Methodological Challenges in Estimating Carbon Sequestration Potential of Agroforestry Systems

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Abstract The methods used to estimate carbon sequestration in agroforestry systems (AFS) vary widely. Consequently, there is enormous inconsistency in the available datasets. Moreover, the estimations entail several assumptions, some of which are erroneous. A serious one is that C in the biomass and soil are equated to sequestered C. The amount of C stored in root biomass is also subject to widely variable estimations. Large-scale global models that are based on extrapolation of field measurements from sample plots, as used for C sequestration estimates in forestry, are thus likely to result in serious under- or overestimations of total C stock. These methodological problems that are common to most land use systems are of a higher order of magnitude in AFS compared with agricultural systems because of the integrated nature of AFS and the lack of rigorous data on the area under the practice. While there are no easy, fast, and pragmatic solution to these complex issues in the short term, agroforestry researchers could, at the very minimum, include accurate description of the methods and procedures they use while reporting results. That will help researchers at large to examine the datasets even at a later time and possibly incorporate the reported results in larger databases and help agroforestry earn its deserving place in mainstream efforts. Missing the opportunity to capitalize on the environmental services of agroforestry for the lack of rigorous research and consistent procedures for data reporting will be a serious setback to the development of agroforestry.

Keywords Allometric equations • Biomass determination • Global carbon models • Design and sampling problems • Soil bulk density

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Introduction

Agroforestry practices are said to be characterized by four "I" words: intentional, intensive, integrated, and interactive (Gold and Garrett 2009). Perhaps another one could be added: imprecise. This is not said in a pejorative sense. It only reflects the lack of precision in dealing with issues concerning agroforestry. Starting with the definition, agroforestry is not entirely precise or definitive in many of its attributes. In fact, that is just the "nature of the beast": various attributes of integrated and interactive land use systems that are practiced in concert with nature and environment in accordance with the local socio-cultural norms and traditions cannot be expected to be measured in quantitative terms with 100% precision and accuracy because of the multiplicity of factors involved and their complex interactions. This lack of precision may not be a serious problem in managing the systems because they are location-specific and their management is less dependent on machinery than in the case of commercial agriculture and forestry systems. However, when it comes to quantifying their attributes to lay the foundations for future scientific developments, accurate measurements are important. Thus, measurement of the perceived benefits and advantages of agroforestry is essential; but it is a challenge, indeed a serious one. We are faced with such a serious challenge in our efforts to estimate carbon (C) sequestration in agroforestry systems (AFS).

The role of land use systems in capturing atmospheric carbon dioxide (CO_2) and storing the C in plant parts and soil became an important area of research during the past decade. Agroforestry attracted special attention as a C sequestration strategy following its recognition as a C sequestration activity under the afforestation and reforestation (A & R) activities of the Kyoto Protocol. This was in recognition of the perceived advantages of the large volume of aboveground biomass (AGB) and deep root systems of trees in accomplishing that task. Consequently a large number of estimates and reports on C sequestration potential of various agroforestry systems under different ecological regions have become available since the mid-1990s starting with the reports of Dixon et al. (1994), Schroeder (1994), and others. Most of these available reports on C sequestration in AFS are estimates of C stocks: how much C is, or potentially could be, accumulated and stored in above- and belowground compartments of AFS under different conditions of ecology and management. The estimates range from 0.29 to 15.21 Mg ha^{-1} year^{-1} aboveground, and 30–300 Mg C ha^{-1} up to 1-m depth in the soil (Nair et al. 2010).

Collecting (or estimating) such C stock data is important in itself for feeding into massive global datasets such as those of the IPCC (Intergovernmental Panel on Climate Change: www.ipcc.ch, accessed 13 February 2011) and for other planning and developmental purposes. The methods and procedures adopted in collecting such datasets have to be consistent and standardized, so that development plans for the future are based on rigorous databases of unquestionable value. Therefore, we have the responsibility of stepping up our norms, criteria, and standards for reporting C sequestration data in AFS. With that in mind, this chapter aims to bring together, first of all, some basic concepts of C sequestration and then identify some of the common mistakes and pitfalls in C sequestration studies in AFS and ways to avoid them. Developing a uniform or standardized set of procedures is a long and arduous task; that is not even attempted here; the hope, however, is that this effort will stimulate some thinking in organizing future efforts in that direction. While raising these issues, it is recognized that most of them deserve considerable discussion. That, however, is beyond the scope of this paper. Furthermore, all the supporting literature, based on which many statements are made in an abstract manner in the text, is not cited for reason on brevity.

