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'Solid–fluid–gas': the state of knowledge on carbon-sequestration potential of agroforestry systems in Africa

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Abstract

The perception that agroforestry systems have higher potential to sequester carbon than comparable single-species crop systems or pasture systems is based on solid scientific foundation. However, the estimates of carbon stock of agroforestry systems in Africa — reported to range from 1.0 to 18.0 Mg C ha^{-1} in aboveground biomass and up to 200 Mg C ha^{-1} in soils, and their C sequestration potential from 0.4 to 3.5 Mg C ha^{-1} yr^{-1}–are based on generalizations and vague or faulty assumptions and therefore are of poor scientific value. Although agroforestry initiatives are promising pathways for climate-change mitigation, rigorous scientific procedures of carbon sequestration estimations are needed for realizing their full potential.

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Introduction

The importance of carbon (C) sequestration in mitigating climate change needs no special introduction. Numerous reports are available on C sequestration potential of various agroforestry systems (AFS) from different parts of the world including Africa [1••,2]. They all portray the perception that AFS have higher potential to sequester C than comparable single-species crop systems or pasture systems. The underlying premise of this perception is the niche complementarity hypothesis, which states that a larger array of species in a system leads to a broader spectrum of resource utilization making the system more productive [3: Tilman 1990], and implies that plant species in a mixed system use resources in a complementary way [4: Kahmen *et al.*, 2006]. However, in spite of this commonality in the perception and its underlying premise, enormous variability exists in these reports in terms of the nature, rigor, and details of studies, so that it becomes difficult to compare the datasets based on uniform criteria to draw widely applicable conclusions. In other words, the poor quality (high degree of variability and lack of rigor in the reported results) of available reports seriously limit their potential use for arriving at widely applicable land-management decisions and recommendations. The objective of this paper is to summarize the reported results of C sequestration potential of AFS in Africa and highlight the common methodological weaknesses and drawbacks in the reported data so that future efforts could endeavor to overcome such problems.

Carbon sequestration potential of agroforestry systems: what the literature shows

A comprehensive literature search was conducted on C sequestration in AFS, including reports that are directly related to AFS as well as those of a methodological nature that are relevant to AFS: see http://sfrc.ufl.edu/pdf/faculty/nair_afcsliterature.pdf for the nearly 600 references. Among these, the most frequently quoted and/or recent references that focused on AFS include [1••,2,5,6,7,8,9,10,11,12•,13,14,15••,16–28], whereas those of a broader and methodological nature include [29–48,49••,50–52,53•,54–56]. Following that compilation, the various AFS reported in the literature were grouped under five subgroups [Table 1]. The reported C sequestration values from 22 countries representing different ecoregions of Africa were then compiled including details such as agroecological characteristics (location, climate, major trees and crops), and values of C sequestration aboveground and in soils [PKR Nair, unpublished]. The estimated C sequestration rates for the different AF systems across Africa from this dataset are summarized in Table 2 [18].

Common problems and weaknesses in the reported data

In general, the reported values [Table 2] are mostly speculative, based on circumstantial and experiential rather than empirical and experimental evidence. Even the few that are empirical are not based on uniform or rigorous procedures, and have high variability. Although this is common to many aspects of agroforestry, it is particularly so in the case of carbon sequestration and climate-change-mitigation discussions partly because these are trendy and fashionable subjects to talk about. The extreme site-specificity of AFS also contributes to the lack of uniformity in

Table 1

Subgroups of Agroforestry Systems (AFS): major forms of agroforestry and their agroecological distribution in the tropics.

