SHAMBA v 1.0

Methodology

The Small-Holder Agriculture Mitigation Benefit Assessment model for estimation of greenhouse gas emission reductions and removals that result from smallholder farmers using Climate Smart Agriculture and/or tree planting in sub-Saharan Africa

Woollen, E., Berry, N., Cross, A., Hagdorn, M., Hughes, M., Ryan, C.M.

The University of Edinburgh

Tropical land use team

School of GeoSciences

Edinburgh, EH9 3JN, UK

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Definitions

Accounting period: length of time over which greenhouse gas emissions and removals are quantified

Activity: a component of an intervention, such as agroforestry of a specific type

Agroforestry: agriculture incorporating the cultivation of trees

Baseline: land use/management practice(s) without any intervention(s) (i.e. “business as usual”)

Climate Smart Agriculture (CSA): using conservation agriculture and agroforestry techniques for improved GHG mitigation in agriculture

Conservation agriculture: uses agricultural methods (minimal soil disturbance, permanent soil cover and crop rotations) to achieve sustainable and profitable agriculture

Intervention: change in land use/management practice from baseline

Project: a collection of interventions

Scenario: a set of unique land use/management practices

Small-holding/holders*:* farms supporting single families with a mixture of cash crops and or subsistence farming

User(s): person(s) using the model

1. Model summary

The SHAMBA (Small-Holder Agriculture Mitigation Benefit Assessment) model estimates greenhouse gas (GHG) emissions or removals resulting from a change in land management practices. SHAMBA is designed to model a **baseline scenario** (where land management activities continue as business as usual) and an **intervention scenario** consisting of **activities** that can be described as Climate Smart Agricultural practices (CSA) including, conservation agriculture, agroforestry and other tree planting. SHAMBA models the changes in carbon stocks in soils and woody biomass, and the GHG emissions from biomass burning, plant nitrogen inputs to soils, and fertiliser use over the **accounting period** for baseline and intervention activities. Net emissions and removals are calculated on a yearly basis for the length of the accounting period, in units of tonnes (t) of carbon dioxide equivalent (CO_{2e}) per hectare (ha). Version one of the SHAMBA model is designed to work with **smallholder** systems in sub-Saharan Africa.

This document describes the science of the SHAMBA model, and details the calculations and parameters, as well as outlining the data requirements to use the model. For a full description of how to use the model for carbon accounting, please see the SHAMBA methodology (http://shambatool.wordpress.com/). The methodology also outlines **applicability conditions** for using the SHAMBA tool to estimate GHG emissions and removals for carbon accounting projects in sub-Saharan Africa.

2. Overview of GHG accounting approach

This model was developed for the purpose of accounting for changes in soil and woody biomass carbon stocks and GHG emissions due to changing agricultural practices and tree planting. Soil carbon and woody biomass changes are modelled with simple quasi-process-based approaches, whilst emissions from other sources (e.g. biomass burning, the use of fertilisers) are accounted for using simpler (IPCC Tier 1-type) approaches. The model consists of three sub-models, one for soil, crops and woody biomass, working on a hectare basis.

Soil organic carbon is modelled using RothC, one of the most widely used soil carbon models. It has been used to model soil carbon dynamics globally, and is freely available to download[1]. RothC was originally developed and parameterised to model turnover of organic carbon in arable surface soils from the Rothamsted UK long-term field experiments, but has since been applied at a range of different scales and systems (Milne et al. 2007). It has been widely used to model the effects of agricultural (Farage et al. 2007, Traoré et al. 2008, Nakamura et al. 2010) and agroforestry practices (Diels et al. 2004, Kaonga and Coleman 2008), on soil carbon in sub-Saharan Africa.

However, several key effects of CSA and other land management practices are not represented in RothC. Therefore in the SHAMBA model the woody biomass growth and carbon inputs to the soil pool from agroforestry and tree planting activities are estimated with a new stock and flow biomass model

[1] http://www.rothamsted.ac.uk/aen/carbon/mod26_3_win.pdf

driven by assumed tree growth rates. The carbon inputs to the soil pool from crops are estimated using IPCC (2006) guidelines. External organic inputs, such as additions of litter from outside sources, to the field are also included. Emissions from biomass burning, the volatisation of nitrogen (N) in soils from plant inputs, and N fertiliser use are estimated through the use of simple equations and IPCC[2] default values. The following equations define the sources and sinks of GHGs included in this model.

For a baseline scenario, GHG emissions or removals per hectare in year *y* are calculated as:

$$BE_y = BE_{BB_y} + BE_{NI_y} + BE_{NF_y} + BE_{SO_y} + BE_{WB_y} \quad \text{(Equation 1)}$$

For the intervention scenario, the calculation is identical:

$$PE_y = PE_{BB_y} + PE_{NI_y} + PE_{NF_y} + PE_{SO_y} + PE_{WB_y} \quad \text{(Equation 2)}$$

Where for baseline (variables starting with B) and intervention (variables starting with P) emissions:

E_y is the GHG emissions under the scenario for year *y* (tCO_{2e}/ha);

E_{BB_y} is the emissions from biomass burning in year *y* of the scenario (tCO_{2e}/ha);

E_{NI_y} is the emissions resulting from the nitrogen inputs to soils from plants in year *y* of the scenario (tCO_{2e}/ha);

E_{NF_y} is the direct emissions resulting from the use of N fertilisers in year *y* of the scenario (tCO_{2e}/ha);

E_{SO_y} is the emissions from change in soil organic carbon stocks in year *y* of the scenario (tCO_{2e}/ha); and

E_{WB_y} is the emissions from change in woody biomass of trees planted through scenario activities in year *y* of the scenario (tCO_{2e}/ha).

For all emissions, positive numbers refer to emissions and negative numbers refer to removals. The units of all terms are tCO_{2e}/ha, obtained for carbon stocks by multiplying by the ratio of the molecular weights of CO_2 and C (44/12), and for non-CO_2 fluxes, the appropriate global warming potential (GWPs).

Total emissions/removals for each scenario are given by summing over the years *y* = 1 to *y* = *d,* where *d* is the accounting period:

$$BE = \sum_{y=1}^{d} BE_y \quad \text{(Equation 3)}$$

$$PE = \sum_{y=1}^{d} PE_y \quad \text{(Equation 4)}$$

Where:

BE is the total emissions for the baseline scenario (tCO_{2e}/ha) over the accounting period

PE is the total emissions for the intervention scenario (tCO_{2e}/ha) over the accounting period

The overall net impact of the intervention is given by the difference between the total baseline and intervention emissions:

$$E_{net} = PE - BE \qquad \text{(Equation 5)}$$

Where:

E_{net} is the total net emissions/removals as a result of the intervention (tCO_{2e}/ha)

Again, all terms are in units of tCO_{2e}/ha, and negative numbers represent removals. Note that this formulation implies that all mitigation is considered to have an equal weight, regardless of the year in which it occurs.

3. SHAMBA model overview

Each section (Table 1) of this document details how to calculate the terms in Eq. 1 and Eq. 2, such that the modelled intervention and baseline emissions can be calculated (Eq. 3, 4), and the net impact estimated (Eq. 5). All calculations are performed on a per hectare basis on a yearly time step.

Table 1: Summary of main sections of the model description and the origin of the approach

Modelled Effect	Parameter in Eq 1 & 2	Section	Source of approach
Woody biomass carbon changes	E_{WB}	4	UoE tropical land use team
Crop residues and resultant soil inputs		5	IPCC[2]
External organic inputs		6	UoE tropical land use team
Emissions from biomass burning	E_{BB}	7	IPCC[2] and SALM[3]
Soil organic carbon changes	E_{SO}	8	RothC and UoE tropical land use team
Emissions from plant nitrogen inputs to soils	E_{NI}	9	IPCC and SALM
Emissions from N fertiliser use	E_{NF}	10	SALM and CDM[4] tool

SHAMBA models each component (Table 1) based on input data, using outputs from some components as inputs to others. A diagram of the basic structure of the model and links between components is shown below (Fig. 1).

[2] IPCC (2006) 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan

[3] http://v-c-s.org/sites/v-c-s.org/files/VM0017%20SALM%20Methodolgy%20v1.0.pdf

[4] http://cdm.unfccc.int/methodologies/ARmethodologies/tools/ar-am-tool-07-v1.pdf

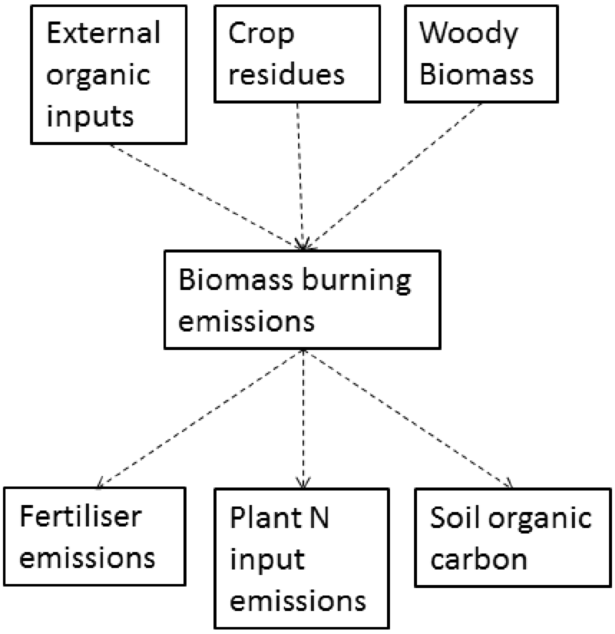

Fig. 1: SHAMBA model showing each modelled component and the flow of information between them.

4. Modelling changes in woody biomass

This section details the parameterisation and use of the SHAMBA biomass model, which is used to estimate woody biomass growth and tree inputs to the soil for agroforestry and tree planting activities. The following section details the method.

4.1 Biomass model description

The SHAMBA biomass model (Fig. 2) estimates changes to woody biomass carbon pools over the project duration using a mass balance approach. It keeps track of the following pools; stem, branches, leaves (the sum of these three = AGB), fine roots, coarse roots (= BGB). Biomass flows into all the pools, based on a simple allocation of each year's net primary productivity (NPP), estimated from tree growth rates and an allometric equation (see below). Biomass flows out of each pool via a litter flux, determined by the turnover rate. Each pool is defined as the biomass in that pool per tree multiplied by the stand density per hectare, in units of tC/ha. Stand density, (also known as stocking density), is a function of initial planting density, tree mortality and thinning. As such the biomass model must be parameterised and run for a cohort of trees, where the cohort is planted at the same time and is made up of the same species (or generic tree type, see below). Thinned and dead biomass can be removed from the system, or can be left, in which case it is added to the litter flux. The litter flux drives the biomass burning model (section 7), the soil carbon model (section 8) and the emissions from plant N input model (section 9). Each pool is updated yearly, with fluxes calculated based on the previous year's pool sizes.

