Targeted Column: Letters

Title: Soil Carbon in Agro forestry Systems: An Unexplored Treasure?

Statement of the Main Point

Agroforestry (AF), the growing of crops and trees together, is suggested as a strategy for soil carbon sequestration (SCS) under the afforestation and reforestation activities that are among the accepted GHG (greenhouse gas) reduction strategies. Our understanding about C storage and dynamics under agroforestry systems (AFS), however, is minimal. Since subsistence farmers in developing countries are the major practitioners of AF, there could be an attractive opportunity for them to benefit economically through SCS under AFS. Although practised in more than one billion hectares of land, this traditional land-use practice has not been given deserving attention in the agricultural and forestry development pathways. Recent studies suggest the possibilities for higher C storage in soils under agroforestry systems compared with treeless systems. It is time that we pay more attention to understanding the science underlying these integrated land-use systems to better exploit their potential.

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Soil Carbon in Agroforestry Systems: An Unexplored Treasure?

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Soil organic matter (SOM), which contains more reactive organic carbon (C) than any other single terrestrial pool, plays a major role in determining C storage in ecosystems and regulating atmospheric concentrations of carbon dioxide (CO_2)[1]. Agroforestry, the practice of growing trees and crops in interacting combinations on the same unit of land[2], primarily by resource-poor smallholder farmers in developing countries, is recognized as a strategy

for soil carbon sequestration (SCS) under the Clean Development Mechanism (CDM) of the Kyoto Protocol[3]. The understanding about C storage and dynamics under agroforestry systems (AFS), however, is minimal. Our studies under various AFS in diverse ecological conditions in five countries showed that tree-based agricultural systems, compared to treeless systems, stored more C in deeper soil layers up to 1 m depth under comparable conditions. More C is stored in soil near the tree than away from the tree; higher SOC content is associated with higher species richness and tree density; and C3 plants (trees) contribute to more C in the silt- + clay-sized (<53 µm) fractions that constitute more stable C, than C4 plants, in deeper soil profiles[4 – 8]. These results provide clear indications of the possibilities for climate change mitigation through SCS in AFS, and opportunities for economic benefit – through carbon trading – to millions of smallholder farmers in developing countries.

The Intergovernmental Panel on Climate Change recognized[3] that potential increases in carbon (C) storage might occur in forest and agricultural lands via (a) improved management within a land use, (b) conversion of land use to one with higher C stocks, or (c) increased C storage in harvested products. Soils play a direct role in both (a) and (b) of these. Indeed, soils play a major role in the global C cycle: the soil C pool to 1 m depth comprises organic C, estimated at 1550 Pg, and inorganic C, about 750 Pg[1]. Soil organic matter (SOM) contains more reactive organic C than any other single terrestrial pool. Consequently, SOM plays a major role in determining C storage in ecosystems and in regulating atmospheric CO_2 concentrations. A reduction in soil C pool by 1 Pg is equivalent to an atmospheric enrichment of CO_2 by 0.47

ppm[9]. Thus, soil C that traditionally has been a sustainability indicator of agricultural systems has now acquired the additional role as an indicator of environmental health.