Carbon Sequestration

During the past two decades, there has been a veritable explosion of the literature on C sequestration. Internet search engines and abstracting services are virtually flooded with all sorts of literature on all aspects of the process. Unfortunately, considerable variations exist among different user groups about the concept of C sequestration and the term is not used or understood uniformly in different contexts. This has led to serious difficulties in consolidating and synthesizing available reports and publications according to a uniform pattern and set of norms.

The United Nations Framework Convention on Climate Change (UNFCCC) defines carbon sequestration as the process of removing C from the atmosphere and depositing it in a reservoir. It entails the transfer of atmospheric CO_2, and its secure storage in long-lived pools (UNFCCC 2007). From the agroforestry point of view, C sequestration primarily involves the uptake of atmospheric CO_2 during photosynthesis and the transfer of fixed C into vegetation, detritus, and soil pools for "secure" (i.e. long-term) storage (Nair et al. 2010). It occurs in two major segments of the AFS: aboveground and belowground. Each can be partitioned into sub-segments: the former into specific plant parts (stem, leaves, etc., of trees and herbaceous components), and the latter into living biomass such as roots and other belowground plant parts, soil organisms, and C stored in various soil horizons. The total amount sequestered in each compartment differs greatly depending on a number of factors including the ecoregion, the type of system (and the nature of components and age of perennials such as trees), site quality, and previous land use. On average, the aboveground parts and the soil (including roots and other living biomass) are estimated to hold roughly one-thirds and two-thirds, respectively, of the total C stored in tree-based land use systems (Lal 2010). Based on the notion that tree incorporation in croplands and pastures would result in greater net C storage above- and belowground (Palm et al. 2004; Haile et al. 2008), AFS are believed to have a higher potential to sequester C than pastures or field crops growing under similar ecological conditions (Roshetko et al. 2002; Kirby and Potvin 2007).

Measurement of Carbon Sequestration in Agroforestry Systems

Aboveground (Vegetation)

Aboveground measurements of C stock (and, by implication, C sequestration) are direct derivatives of aboveground biomass (AGB) measurements/estimates, assuming that 50% of the biomass is made up by C. The AGB is often derived by summing up the amount of harvested and standing biomass, and the measurements are relatively straight-forward compared to those of the belowground compartment. Estimation of tree biomass by whole-tree harvesting is an old approach: it consists of cutting down sample trees, separating various parts (stem, leaves, inflorescence, etc.), digging out and washing the roots, determining their dry weights from samples of each part, and adding them up to get the total biomass. After dividing up the harvested representative trees into their various components (branches, dead branches, branchlets, leaves, roots and fine roots), and determining their dry weight, the C content in each is measured. Using the data, allometric equations are developed as regression models with the measured variables such as diameter at breast height (DBH), total tree height or commercial bole height, and sometimes wood density, as the independent variables and total dry weight as the dependent variable. The destructive method of determining tree biomass, though comparatively accurate, is extremely time- and labor-intensive, especially for large trees. It is often used to validate other, less invasive and costly methods, such as the estimation of C stock using nondestructive in-situ measurements and remote sensing. Such allometric equations developed based on biophysical properties of trees and validated by occasional measurements of destructive sampling are widely used in forestry for estimating standing volumes of forests. With increasing understanding about the role of forests in sequestering C, various allometric equations have been developed for different forest types (Brown 1997; FAO 2004; Pearson et al. 2005; Chave et al. 2005; Basuki et al. 2009; Fernández-Núñez et al. 2010).

Efforts in developing allometric equations for agroforestry situations have generally been slow and researchers trying to use this approach are forced to use broad approximations. For example, for estimating the standing tree biomass in the parkland AFS in the Sahel where species-specific allometric equations were not available for the region, Takimoto et al. (2008) followed the UNFCCC (2006) recommendation to use the Brown (1997) general equations for parkland trees. In other cases, more simple analyses were used for large-scale estimations. Dixon et al. (1993) made estimations by measuring the volume of stem wood and multiplying it with species-specific wood density; that number was then multiplied by 1.6 to get an estimation of whole-tree biomass; C content was assumed as 50% of the estimated whole-tree biomass, and root biomass was excluded. This rough estimation was then used for more extensive estimations of global forest biomass. More recently, databases for tree characteristics such as wood density for agroforestry species http://www.worldagroforestrycentre.org/sea/Products/AFDbases/WD/ (accessed 13 February 2011) developed at the World Agroforestry Centre (www.cgiar-icraf.org, accessed 13 February 2011) are being used in such allometric calculations.