The biomass model assumes:

- The allometric equation is appropriate for the planted tree species

- If pruning occurs the allometric equation is appropriate for pruning (pruning will change the tree allometry)
- All trees planted in a cohort have similar growth rates and allocation parameters

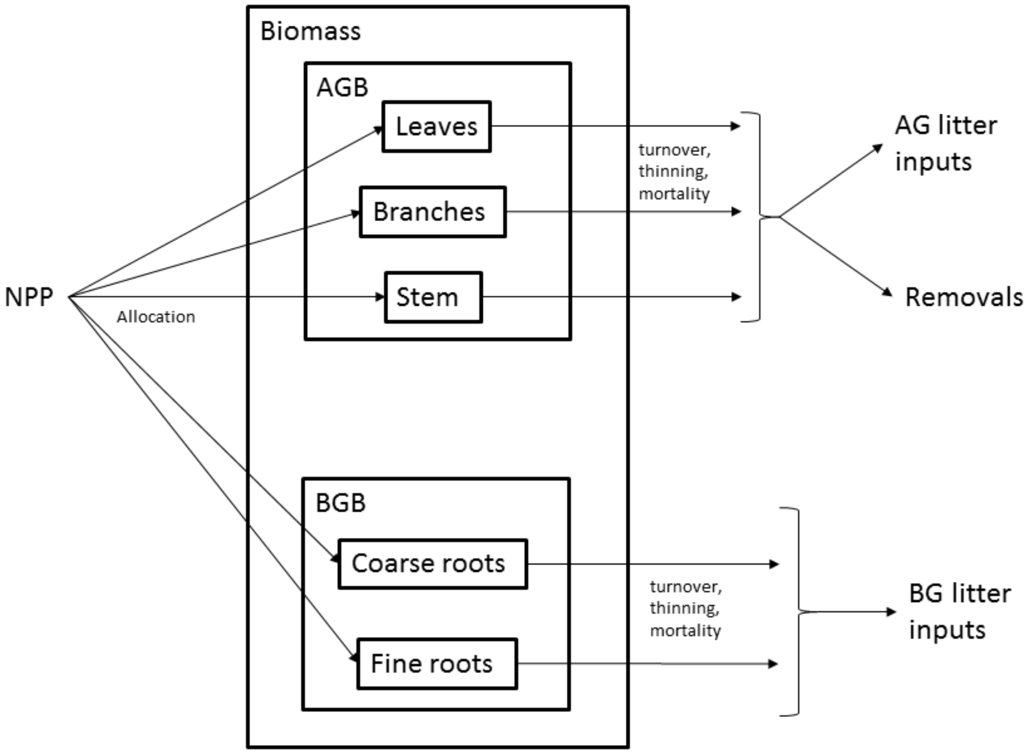

Fig. 2: Graphical representation of the biomass model where growth of biomass (NPP) is allocated to each of the five biomass pools; leaves, branches, stem = above ground biomass (AGB), coarse roots, fine roots = below ground biomass (BGB). Biomass in each pool is lost due to turnover, thinning and mortality, entering the litter flux or removal flux.

4.2 Biomass model parameterisation

The data needed to parameterise and drive the model for a single tree species and/or cohort are shown in Table 2. The parameters for the biomass model should either be entered from user data, or defined by defaults if applicable (default parameter values are given in Appendix 1).

Table 2: Model parameters required for each tree species/cohort planted

Parameter	Symbol	Units	Default value	Notes
Expected growth rate of aboveground biomass of a single tree in year *y*	$B_{inc,y}$	ABG kg C/ year	*Users must provide this, or calculate it from the DBH increment*	See 4.3.1
Initial stand or planting density	$SD_{y=0}$	trees/ ha	*Users must provide this*	
Fraction of stand density thinned in year y	th_y	stems removed / total SD	*Users must provide this*	See 4.6
Fraction of thinned stems left in the field	thf_{stem}	t C stems left/ total t C of thinned stems	*Users must provide this*	See 4.4
Fraction of thinned branches left in the field	thf_{branch}	t C branches left / total t C thinned branches	*Users must provide this*	See 4.4

Fraction of thinned leaves left in the field	thf_{leaf}	t C leaves left / total t C thinned leaves	1	See 4.4
Fraction of thinned coarse roots left in the field	thf_{croot}	t C coarse roots left / total t C thinned coarse roots	1	See 4.4
Fraction of thinned fine roots left in the field	thf_{froot}	t C fine roots left / total t C thinned fine roots	1	See 4.4
Tree mortality in year *y*	tm_y	trees that die in year *y*/ total SD in year *y*	*Users must provide this*	See 4.4
Fraction of dead stems left in the field	tmf_{stem}	t C stems left/ total t C of dead stems	*Users must provide this*	See 4.4
Fraction of dead branches left in the field	tmf_{branch}	t C branches left / total t C dead branches	*Users must provide this*	See 4.4
Fraction of dead leaves left in the field	tmf_{leaf}	t C leaves left/ total t C of dead leaves	1	See 4.4
Fraction of dead coarse roots left in the field	tmf_{croot}	t C coarse roots left / total t C dead coarse roots	1	See 4.4
Fraction of dead fine roots left in the field	tmf_{froot}	t C fine roots left / total t C dead fine roots	1	See 4.4
NPP allocation to stem	al_{stem}	t C to stem/ total t C NPP	0.69	See 4.3.2
NPP allocation to branches	al_{branch}	t C to branches/ total t C NPP	0.31	See 4.3.2
NPP allocation to leaves	al_{leaf}	t C to leaves/ total t C NPP	0.10	See 4.3.2
NPP allocation to fine roots	al_{froot}	t C in fine roots/ total t C NPP	0.10	See 4.3.2
NPP allocation to coarse roots	al_{croot}	t C to roots/ total t C NPP	Equals product of root:shoot ratio and al_{stem}	See 4.3.2
Turnover rate of stem	to_{stem}	t C stem turned over /total t C stem	0	See 4.4
Turnover rate of branches	to_{branch}	t C branches turned over / total t C branches	0.05	See 4.4
Turnover rate of leaves	to_{leaf}	t C leaves turned over/ total t C leaves	1	See 4.4
Turnover rate of fine roots	to_{froot}	t C fine roots turned over / total t C fine roots	0.8	See 4.4
Turnover rate of coarse roots	to_{croot}	t C coarse roots turned over / total t C coarse roots	0	See 4.4
Root:shoot ratio	t_{rs}	t C BGB / t C AGB	0.26	
Fraction of roots in the top 0-30 cm of soil	t_{30}	t C roots in top 0-30 / total t C roots	0.7	
Wood density	t_d	g/ cm^3	0.60	Only needed if using the Chave 2009 allometric eqs.
Stem carbon content	tc_{stem}	g C/ g DM	0.5	See 4.7
Branch carbon content	tc_{branch}	g C/ g DM	0.5	See 4.7
Leaf carbon content	tc_{leaf}	g C/ g DM	0.5	See 4.7
Fine root carbon content	tc_{froot}	g C/ g DM	0.5	See 4.7
Coarse root carbon content	tc_{croot}	g C/ g DM	0.5	See 4.7
Stem wood nitrogen content	tn_{stem}	g N/ g DM	0.0015	See 4.7
Branch wood nitrogen content	tn_{branch}	g N/ g DM	Assumed same as stem	See 4.7
Leaf litter nitrogen content	tn_{leaf}	g N/ g DM	0.01 if non-legume 0.02 if legume	See 4.7

Fine root nitrogen content	tn_{froot}	g N/ g DM	0.0113	See 4.7
Coarse root nitrogen content	tn_{croot}	g N/ g DM	Assumed same as stem	See 4.7

4.3 Biomass growth

4.3.1 Net primary productivity

The SHAMBA biomass model uses growth models to estimate the net primary productivity (NPP) of tree growth. Given a dataset of age (years) and stem diameter (cm) of the planted tree speices or generic type, the stem diameter data is converted to AGB using an allometric equation appropriate to the planted tree species/type, giving AGB (stem and branches) in units of kg C. The model provides several defaults allometric equations which are appropriate for generic tree types of dry tropical species, moist tropical species or wet tropical species (Chave et al. 2005), miombo tree species (Ryan et al. 2011), or tree species of *Markhamia lutea, Grevillea robusta,* and *Maesopsis eminii* (Tumwebaze et al. 2013). If none of the allometric equations are appropriate to the planted tree, user defined allometric equations can be used instead.

The biomass data is plotted against age of tree (Fig. 3), and several growth models are fitted to the data using optimisation methods:

$$agb = ax \qquad \text{(Linear, Equation 6.1)}$$

$$agb = (1 + a)^x - 1 \qquad \text{(Exponential, Equation 6.2)}$$

$$agb = a(1 - e^{-bx}) \qquad \text{(Hyperbolic, Equation 6.3)}$$

$$agb = \frac{a}{1 + e^{-b(x-c)}} \qquad \text{(Logistic, Equation 6.4)}$$

which when differentiated give:

$$\frac{dagb}{dx} = a \qquad \text{(Equation 7.1)}$$

$$\frac{dagb}{dx} = (1 + a)^x \cdot log(1 + a) \qquad \text{(Equation 7.2)}$$

$$\frac{dagb}{dx} = a \cdot b \cdot e^{-bx} \qquad \text{(Equation 7.3)}$$

$$\frac{dagb}{dx} = \frac{a \cdot b \cdot e^{-b(x-c)}}{\left(e^{-b(x-c)} + 1\right)^2} \qquad \text{(Equation 7.4)}$$

Where: agb is the modelled tree AGB (kg C)

x is the age of the tree

a, b, c are fitted parameters

$dagb$ is the growth in AGB (kg C for the period dx)

The derivative of the best-fit equation is used to calculate the growth of AGB as a function of last year's AGB. This growth represents the NPP of above ground biomass of a single tree in year *y*:

$$NPP_{agb} = f(agb_{y-1}) \quad \text{(Equation 8)}$$

Where: $NPP_{agb,y}$ is the AGB growth of a single tree in year *y* (kg C)

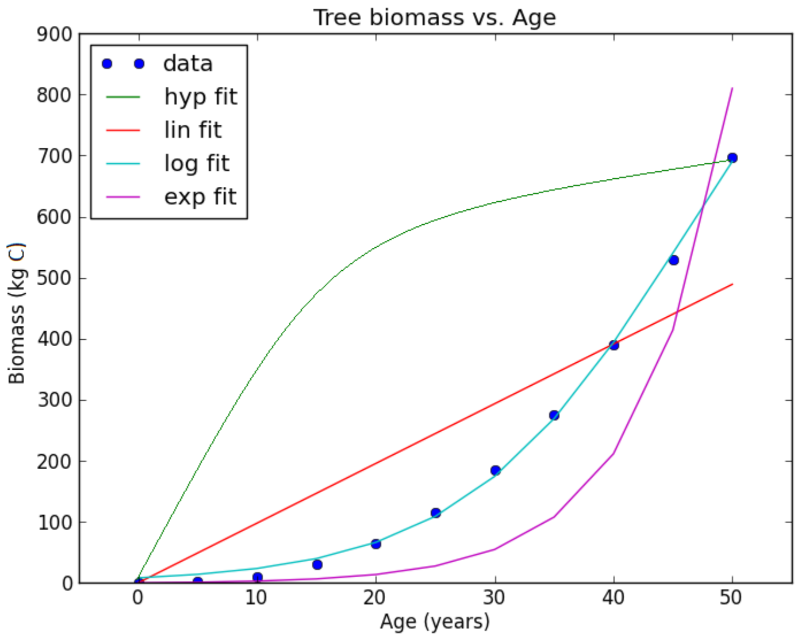

Fig. 3: Growth curves (Eqs. 6.1-6.4) fitted to example data of age and biomass for a single tree species/type.

4.3.2 Allocation to biomass pools

The NPP of a single tree is then converted to tonnes and scaled to the hectare by multiplying by the stand density, to obtain total NPP (t C/ha), assuming all trees of a particular species or cohort are of equal size and grow at similar rates. Total NPP is allocated to each of the five pools by the allocation parameters, giving biomass growth in each pool, *i* = {stem, leaf, branch, coarse roots, fine roots}:

$$NPP_{i,y} = \left(NPP_{agb,y}/1000\right) \cdot SD_{y-1} \cdot al_i \quad \text{(Equation 9)}$$

Where: $NPP_{i,y}$ is the NPP in pool *i* in year *y* (t C/ha)

SD_{y-1} is the stand density in the year before *y* (trees/ha)

al_i is the allocation of AGB NPP to pool *i*

The default above-ground allocation parameters (al_{stem}, al_{branch}, al_{leaf}) were determined using measurements taken from tree species planted as part of agroforestry activities (Tumwebaze et al. 2013), and several miombo woodland tree species (Ryan et al. 2011) (Table 3).

Table 3: Allocation patterns for several tree species, where allocation is a ratio to total above-ground biomass (AGB = stems and branches). nd indicates no data was available.