The United Nations Framework Convention on Climate Change (UNFCCC) allows the use of C sequestration through afforestation and reforestation as greenhouse gas (GHG) offset activities under the Clean Development Mechanism (CDM) of the Kyoto Protocol[10]. Recently, REDD (Reducing Emissions from Deforestation and Forest Degradation in Developing Countries: http://unfccc.int/methods_science/redd/items/4531.php) has gained serious attention in the post-Kyoto Protocol negotiations. Agroforestry (AF), which refers to the practice of growing trees and crops and sometime animals in interacting combinations for a variety of objectives[2], is suggested as a strategy for soil carbon sequestration (SCS) under such activities; therefore the role of AF as a strategy for C sequestration has raised considerable expectations[11]. Agroforestry has come of age forcefully during the past three decades, consequent to the increasing recognition of the production- and sustainability attributes of agroforestry systems (AFS) in a variety of circumstances[2, 12]. During this period, the age-old practice that had been bypassed in the single-commodity oriented paradigms of commercial agriculture and forestry[13] has slowly been transformed into a science-based land-use activity. Developments based on scientific foundations of agroforestry and the potential it offers as a sustainable land-use option especially in low-resource situations have been amply illustrated through various avenues including the World Congresses of Agroforestry held every five years – the second one in August 2009, in Nairobi, Kenya (www.worldagroforestry.org/wca2). Nevertheless, our understanding about C storage and dynamics under AFS is minimal: the notion that tree incorporation in croplands and pastures would result in greater net sequestration of C both above- and below ground[14] has not been adequately studied.

Soil organic carbon (SOC) is known to be retained in the soil profile through physical protection as organomineral complexes, biochemical recalcitrance to decomposition of lignin and such other substances, and chemical stabilization such as adsorption to clay surfaces (exchange complex)[15]. The extent of C retention in soils depends, among other things, on the nature of soil aggregation[16]. It can be short-term storage in macroaggregates (> 250 µm diameter) and long-term storage in microaggregates (< 250 µm diameter) including the widely accepted stability of C stored in the smallest size class, the silt and clay size fraction (< 53 µm)[17]. Mean residence times for macroaggregates, microaggregates, and silt+ clay sized aggregates vary from 1 – 10, 10 – 100, and 100 – 1000 years[18].

We studied the extent of C stored in soils under diverse AFS in different ecological conditions in five countries in as many continents (Fig. 1) in the above three categories of soil fraction-size classes, at various soil depths to at least 1 m depth. We calculated the differences in the amount of C stored in different soil layers under tree-based systems and treeless agricultural systems under different situations and found that tree-based systems stored more C in deeper soil layers under comparable ecological conditions (Fig. 2). In the semiarid farmland sites with scattered tree cover, we found more C in soil near the tree than away from the tree, both in the West African Sahel[7] and in the ‘dehesa’ system (Table 1) in central Spain (Fig. 3). Furthermore, we found that SOC storage in upper layers of soils in AFS with high tree density per unit land area was comparable to that under adjacent natural forests, both in homegardens in Kerala, India[5] and the shaded cacao (*Theobroma cac*ao L.) system in southern Bahia, Brazil.

Soil aggregates that are secondary particles formed through the combination of mineral particles with organic and inorganic substances ranging in size from microns to millimeters have an important effect on the retention of C in soil. Increases in aggregation concomitant with increases in organic C have been observed in no-till systems[19]. The silt-and-clay-protected C pool depends on the silt- and clay proportions in soils. In 1:1 clay-mineral-dominated soils, such as Oxisols (FAO: Ferralsols), that have a low level of silt-and-clay-protected C pool[17], oxides are the main binding agents, rather than SOM; thus, Oxisols do not show the same aggregate hierarchy as other soils[20, 21]. In our studies at Bahia, Brazil (Oxisols), on average, 72% of SOC was in macroaggregate-size-, 20% in microaggregate-size-, and 8% in silt-and-clay-size fraction in soil, suggesting that occlusion of C in soil aggregates can be a major mechanism of C protection in those soils. Therefore, clay content alone may not be an appropriate measure for protection of C in such soils. A strong relationship between organic C and aggregate size in our study suggests, however, that high levels (~ 300 Mg ha^{-1}) of SOM could lead to a change in the dominant binding agents of these aggregates from oxides to organic molecules in these soils.

