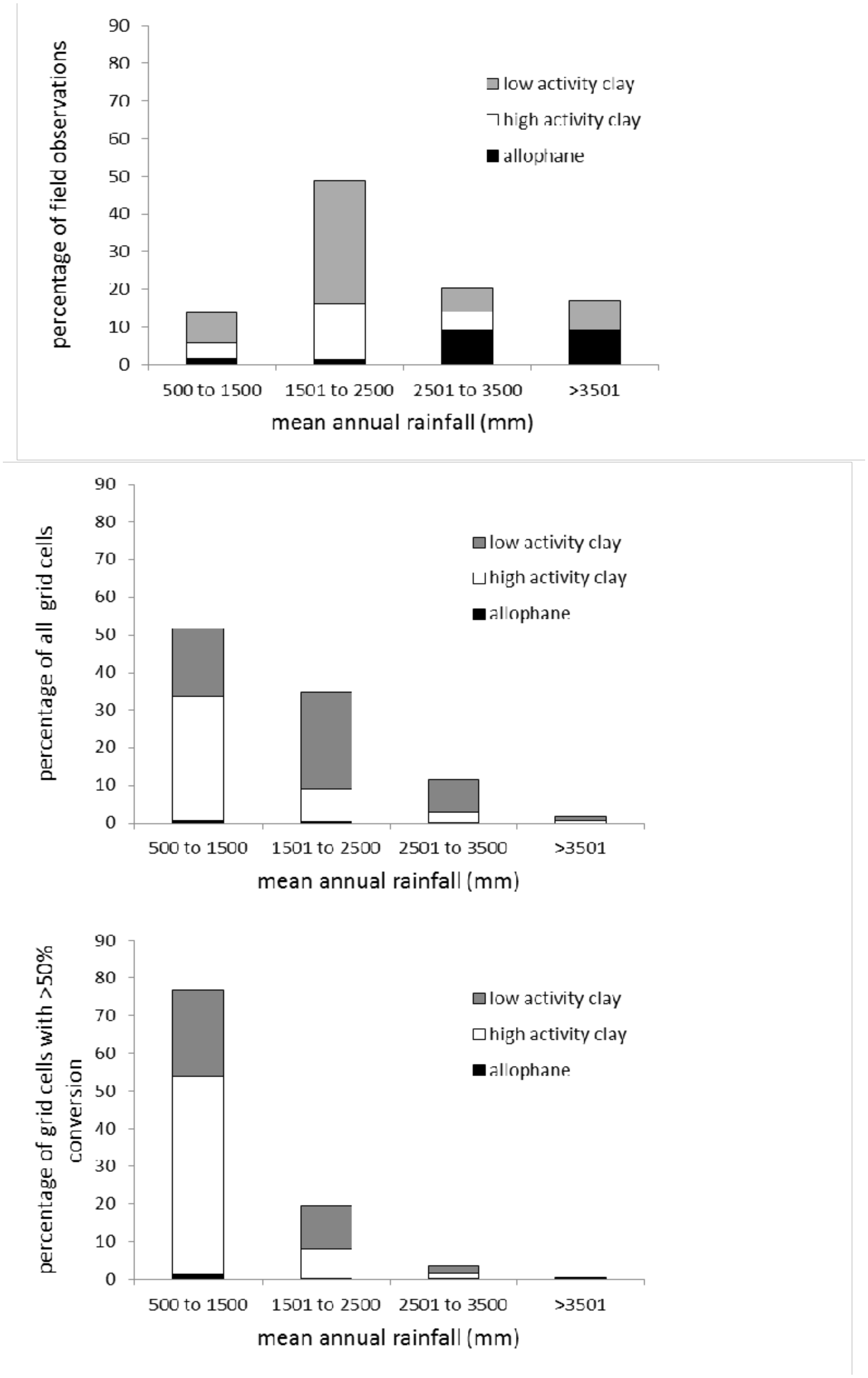
90
80
70
60
50
40
30
20
10
0
percentage of field observations
low activity clay
high activity clay
allophane
500 to 1500
1501 to 2500
2501 to 3500
>3501
mean annual rainfall (mm)
percentage of all grid cells
low activity clay
high activity clay
allophane
500 to 1500
1501 to 2500
2501 to 3500
>3501
mean annual rainfall (mm)
percentage of grid cells with >50% conversion
low activity clay
high activity clay
allophane
500 to 1500
1501 to 2500
2501 to 3500
>3501
mean annual rainfall (mm)

Fig. 2