As Kumar et al. (1998) noted following their efforts to develop allometric equations for some common agroforestry tree species in Kerala, India, such equations vary greatly with species, age, wood density, bole shape, and other factors, and could lead to excessive inaccuracies. Besides, such determinations can be difficult for smallholder agroforestry plots that comprise much of the agroforestry in developing countries. These systems involve a multitude of plants of varying growth habits yielding diverse economic products, and the species are planted and their products harvested, mostly for household consumption, throughout the year. Variations in tree management can be another issue: trees in AFS may be pruned depending on management practices or may have different growth forms due to differences in spacing compared to natural (forest) systems. Furthermore, no two agroforestry plots are similar: each may be unique in terms of plant composition, planting arrangements, and stand densities. Thus, determination of biomass production from indigenous AFS is a challenging task, and makes extrapolation from one system to others very difficult.

Belowground (Soils)

The determination of belowground organic C dynamics in AFS is crucial for understanding the impact of the system on C sequestration, but it is difficult – more difficult than that for aboveground C. Organic C occurs in soils in a number of different forms including living root and hyphal biomass, microbial biomass, and as soil organic matter (SOM) in labile and more recalcitrant forms. Difficulties of separating these different forms and their complex interactions make measurement, estimation and prediction of soil C sequestration a daunting task. The most common method of estimating the amount of C sequestered in soils is based on soil analysis, whereby the C content in a sample of soil is determined (mass per unit mass of soil, such as g C per 100 g soil) and expressed usually in megagrams ($Mg = 10^6$ g or tons) per hectare.

Soil organic C (SOC) is often measured on a whole soil basis. The Walkley-Black procedure that used to be employed extensively in the past, and is perhaps used even now in some places, is no longer recommended because of concerns about the accuracy of determination (in view of the correction factor that is usually applied, leading to over- or underestimations) as well as environmental concerns due to the impact of the use of potassium dichromate (Kimble et al. 2001). Currently, many studies measure SOC by quantifying the amount of CO_2 produced through heating in a furnace. Other studies measure the change in weight of the sample after heating. However, the temperature used can vary; it needs to be standardized for accurate comparison of different studies. The presence of carbonates and charcoal in the soil can also skew results (Kimble et al. 2001). These measurements of C on a whole soil basis give information about total concentrations, but other analytical procedures are needed to determine details of the form and recalcitrance of the stored C as well as where it is stored. In order to gain a better understanding of such details of C sequestration in soils, attention has focused on the study of soil aggregates (Nair et al. 2010).

Since the majority of SOC is found in soil aggregates, understanding the structure and cycling of these aggregates will give us a better understanding of how C is entering, moving through, and leaving the soil, and thus the ability to predict future levels based on inputs and current conditions. By knowing the factors that are likely to influence aggregate formation and stability, we can predict the factors to be taken into consideration, and thus be able to better develop and adopt new agricultural and land management practices to optimize C sequestration both immediately and for the long term. Soil aggregate analyses, however, have not yet become a step in routine soil C determination.

Belowground Living Biomass

In addition to SOM, belowground biomass is a major C pool (Nadelhoffer and Raich 1992). However, belowground biomass is difficult to measure. The root-to-shoot ratio is therefore commonly used to estimate below ground living biomass. The ratios differ considerably among species (e.g., higher in palms than in dicot trees) and across ecological regions (e.g., higher in cold than in warm climates). In the absence of measured values, many researchers assume that the belowground biomass constitutes a defined portion of the aboveground biomass and the values so assumed range from 25% to 40% depending on such factors as nature of the plant and its root system and ecological conditions.

Modeling

In order to understand global carbon cycling, models that incorporate rates of terrestrial C cycling are used. Such models are based on a set of assumptions that are formed from our understanding of ecological processes including tree growth, and decomposition processes in the soil. The CENTURY and RothC models are the most widely used soil C models. The former models the cycling of C and other elements (phosphorus, nitrogen and sulfur) and their interactions, focusing specifically on the effects of species type and management practices such as tillage to model agricultural systems. It accounts for agricultural systems, forests, or savannas but not for integrated tree-crop systems such as agroforestry; adding agroforestry could be interesting and important to this model in order to improve its C sequestration estimates in global soils. The RothC model (Rothamsted model), based on the long-term experiments studying organic matter on the Rothamsted sites in England, takes into consideration organic pools in terms of how labile they are. Although the parameters of the model are comparatively simple, the model may not be quite appropriate for predictions of tropical agroforestry sites.