Species	DBH	Allocation to stems	Allocation to branches	Allocation to leaves	Reference

Units	cm	mass stems/ total AGB	mass branches/ total AGB	mass leaves/ total AGB)	
Grevillea robusta	31.08	0.63	0.37	0.08	Tumwebaze *et al*. (2013)
Maesopsis eminii	29.28	0.68	0.32	0.09	Tumwebaze *et al*. (2013)
Markhamia lutea	23.93	0.72	0.28	0.12	Tumwebaze *et al*. (2013)
Julbernardia globiflora	30.0	0.70	0.30	nd	Ryan *et al*. (2011)
Brachystegia spiciformis	32.3	0.69	0.31	nd	Ryan *et al*. (2011)
Brachystegia bohemii	28.0	0.69	0.31	nd	Ryan *et al*. (2011)
Mean	**29.10**	**0.69**	**0.31**	**0.10**	

The allocation patterns are fairly consistent between species (Table 3), and the default values for allocation of above-ground pools were therefore designated as the means. The default root allocation (al_{croot}) parameter is determined from root:shoot ratios. Due to a paucity of data for agroforestry trees, we use the average root:shoot ratio as reported in a global meta-analyses of tree root:shoot ratios (Cairns et al. 1997), which was within the range reported in Mokany et al. (2006) for tropical forest trees. We further assume that fine roots have the same allocation ratio as leaves (i.e. fine root productivity is the same as leaves). Other studies in temperate forests using a range of methods have found a wide range of fine root:leaf productivity ratios, but with a mean (±SD) of 1.08 ± 1.35 (Hendricks et al. 2006), suggesting our assumption is reasonable. Finally, the default allocation parameters chosen for stems, leaves and roots agreed closely with a meta-analysis of biomass allocation (Poorter et al. 2012), where the mean allocation for natural tropical forests and woodlands ranged from 0.8-0.6 for stems, 0.02-0.06 for leaves, and 0.16-0.36 for roots.

The default allocation values, as used in the SHAMBA biomass model (Table 2), are therefore generally applicable across most tree species. However, as demonstrated for *Casuarina equisetifolia* (Tumwebaze et al. 2013), some trees may have a differing allometry to the 'generic' tree. Therefore, if local project data is available, or species specific data from peer reviewed literature is available, more specific allocation parameters should be used in the model.

4.4 Biomass loss

From the growth model, biomass C stocks (t C/ha) are increased in each of the five pools over time. Some of the biomass from each pool is lost every year due to turnover, mortality and thinning. The flux of biomass from each pool is determined by the rate of loss:

$$BL_{i,y} = B_{i,y-1} \cdot to_i \quad \text{(Equation 10)}$$

$$BT_{i,y} = B_{i,y-1} \cdot th_y \quad \text{(Equation 11)}$$

$$BM_{i,y} = B_{i,y-1} \cdot tm_y \quad \text{(Equation 12)}$$

$$B_{loss,i,y} = BL_{i,y} + BT_{i,y} + BM_{i,y} \quad \text{(Equation 13)}$$

Where: $BL_{i,y}$ is the biomass turned over in pool *i* in year *y* (t C/ha)

$B_{i,y-1}$ is the biomass in pool *i* in the year before *y* (t C/ha)

to_i is the turnover rate of pool *i* (t C turned over/ total t C)

$BT_{i,y}$ is the biomass thinned in pool *i* in year *y* (t C/ha)

th_y is the thinning fraction in year *y (*thinned trees/ total stand density)

$BM_{i,y}$ is the dead biomass in pool *i* in year *y* (t C/ha)

tm_y is the mortality rate in year y (dead trees/ total stand density)

$B_{loss,i,y}$ is the total biomass lost in pool *i* in year *y* (t C/ha)

The default values for turnover (table 2) of each pool is based on the assumption that stems and coarse roots will not have significant losses of biomass as litter annually, and that trees are fully deciduous (see appendix 1). If planted trees are not deciduous (or have a leaf life span > 1year), or have significant inputs from stem bark shedding or branches, the turnover rates should be specified by the user.

Thinning is defined as the removal of whole trees in this model, and not just pruning of branches or other parts. Mortality and thinning of trees can occur in any year, with different fractions dead or thinned in every year, if applicable. Biomass from the thinned (BT_i) and dead (BM_i) pools can be left in the field or removed. The fraction of dead and thinned biomass (e.g tmf_{stem}, $thfs_{tem}$) which is left in the field determines the amount of thinned and dead biomass which is added to the litter flux. All coarse roots, fine roots and leaves of dead and felled trees are assumed to remain in the field in default settings. Thereby, biomass from the thinned and dead trees which is removed or left in the field is determined:

$$BT_{on,i,y} = BT_{i,y} \cdot thf_i \quad \text{(Equation 14)}$$

$$BM_{on,i,y} = BM_{i,y} \cdot tmf_i \quad \text{(Equation 15)}$$

$$BT_{off,i,y} = BT_{i,y}(1 - thf_i) \quad \text{(Equation 16)}$$

$$BM_{off,i,y} = BM_{i,y}(1 - tmf_i) \quad \text{(Equation 17)}$$

Where: $BT_{on,i,y}$ is the biomass from pool *i* which is left in the field from thinned trees in year *y* (tC/ha)

thf_i is the fraction of thinned biomass in pool *i* which is left in the field (t C left/ total t C thinned)

$BM_{on,i,y}$ is the biomass from pool *i* which is left in the field from dead trees in year *y* (tC/ha)

tmf_i is the fraction of dead biomass in pool *i* which is left in the field (t C left/ total t C dead)

$BT_{off,i,y}$ is the biomass from pool *i* which is removed from the field from thinned trees in year *y* (tC/ha)

$BM_{off,i,y}$ is the biomass from pool *i* which is removed from the field from dead trees in *y* (tC/ha)

4.5 Biomass change

Biomass in each pool is thereby a function of the biomass growth and the biomass loss in each year:

$$B_{i,y} = B_{i,y-1} + NPP_{i,y} - B_{loss,i,y} \quad \text{(Equation 18)}$$

Where: $B_{i,y}$ is biomass in pool *i* in year *y* (t C/ha)

Thereby, total biomass carbon stocks (stems, leaves, branches, coarse roots and fine roots) which remains each year is used to calculate the total emissions from woody biomass (Eq. 1-2) due to tree planting (negative values are an uptake):

$$B_{total,y} = \sum_{i=1}^{5} B_{i,y} \qquad \text{(Equation 19)}$$

$$E_{WB,y} = \left(B_{total,y-1} - B_{total,y}\right) \cdot mw_{CO2} \qquad \text{(Equation 20)}$$

Where: $B_{total,y}$ is the total woody biomass in year *y* (t C/ha)

$E_{WB,y}$ is the emissions from woody biomass change in year *y* (tCO2e/ha)

$B_{total,y-1}$ is the total woody biomass in the year before *y* (t C/ha)

mw_{CO2} is the molecular ratio of CO_2 and C (44/12)

From this equation the biomass removed due to thinning and mortality are included as an emission. Biomass removed from the field is assumed to be short lived and converted to CO_2 in the atmosphere immediately. Long-lived timber products are not included in this version of the model.

4.6 Stand density change

The model accounts for tree mortality and thinning events by reducing the stand density:

$$SD_y = SD_{y-1}\left(1 - \left(tm_y + th_y\right)\right) \qquad \text{(Equation 21)}$$

Where: SD_y is the stocking or stand density in year *y* (trees/ha)

4.7 Tree-soil inputs

The carbon inputs to the soils (t C/ha) from trees are the sum of all the inputs from turned over biomass, thinned biomass and dead biomass left in the field from each of the five pools:

$$B_{CI,i,y} = BL_{i,y} + BT_{on,i,y} + BM_{on,i,y} \qquad \text{(Equation 22)}$$

Where: $B_{CI,i,y}$ is the C inputs from pool *i* in year *y* (t C/ha)

These inputs can be used to determine dry mass and soil N inputs of each pool as well, using the C and N content of each pool:

$$B_{DM,i,y} = \frac{B_{CI,i,y}}{tc_i} \qquad \text{(Equation 23)}$$

$$B_{NI,i,y} = B_{DM,i,y} \cdot tn_i \qquad \text{(Equation 24)}$$

Where: $B_{DM,i,y}$ is the dry biomass inputs of pool *i* in year *y* (t DM/ha)

tc_i is the carbon content of pool *i* (g C/g DM)

$B_{NI,i,y}$ is the N inputs of pool *i* in year *y* (t N/ha)

tn_i is the N content of pool *i* (g N/g DM)

Total above and below ground tree inputs are thus:

$$T_{CIag,y} = B_{CI,stem,y} + B_{CI,branch,y} + B_{CI,leaf,y} \quad \text{(Equation 25)}$$

$$T_{CIbg,y} = (B_{CI,croot,y} + B_{CI,froot,y}) \cdot t_{30} \quad \text{(Equation 26)}$$

$$T_{NIag,y} = B_{NI,stem,y} + B_{NI,branch,y} + B_{NI,leaf,y} \quad \text{(Equation 27)}$$

$$T_{NIbg,y} = (B_{NI,croot,y} + B_{NI,froot,y}) \cdot t_{30} \quad \text{(Equation 28)}$$

$$T_{DMag,y} = B_{DM,stem,y} + B_{DM,branch,y} + B_{DM,leaf,y} \quad \text{(Equation 29)}$$

$$T_{DMbg,y} = (B_{DM,croot,y} + B_{DM,froot,y}) \cdot t_{30} \quad \text{(Equation 30)}$$

Where: $T_{CIag,y}$ is the total tree carbon inputs from above ground pools in year *y* (t C/ha)

$T_{CIbg,y}$ is the total tree carbon inputs from below ground pools in year *y* (t C/ha)

t_{30} is the below ground biomass found in the top 0-30 cm of soil (t C BGB in 0-30 cm/ total t C BGB)

$T_{NIag,y}$ is the total tree nitrogen inputs from above ground pools in year *y* (t N/ha)

$T_{NIbg,y}$ is the total tree nitrogen inputs from below ground pools in year *y* (t N/ha)

$T_{DMag,y}$ is the total tree dry matter inputs from above ground pools in year *y* (t DM/ha)

$T_{DMbg,y}$ is the total tree dry matter inputs from below ground pools in year *y* (t DM/ha)

These inputs are then passed to the biomass burning model (section 7) before being passed to the soil model (section 8) and the emissions from plant N input model (Section 9).

5. Crop model

This section details the parameterisation and use of the SHAMBA crop model, which is used to estimate annual crop residues and inputs to the soil. The following section details the method.

5.1 Crop model description

Crop inputs to the soil are difficult to measure and rarely directly observed. Instead, they may be estimated using more readily available data such as crop yields. The SHAMBA crop model uses an IPCC Tier-1 type approach (equations as outlined in table 11.2 of the IPCC[5] guidelines) to estimate crop above and below ground residues for various crop types. The model calculates the annual total above and below ground crop residues (t DM/ha), and the resultant above and below ground crop C (t C/ha) and N (t N/ha) inputs to the soil, on a hectare basis. The total nitrogen inputs to soils are estimated using the values given by the IPCC for nitrogen content of above and below ground residues. Carbon inputs are similarly calculated using peer reviewed values for crop carbon content.

As several different crops are often planted in one field over the course of a year, the crop model is parameterised and run for each crop type planted, summing together the results on a hectare basis to estimate total annual crop residues. The crop types planted and yields are assumed to be the same

[5] http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_11_Ch11_N2O&CO2.pdf

for every year of the model run. Therefore, it is important that the model is parameterised with common crop types and mean yields for a typical year for each scenario.

The model assumes:

- Planted crop(s) are definable as one of the IPCC listed crop types or species
- The type or species of crops planted, and crop yields, do not vary between years. Different yields in each year can be accounted for in the model, but not as currently implemented.
- Crop yields are known for each planted crop type/species

5.2 Crop model parameterisation

The data required to parameterise the crop model are outlined in Table 4. For full details on default parameters and applicability see Appendix 1.