AFS subgroup	Major forms of agroforestry	Major agroecological distribution in the tropics
Tree intercropping	Alley cropping, improved fallows	Regions with >800 mm rain/yr;
	Multipurpose trees (MPTs) on farmlands	Throughout the tropics
Multistrata systems	Homegardens	Tropical wet (mostly elevations up to 1000 m asal)
	Shaded perennials	Wet, Moist & Montane regions with >1000 mm rain/yr
Silvopasture	Browsing, cut-and-carry	Tropical wet and moist regions
	Trees on pasture/grazing lands	Semiarid to arid regions
Protective systems	Windbreaks, shelterbelts	Tropical dry (arid, semiarid), coastal regions
	Soil conservation hedges	Sloping areas: moist, montane
	Boundary planting	Throughout
Agroforestry tree woodlots	Woodlots for firewood, fodder, land reclamation	Dry: firewood; land reclamation trop wet & moist: fodder; Land reclamation: eroded/degraded lands)

Source: Nair [18].

assessment methodologies. The systems even within a region vary considerably in structure (arrangements of components), function (expected outputs), species diversity (of crops and trees), management, and socioeconomics, such that no two agroforestry fields are identical. As a result, the reported research results vary extremely in the methods used and/or level of details reported. Therefore it is difficult to subject such results to integrated analyses such as meta-analysis and other well-known statistical tools used to elucidate trends among a disparate set of studies with different experimental approaches and methods. Furthermore, most published studies are of short duration, which cannot be used for predicting long-term consequences. Difficulty to model discontinuous multispecies stands also adds to the problem. Most models used in forestry (for estimating stand volume, C content, growth patterns, among others) have been developed for continuous, single-species stands; agroforestry systems represent discreet stands of multiple species; trying to apply available forestry models to study AFS presents the 'round-peg-in-square-hole' situation.

Each of the above difficulties could be discussed in detail. For reasons of brevity, however, only some of issues that are specific to C sequestration studies in AFS are discussed in some detail here.

Biomass

Tree biomass

As discussed by Nair *et al.* [1••] and Malmer *et al.* [53•], extensive estimations of global forest biomass are based on rough estimations: mostly estimating the stem-wood volume and multiplying it with species-specific wood density, and other 'correction factors' to get an estimation of whole-tree biomass. Such estimations have mostly been done for forest ecosystems with attempts to extrapolating them to AFS at a global scale [e.g. 40: Dixon *et al*., 1993]. Carbon content is assumed to be 50% of the estimated whole-tree biomass, and root biomass is generally excluded. Although whole-tree harvesting method, which involves summing up the amount of harvested and standing biomass, has traditionally been used for more accurate estimations of tree biomass, the extremely

Table 2

Estimates of carbon stock and carbon sequestration potential under major agroforestry systems (AFS) in Africa[a].

AFS subgroup	Major agroforestry practices	Estimated carbon stock ($Mg\ ha^{-1}$)		Carbon sequestration potential ($Mg\ ha^{-1}\ yr^{-1}$)	
		Aboveground	Soils	Aboveground	Soils
Tree intercropping	Alley cropping, improved fallows	Up to 15	Up to 150	0.5–4.0	1.5–3.5
	MPTs on farmlands	Up to 12	Very low to 150	0.2–2.5	1.5–3.5
Multistrata systems	Homegardens	2–18	Up to 200	0.5–3.0	1.5–3.5
	Shaded perennials	5–15	Up to 300	1.0–4.0	1.0–5.0
Silvopasture	Browsing, cut and carry	1.8–3.0	1.5–3.5 low to 80	0.3–4.0	1.0–2.5
	Trees on pasture/grazing lands	1.5–8.0	Very low to 60	0.3–2.0	0.4–1.0
Protective systems	Windbreaks, shelterbelts Soil conservation hedges Boundary planting	1.5–7.0	Very low to 60	0.7–2.0	0.4–1.0
AF Tree Woodlots	Woodlots for firewood, fodder, land reclamation	(Highly variable)	Very low to 60	1.0–5.0	1.0–6.0

Source: Nair [18].

[a] Estimated based on reported literature values.

tedious nature of the method limits its application to research purposes only.

Allometric equations developed based on biophysical properties of trees and validated by occasional measurements of destructive sampling are widely used in forestry for estimating volumes of standing forests. These 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. Various allometric equations have been developed for different forest types and forestry species [53•]; similar studies are now being undertaken for some trees in AFS as well [46–48,54]. ICRAF's databases for tree characteristics such as wood density are valuable resources for such efforts (http://www.worldagroforestrycentre.org/sea/products/afdbases/af/asp/SpeciesInfo).