Stable C isotope-ratio analysis has been successfully used in SOC studies to trace the source of SOC to C3 and C4 components in vegetation[22]. Combining SOM fractionation techniques with the ^{13}C natural abundance technique, we assessed the effect of integrating trees in pastures systems on the SOC content and SOM fraction size compared to open pasture systems, and quantified the relative SOC contribution of trees and the warm-season grasses of silvopastoral systems in Central and North Florida, USA, using their natural C isotopic differences. The C3-derived SOC in silvopasture was double at the surface soil layer and was generally higher at the other depths as compared to that in treeless pasture sites[8]. Slash pine (*Pinus elliottii* Engelm.) trees (C3 plant) seemed to contribute more C in the silt- + clay- sized (<53 µm) fractions than bahiagrass, *Paspalum notatum* Flüggé (C4 plant), particularly deeper in the soil profile. Spodosols (FAO: Podzols) sites contained more C in the <53µm fraction at and below the spodic horizon (occurring between 15 – 50 cm) in silvopasture compared to treeless pastures. The results indicate that most of SOC in deeper soil profiles and the relatively stable <53µm C fraction were derived from tree components (C3 plants), suggesting that the tree-based pasture system has relatively greater potential to store more stable C in the soil compared with the treeless system. The report[23] that C4-derived SOC decomposed faster than C3-derived SOC in mixed C3/C4 soils would suggest that the higher amount of C3-derived SOC at lower depths in silvopastoral systems could also be a result of lower decomposition rate of C3-derived SOC and not only of its higher input.

These results show the extent of soil C stock under various AFS, the increase in C storage under AFS compared with non-AFS under similar conditions, and the importance of the nature and properties of soils in the magnitude of their CSP. Overall, these results provide clear indications of the possibilities for climate change mitigation through SCS in AF systems. Recent geospatial analyses of remote-sensing derived global datasets by the World Agroforestry Centre (www.worldagroforestry.org) and collaborators based on geospatial analysis of remote sensing derived global datasets at 1 km resolution have confirmed previous estimates that agroforestry is practiced on about one billion hectares of agricultural lands worldwide[5], servicing about 1.5 billion farmers, primarily smallholders, in developing countries. It is also a potentially important land-use activity in the industrialized North America[24] and Europe[25]. Since subsistence farmers in developing countries are the major practitioners of AF, there is an added and attractive opportunity for them to benefit economically from agroforestry[6] if the C sequestered through AFS is sold to developed countries. This is particularly relevant to the Clean Development Mechanism (CDM) of UNFCCC, which allows industrialized countries with a GHG reduction commitment to invest in mitigation projects in developing countries as an alternative to what is generally more costly in their own countries; admittedly, the ideological argument about the desirability of such practices is a contentious issue. Furthermore, traditional AFS with diverse and structurally complex shade canopies are among the agricultural land uses that are most likely to conserve a significant portion of the original forest biodiversity[26]. The current debate on land use and carbon mitigation is focused more on economics and accounting, and not enough on science. Clearly, it is time that in the poverty alleviation – conservation – environmental protection paradigms, we pay more attention to these hitherto ignored or bypassed integrated land-use systems that are practised on small farms by millions of farmers around the world, and the underlying science of the practice.

METHODS SUMMARY

At all sites, soils were sampled up to at least 1 m depth in multiple depth classes. Samples were fractionated into three classes (250 – 2000, 53 – 250 and <53 µm) by wet sieving[27], and the C content in each fraction determined. Stable isotope ratio was used to determine, wherever applicable (samples from Florida, Mali, and Minas Gerais – Brazil), for determination of the relative contribution of trees and grasses to soil C. The soil samples from the Bahia (Brazil) site were sonicated to quantify the amount of carbon occluded within aggregates in soils under cacao AFS[28, 29].

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Author Contributions P. K. R. N. conceptualised, designed field sampling procedures, and directed the overall project; and V. D. N. designed and supervised the laboratory analyses at the University of Florida; both of them were involved in all studies at all locations. Individuals responsible for studies at different locations are: Bahia, Brazil: E. F. G.-R.; Florida, U. S. A.: S. G. H.; Northern and Central Spain: D. S. H., M. R. M.-L.; Kerala, India: S. K. S., B. M. K.; Mali: A. N. G. T.; Minas Gerais, Brazil: R. G. T., R. G. All authors other than the first two are listed in alphabetical order; they made equal contributions through their involvement in the sub-projects at their respective sites from which the data derive. All authors contributed to the interpretation, content, and discussion.