Numerous mathematical models have been developed to predict the response of SOM to agricultural practices at various scales, from soil profile or small plot scales to larger spatial extents, especially in response to the demand for national inventories of soil C sequestration potential (Viaud et al. 2010). Discussing such models, Nair et al. (2010) have noted that difficulties in obtaining information that is essential for the models could limit the applicability of the models to many tropical AFS. In general, models used in agroforestry research are developed for natural ecosystems and planted forests or agricultural systems; they rely on assumptions that are not fully relevant to AFS, and are often hard to incorporate into larger ecosystem models.

Global Estimates: Seeing the World for Trees and Forests

In the wake of increasing global initiatives and agreements such as REDD + (Reducing Emissions from Deforestation and Forest Degradation: www.un-redd.org: accessed 7 February 2011), various massive efforts are under way to assess the extent and health of the Earth's forests and other ecosystems. For example, ALERTS [Automated Land-change Evaluation, Reporting, and Tracking System: www.planetaryskin.org (accessed 7 February 2011), a unit of the Planetary Skin Institute (PSI), a not-for-profit organization set up jointly by NASA (the US National Aeronautics and Space Administration) and Cisco Systems, a large computing firm] is a decision support system – and one of several such tools – that has been launched in collaboration with several national agencies around the world to assess the actual weight of the world forest biomass and how much C they are storing. To calculate this, tree data such as DBH measured from sample plots are combined with images from NASA's 'super' cameras and satellites to estimate the plant biomass and therefore C in an area. As better ways of measurements and monitoring become more available, it will be possible to arrive at more accurate figures on amounts of CO_2 released from deforestation and forest degradation, used up in photosynthesis, and stored in "long-lived" above- and belowground compartments of ecosystems. They appear massive and impressive; nevertheless, their application in the short term and to small and scattered agroforestry plots sound uncertain. Furthermore, the accuracy and reliability of all these efforts depend on field measurements and calibration.

Methodological Challenges

As can be seen from the above, the methods and procedures adopted in collecting or estimating the data are quite inconsistent and are often incomparable and inconclusive. They vary widely in details of all aspects such as sampling, analytical methods, computations, data interpretation and presentation. This can greatly affect the conclusions made when comparing the differences under various management practices, soils, environments, social conditions, etc. Obviously, these problems and challenges have to be addressed; but that is not an easy or simple task. As a preliminary effort in that direction, let us analyze the major types of challenges and examine what, if anything at all, can be done until proper procedures are developed, tested, and put in place. But, first, the concept of C sequestration itself needs to be examined and understood.

The Concept of Carbon Sequestration

An important part of the UNFCCC definition of C sequestration is the secure storage C (CO_2) that is removed from the atmosphere in long-lived pools. There is considerable ambiguity in the understanding of this concept, especially when it comes to “long-lived” pools. The literature on C sequestration in land use systems, especially AFS, is not clear on this. Most reports equate C stock to C sequestration. Most such determinations are simple computations, in which aboveground biomass is estimated from arbitrarily chosen or general allometric equations; belowground biomass is considered as a fraction, usually 30%, of AGB, and 50% of the total biomass is taken as C stock (and sequestered C). Some reports do not specify if belowground biomass is factored into the estimations. In the case of soil, the C content as determined by soil analysis (which is then extrapolated to a region or country with or without the aid of remotely sensed or otherwise computed data) is expressed as C stock (= sequestered C).

Erroneous Assumptions

Estimations and computations of C stock in AFS as described above are approximations. Depending on the procedures used, the estimates may have deficiencies and inadequacies arising from both the assumptions used and the procedures adopted. Some of the commonly used assumptions and the errors involved in them are listed below:

- Carbon content in biomass is 50%. Often it is less than that.
- All biomass represents sequestered C. All biomass does not end up in “long-lived” pools. The foliage that falls on ground decomposes rapidly and releases CO_2 back to the atmosphere. The fraction of the biomass that can be considered as sequestered C is variable depending on a number of factors including the species, plant part, and ecological conditions.
- All C in soil represents sequestered C. Recent additions to organic C in surface soil through litterfall and external additions are subject to rapid decomposition and release of CO_2 with only a small percentage of it getting transformed to stable C in “long-lived” pools. If C stocks increase through time, that is a form of sequestration because the total amount is greater. These and other issues imply that there are some complexities to quantifying C sequestration and how it relates to C stocks.