Table 4: Parameters required for each crop species or type planted in each scenario

Parameter	Symbol	Units	Default value
Crop type or species	c_s	*category*	*User must provide this*
Annual mean crop yield	c_{yield}	t DM/ha	*User must provide this*
Fraction of AG crop residues removed from the field post-harvest	c_f	t DM removed ha^{-1}/ total t DM ha^{-1}	*User must provide this*
Crop root:shoot ratio	c_{rs}	t BG DM/ t AG DM	IPCC default value for crop type
Crop AG residue C content	c_{ac}	g C /g DM	0.4
Crop BG residue C content	c_{bc}	g C /g DM	0.4
Crop AG residue N content	c_{an}	g N /g DM	IPCC default value for crop type
Crop BG residue N content	c_{bn}	g N /g DM	IPCC default value for crop type
Fraction of crop BG residues in the top 0-30 cm of soil	c_{30}	t BG residues in 0-30/ total t BG residues	0.7

*AG is above-ground, BG is below ground, DM is dry matter, C is carbon, N is nitrogen

5.3 Crop model calculations

Yield data should be gathered from local measurements for a typical year for each crop type, or alternatively country specific estimates can be obtained from the FAOSTAT[6] for specified crop species. The yield data can be used to calculate the mass of above-ground crop residues for each crop type (*i*):

$$C_{ag,i} = c_{yield,i} \cdot a_i + b_i \qquad \text{(Equation 31)}$$

Where: $C_{ag,i}$ is the mass of total crop above-ground residues for crop type *i* (t DM/ha)

$c_{yield,i}$ is annual mean crop dry matter yield for crop type *i* (t DM/ha)

a_i and b_i are model parameters defined for specific crop types *i* by the IPCC

[6] http://faostat.fao.org/site/567/DesktopDefault.aspx?PageID=567#ancor

Users must provide information on crop residue management, such as if crop residues are removed from the field post-harvest or not. If residues are removed from the field post-harvest, the amount of crop residue which is taken off field can be calculated by:

$$C_{ag-off,i} = C_{ag,i} \cdot c_{f,i} \quad \text{(Equation 32)}$$

Where: $C_{ag-off,i}$ is the mass of above-ground residues that are removed from the field post-harvest for crop type *i* (t DM/ha)

$C_{f,i}$ is the fraction of total above-ground residues which are removed from the field post-harvest for crop type *i* (1 if all crop residues are removed, 0 if none are removed)

This will determine the amount of above-ground crop residue biomass that is left on the field post-harvest:

$$C_{ag-on} = C_{ag} - C_{ag-off} \quad \text{(Equation 33)}$$

Where: C_{ag-on} is the mass of above-ground residues that are left in the field post-harvest (t DM/ ha)

Using default parameters of root-to-shoot ratios, the model estimates the total below ground crop residues for each crop type planted based on the total above ground biomass:

$$C_{bg,i} = (C_{yield,i} + C_{ag,i}) \cdot c_{rs,i} \quad \text{(Equation 34)}$$

Where: $C_{bg,i}$ is the mass of below ground residues for crop type *i* (t DM/ha)

$c_{rs,i}$ is the crop root:shoot ratio for crop type *i* (t below ground biomass/t above ground biomass)

Using further default parameters, the above and below ground C and N inputs to the soil from crop residues are estimated for each crop type (*i*) planted:

$$C_{NIag,i} = C_{ag-on,i} \cdot c_{an,i} \quad \text{(Equation 35)}$$

$$C_{NIbg,i} = C_{bg,i} \cdot c_{bn,i} \cdot c_{30,i} \quad \text{(Equation 36)}$$

$$C_{CIag,i} = C_{ag-on,i} \cdot c_{ac,i} \quad \text{(Equation 37)}$$

$$C_{CIbg,i} = C_{bg,i} \cdot c_{bc,i} \cdot c_{30,i} \quad \text{(Equation 38)}$$

Where: $C_{NIag,i}$ is the mass of above ground crop N inputs for crop type *i* (t N/ha)

$c_{an,i}$ is the crop above-ground residue N content for crop type *i* (g N/g DM)

$C_{NIbg,i}$ is the mass of below ground crop N inputs for crop type *i* (t N/ha)

$c_{bn,i}$ is the crop below-ground residue N content for crop type *i* (g N/g DM)

$c_{30,i}$ is the fraction of below-ground residues which can be found in the top 0-30 cm of soil for crop type *i* (t C_{bg} 0-30 cm/ total t C_{bg})

$C_{CIag,i}$ is the mass of above ground crop C inputs for crop type *i* (t C/ha)

$c_{ac,i}$ is the crop above-ground residue C content for crop type *i* (g C/g DM)

$C_{CIbg,i}$ is the mass of below ground crop C inputs for crop type *i* (t C/ha)

$c_{bc,i}$ is the crop below-ground residue C content for crop type *i* (g C/g DM)

Finally, the crop on and off farm above ground residues, below ground residues, above and below ground C and N inputs are summed for all planted crop types/species (*i*):

$$C_{ag-off} = \sum_{i=1}^{n} C_{ag-off,i}$$ (Equation 39)

$$C_{ag-on} = \sum_{i=1}^{n} C_{ag-on,i}$$ (Equation 40)

$$C_{bg} = \sum_{i=1}^{n} C_{bg,i}$$ (Equation 41)

$$C_{NIag} = \sum_{i=1}^{n} C_{NIag,i}$$ (Equation 42)

$$C_{NIbg} = \sum_{i=1}^{n} C_{NIbg,i}$$ (Equation 43)

$$C_{CIag} = \sum_{i=1}^{n} C_{CIag,i}$$ (Equation 44)

$$C_{CIbg} = \sum_{i=1}^{n} C_{CIbg,i}$$ (Equation 45)

These annual totals are assumed to be the same for every year of the model run, and are passed to the biomass burning model (section 7) before they are passed to the soil model (Section 8) and the emissions from plant N input model (section 9).

6. External organic soil inputs

6.1 External organic soil input description

Organic inputs such as litter, mulch or manure originating from outside of the boundaries of the intervention area can be added to fields or plots for additional soil inputs or as fertiliser. If applicable, the additional biomass, carbon, and nitrogen inputs to soils from external organic inputs are calculated using a Tier-1 type approach. External inputs are included in the model, but are not included in C accounting for projects (see the SHAMBA methodology), as external inputs to the soils reduce inputs outside of the project boundary and are therefore a source of leakage. For project accounting, external inputs are omitted from further calculations. The SHAMBA model has maintained external soil inputs here for added functionality.

To include external organic inputs in the model calculations, data on the amount of added material, and the C and N content are required (Table 5). The default values provided assume organic inputs are sourced from the surrounding forests/woodlands, or originate from woody tree/shrubs (i.e. tree litter). Other inputs, such as manure or mulch, can be included if data are available. However, further data on the decomposability of the organic matter is required (see section 8), and the emission and combustions factors when fire occurs (see section 7). The years when external organic inputs are added to fields can be estimated using a frequency interval (where a frequency interval of 2 would mean addition of external inputs occurred every other year), or specified in known years of addition. The external organic soil inputs are incorporated into the emissions from biomass burning model (section 7), the soil C model (Section 8), and the emissions from fertiliser use (section 10).

The model assumes:

- The external inputs are organic
- The C and N content of the inputs are known, and do not differ between years

6.2 External organic input parameterisation

The data required to calculate the total external inputs of C and N to the field are outlined in table 5.

Table 5: Parameter requirements to calculate external inputs to soils for each organic input type

Parameter	Symbol	Units	Default value
Addition of external organic input to field in year *y* ?	$a_{f,y}$	1 or 0 (Yes/No)	*User must provide this*
Mass of external input added in year *y*	A_y	t DM/ ha	*User must provide this*
N content of input	a_n	g N/ g DM	0.018
C content of input	a_c	g C/ g DM	0.5

6.3 External organic input calculations

Using data as outlined in table 5, external organic C and N inputs are calculated on a yearly time step for each organic input type (*i*):

$$A_{CI,i,y} = A_{i,y} \cdot a_{f,i,y} \cdot a_{c,i} \quad \text{(Equation 46)}$$

$$A_{NI,i,y} = A_{i,y} \cdot a_{f,i,y} \cdot a_{n,i} \quad \text{(Equation 47)}$$

Where: $A_{CI,i,y}$ is the mass of external C inputs for input type *i* in year *y* (t C/ha)

$A_{NI,i,y}$ is the mass of external N inputs for input type *i* in year *y* (t N/ha)

$A_{i,y}$ is the dry mass of external input added to the field for input type *i* in year *y* (t DM/ha)

$a_{f,i,y}$ is if external inputs type *i* are added in year *y* (1 if yes, 0 if no)

$a_{c,i}$ is the C content for input type *i* (g C/ g DM)

$a_{n,i}$ is the N content for input type *i* (g N/ g DM)

Total C and N inputs from all organic input types (*i*) are then the sum of all inputs in each year:

$$A_{CI,y} = \sum_{i=1}^{n} A_{CI,y,i} \quad \text{(Equation 48)}$$

$$A_{NI,y} = \sum_{i=1}^{n} A_{NI,y,i} \quad \text{(Equation 49)}$$

Where: $A_{CI,y}$ is the total mass of external C inputs in year *y* (t C/ha)

$A_{NI,y}$ is the mass of external N inputs in year *y* (t N/ha)

7. Emissions due to biomass burning

The following section details the calculation of emissions from biomass burning.

7.1 Biomass burning model description

Non-CO_2 emissions from burning of biomass can be estimated using a Tier-1 type approach, as outlined by IPCC (2006) and SALM[7]. The model accounts for emissions from burning of above ground crop residues, on and off the field, above ground tree litter and external organic input biomass on the field. Standing live trees, below ground biomass, or litter from previous years are not burnt during fires. The amount of crop biomass available to burn on and off the field (t DM/ha) is calculated from the crop model (section 5). The amount of biomass from tree litter available to burn on the field is calculated from the woody biomass model (section 4), and the biomass available to burn on the field from external inputs are calculated (section 6). Using default values of combustion factors and emission factors given by the IPCC (2006) for burning of crop residues and tree litter, we can calculate the emissions from burning of biomass from each of these sources. Combustion and emission factors for external organic inputs will need to be specified if not similar to tree litter.

In order to assess when fires will occur in the field, if at all, fire occurrence is either estimated using a fire return interval (where a fire return interval of 5 causes fields to be burnt every 5 years), or fire occurrence can be specified to particular years when fire was known to occur. When a fire occurs the biomass from above-ground sources on the field are combusted by an amount equivalent to the combustion factors, creating emissions from biomass burning and reducing the C inputs to the soil carbon model (section 8), the N inputs for the calculation of emissions from plant N inputs (section 9), and reducing N inputs from organic fertilisers and associated emissions (section 10). Emissions from biomass burning (tCO_{2e}/ha) are calculated for baseline and intervention scenarios separately.

The model assumes:

- Only above-ground crop residues, tree litter and external organic inputs are burnt
- Only biomass added in the year of a field fire are burnt
- A field fire occurs at the end of the year, or post-harvest
- Removed crop residues are burnt annually post-harvest
- Live trees are not killed in fires, and live tree biomass is not burnt
- Soil organic C stocks are not directly affected by fire

7.2 Biomass burning model parameterisation

The data requirements for the biomass burning model are outlined in table 6.