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Figure Captions

Figure 1. Various agroforestry systems in the study. See Table 1 for location details and brief system-descriptions. At all sites, soils were sampled up to at least 1 m depth in multiple depth classes and fractionated into three classes (250 – 2000, 53 – 250 and <53 μm), and the C content in each determined. Stable isotope ratio was used to determine, wherever applicable, the relative contribution of trees and grasses to soil C.

Figure 2. Differences in soil carbon stock to 1 m depth between comparable agroforestry (AF) and agricultural systems, near the trees and away from trees in AF systems, and AF and natural forests, expressed as percent of non AF system values, at different locations. See Figure 1 for additional site details.

Site- and system details[§]

	Systems	Location	Soil Order[@]
1	Pine + pasture vs. treeless pasture	Florida, USA	Spodosols (Podzols)
2	Pasture under birch and pine trees vs. treeless pasture	Northern Spain	Inceptisols (Cambisols)
3	Homegardens vs. rice paddy	Kerala, India	Inceptisols (Gleysols)
4	Under tree vs. away from trees (Dehesa)	Northern Spain	Alfisols (Luvisols)
5	Under tree vs. away from trees in parkland system	Ségou, Mali	Alfisols (Luvisols)
6	Homegardens vs. forest	Kerala, India	Inceptisols (Cambisols)
7	Cacao under shade vs. forest	Bahia, Brazil	Oxisols (Ferralsols)
8	Brachiaria + Eucalyptus vs. forest	Minas Gerais, Brazil	Oxisols (Ferralsols)

[§] See Table 1 for additional site details.

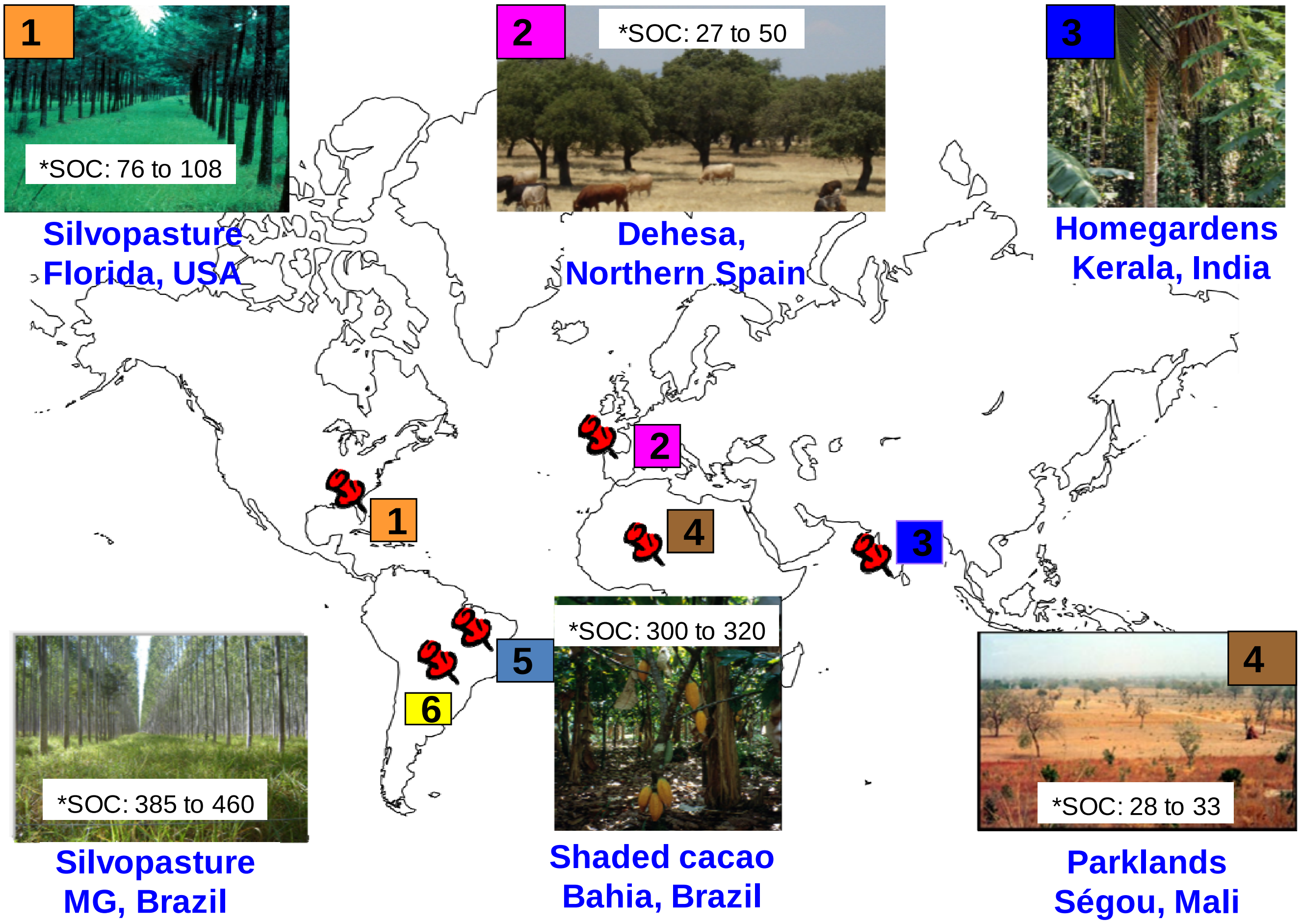
[@] USDA Soil Taxonomy terms with approximate FAO terms in parentheses;

