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Modelling soil organic carbon in agroforestry system

Agroforestry is a form of productive land management that includes the combination of perennial (in general woody) and annual crops. Although the concept is present in traditional agriculture in several parts of the world, this particular form of cultivation is gaining importance due to the benefits it can bring in terms of food security and increased soil organic carbon (SOC) sequestration, compared to conventional agriculture. The aim of an AgriFoSe2030 supported project, Agroforestry Carbon balance, was to integrate knowledge available from agroforestry experiments across the world and produce a model tool for predicting agroforestry SOC sequestration. The resulting model (ICBMAgro) can be utilized for planning land use and forecast SOC sequestration outcomes and provides a useful tool for both farmers and policy makers.

Key messages

- Soil organic carbon (SOC) sequestration potential in agroforestry is often reported as average rates. This is unrealistic for time scales of decades, and the consequent error in predictions can lead to mistakes in mid-term policy decisions.
- The reporting of carbon stocks for agroforestry systems must instead consider that sequestration rates vary greatly over time.
- The developed model has the advantage of being the simplest possible structure for a compartmental SOC model. It is therefore relatively easy to use and understand also in situations where data are scarce or uncertain.
- We recommend this approach whenever agroforestry systems should be considered for their benefits and compared with other possible management in terms of carbon sequestration, especially on time scales longer than scale longer than just a few years.

Modelling SOC in agroforestry systems

Agroforestry systems can be diverse, and this variety is often difficult to account for with detailed SOC models (see Box 1). This, together with the relatively little amount of data available, is one of the reasons causing agroforestry SOC sequestration data, measured with field experiments, to be reported only as average linear sequestration rates over the duration of an experiment. However, such an approach makes it difficult to compare results in reality as sequestration rates are variable over time (further explained in Box 1). A rate calculated over a 3 years experiment will not give realistic predictions, when applied over a long-term period, and we cannot base mid-term planning on such approach. Moreover, SOC sequestration rates are also strongly dependent on the former carbon stocks of the soil where the agroforestry system is established. If SOC

Box 1: Soil organic carbon (SOC) models: what are they and why do we need them?

Soil carbon is a parameter for many ecosystem services such as soil fertility and greenhouse gas regulation (since more carbon in the soil means less CO2 in the atmosphere). It also contributes to positive climate change adaptation, since a soil with more carbon retains more water and is less prone to erosion. By increasing SOC we can, for example, decrease the greenhouse gases in the atmosphere and thus reduce their climate change impact. SOC can also increase soil fertility and soil water retention potential, thus mitigating climate change effects and increasing food security. A loss in carbon stored in the soil can, in turn, lead to decreased soil fertility and even desertification.

SOC levels are highly sensitive to land management practices, and we can lose or gain a lot of carbon in a few decades depending on our choices. In order to maintain, and possibly increase, SOC we need to plan land management based on current estimates of the carbon stored in soil, and predictions of such storage in the future. This is where models came to help. SOC in the development of more reliable models provide a representation of what happens to SOC with varying parameters, mostly land management practices and time. For example models can answer to the questions *"How much soil carbon will we have in thirty years from now in this field, if we convert it to agroforestry, and how much will we have with the current practices?"*.

sequestration is measured in an experiment on a carbon-rich soil, those results cannot be compared to another agroforestry conversion system if that soil is poor in carbon, as results will vary significantly between these two contexts, even on short time scales.

Long-term experiments measuring SOC sequestration for agroforestry systems are currently missing and we need to consider the changes in soil carbon triggered by our management choices in order to choose the best option, but we need to do so with predictions on a long-term time scale (30-50 years), for which we do not have direct measurements.

Lacking direct measurements, we, therefore, need to rely on SOC models, which extrapolate information from many sources and experiments to predict the consequences of a certain land use change in regard to its ability to release or store carbon in the future. It is therefore of paramount importance to enable comparison of different management approaches and choose the most effective in the trade-off between SOC sequestration and other ecosystem services such as food production, based on investment plans longer than a few years. SOC models need to be accurate for managing the available resources (for example land) in the most effective way.