Table 6: Parameter requirements to calculate emissions due to biomass burning for each scenario

Parameter	Symbol	Units	Default value
Fire occurrence in field in year *y*	ff_y	1 or 0 (Yes/No)	*User must provide this*
Are removed crop residues burnt else-where?	c_{burn}	1 or 0 (Yes/No)	*User must provide this*
Mass of above-ground crop residues removed from the field in year *y*	$C_{ag\text{-}off,y}$	t DM/ha	*Calculated in section 5*

[7] http://v-c-s.org/sites/v-c-s.org/files/VM0017%20SALM%20Methodolgy%20v1.0.pdf

Mass of above-ground crop residues available for fire in the field in year *y*	$C_{ag\text{-}on,y}$	t DM/ha	*Calculated in section 5*
Mass of above-ground tree litter available for fire in the field in year *y*	$T_{DMag,y}$	t DM/ha	*Calculated in section 4*
Mass of external organic input available for fire in the field in year *y*	A_y	t DM/ha	*Calculated in section 6*
Combustion factor for crop residues burned	cf_c	*unitless*	0.8
Combustion factor for tree litter burned	cf_f	*unitless*	0.74
Combustion factor for external input type *i* burned	cf_a	*unitless*	Assumed the same as for tree litter
Emission factor for the production of methane for crop residues burned	$ef_{CH4,c}$	g CH_4/kg	2.7
Emission factor for the production of methane for tree litter burned	$ef_{CH4,f}$	g CH_4/kg	6.8
Emission factor for the production of methane for external input burned	$ef_{CH4,a}$	g CH_4/kg	Assumed the same as for tree litter
Emission factor for the production of nitrous oxide for crop residues burned	$ef_{N2O,c}$	g N_2O/kg	0.07
Emission factor for the production of nitrous oxide for tree litter burned	$ef_{N2O,f}$	g N_2O/kg	0.20
Emission factor for the production of nitrous oxide for external input type *i* burned	$ef_{N2O,a}$	g N_2O/kg	Assumed the same as for tree litter
Global warming potential of methane for 100 years accounting period	gwp_{CH4}	t CO_{2e}/t gas	21
Global warming potential of nitrous oxide for 100 years accounting period	gwp_{N2O}	t CO_{2e}/t gas	310

7.3 Biomass burning model calculations

To calculate the emissions from burning of biomass the following equation is used:

$$E_{BB,y} = \begin{bmatrix} \left(\left(C_{ag-off} \cdot c_{burn}\right) + \left(C_{ag-on,y} \cdot ff_y\right)\right) \cdot cf_c \cdot \left(ef_{CH4,c} \cdot gwp_{CH4} + ef_{N2O,c} \cdot gwp_{N2O}\right) + \\ \left(T_{DMag,y} \cdot ff_y\right) \cdot cf_f \cdot \left(ef_{CH4,f} \cdot gwp_{CH4} + ef_{N2O,f} \cdot gwp_{N2O}\right) + \\ \sum_{i=0}^{n}\left(A_{i,y} \cdot ff_y\right) \cdot cf_{a,i} \cdot \left(ef_{CH4,a,i} \cdot gwp_{CH4} + ef_{N2O,a,i} \cdot gwp_{N2O}\right) \end{bmatrix} 10^{-3}$$

(Equation 50)

Where: $E_{BB,y}$ is the emissions from burning above-ground biomass in year *y* (tCO_{2e} /ha)

C_{ag-off} is the mass of above ground crop residues removed from the field annually (t DM/ha)

c_{burn} is if crop residues removed from the field are burnt annually (1 if yes, 0 if no)

$C_{ag-on,y}$ is the mass of above-ground crop residues available to burn in the field in year *y* (t DM /ha)

ff_y is if fire occurs in the field in year *y* (1 for fire, 0 for no fire)

cf_c is the combustion factor appropriate for burning crop residues (IPCC, 2006)

$ef_{CH4,c}$ and $ef_{N2O,c}$ are the emission factors for the production of methane and nitrous oxide when burning crop residues (g CH_4/kg and g N_2O/kg, respectively) (IPCC, 2006)

gwp_{CH4} and gwp_{N2O} are the global warming potentials (t CO_{2e}/ t gas) of CH_4 and N_2O, respectively (IPCC, 2006)

$T_{DMag,y}$ is the mass of above ground tree litter available to burn in the field in year *y* (t DM/ha)

cf_f is the combustion factor appropriate for burning litter from forests/woodlands (IPCC, 2006)

$ef_{CH4,f}$ and $ef_{N2O,f}$ are the emission factors for the production of methane and nitrous oxide when burning tree litter (g CH_4/kg and g N_2O/kg, respectively) (IPCC, 2006)

$A_{i,y}$ is the mass of external organic input type *i* available to burn in the field in year *y* (t DM/ha)

$cf_{a,i}$ is the combustion factor appropriate for burning external biomass input type *i*

$ef_{CH4,a,i}$ and $ef_{N2O,a,i}$ are the emission factors for the production of methane and nitrous oxide when burning external input type *i* (g CH_4/kg and g N_2O/kg, respectively)

7.4 Soil inputs reduced by fire

When fire occurs biomass is combusted, decreasing the above ground C and N inputs to the soils in that year. Therefore, soil inputs need to be corrected for effects of fire before they can pass to the soil model (section 8), the emissions from plant N input model (section 9) and the fertiliser emissions model (section 10).

Using the outputs from the woody biomass model ($T_{NIag,y}$, $T_{NIbg,y}$, $T_{CIag,y}$, $T_{CIbg,y}$), the crop model (C_{NIag}, C_{NIbg}, C_{CIag}, C_{CIbg}), and external organic inputs ($A_{NI,y}$, $A_{CI,y}$), the soil inputs are corrected for losses to fire in the above-ground fraction using the respective combustion factors:

$$T_{NItotal,y} = \left(T_{NIag,y} - \left(T_{NIag,y} \cdot ff_y \cdot cf_f\right)\right) + T_{NIbg,y} \quad \text{(Equation 51)}$$

$$T_{CItotal,y} = \left(T_{CIag,y} - \left(T_{CIag,y} \cdot ff_y \cdot cf_f\right)\right) + T_{CIbg,y} \quad \text{(Equation 52)}$$

$$C_{NItotal,y} = \left(C_{NIag} - \left(C_{NIag} \cdot ff_y \cdot cf_c\right)\right) + C_{NIbg} \quad \text{(Equation 53)}$$

$$C_{CItotal,y} = \left(C_{CIag} - \left(C_{CIag} \cdot ff_y \cdot cf_c\right)\right) + C_{CIbg} \quad \text{(Equation 54)}$$

$$A_{NItotal,y} = \sum \left(A_{NI,i,y} - \left(A_{NI,i,y} \cdot ff_y \cdot cf_{a,i}\right)\right) \quad \text{(Equation 55)}$$

$$A_{CItotal,y} = \sum \left(A_{CI,i,y} - \left(A_{CI,i,y} \cdot ff_y \cdot cf_{a,i}\right)\right) \quad \text{(Equation 56)}$$

Where: $T_{NItotal,y}$ is the total N inputs to soils from trees in year *y* (t N/ha)

$T_{CItotal,y}$ is the total C inputs to soils from trees in year *y* (t C/ha)

$C_{NItotal,y}$ is the total N inputs to soils from crops in year *y* (t N/ha)

$C_{CItotal,y}$ is the total C inputs to soils from crops in year *y* (t C/ha)

$A_{NItotal,y}$ is the total N inputs to soils from all external organic inputs in year *y* (t N/ha)

$A_{CItotal,y}$ is the total C inputs to soils from all external organic inputs in year *y* (t C/ha)

8. Modelling changes in soil organic carbon

This section details the parameterisation and use of the RothC model in SHAMBA, which is used to estimate soil organic carbon changes for baseline and intervention scenarios. The following sections describe the method.

8.1 SOC model overview

Soil organic carbon (*SOC*) stocks and changes, under baseline and intervention scenarios, are calculated using the RothC soil carbon model (Coleman and Jenkinson 1999), and implemented in Python (v 2.6.6). In SHAMBA, the RothC model runs on a yearly time step for the top 0-30 cm of soil, using annual C inputs (calculated in sections 4-7), modelling the turnover of organic carbon allowing for the effects of soil type, temperature, moisture content and plant cover on the turnover process.

As the equations for RothC are outlined in the user manual[8], we describe the use of RothC in SHAMBA and show equations where they differ from RothC. Full model description and assumptions are described in the following section.

8.2 SOC model parameterisation

Some of the data needed to parameterise and drive the soil carbon model in SHAMBA are shown in Table 7. The data can either be entered from local measurements or other relevant data sources, or use default values (see Appendix 1).

Table 7: Parameters and drivers required by the SHAMBA soil carbon model for each scenario

Parameter/ driver	Symbol	Units	Default value
Monthly mean temperature	*t*	Degrees C	CRU TS 3.10 global dataset [9], based on location
Monthly evapotranspiration*	*et*	mm	
Monthly rainfall	*p*	mm	
Soil carbon content at equilibrium	soc_f	t C/ha	Assumed to be 25 % higher than initial SOC stocks
Soil carbon content at start of intervention (initial)	$soc_{y=0}$	t C/ha	Harmonized World Soil Database[10], based on location
Soil clay content at start of intervention (initial)	$clay_{y=0}$	%	
Is land covered or bare in each month of the year?	*sc*	Yes/No	*User must provide this*
Decomposable fraction of crop residue plant material	dpm_c	decomposable mass/ total mass	0.59
Resistant fraction of crop residue plant material	rpm_c	resistant mass/ total mass	0.41
Decomposable fraction of tree litter plant material	dpm_f	decomposable mass/ total mass	0.20
Resistant fraction of tree litter plant material	rpm_f	resistant mass/ total mass	0.80

[8] http://www.rothamsted.ac.uk/aen/carbon/mod26_3_win.pdf

[9] University of East Anglia Climatic Research Unit (CRU). [Phil Jones, Ian Harris]. CRU TS3.10: Climatic Research Unit (CRU) Time-Series (TS) Version 3.10 of High Resolution Gridded Data of Month-by-month Variation in Climate (Jan. 1901 - Dec. 2009). Available at: http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__ACTIVITY_fe67d66a-5b02-11e0-88c9-00e081470265

[10] FAO/IIASA/ISRIC/ISSCAS/JRC, 2009. *Harmonized World Soil Database (version 1.1)*. Food and Agriculture Organization of the United Nations, Rome, Italy and IIASA, Laxenburg, Austria. Available at: http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/index.html

Decomposable fraction of the un-disturbed plant inputs	dpm_e	decomposable mass/ total mass	0.2 (Assumed the same as dpm_f)
Resistant fraction of the un-disturbed plant inputs	rpm_e	resistant mass/ total mass	0.8 (Assumed the same as rpm_f)
Decomposable fraction of external organic input	dpm_a	decomposable mass/ total mass	0.2 (Assumed the same as dpm_f)
Resistant fraction of external organic input	rpm_a	resistant mass/ total mass	0.8 (Assumed the same as rpm_f)
Humified fraction of external organic input	hum_a	humified mass/ total mass	0

*If evapotranspiration is not available, pan evaporation (*e*) can be used instead

8.3 Model structure and SOC partitioning

The structure of RothC (Fig. 4) is such that the organic inputs (t C/ha) to the soil are split into four active pools; the decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (BIO) and humified organic matter (HUM). Each pool then decomposes with its own characteristic rate. A small amount of inert organic matter (IOM) is present, but remains resistant to decomposition. SOC is defined as the total of all the organic carbon pools (DPM, RPM, BIO, HUM and IOM).