- Carbon stock is the same as C sequestration: C sequestration is a rate process involving the time factor (e.g., Mg C ha^{-1} $year^{-1}$), whereas C stock (Mg ha^{-1}) does not have the time factor.
- Growth form of trees has little to do with root biomass. Differences in growth form of trees and management practices can lead to under- or over-estimations of root biomass.
- Amount of C sequestered is generally uniform for a given agroforestry practice. High levels of spatial heterogeneity exist among similar types of agroforestry practices at different locations such that extrapolation between one AFS and another or even from one area of an agroforestry farm to another can be misleading.

Operational Inadequacies and Inaccuracies

The procedures for collecting and processing plant- and soil samples for nutrient analyses and productivity measurements are well established; the lack of such procedures is not the issue in the context of this discussion; the "devil is in the details." The problem about the lack of rigorous allometric equations for estimating biomass has already been presented. The uncertainty arising from the lack of uniform methods for describing area under agroforestry (Nair et al. 2009; Udawatta and Jose 2011) is another difficulty in gauging the importance of agroforestry in carbon sequestration. While some progress has been made in resolving this puzzle in the tropical arena (thanks to the ICRAF-sponsored study, which, using geospatial analysis of remote sensing derived global datasets at 1 km resolution, reported the area under agroforestry as about one billion hectares of agricultural lands worldwide: Zomer et al. 2009), no such progress seems to have been made in assessing the area under agroforestry in the industrialized world. Additionally, a few of the common challenges, primarily in soil-related estimates, are considered briefly here.

Sampling depth: A major issue that lacks uniformity is soil sampling depth. Most soil studies are limited to the surface soils to 20 or 30 cm depth. The importance of sampling beyond the surface soil cannot be overemphasized while studying tree-based systems such as agroforestry, not only because tree roots extend to deeper soil horizons, but also because of the role of subsoil in long-term stabilization of C. The lack of uniformity in breaking points between soil-horizon depths is another procedural problem: results of a C study in the 0–5 cm surface horizon cannot realistically be compared with those of 0–50 cm study.

Sample preparation (sieve size): The 2 mm sieve that is almost universally used for preparing soils for laboratory analyses is also an issue to be considered. The fractions more than 2 mm in size (retained in the sieve) are often discarded; but they may constitute a sizeable amount of the soil and may contain some C (Howlett et al. 2011).

Pseudoreplication: Repeated sampling from the same contiguous experimental unit without true replicates of treatments is an issue that comes up often in sampling procedures in agroforestry field research. The purpose of replication is to reduce random or stochastic error and increase the precision of comparisons. Therefore, if true replicates are not used, the treatments cannot be statistically compared. While the results from such studies may still be valid, statistical comparisons between treatments may be invalid and the treatments cannot be declared as statistically different or not. While this is unquestionable in the statistical sense, the concept of replication needs to be taken into consideration in these discussions. For example, C stock is estimated based on samples drawn from existing field plots rather than replicated field experiments as in many ecological studies where pre-existing conditions are used for research. The question may arise as to what constitutes true replication in the case of treatments that extend over several hundred hectares of land as in some commercial agroforestry operations such as the silvopastoral systems in Brazil (Tonucci et al. 2011). Some argue that when a treatment occupies such a large area, randomly distributed sampling plots that are replicated within the "contiguous" unit itself but are quite far (200 m or more) from each other can be taken as having fulfilled the concept of replication. In such studies, spatial interspersion of replications together with the use of a systematic design is used to alleviate possible pseudoreplication problems (Stamps and Linit 1999; Peichl et al. 2006; Dube et al. 2011; Tonucci et al. 2011). Forestry researchers have used composite samples drawn from large experimental units as replicates considering the land use systems as fixed effect treatments (Lugo et al. 1990). In the statistical sense, a fixed effect model means that inferences are restricted to the treatments in the study; the results cannot be used to make conclusions about other agroforestry systems. The fixed effects model also applies to the so-called "repeated measures."

Repeated measures: These refer to measurements made in time or space on the same subject or experimental unit, such as a tree or a plot. For example, in agroforestry experiments, we may draw soil samples from depth increments from the same sites, or at defined horizontal distances from trees or transects. In experimental designs, measurements are made statistically independent by randomly assigning treatments to the experimental units. However, when time and space are considered as treatments, they cannot be randomly assigned; the depth/distance increments are treated as repeated measures rather than as independent measurements (Moser et al. 1990; Stern et al. 2004). The non-randomized nature of repeated measures designs often results in the violation of the assumptions necessary for valid univariate analysis. However, statistical procedures are available to address the limitations imposed by the model. In certain instances, standard univariate approaches, such as ANOVA (analysis of variance) with randomized block or split-plot models can be applied and valid tests of hypothesis obtained (Moser et al. 1990). In the case of soil depths at the same site, they could be stratified and each soil depth considered independently treating each site as a replication.