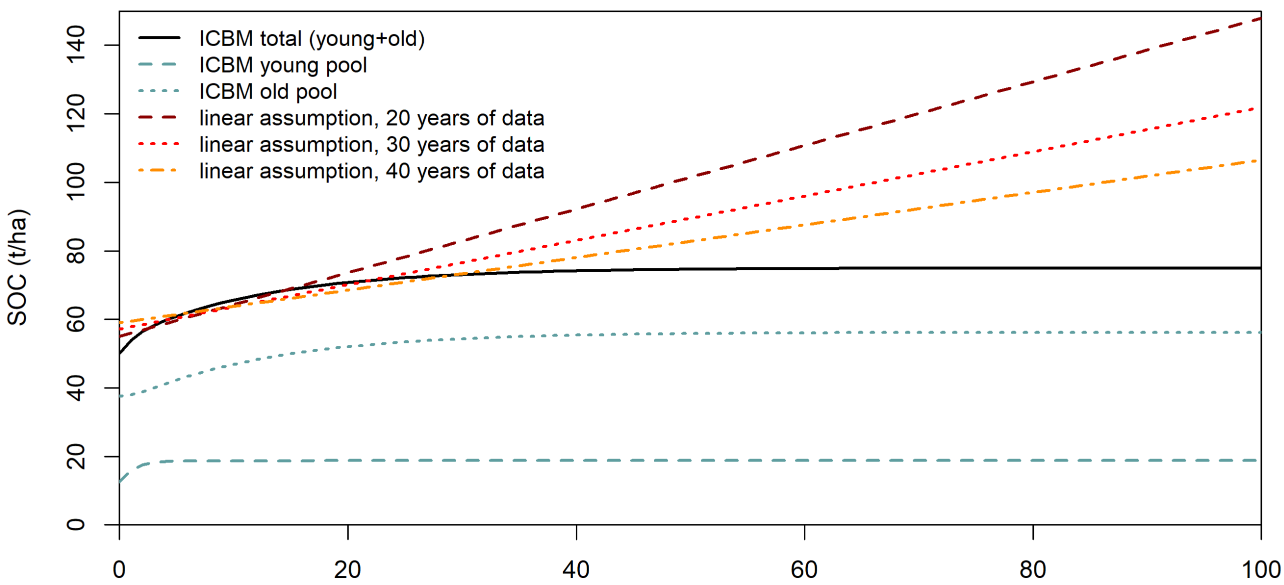


Figure 1: The difference between average sequestration rates (line) and a first-order model (the exponential curve)

Developing more reliable SOC models

To describe, predict and compare SOC sequestration when converting for example intensive crop cultivation to agroforestry we need to simulate SOC in the systems over several decades. Due to the diversity of agroforestry systems, the SOC sequestration models must be able to accommodate variable input data, for example considering the photosynthetic productivity. These highly variable data are difficult to use and cause the final predictions to be highly uncertain.

The only way to deal with such uncertainty is to quantify it and consider it in the SOC predictions, which also implies implementing risk management strategies (considering therefore the uncertainty of the predictions) to decide between different alternatives relying on data with significant uncertainties. This, in turn, result in that those climate risk strategies remain uncertain.

The main aim of the AgriFoSe2030 supported project agriculture-focused Introductory Carbon Balance Model (hereinafter ICBMAgro) was to integrate knowledge available from agroforestry experiments over the world and produce a model tool for reporting agroforestry SOC sequestration data compatible with, and with same precision as in the IPCC Tier II-III model approaches. This allows for predictions of soil and agricultural management consequences over decades, and it enables a comparison between different systems regardless of the initial conditions.

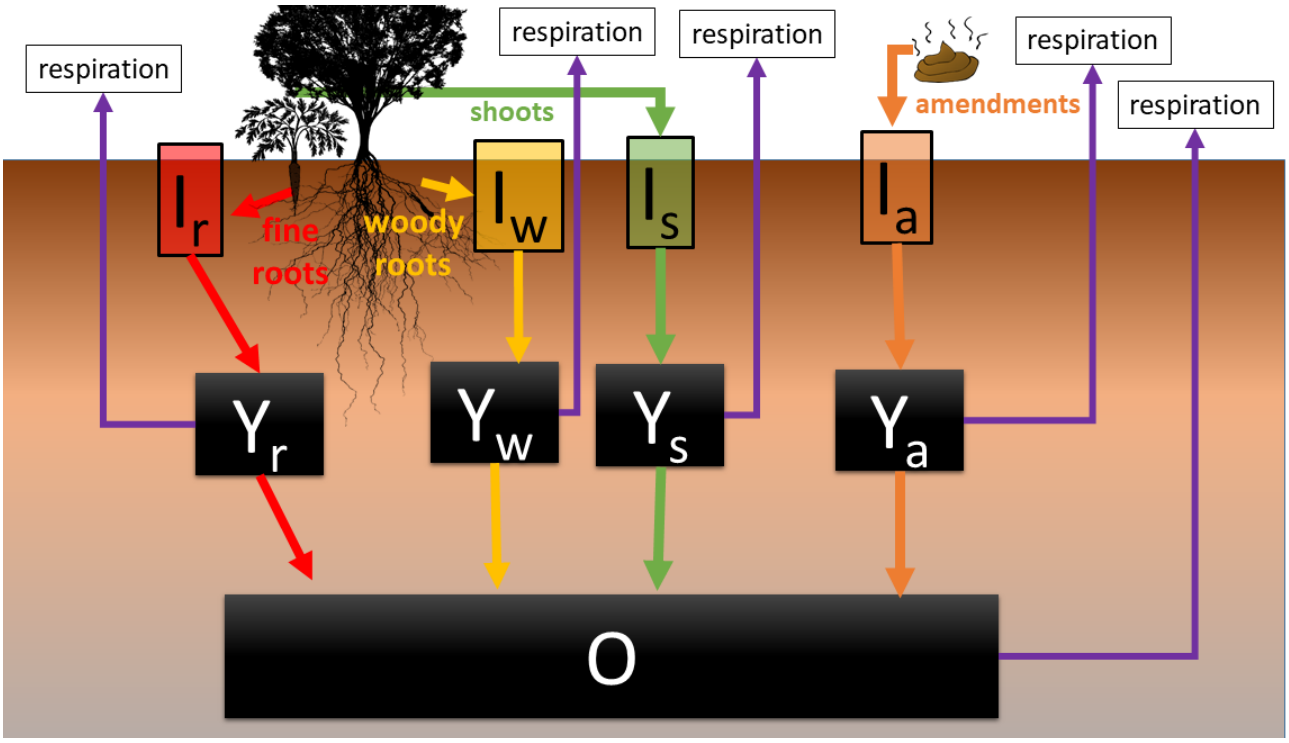
ICBMagro is a SOC model focused on minimalism, and it is one of the simplest SOC models in its class. In adapting the ICBMagro model to the agroforestry systems, (Figure 2) we calibrated it within a Bayesian framework on global agroforestry data. Bayesian statistic considers our degree of knowledge of something as a continuous function before and after some observations, and updates it with new knowledge from the observations. The Bayesian approach allows for estimating the uncertainty of predictions in model usage. Knowing the uncertainty of the predictions allows to plan strategies that can take care of climate risk management.