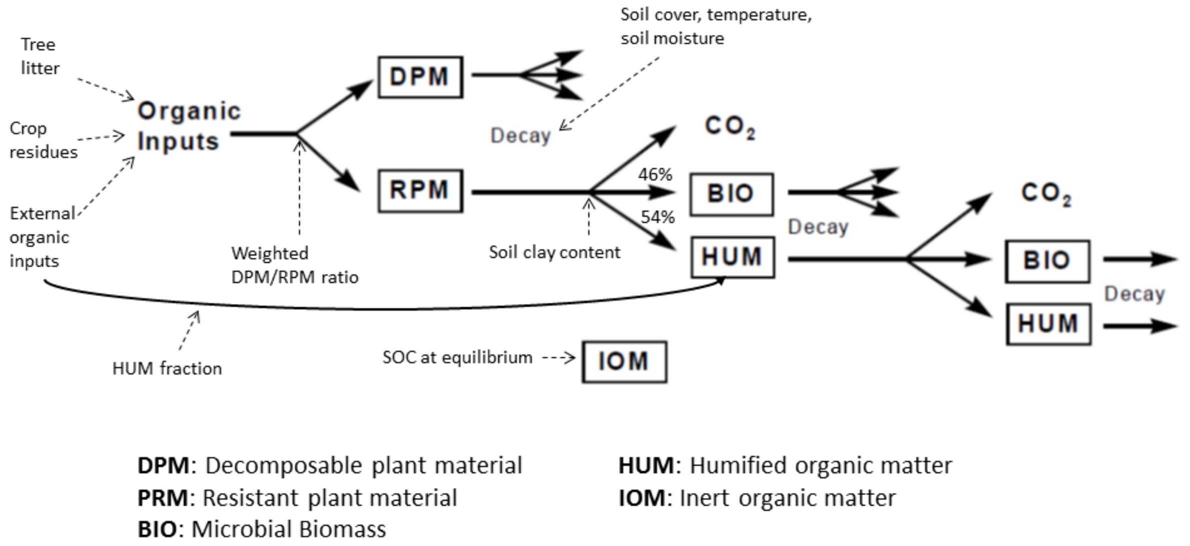

Fig.4: Structure of RothC, showing the partitioning of organic inputs to soil into the four active compartments, each decomposing at a specific rate (figure modified from Coleman & Jenkinson (1999), p.8).

The plant inputs or organic matter inputs to the soil pool are modelled for crop ($C_{CItotal}$) and tree ($T_{CItotal}$) inputs, and calculated for each external organic input type ($A_{CItotal}$) mediated by losses due to fire (section 7.4). Each year the incoming inputs are split between DPM and RPM fractions, depending on a DPM/RPM ratio. This ratio is based on the default values given by RothC for agricultural crop residues (59% DPM, 41% RPM) and tropical deciduous woodland litter (20% DPM, 80% RPM), and uses the DPM/RPM ratio provided by the user for each external organic input type. RothC provides a default value for manure (49% DPM, 49% RPM, 2% HUM), including a humified fraction to account for the fact that manure is more decomposed than plant material is. Any other external organic inputs which are not from woodland litter or manure needs to have a specified DPM/RPM and HUM ratio in order to be incorporated into the soil model (Table 7).

The model uses a weighted DPM/RPM (and HUM) ratio calculated from the fraction of total inputs originating from crops, trees and external organic inputs:

$$dpm_y = (dpm_c \cdot f_{c,y}) + (dpm_f \cdot f_{f,y}) + \sum_{i=0}^{n}(dpm_{a,i} \cdot f_{a,i,y})$$ (Equation 57)

$$rpm_y = (rpm_c \cdot f_{c,y}) + (rpm \cdot f_{f,y}) + \sum_{i=0}^{n}(rpm_{a,i} \cdot f_{a,i,y})$$ (Equation 58)

$$hum_y = \sum_{i=0}^{n}(hum_{a,i} \cdot f_{a,i,y})$$ (Equation 59)

Where: dpm_y is the weighted fraction of the total inputs which are decomposable in year *y* (t decomposable/ total t input)

dpm_c is the decomposable fraction of crop residue inputs (t decomposable crop input/ total t crop input)

$f_{c,y}$ is the fraction of total inputs which are from crops in year *y* (t crop inputs/ total t inputs)

dpm_f is the decomposable fraction of tree litter inputs (t decomposable tree input/ total t tree input)

$f_{c,y}$ is the fraction of total inputs which are from trees in year *y* (t tree inputs/ total t inputs)

$dpm_{a,i}$ is the decomposable fraction of external organic inputs of type *i* (t decomposable organic input/ total t organic input)

$f_{a,i,y}$ is the fraction of total inputs which are from external organic input of type *i* in year *y* (t organic input/ total t inputs)

rpm_y is the weighted fraction of the total inputs which are resistant in year *y* (t resistant/ total t input)

rpm_c is the resistant fraction of crop residue inputs (t resistant crop input/ total t crop input)

rpm_f is the resistant fraction of tree litter inputs (t resistant tree input/ total t tree input)

$rpm_{a,i}$ is the resistant fraction of external organic inputs of type *i* (t resistant organic input/ total t organic input)

hum_y is the weighted fraction of total inputs which are humified in year *y* (t humified/ total t input)

$hum_{a,i}$ is the humified fraction of external organic input of type *i* (t humified organic input/ total t organic input)

Once the inputs have been split between decomposable and resistant fractions, the DPM and RPM fractions decompose further to form BIO, HUM and CO_2. The proportion that goes to CO_2 and to BIO+HUM is determined by the soil clay content. The BIO+HUM is then split between BIO and HUM using set partitioning coefficients (46% to BIO, 54% to HUM). BIO and HUM decompose to form more CO_2, BIO and HUM, and so on (Fig. 4).

The inert organic matter fraction (IOM) remains constant, as no decomposition occurs in this fraction. IOM is calculated using the equation from Falloon et al. (1998):

$$IOM = 0.049 \cdot soc_f^{\ 1.139} \qquad \text{(Equation 60)}$$

Where: IOM is the inert organic matter fraction (t C/ha)

soc_f is the total organic carbon (t C/ha) of soils when at equilibrium (see sections 8.1.2)

Each active compartment of soil organic carbon (DPM, RPM, BIO, HUM) decays at a rate determined by individual decomposition rate constants (*k*) and a rate modifying factor (*r*) determined by temperature, soil moisture and soil cover (see the RothC[11] description for full details of calculations). The rate modifying factor (*r*) is calculated using data on soil cover and monthly climate variables (Table 2). The model default uses a global climate dataset to extract climate variables based on a specified geographical location. The climate dataset is the CRU TS 3.10[12] high resolution (0.5^0) month-by-month global climate dataset (Harris et al. 2013), where climate variable are monthly means calculated from 1960-2009. If local measurements of monthly climate variables are available, users can enter these values into the model instead of using the defaults. The model currently assumes climate variables do not change between years or scenarios. Therefore, the rate modifier (*r*) will only change if the monthly soil cover changes (i.e. if soil is bare or covered in each month) between years or baseline and intervention scenarios.

8.4 SOC model initialisation

Before we can model baseline and intervention SOC changes, the soil model needs to be initialised to the y=0 soil conditions if it is to accurately simulate future changes to soil carbon. Soils take decades to reach a steady state after changes to inputs or output fluxes of carbon. Therefore, unless land management has been consistent over ~30 years, which is rare and usually unknown, the soils are unlikely to be in equilibrium and may be losing or gaining carbon. The SHAMBA model allows the simulation of situations where SOC is changing rapidly, as it often is in situations where interventions are implemented. This means there is no assumption that the SOC is in equilibrium at the start of the interventions.

To initialise the SOC model, data on SOC stocks at equilibrium (soc_f) and SOC stocks and clay content at the start of intervention activities ($soc_{y=0}$, $clay_{y=0}$) are required (Table 7). The model default uses the Harmonized World Soil Database[13] (HWSD) (FAO/IIASA/ISRIC/ISSCAS/JRC 2009) to estimate initial SOC stocks and clay content at the start of interventions, based on a geographical location. We assume the value given by HWSD is appropriate for disturbed soils, such as agricultural

[11] http://www.rothamsted.ac.uk/aen/carbon/mod26_3_win.pdf
[12] http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__ACTIVITY_fe67d66a-5b02-11e0-88c9-00e081470265
[13] http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/

fields, based on the assumption that soil measurements used in the HWSD are more likely to come from disturbed soils. The HWSD provides soil characteristics for several different soil types at any one location. Therefore, the initial SOC stock and clay content values are calculated based on a weighted mean at the given location. The model default assumes SOC under equilibrium conditions are 25 % higher than the value given by HWSD (based on Guo and Gifford 2002, Don et al. 2011). The assumption is that the land was wooded before disturbance and that woodland or forest cover represent a pre-disturbance state where SOC was in equilibrium. If defaults are not applicable, local data on equilibrium and initial SOC stocks and soil clay content should be entered into the model instead.

The following procedure (illustrated in Figure 5) allows the simulation of non-steady state conditions:

1. SOC levels at steady state are simulated to estimate the pre-disturbance state of the SOC pools (i.e. the DPM, RPM, BIO, HUM and IOM) at equilibrium.
2. The change from this undisturbed state to the current state is modelled by imposing the baseline land management activities upon the undisturbed state until initial SOC levels observed in e.g. the HWSD are reached.
3. The distribution of soil carbon in the different modelled pools (i.e. the DPM, RPM, BIO and HUM) at the initial state can then be used to initialise the model prior to modelling of the baseline and intervention scenarios.

Step 1 requires an estimate of SOC stock at equilibrium, appropriate for the undisturbed soils (see above). The model uses a parameter search to find the mass of annual plant inputs to the soils, under the assumed forest/woodland cover, which allows SOC to reach the equilibrium value over 10,000 years. A DPM/RPM ratio of 0.25 is used as default and is appropriate for most deciduous and tropical woodlands (Coleman and Jenkinson 1999). IOM is based on SOC at equilibrium (Eq. 60), and remains constant throughout the model run.

Step 2 is to model the soil inputs to simulate the baseline scenario until the size of the total SOC pool equals initial SOC stocks (i.e SOC stocks at the start of interventions), in order to simulate the change in SOC pools following disturbance.

Step 3, at the time point where initial SOC stocks are reached, the relevant values for the carbon pools (DPM, RPM, BIO, HUM) are extracted and used as initial conditions for baseline and intervention scenarios.

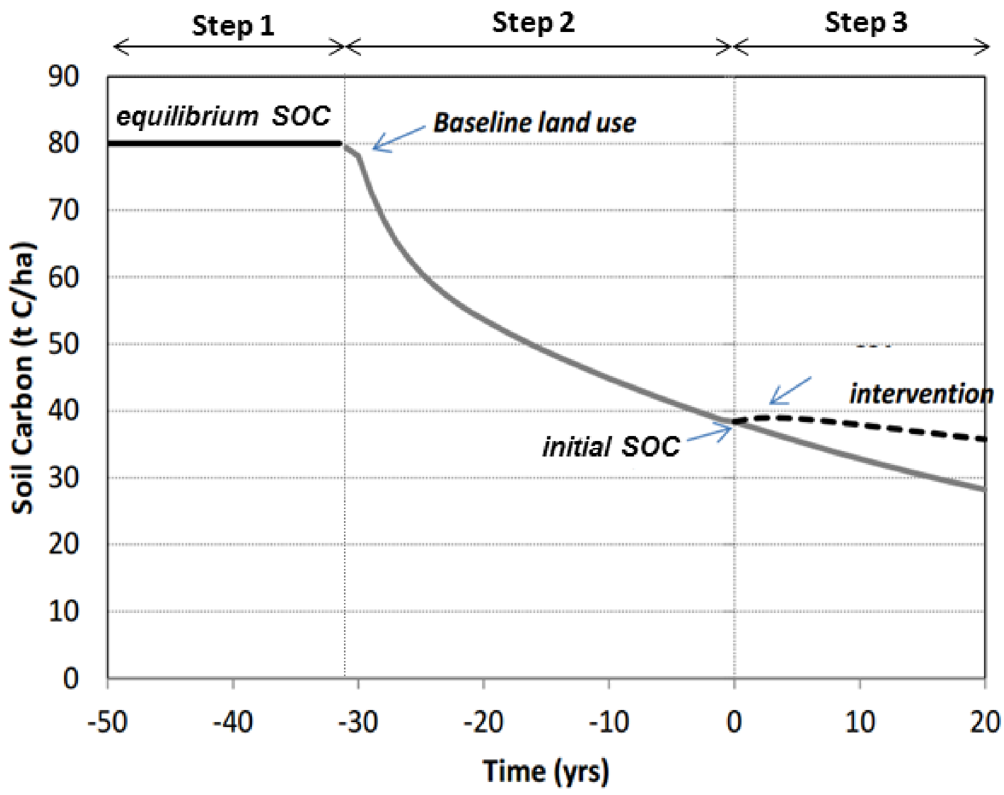

Fig. 5: Schematic of soil model initialisation. The soil model is optimised to equilibrium conditions under woodland or forest conditions before modelling changes in SOC following conversion to baseline land use. The effects of the relevant interventions can then be modelled using initial soil carbon pool values derived at *y* = 0.