Chronosequence studies: Although some studies carry out chronosequences to see the change in C, these are few and not well standardized. Since changes in C stock is unlikely to be linear through time, understanding the nature of the curve of C storage over time is important to understand the periods when most C is being sequestered.

In addition, it is difficult to know if the residence time of C that is sequestered initially in a system differs from that of C that is sequestered later. Are the cycles that the initial C and later C additions go through the same? A large number of many such questions need to be answered for realistically assessing the impact of agroforestry and other management practices on C sequestration.

Calculations and Reporting of Results

The most common inconsistency in reporting C stock and C sequestration data in AFS from different locations is related to soil. Soil C stock is conventionally expressed in mass per area such as Mg C ha^{-1}. These data are derived by multiplying the analytical data, which is usually in mass per unit mass of soil (g C 100 g soil^{-1}) with the soil's bulk density (BD), which is expressed in mass per volume of soil (g cm^{-3} or Mg m^{-3}), and with soil (sampling) depth. There is an anomaly in this conversion because the BD value involves a volume measure whereas the C stock value is expressed in an area measure (ha). To overcome this, C stock reported in Mg ha^{-1} is assumed to be for 1 cm thickness (depth) of the soil unless the depth is otherwise specified. Thus, when the C stock to, say 40 cm or 100 cm depth is reported, that depth should be mentioned. Unfortunately, many reports on soil C stock in AFS, either do not report such details, or do not follow any uniform norm about the depth (for example, Table 3, Nair et al. 2010). This can lead to confusion and speculation when the data are compiled or compared. Based on the results accrued so far from AFS research (Nair et al. 2010), it seems fair to stipulate that soil C stock in AFS should be reported to at least 1 m depth.

The soil BD is an important factor in these computations, but is not reported in many research papers on soil C sequestration in AFS. Consider two soils, soil A and soil B, both with the same C concentration of 2 g C 100 g soil^{-1}, but with different BD values, 1.0 and 1.2 Mg m^{-3}, respectively. The total soil C stock to 1 m depth in the two soils will be as follows:

$$\text{Soil A}: 2.0\ \text{g}\ 100\text{g}^{-1} \times 1.0\ \text{Mg m}^{-3} \times 1\ \text{m} = 200\ \text{Mg ha}^{-1}$$
$$\text{Soil B}: 2.0\ \text{g}\ 100\text{g}^{-1} \times 1.2\ \text{Mg m}^{-3} \times 1\ \text{m} = 240\ \text{Mg ha}^{-1}$$

[Note that the units of ha (=10,000 m^2) and 1 m depth are used in the calculation.]

Thus, soil B will have 20% more C stock than soil A to the same depth although both soils have the same C concentration (It is a different matter if both soils have same C concentrations throughout the 1-m depth). The point here is that while estimating C stock to 1 m depth factoring in BD values, soil B consisted of 20% more soil mass than soil A. Such differences are often overlooked while compiling regional and global datasets based on "standard" values of soil C stock (Mg C ha^{-1}). Therefore, the influence of soil bulk density on measured C stocks is particularly important when comparing land use treatments that result in different BD values, as may be the case with AFS compared with annual crops or pastures. The problem is compounded when soil depth, to which the value reported is related, is not specified. These highlight the importance of reporting soil BD data and soil depth on the one hand, and the need for exercising caution while using reported values of soil C sequestration on the other.

Another issue is the "one-size fits all" approach to computations of regional and global statistics. Currently, most policy documents and projections including major ones such as the IPCC reports have the tendency to assign a single, uniform value or sets of narrow-range values, for C stock and C sequestration potential of AFS irrespective of their site conditions and system characteristics. For example, the IPCC estimated a global value of 630 million hectares of unproductive croplands and grasslands that could be converted to agroforestry and could potentially sequester 1.43 and 2.15 Tg (10^{12}g = megatons) of CO_2 annually by 2010 and 2040, respectively (IPCC 2000). Several other such estimates are also available (for example, MIT, 2010, Mission 2013, Carbon sequestration, Massachusetts Institute of Technology: http://igutek.scripts.mit.edu/terrascope/index.php?page=Agroforestry, accessed 13 February 2011). It is important that the variability among soils to store C is factored into such global estimates and projections.