Figure 3: Soil C storage to 1 m depth and at 2, 5 and 15 m distances from *Q. suber* tree in the dehesa silvopastoral system, Spain. See Table 1 for site and system details.

Table 1. Details of the agroforestry systems at the different study locations.

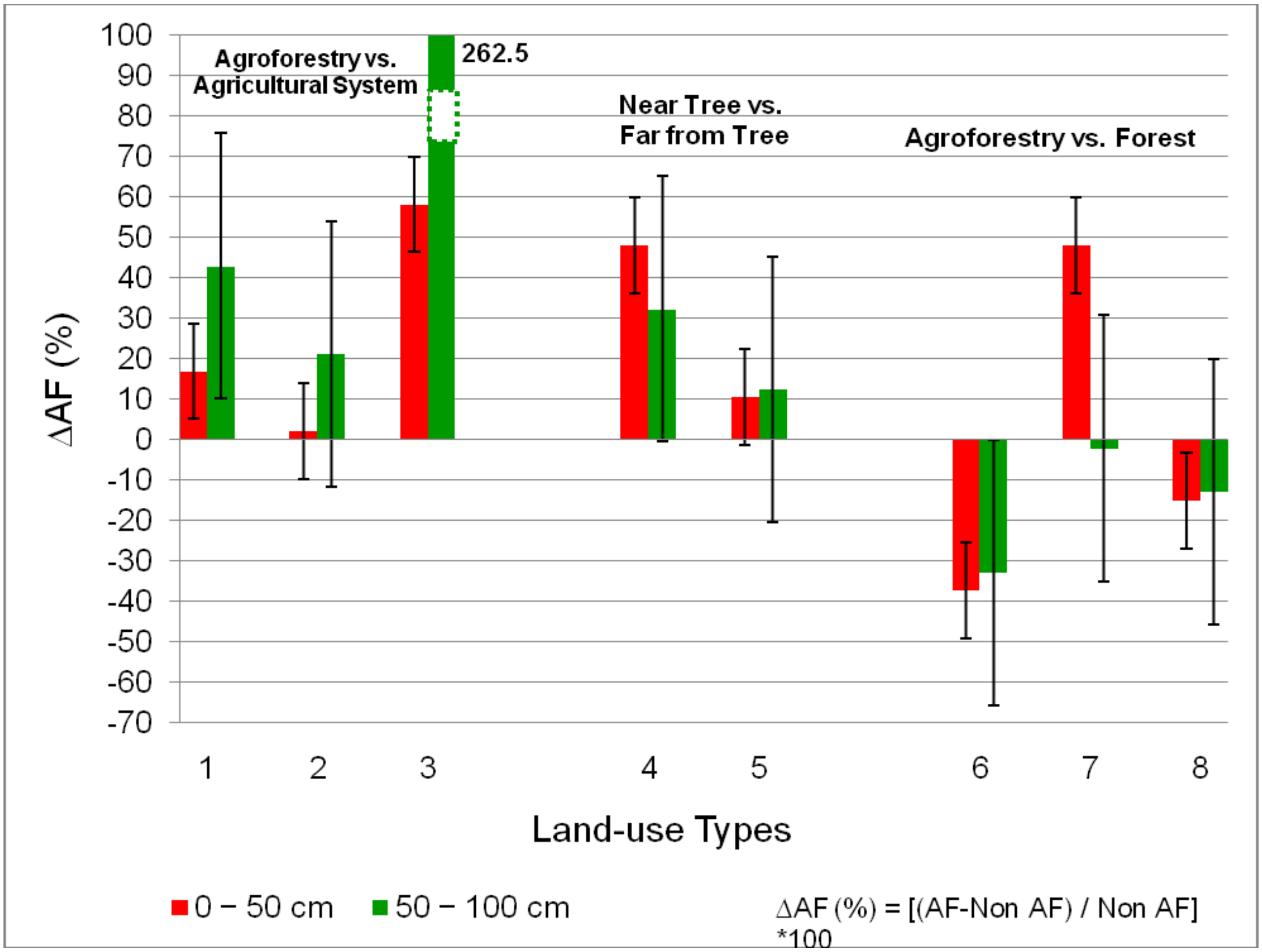
Sites			Agroforestry systems
Location; Coordinates	Climate (m.a.p, mm; mean temp. range, C)	Soil order[@]	
1. Florida, USA; 28° to 29° N; 81° to 83° W	Humid subtropical; 1330; -3 to 28	Spodosols (Podzols)	Silvopasture: slash pine (*Pinus elliottii*) + bahiagrass (*Paspalum notatum*); 12–14 yr "old" (i.e., since establishment)
2. Central Spain; 39^{0} 59' N; 6^{o} 6' W	subhumid Mediterranean; 600; 8 to 26	Alfisols (Luvisols)	Dehesa oak silvopasture (*Quercus suber*); > 80-yr old