8.3 SOC changes

The soil organic carbon model initialises the SOC pools using data on equilibrium and initial SOC stocks and clay content. Once initialised, the baseline and intervention scenarios are modelled separately with modelled organic inputs, weighted DPM/RPM ratios, and climate and soil cover data. Total SOC stocks (i.e. DPM, RPM, HUM, BIO and IOM) in each year are modelled in units of t C/ha. Emissions from changes in total SOC stocks for each year (Eq.1 & 2) are calculated by SHAMBA for baseline and intervention scenarios:

$$E_{SOy} = (SOC_{y-1} - SOC_y) \cdot mw_{CO2} \qquad \text{(Equation 61)}$$

Where: E_{SOy} is the emissions from changes in SOC stocks (tCO_{2e}/ha), where a negative is an uptake

SOC_{y-1} is the SOC stocks in the year before *y* (t C/ha)

SOC_y is the SOC stocks in the year *y* (t C/ha)

mw_{CO2} is the ratio of molecular weights of CO_2 and C (44/12)

8.4 SOC model limitations

The model has a few limitations in that it cannot: model the effects of tillage on SOC stocks, include the impacts of fire on SOC, or incorporate other organic inputs such as charcoal from fire or bio-char. Furthermore, it assumes that the initialisation process is representative of past conditions. If soils have experienced several disturbance and recovery periods since equilibrium, the model initialisation may not be appropriate.

The model assumes:

- Soils are not waterlogged or seasonally flooded
- Only plant and organic inputs to the soil enter the soil carbon pool
- Impacts of fire and tillage on SOC are not considered
- Soils are at least 30 cm deep
- SOC losses through erosion or leakage are minimal
- Climate does not change over the model run

Due to the use of a yearly time step in the soil model, and not a monthly one as per RothC, the total modelled SOC stocks differ slightly between SHAMBA and the Rothamsted Carbon Model (v 26.3)[14]. In a test, based on a range of scenarios the difference in SOC at the end of the simulations between RothC (v 26.3) and the annual timestep implementation in SHAMBA never differed by more than 0.5 t C/ha.

9. Emissions due to nitrogen inputs from plants

This section details the calculations for estimating the emissions from plant nitrogen inputs to the soils.

9.1 Plant nitrogen input emissions description

Direct nitrous oxide emissions from plant nitrogen inputs to soils can be estimated using a Tier-1 type approach, as described in the SALM methodology. As all plants can fix nitrogen and contain some N in their biomass, we calculate emissions from all crop and tree N inputs to the soil, adopting a conservative approach to the calculation of emissions from this source. This differs to other approaches (e.g. SALM), which only account for emissions from the planting of N-fixing plants. The emissions from plant N inputs do not include N inputs from external organic inputs (section 6), as they are not always from plant sources, and are instead included in emissions from fertilisers (section 10).

The model assumes:

- All plant N inputs from crops and trees are included in emissions calculations

9.2 Plant nitrogen input emission parameterisation

The data required to estimate N emissions from plant inputs are outlined in Table 8.

[14] http://www.rothamsted.ac.uk/sustainable-soils-and-grassland-systems/rothamsted-carbon-model-rothc

Table 8: Parameters required for calculating emissions due to plant N inputs for each scenario

Parameter	Symbol	Units	Default value
Mass of total crop N inputs in year *y*	$C_{NItotal,y}$	t N/ha	Calculated in section 5 and 7.4
Mass of total tree N inputs in year *y*	$T_{NItotal,y}$	t N/ha	Calculated in section 4 and 7.4
Emission factor for emissions of N_2O-N from N inputs	ef_N	t N_2O-N/ t N input	0.01
The ratio of molecular weights of N_2O and N_2	mw_{N2O}	*unitless*	44/28
Global warming potential for N_2O for 100 years accounting period	gwp_{N2O}	t CO_{2e}/t N_2O	310

9.3 Plant nitrogen input emission calculations

To calculate the emissions from plant N inputs the following method, based on the SALM methodology, was used:

$$E_{NI,y} = \left(C_{NItotal,y} + T_{NItotal,y}\right) \cdot ef_N \cdot mw_{N2O} \cdot gwp_{N2O} \quad \text{(Equation 62)}$$

Where: $E_{NI,y}$ is the emissions due to the N inputs to soils from plants in year *y* (tCO_{2e}/ha)

$C_{NItotal,y}$ is the total crop nitrogen inputs in year *y* (t N/ha)

$T_{NItotal,y}$ is the total tree nitrogen inputs in year *y* (t N/ha)

ef_N is the emission factor for emissions of N_2O-N from N inputs (t N_2O-N/t N input) (IPCC, 2006)

mw_{N2O} is the ratio of molecular weights of N_2O and N (44/28)

gwp_{N2O} is the global warming potential for N_2O over 100 years accounting period (tCO_{2e}/ tN_2O) (IPCC, 2006)

10. Emissions due to fertiliser use

This section details how emissions from fertiliser use are calculated.

10.1 Emissions from fertiliser use description

If applicable, emissions from the use of synthetic and/or organic nitrogen fertilisers are calculated using the CDM A/R Working Group Tool[15] *Estimation of direct nitrous oxide emission from nitrogen fertilisation (version 01)*. Using emission factors and volatisation values as provided by the IPCC Guidelines (2006), emissions from organic and synthetic fertilisers are calculated. All external organic N inputs (section 6) are included as organic N fertilisers, and are assumed to have the same emission and volatisation values as defined by the IPCC (2006) for organic fertilisers.

The model assumes:

- All external organic inputs (section 6) can be classified as organic fertilisers

[15] http://cdm.unfccc.int/methodologies/ARmethodologies/tools/ar-am-tool-07-v1.pdf

- All external organic inputs have similar emission and volatisation parameters

10.2 Emissions from fertiliser use parameterisation

The data required to calculate the emissions from fertiliser use are outlined in table 9.

Table 9: Parameter requirements to calculate emissions due to fertiliser use

Parameter	Symbol	Units	Default value
Synthetic fertiliser application in year *y*	sf_y	1 or 0 (Yes/No)	*User must provide this*
Mass of synthetic fertiliser applied in year *y*	S_y	t/ha	*User must provide this*
Nitrogen content of synthetic fertiliser	s_n	g N/ g fertiliser	*User must provide this*
Mass of N inputs from external organic inputs in year *y*	$A_{NItotal,y}$	t N/ha	Calculated in section 6 and 7.4
Emission factor for emissions of N_2O-N from N inputs	ef_N	t N_2O-N/t N input	0.01
Fraction that volatises as NH_3 and NO_x for synthetic fertilisers	v_s	(t NH_3-N + NO_x-N)/ t N applied	0.1
Fraction that volatises as NH_3 and NO_x for organic fertilisers	v_o	(t NH_3-N + NO_x-N)/ t N applied	0.2
Ratio of molecular weights of N_2O and N	mw_{N2O}	*unitless*	44/28
Global warming potential of N_2O for 100 years accounting period	gwp_{N2O}	t CO_{2e}/t gas	310

10.3 Emissions from fertiliser use calculations

The direct nitrous oxide emissions from N fertilisation can be estimated as follows:

$$E_{NF,y} = \left[\left(S_y \cdot sf_y \cdot s_n \cdot (1 - v_s)\right) + \left(A_{NItotal,y} \cdot (1 - v_o)\right)\right] ef_N \cdot mw_{N2O} \cdot gwp_{N2O} \qquad \text{(Equation 63)}$$

Where: $E_{NF,y}$ is the direct N_2O emission as a result of nitrogen application in year *y* (tCO_{2e}/ha)

S_y is the mass of synthetic nitrogen fertiliser applied in year *y* (t /ha)

sf_y is if synthetic fertiliser was applied in year *y* (1 if yes, 0 if no)

s_n is the N content of synthetic fertiliser (g N/ g fertiliser)

v_s is the fraction that volatises as NH_3 and NO_x for synthetic fertilisers (IPCC, 2006)

$A_{NItotal,y}$ is the total mass of N inputs from external organic inputs (t N/ha)

v_o is the fraction that volatises as NH_3 and NO_x for organic fertilisers (IPCC, 2006)

ef_N is the emission factor for emissions of N_2O-N from N inputs (t N_2O-N /t N input) (IPCC, 2006)

mw_{N2O} is the ratio of molecular weights of N_2O and N

gwp_{N2O} is the global warming potential of N_2O (IPCC, 2006)

11. Future model developments

Here we suggest ways the model could be improved and further developed in subsequent versions, and outline some of the limitations of the SHAMBA model v1.0. Specific improvements are outlined in context of each model section.

SOC model

- The SOC model runs on an annual time step, but RothC is designed to run on a monthly time step, causing some small errors in total SOC changes. Future versions should run RothC on a monthly time step, using annual plant inputs divided evenly over the year, or using plant inputs calculated for every month. This will require more data inputs, but the accuracy may be increased as a result.

Biomass model

- The growth model choses the best-fit model based on optimisation methods, which will bias those models with a greater number of fitted parameters (i.e. logistic model). To allow a more flexible growth model choice, users should be able to choose the best model to describe the growth of their trees.
- The biomass model is currently a mass-balance model and could be improved by using a process-based model of NPP, which would allow the effects of competition and nutrients to be modelled as well.
- Allocation parameters are static in time. Allocation changes with tree size/age and a more dynamic approach to allocation would be more realistic. Species specific allocations based on tree growth form would also increase the accuracy of the biomass model.
- If the default parameters are not applicable, a set of species specific parameters should be available for a range of commonly planted tree species to decrease the need for users to parameterise the model for each planted tree species themselves.

Crop model

- The crop model assumes crops and yields do not change between years. It would be useful to allow crops planted and yields to change annually.
- If crops are not one of the default species listed in the IPCC, it should be possible for the user to parameterise the model for a different crop species, allowing a greater number of crop types (e.g. banana's, coffee).

External organic inputs

- External organic inputs cannot easily be modelled if the N content, DPM/RPM ratio and combustion and emission factors are not known. These parameters are difficult to determine for various organic inputs. Default values for a range of typical organic inputs would make it easier for users to include these in calculations.

Emissions from biomass burning

- The model does not take into account the emissions from burning of woody biomass taken off-farm, such as fire wood. The inclusion of emissions from burning of woody biomass removed from the fields would increase the accuracy of the emissions from this source.
- Fires do not volatise SOC in this model or deposit carbon to the soil C pool. Emissions from these sources and impacts on these carbon stores should be considered in future versions, as fire can have a significant impact on SOC.
- Fire does not impact on living biomass in fields, including live trees. Fires only burn litter and crop residues, and assumes fire occur post-harvest. If a fire occurs before harvest, or burns whole standing trees, the emissions would be underestimated in the current model.

Emissions from plant N inputs

- The N content of different plants and plant components can vary widely. Default values should be available for a range of different plant growth forms and/or N-fixing abilities to increase the accuracy of the model and decrease user data requirements.

Emissions from fertiliser use

- Users are required to specify the N content of all applied synthetic and organic fertilisers. This process would be simplified if a set of default values were provided for various synthetic and organic fertiliser types, minimising the data requirements from users.

General

- Increase the time steps from annual to monthly resolutions to capture the complexity of land management and subsequent emissions and removals within a year.

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Appendix 1: Model default values, sources, justification and applicability

This appendix outlines the default parameters used in the SHAMBA model. Their values, sources, justification and applicability are discussed for each parameter or set of parameters. These default values can be used by model users if applicability criteria are met. If they are not met, appropriate values must be found either through local measurements, appropriate databases, peer reviewed literature search, or other means.