Conclusions

Carbon sequestration in land use systems is a rather loosely defined concept. Several methodological challenges, arising from difficulties related to sampling, analysis, computations, and interpretation make its measurement a difficult task. These difficulties are of a higher magnitude in the case of AFS because often the systems involve complex multispecies combinations and the measurements are made from pre-existing sites rather than randomized and replicated experiments. There is no easy, fast, and pragmatic solution to these issues in the short term. In the circumstances what can the common researcher do? The author's recommendation is that before setting out to undertake the study, the researcher should think through the problems they might encounter while reporting the results. While reporting results, they should describe accurately how the data were collected, analyzed, and managed. That means, explaining unambiguously how the samples were drawn, estimations were made and computations were calculated for extrapolation to broader scale such as Mg ha^{-1}. Such a clear presentation of the results will make it possible for researchers at large to understand and decide whether, how, and to what extent to incorporate the reported results in larger databases, and help agroforestry earn its deserving place in the mainstream of such efforts. Mistakes might be made; but that is better than not doing anything for fear of making mistakes. In this era of rapid progression of science and efforts to understand and quantify the underexploited ecosystem services, agroforestry researchers have to position themselves to ensure that agroforestry is not left behind in these global efforts, because, only what gets measured gets recognized and managed.

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References

Basuki TM, van Laake PE, Skidmore AK, Hussin YA (2009) Allometric equations for estimating the above-ground biomass in tropical lowland dipterocarp forests. For Ecol Manag 257:1684–1694

Brown S (1997) Estimating biomass and biomass change of tropical forests: a primer. FAO Forestry paper 134, Rome, 55 p

Chave J, Andalo A, Brown S, Cairns MA, Chambers JQ, Eamus D, Fölster H, Fromard F, Higuchi N, Kira T, Lescure J-P, Nelson BW, Ogawa H, Puig H, Riéra B, Yamakura T (2005) Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oceologia 145:87–99

Dixon RK, Winjum JK, Schroeder PE (1993) Conservation and sequestration of carbon: the potential of forest and agroforest management practices. Global Environ Chang 2:159–173

Dixon RK, Wimjum JK, Lee JJ, Schroeder PE (1994) Integrated systems: assessing of promising agroforest and alternative land use practices to enhance carbon conservation and sequestration. Clim Chn 30:1–23

Dube F, Thevathasan NV, Zagal E, Gordon AM, Stolpe NB, Espinosa M (2011) Carbon sequestration potential of silvopastoral and other land use systems in the Chilean Patagonia. In: Kumar BM, Nair PKR (eds.) Carbon sequestration potential of agroforestry systems: opportunities and challenges. Springer, Dordrecht, pp 101–127

FAO (2004) Assessing carbon stocks and modelling win–win scenarios of carbon sequestration through land-use changes. FAO, Rome. Available at http://www.fao.org/docrep/007/y5490e/y5490e00.htm. Accessed 13 Feb 2011

Fernández-Núñez E, Rigueiro-Rodríguez A, Mosquera-Losadaa MR (2010) Carbon allocation dynamics one decade after afforestation with *Pinus radiata* D. Don and *Betula alba* L. under two stand densities in NW Spain. Ecol Eng 36:876–890

Gold MA, Garrett HE (2009) Agroforestry nomenclature, concepts, and practices. In: Garrett HE (ed.) North American Agroforestry: an integrated science and practice, 2nd edn. American Society of Agronomy, Madison, pp 45–55

Haile SG, Nair PKR, Nair VD (2008) Carbon storage of different soil-size fractions in Florida silvopastoral systems. J Environ Qual 37:1789–1797

Howlett DS, Mosquera-Losada MR, Nair PKR, Nair VD, Rigueiro-Rodríguez A (2011) Soil C storage in silvopastoral systems and a treeless pasture in northwestern Spain. J Environ Qual 40:784–790. doi:10.2134/jeq2010.0145

IPCC (Intergovernmental Panel on Climate Change) (2000) In: Watson RT, Noble IR, Bolin B, Ravindranath NH, Verardo DJ, Dokken DJ (eds.) Land use, land-use change, and forestry. A special report of the IPCC. Cambridge University Press, Cambridge, 375 p

Kimble JM, Lal R, Follett RF (2001) Methods for assessing soil C pools. In: Lal R, Kimble JM, Follett RF, Stewart BA (eds.) Assessment methods for soil carbon. Lewis Publishers, Boca Raton, pp 3–12