3. Kerala, India; 10^{o}32' N; 76^{o}14'E	Humid tropical; 2700; 27 to 32	Inceptisols (Cambisols; Gleysols)	Homegardens: Intensive multispecies mixtures of trees, shrubs, and herbs in small (< 0.5 ha) holdings; > 40-yr old.
4. Ségou, Mali; 13^{o} 20' N; 6^{o} 10' W	Semiarid tropical; 500 to 700; 29 to 36	Alfisols (Luvisols)	Intercropping under scattered trees, > 30 yr old; and 9-yr-old plantings of live fences and fodder banks
5. Bahia, Brazil; 14^{o} 0' S; 39^{o} 2' W	Humid tropical; 1500; 25 to 32	Oxisols (Ferralsols)	Cacao (*Theobroma cacao*) under thinned natural forest (*cabruca*) or planted shade trees; 30-yr old
6. Minas Gerais, Brazil 17^{o} 36' S; 46^{o} 42' W	Cerrado: Subhumid tropical; 1350; 20 to 30	Oxisols (Ferralsols)	Silvopasture: *Eucalyptus* spp. with understory of *Brachiaria* spp (fodder grass) ; 40-yr old

[@] Soils orders are listed in USDA Soil Taxonomy terms with approximate FAO terms in parentheses.