Model component	Soil carbon model
Parameter	***t, et, p***
Description	Monthly climatic variables
Value	Depends on geographical location
Source of data	CRU TS 3.10 monthly global dataset
Reference	University of East Anglia Climatic Research Unit (CRU). [Phil Jones, Ian Harris]. CRU TS3.10: Climatic Research Unit (CRU) Time-Series (TS) Version 3.10 of High Resolution Gridded Data of Month-by-month Variation in Climate (Jan. 1901 - Dec. 2009),]. Available from: http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__ACTIVITY_fe67d66a-5b02-11e0-88c9-00e081470265
Justification of choice of data or description of measurement methods and procedures applied	The dataset is based on weather station measurements worldwide, and has been peer reviewed. The dataset has been widely used in research and peer reviewed literature.
Applicability criteria	Climate data are representative of mean monthly climate conditions at the specified location
Comments	*NA*

Model component	[illegible]
Parameter	[illegible]
Description	[illegible]
Value	[illegible]
Source of data	[illegible]
Reference	[illegible]
Justification of choice of data or description of measurement methods and procedures applied	[illegible]
Applicability criteria	[illegible]
Comments	[illegible]
Comments	[illegible]
Applicability criteria	Trees must have a similar allometry to species such as *G. robusta, M. lutea, M. eminii, J. globiflora, and B. spiciformis* (see section 4.4), as used in the studies. No pruning of branches or other biomass may occur, as this will change the allometry of trees.
Comments	If planted tree species have a differing allometry, species specific allocation parameters must be sought in peer reviewed literature.

Model component	Biomass model
Parameter	***to_{leaf}***
Description	Annual turnover rate of leaves
Value	1
Source of data	Estimate
Reference	*NA*
Justification of choice of data or description of measurement methods and procedures applied	The default assumes the trees lose all their leaves annually as litter, and that trees are either deciduous or have a leaf life span <= 1. This is set as the default as it was the simplest assumption to make.
Applicability criteria	Trees are deciduous or have a leaf life span <=1 year
Comments	If trees are evergreen, or have a leaf life span >1, the leaf turnover rate can be estimated as follows: 1 / leaf lifespan = turnover rate per year

Model component	Biomass model
Parameter	$\boldsymbol{to_{froot}}$
Description	Annual turnover rate of fine roots
Value	0.8
Source of data	Peer reviewed literature
Reference	Gill, R. & Jackson, R., 2000. Global patterns of root turnover for terrestrial ecosystems. New Phytologist, pp.13–31.
Justification of choice of data or description of measurement methods and procedures applied	Fine root turnover is difficult to measure and rarely reported in the literature. We base our default on a peer reviewed global meta-analysis of root turnover (Gill & Jackson, 2000), using the mean turnover rate reported for tropical tree fine roots.
Applicability criteria	*NA*
Comments	Local or species specific values for fine root turnover should be used where possible

Model component	Biomass model
Parameter	$\boldsymbol{to_{croot}}$
Description	Annual turnover rate of coarse roots
Value	0
Source of data	Conservative estimate
Reference	*NA*
Justification of choice of data or description of measurement methods and procedures applied	Turnover rates of coarse roots are assumed to be zero as the default. This represents a conservative estimate, given the relatively low rates reported and the high uncertainty of this pool in the literature.
Applicability criteria	Coarse roots are not expected to have a high turnover rate
Comments	Local or species specific values for coarse root turnover should be used where possible

Model component	Biomass model (*Chave allometric equations only*)
Parameter	[illegible] tc_{branch}, tc_{leaf}, tc_{croot}, tc_{froot}
Description	[illegible] in the top 0-30 cm of soil
Value	[illegible]
Source of data	[illegible]
Reference	[illegible] ts. Oecologia, 145(1), pp.87–99.
Justification of choice of data or description of measurement methods and procedures applied	[illegible] (Cairns et al., 1997), which was within the range of values reported in Mokany et al. (2006) for tropical forest trees.
Applicability criteria	If one of the Chave allometric equations is selected, and the planted trees are similar to a tropical African tree Total tree roots biomass is mostly found in the top 0-30 cm of soil *NA*
Comments	Species specific values for wood density should be used where possible, and can be found at the following websites: • http://db.worldagroforestry.org/wd • https://datadryad.org/repo/handle/10255/dryad.235 Trees have approx. 20 % of their biomass below-ground *NA* If species specific or local measurements are available for root:shoot ratios, these values should be used [illegible]

Model component	Biomass model
Parameter	tn_{stem}
Description	Nitrogen content of tree stems
Value	0.0015
Source of data	Peer reviewed literature
Reference	- Chave, J. et al., 2009. Towards a worldwide wood economics spectrum. Ecology letters, 12(4), pp.351–66. - Weedon, J.T. et al., 2009. Global meta-analysis of wood decomposition rates: a role for trait variation among tree species? Ecology letters, 12(1), pp.45–56.
Justification of choice of data or description of measurement methods and procedures applied	Nitrogen content of wood can vary widely depending on location, tree species and other factors. Furthermore, few studies report wood N content for agroforestry trees. Therefore, a mean for woody debris N content is used, based on values reported in global meta-analyses of woody traits from peer reviewed literature.
Applicability criteria	*NA*
Comments	The default value is a very rough estimate of wood N content, and it is recommended that species specific values for wood N content are used where possible, especially if trees are N fixing or leguminous.

Model component	Biomass model
Parameter	***tn_{branch}, tn_{croot}***
Description	Nitrogen content of branches and coarse roots
Value	0.0015 (*same as N_{stem}*)
Source of data	*NA*
Reference	*NA*
Justification of choice of data or description of measurement methods and procedures applied	Branches and coarse root N content are rarely reported in the literature. Therefore, we assume the N content of branches and coarse roots would be the same as for woody stems, as branches and coarse roots are also largely woody biomass.
Applicability criteria	*NA*
Comments	

Model component	Biomass model
Parameter	***tn_{leaf}***
Description	Nitrogen content of leaf litter from agroforestry trees (not fresh green leaves)
Value	0.01 if non-legume, 0.02 if legume
Source of data	Peer reviewed literature
Reference	- Constantinides, M. & Fownes, J., 1994. Nitrogen mineralization from leaves and litter of tropical plants: relationship to nitrogen, lignin and soluble polyphenol concentrations. Soil Biology and Biochemistry, 26(I), pp.49–55. - Ratnam, J. et al., 2008. Nutrient resorption patterns of plant functional groups in a tropical savanna: variation and functional significance. Oecologia, 157(1), pp.141–51. - Vitousek, P., 1984. Litterfall, nutrient cycling, and nutrient limitation in tropical forests. Ecology, 65(1), pp.285–298.
Justification of choice of data or description of measurement methods and procedures applied	Nitrogen content of leaf litter can vary widely depending on location, tree N-fixing ability, tree age and other factors. Therefore, a conservative value for leaf litter N content is used for leguminous trees and non-leguminous trees based on a study of several agroforestry trees (Constantinides et al., 1994). These values show close agreement to other studies of leaf litter N content from tropical Africa (Vitousek, 1984), and South Africa (Ratnam, 2008).
Applicability criteria	*NA*
Comments	This mean value is an estimate of leaf litter N content, and it is recommended that species specific values for leaf litter N content are used where possible, especially if trees are N-fixing or leguminous.

Model component	Crop model
Parameter	c_{rs}, n_{can}, c_{bn}
Description	Crop root:shoot ratio, crop residue above-ground N content and below-ground N content
Value	*Depends on crop species/type*
Source of data	IPCC, Table 11.2
Reference	IPCC (2006) 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Available at: http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_11_Ch11_N2O&CO2.pdf
Justification of choice of data or description of measurement methods and procedures applied	The IPCC Guidelines for National Greenhouse Gas Inventories is internationally recognised and the data provided in the guidelines is peer-reviewed.
Applicability criteria	Crops must be one of the IPCC listed crop species or types
Comments	*NA*

Model component	Biomass model
Parameter	tn_c
Description	Nitrogen content of agroforestry fine roots
Value	0.0113
Source of data	Peer reviewed literature
Reference	- Gordon, W. & Jackson, R., 2000. Nutrient concentrations in fine roots. Ecology, 81(January), pp.275–280. - Jackson, R.B., Mooney, H. a & Schulze, E.D., 1997. A global budget for fine root biomass, surface area, and nutrient contents. PNAS, 94(14), pp.7362–6.
Justification of choice of data or description of measurement methods and procedures applied	Fine root nutrient contents are dynamic and can change widely depending on local conditions, tree species, and other factors. Therefore, we use a mean value of fine root nitrogen content as reported by a global meta-analysis, using the mean value reported for fine roots of broadleaf and coniferous trees (Gordon & Jackson, 2000), in close agreement with other global meta analyses (Jackson *et al.*, 1997).
Applicability criteria	*NA*
Comments	Local or species specific values should be used where possible

Model component	Crop model
Parameter	c_{ac}, c_{bc}
Description	Crop residue above-ground C content and below-ground C content
Value	0.40
Source of data	Peer reviewed literature
Reference	- Johnson, J.M.-F., Allmaras, R.R. & Reicosky, D.C., 2006. Estimating Source Carbon from Crop Residues, Roots and Rhizodeposits Using the National Grain-Yield Database. Agronomy Journal, 98(3), p.622. - Latshaw, W. & Miller, E., 1924. Elemental composition of the corn plant. Journal of Agricultural Research, XXVII(11).
Justification of choice of data or description of measurement methods and procedures applied	A default value of 0.4 was chosen as other studies have used this estimated mean C content for crop residues in shoots and roots (Johnson et al., 2006), and it agrees with the C content values reported for maize plants (Latshaw & Miller, 1924).
Applicability criteria	*NA*
Comments	Local or species specific values should be used where possible

Model component	Crop root distribution
Parameter	[illegible]
Description	Fraction of crop roots (Nominal) in the top 0.30 cm of soil
Value	[illegible]
Source of data	Peer reviewed literature
Reference	Jackson, R.B. et al., 1996. A global analysis of root distributions for terrestrial biomes. Oecologia, 108(3), pp.389–411.
Justification of choice of data or description of measurement methods and procedures applied	Crop root distributions in the soil profile vary depending on crop type, soil characteristics and other factors. Therefore, a mean value for crop root distributions was used as the best available estimate, derived from a peer reviewed meta-analysis of root distributions for terrestrial biomes.
Applicability criteria	Local or species specific values should be used where possible.
Comments	*NA*

Model component	External organic inputs
Parameter	[illegible]
Description	Carbon content of external organic inputs (Nominal)
Value	0.50
Source of data	Peer reviewed literature
Reference	- Mtambanengwe, F. & Kirchmann, H., 1995. Litter from a tropical savanna woodland (miombo): chemical composition and C and N mineralization. Soil Biology and Biochemistry, 27(12), pp.1639–1651. - Musvoto, C., Campbell, B.M. & Kirchmann, H., 2000. Decomposition and nutrient release from mango and miombo woodland litter in Zimbabwe. Soil Biology and Biochemistry, 32(8-9), pp.1111–1119.
Justification of choice of data or description of measurement methods and procedures applied	External organic inputs originating from surrounding woodland/forest is assumed to be a mixture of leaf, twig, bark and other woody litter. We assume a 50% C content, which is a conservative estimate based on reported values for woodland and mixed tree litter C content (Mtambanengwe et al., 1995; Musvoto et al., 2000).
Applicability criteria	External organic inputs must originate from forest/woodland litter, or woody trees/shrubs litter.
Comments	*NA*

Model component	Crop and organic inputs, emissions from plant N inputs, emission from fertiliser use
Parameter	***ef, gwp, v***
Description	Emission factors for N, global warming potentials of greenhouse gases, and volatisation fraction
Value	*See section 7 (Table 6), section 9 (Table 8), section 10 (Table 9) for values*
Source of data	IPCC
Reference	IPCC (2006) 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds).
Justification of choice of data or description of measurement methods and procedures applied	The IPCC Guidelines for National Greenhouse Gas Inventories is internationally recognised and the data provided in the guidelines is peer reviewed.
Applicability criteria	[illegible]
Comments	*NA*