Kirby KR, Potvin C (2007) Variation in carbon storage among tree species: implications for the management of a small-scale carbon sink project. For Ecol Manag 246:208–221

Kumar BM, George SJ, Jamaludheen V, Suresh TK (1998) Comparison of biomass production, tree allometry and nutrient use efficiency of multipurpose trees grown in wood lot and silvopastoral experiments in Kerala, India. For Ecol Manag 112:145–163

Lal R (2010) Managing soils and ecosystems for mitigating anthropogenic carbon emissions and advancing global food security. Bioscience 60:708–721

Lugo AE, Cuevas E, Sanchez MJ (1990) Nutrients and mass in litter and soil of ten tropical tree plantations. Plant Soil 125:263–280

Moser EB, Saxton AM, Pezeshki SR (1990) Repeated measures analysis of variance: application to tree research. Can J For Res 20:524–535

Nadelhoffer KJ, Raich JW (1992) Fine root production estimates and belowground carbon allocation in forest ecosystems. Ecology 73:1139–1147

Nair PKR, Kumar BM, Nair VD (2009) Agroforestry as a strategy for carbon sequestration. J Plant Nutr Soil Sci 172:10–23

Nair PKR, Nair VD, Kumar BM, Showalter JM (2010) Carbon sequestration in agroforestry systems. Adv Agron 108:237–307

Palm C, Tomich T, Van Noordwijk M, Vosti S, Alegre J, Gockowski J, Verchot L (2004) Mitigating GHG emissions in the humid tropics: case studies from the Alternatives to Slash-and-Burn Program (ASB). Environ Dev Sust 6:145–162

Pearson T, Walker S, Brown S (2005) Sourcebook for land use, land use change and forestry project. Winrock International and the BioCarbon Fund of the World Bank, Washington DC, 64 p. Available at http://www.winrock.org/ecosystems/files/winrock-biocarbon_fund_sourcebook-compressed.pdf. Accessed 13 Feb 2011

Peichl M, Thevathasan NV, Gordon AM, Huss J, Abohassan R (2006) Carbon sequestration potentials in temperate tree-based intercropping systems, southern Ontario, Canada. Agroforest Syst 66:243–257

Roshetko JM, Delaney M, Hairiah K, Purnomosidhi P (2002) Carbon stocks in Indonesian homegarden systems: can smallholder systems be targeted for increased carbon storage? Am J Altern Agric 17:138–148

Schroeder P (1994) Carbon storage benefits of agroforestry systems. Agroforest Syst 27:89–97

Stamps WT, Linit MJ (1999) The problem of experimental design in temperate agroforestry. Agroforest Syst 44:187–196

Stern RD, Coe R, Allan EF, Dale IC (2004) Good statistical practice for natural resources research. CABI, Wallingford, UK, 388p

Takimoto A, Nair PKR, Nair VD (2008) Carbon stock and sequestration potential of traditional and improved agroforestry systems in the West African Sahel. Agric Ecosyst Environ 125:159–166

Tonucci RG, Garcia R, Nair PKR, Nair VD, Bernardino FS (2011) Soil carbon storage in silvopasture and related land-use systems in the Brazilian cerrado. J Environ Qual 40:833–841. doi:10.2134/jeq2010.0162

Udawatta RP, Jose S (2011) Carbon sequestration potential of agroforestry practices in temperate North America. In: Kumar BM, Nair PKR (eds.) Carbon sequestration potential of agroforestry Systems: opportunities and challenges. Springer, Dordrecht, pp 17–42

UNFCCC (2006) Revised simplified baseline and monitoring methodologies for selected small-scale afforestation and reforestation project activities under the clean development mechanism. Bonn. Available at http://cdm.unfccc.int/UserManagement/FileStorage/CDMWF_AM_A3II6AX6KGW5GBB7M6AI98UD3W59X4. Accessed 7 Feb 2011

UNFCCC (2007) Report of the conference of parties on its thirteenth session, Bali, Indonesia. United nations framework convention on climate change, Geneva

Viaud V, Angers D, Walter C (2010) Toward landscape-scale modeling of soil organic matter dynamics in agroecosystems. Soil Sci Soc Am J 74:1847–1860

Zomer RJ, Trabucco A, Coe R, Place F (2009). Trees on farm: an analysis of global extent and geographical patterns of agroforestry. ICRAF Working paper no. 89. World Agroforestry Centre, Nairobi. Available at http://www.worldagroforestry.org/downloads/publications/PDFs/WP16263.PDF. Accessed 13 Feb 2011