*SOC (Soil Organic Carbon) to 1 m depth, Mg ha^{-1}

Figure 1.



Number	Systems	Location	Soil Order
1	Pine + pasture vs. treeless pasture	Florida, USA	Spodosols
2	Pasture under birch trees vs. treeless pasture	Northern Spain	Inceptisols
3	Homegardens vs. rice paddy	Kerala, India	Inceptisols
4	Under tree vs. away from trees (Dehesa)	Northern Spain	Alfisols
5	Under tree vs. away from trees in parkland system	Ségou, Mali	Alfisols
6	Homegardens vs. forest	Kerala, India	Inceptisols
7	Cacao under shade vs. forest	Bahia, Brazil	Oxisols
8	Brachiaria + Eucalyptus vs. forest	Minas Gerais, Brazil	Oxisols

Figure 2.

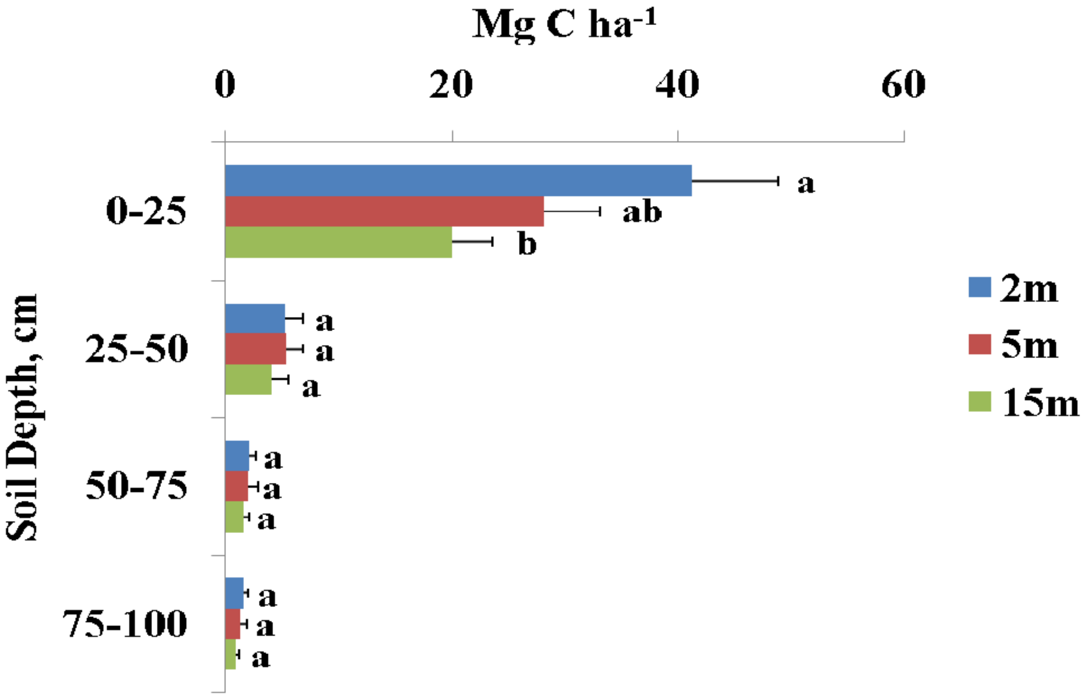

Mg C ha^{-1}
0
20
40
60
Soil Depth, cm
0-25
25-50
50-75
75-100
a
ab
b
a
a
a
a
a
a
a
a
a
2m
5m
15m

Figure 3.