Crop biomass

Unlike the multipurpose trees that are common in AFS, there are no specific agroforestry crops. Most, if not all, of the common agricultural crops grown in a given locality are grown in AF systems as well. Just as in agricultural systems, choice of crops is determined by the local ecological (climate, soil) and socioeconomic factors. Most crops in AFS are herbaceous annuals (except the shaded perennials such as cacao [*Theobroma cacao*], coffee [*Coffea* spp.], tea [*Camellia sinensis*], and black pepper [*Piper nigrum*]). These annuals have high harvest index values (proportion of harvested economic productivity to total biological productivity aboveground), and therefore their biomass contribution to total C sequestration in an AFS is relatively less, compared with trees and perennial shrubs.

Belowground biomass

In general, roots are believed to account for a third of the total NPP (net primary productivity). However, it is very difficult to measure this fraction. The root-to-shoot ratio is therefore commonly used to estimate below ground living biomass. The ratios differ considerably among species and across ecological regions. The living microbial biomass constitutes roughly 1% of the total SOC (soil organic C). In spite of the low total amount of C involved in this pool, it is an important indicator of organic matter decomposition and C sequestration though the breakdown or tying-up of C and their relationship to soil aggregates.

Soils

Soils play a vital role in the global C cycle [7,35] and soil C that traditionally has been a sustainability indicator of agricultural systems has now acquired the additional role as an indicator of environmental health [45,46]. Recent studies have confirmed the niche complementarity hypothesis in relation to soil C sequestration (SCS) in AFS [1••]. However, as mentioned before in the context of AFS in general, the estimated values of SCS in AFS vary greatly depending on biophysical and socioeconomic characteristics of the system parameters and because of the lack of uniformity in study procedures such as depth of sampling and soil analytical procedures. Another major drawback is the lack of essential information about the soils in many reports (e.g. soil bulk density) that are crucial for comparison and extrapolation of data [15••] on SCS.

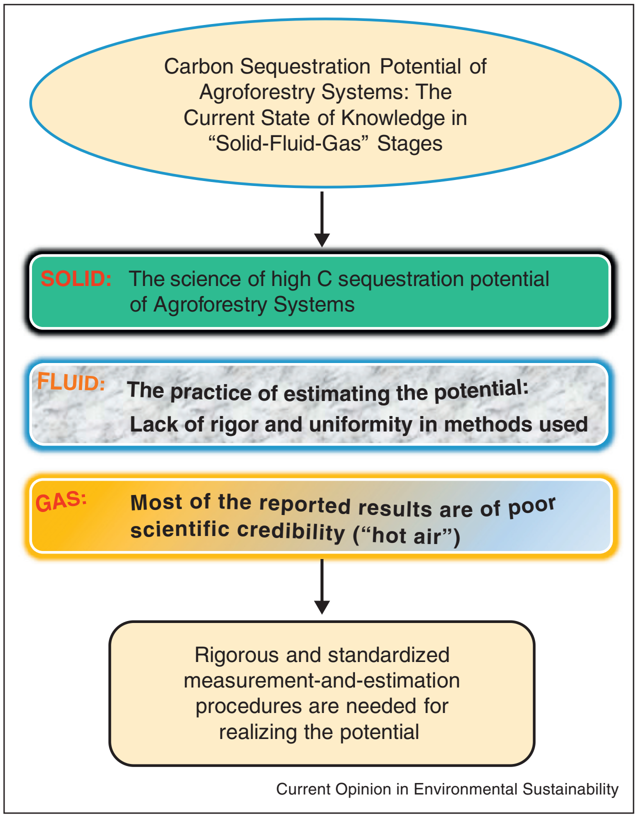
Erroneous assumptions

An important part of the UNFCCC (United Nations Framework Convention on Climate Change) 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.