Our model can be used to plan land use and to forecast the outcome in terms of carbon sequestration of a small agroforestry conversion as well as the effect of a regional policy. It is therefore potentially useful both to farmers, since an increase in organic matter is in general linked with soil fertility besides its carbon sequestration benefits, and to policymakers, for which an increased carbon sequestration also is an important target. Given the model accessibility at this stage (which requires some basic scientific programming skills), the model is probably more suited to be applied either into policymaking processes (so on a relatively large scale that can afford to pay a specialist for SOC forecasting) or for farmers through consultancy companies.

Box 2: Main soil organic carbon (SOC) models approaches

There are many SOC models (for example Century, Yasso or RothC), but they all fall under three major classes:

- **Zero order models:** where the variation of SOC is described as a fixed amount every year. These fixed sequestration rates are what is used in the UNFCCC IPCC TIER I approach (Figure 1). This approach has quite limited validity, however, since over mid-term time scales (e.g. 10 years) this assumption is not realistic as SOC rates change over time as a result of a large number of parameters (such as climatic factors and land management practices).
- **First order models:** that describe SOC variation as proportional to the amount of carbon in the soil. For example, a particularly carbon-rich soil will lose more carbon mass than a poor one each year if converted to intensive agriculture. This causes rates to vary over time. These variable sequestration rates is what is used in IPCC TIER II and III approaches (Figure 1) and are valid over multi-decadal time scales.
- **Second or higher order:** that describe the variation of SOC as proportional to the amount of carbon in the soil and to other variables varying over time, for example microbial biomass. These models are at the moment highly experimental and in general not viable for practical applications over big spatial scales.



The ICBMagro model structure representing the mass fluxes between the model components. Letters r, w, s and a represent the different input classes (roots, woody root, shoots and amendments, respectively), while the capital letters represent the different pools (I for inputs, Y for the young pools and O for the old pool).

Ways forward

To properly consider the impact of agroforestry management on SOC, and therefore to decide between different possible land use options, it is crucial to use models with variable SOC sequestration rates if the time scale of the intervention is more than a few years. Although agroforestry systems still present a high degree of uncertainty for models compared to other land uses, such as agriculture or forestry, their carbon balance can be estimated with first-order models. It can be done through calibration tools that can take into account the the uncertainty of data.

By using the model for SOC forecasting it will be possible to select more effectively which type of land use can be the most effective in terms of SOC sequestration. It can bring both benefits for the society in its whole in terms of climate mitigation, as well as benefits for local communities in terms of soil fertility and water retention.

I suggest the implementation of the model on two levels:

1. Policymaking in support of climate change mitigation and carbon sequestering, for example by assessing the potential in terms of SOC sequestration of agroforestry incentives or related policies. The model could be used for producing reference tables for a specific region. It could consider different starting conditions for the conversions of conventional systems to agroforestry.
2. Supporting local decision making, for example at a farm scale where the model can be applied by farm consultancy companies or state-run organizations with the same scope.

Support for model applications can be obtained directly from the author, and I invite potential model users to contact me directly to plan eventual applications.

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