Furthermore, the estimations and computations of C stock in AFS are approximations and are based on several assumptions, at least some of which are erroneous. For example:

- '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.
- 'Tree biomass (and C) estimates based on existing biomass equations are applicable to agroforestry situations.' Most of the existing biomass equations are based on trees growing either in closely spaced plantation or natural stands; they do not give good biomass estimates for open-grown (widely spaced or scattered) agroforestry trees that could be different in their growth form.
- 'All C in soil represents sequestered C.' Recent C additions to surface soil through litterfall and external additions are subject to rapid decomposition and release of CO_2, with only a small percentage of C becoming stable C in 'long-lived' pools. If C stocks increase through time, that is a form of sequestration.
- 'Carbon stock is the same as C sequestration.' C sequestration is a rate process involving the time factor (e.g. $Mg\ C\ ha^{-1}\ yr^{-1}$); 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-estimations or over-estimations of root biomass.

Figure 1



The current state of knowledge on carbon sequestration potential of agroforestry systems in Africa. Although the science is solid, the methods of estimation are 'fluid' (imprecise), and therefore the available estimates constitute mostly 'hot air'.

- 'Amount of C sequestered is generally uniform for a given agroforestry practice.' High levels of spatial heterogeneity exist among similar agroforestry practices at different locations such that extrapolation across systems and locations can be misleading.

Future directions

On the basis of the synthesis presented above, the current state of knowledge on carbon sequestration in agroforestry systems in Africa can be said to be in a 'solid–fluid–gas' situation as depicted in Figure 1. The gist of the figure is that while the scientific principles support the premise that agroforestry systems have higher carbon sequestration potential than single-species crop systems or pasture systems, the procedures used for estimating CSP are in a 'fluid' state as they are based on generalizations and vague or faulty assumptions, and therefore the estimates lack scientific credibility ('hot air').

Several uncertainties and deficiencies need to be addressed for resolving this problem. These include issues that are of a general nature common to all land-use systems, and others that are specific to AFS. A major general issue is the lack of understanding about carbon dynamics in soils. It is not clearly known 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? 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. Well-planned, process-oriented research is needed to gain clear insights into such issues.

Coming to issues that are specific to AFS, all studies on C sequestration under AFS referred to in the References section of this report are of a short-term nature (less than five years). Chronosequence studies are very important to monitor long-term change in soil C in land-use systems; but no such studies involving AFS have been reported. Furthermore, the lack of uniform methods for describing area under agroforestry is a problem in gauging the importance of agroforestry in carbon sequestration on a regional or larger scale. Estimates of area under AFS that have recently become available [15••,16,29] suggest that while the area under AFS is a little over 1.0 billion ha (2009), there is potential to bring up to 1.6 billion ha under AFS in the near future globally [15••].

A large number of such questions need to be answered for realistically assessing the impact of agroforestry and other management practices on C sequestration. First and foremost, the methodologies for estimating C sequestration need to be standardized. At the same time, efforts could be initiated to set up a 'Carbon Reference Database for Agroforestry Systems (CRD-AFS)' as an approach to estimating carbon benefits of AFS [PKR Nair, unpublished]. The CRD-AFS is an ecological approach based on the premise that the productivity of a land-use system is determined primarily by its ecological features, especially for low-management, low-input systems such as agroforestry. Its essence is a Standard Reference Guide (SRG), a computerized database, which will include relevant drop-down menu for narrowing down to the ecological and system characteristics of any AFS in any region or country. The anticipated range of values for C stock and C sequestration potential for the system could be deduced by referring to the SRG. The database should be updated continuously based on field measurements and new scientific data. The tool is practical and easy to use; it does not involve complicated on-site measurements and computations every time it is used. If properly constructed and rigorously maintained, the tool will be a significant contribution to AFS carbon calculations worldwide. Organized global efforts are needed to undertake such efforts, which could possibly be under the auspices of IPCC (Intergovernmental Panel on Climate Change) with ICRAF (the World Agroforestry

Centre), the only international institution for agroforestry, providing the needed stimulus and leadership.

Conclusions

The lack of rigorous but simple scientific procedures for estimating and reporting the carbon sequestration potential of agroforestry systems seriously affects the quality and usefulness of the available reports and makes it difficult to compare the differences under various management practices, soils, environments, social conditions, among others. In order to capitalize on the high potential for climate change mitigation through carbon sequestration offered by agroforestry systems, the procedures of measuring and estimating C sequestration need to be rigorous and standardized. International efforts should be stepped up to address this issue.

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