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A Conceptual Model of Carbon Dynamics for Improved Fallows in the Tropics

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1. Introduction

Despite the increasing international sense of urgency, the growth rate of carbon (C) emissions continued to speed up, bringing the atmospheric CO_2 concentration to 383 parts per million (ppm) in 2007 (Global Carbon Project [GCP], 2008). Annual fossil CO_2 emissions increased from an average of 6.4 Gt C yr^{-1} in the 1990s to nearly 10 Gt C yr^{-1} in 2008 (Le Quéré et al., 2009), while emissions from land-use change were estimated to be 1.6 Gt C yr^{-1} over the 1990s. About 45% of annual C emissions (3.5 Pg) remained in the atmosphere each year, while oceans and terrestrial ecosystems assimilated the other 55% (Canadell & Raupach, 2008). Increasing the size and capacity of land-based ecosystems that sequester C in plants and the soil expands the terrestrial C sink. Establishment of agroforestry systems is one of the options of reducing deforestation and increasing the terrestrial C sinks (Kaonga & Bayliss-Smith, 2010; Oelbermann et al, 1997).

Over 1 billion hectares of agricultural land, almost 50% of the world's farmland, have more than 10% of their area occupied by trees, while 160 million hectares have more than 50% tree cover (Zomer et al., 2009). Tree-based farming systems, whether mixed or monocultures, store up to 35% of C stored by a primary forest, compared with only 10% at the most in annual cropping systems. Average C storage by agroforestry systems has been estimated as 9, 21, 50, and 63 Mg C ha^{-1} in semi-arid, subhumid, humid, and temperate regions (Montagnini & Nair, 2004). If agroforestry practices are established immediately after slash and burn agriculture, 35% of the original forest C stocks can be regained (Sanchez, 2000) and a hectare of an agroforestry practice can potentially offset 5 ha of deforestation (Dixon, 1995). Carbon stocks in smallholder agroforestry systems in the tropics ranged from 1.5 to 3.5 Mg C ha^{-1} year^{-1}, tripling to 70 Mg C ha^{-1} year^{-1} in a 20-year^{-1} period (Watson et al., 2000). Improved fallows have great potential for increasing the terrestrial C sink through vegetal and soil C sequestration, conservation of forest C, and improved soil productivity (Kaonga & Coleman, 2008; Sanchez, 1999; Sileshi et al., 2007). However, C cycling in agroforestry systems is not clearly understood.

To date, the potential for C sequestration in agroforestry systems has not been adequately described. Despite the large number of publications on C dynamics in land-use systems, it

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has been difficult to construct a simple C budget of an improved fallow because of marked variations in soil characteristics, climatic factors, plant species, and management practices. Comparisons between reported experiments are complicated by great diversity of analytical techniques used by researchers to study C dynamics in land-use systems (Intergovernmental Panel on Climate Change [IPCC], 2000). In addition, ecological processes, which determine C storage in ecosystems, may themselves be controlled by other factors, most of which may interact strongly. In such situations, a conceptual model can assist to explicitly describe relationships between the various components, explore possibilities for modification of ecosystem processes that underpin C stocks and flows, and to examine the effects of ecosystem drivers and stressors on C pools.

This chapter describes a conceptual model that summarises current knowledge on ecological processes, drivers, and stressors responsible for C cycling, and demonstrates how the conceptual model could be used to estimate major C pools and fluxes in improved fallows using data from eastern Zambia. This model will improve our understanding of C dynamics in ecosystems for strategic C management.

2. Methodology

2.1 Conceptual model development

Published literature on tropical improved fallows in southern Africa (Chintu et al., 2004; Kwesiga et al., 1994; Kwesiga et al., 1999; Mafongoya et al., 1998; Sileshi et al., 2006a) and eastern Africa (Albrecht & Kandji, 2003) and other agroforestry practices in tropical Africa (Young, 1989) and Latin America (Oelbermann et al., 2004) was reviewed to determine major C pools and fluxes, and to describe major ecological processes, drivers, and stressors that determine C stocks in these ecosystems. Major C pools and fluxes, and key ecosystem drivers and stressors determining C dynamics in improved fallows were presented using diagrams and mathematical equations accompanied by detailed narratives.

2.2 Estimation of major carbon pools and fluxes using the conceptual model

2.2.1 Study sites

Data on C stocks were collected from two-, four- and 10-year-old tree fallows, established to study the effect of tree species on soil physical and chemical properties. The experiments were carried out at Kalichero (13o29'S 32o27'E), Kalunga (13o51'S 32o33'E) and Msekera (13o39'S 32o34'E) in eastern Zambia, at altitudes of 1000-1100 m (Table 1), and with a mean annual temperature of 23oC. The sites receive a mean annual rainfall of 960 mm in a single rainy season and 85% of rain falls within four months (December through March). Soils in eastern Zambia are yellowish-red to yellowish-brown loamy sandy or sandy soils - Acrisols. Site-specific soil classes and properties are summarized in Table 1.

2.2.2 Experiments

Aboveground plant biomass and soil samples for C analyses were collected from two-, four- and 10-year old improved fallow experiments at Kalichero, Kalunga, and Msekera research sites (Table 1) in eastern Zambia, from November 2002 to July 2003. The experiments, arranged in a randomized complete block design (RCBD) with four replications, included:

i. two-year-old non-coppicing fallow treatments (2000/02) of *Tephrosia candida* (*T. candida*), *T. candida* 02971, *Tephrosia vogelli* (*T. vogelli*) Chambeshi, *T. vogelli* Misamfu, and *Sesbania sesban* (L) Merr (*Sesbania*) at Kalichero and Kalunga.

ii. two-year old coppicing fallow (2000/03) treatments of *Acacia angustissima* (Mill) (*Acacia*), *Gliricidia sepium* (Jacq.) (*Gliricidia*), *Leucaena collinsii* (*L. collinsii*), *Calliandra callothyrsus* Embu (*Calliandra*), and *Senna siamea* (*Senna*) at Msekera and Kalunga.

iii. four-year old (1999-03) non-coppicing fallow treatments of *Cajanus*, *T. vogelli,* and *S. Sesban* (*Sesbania*) grown sequentially with maize at Msekera. The cropping phase was preceded by a three-year tree phase.

iv. 10-year old (1992-03) treatments of coppicing *L. leucocephala* Lam. deWit, *Gliricidia*, and *Senna* trees intercropped with maize at Msekera. The coppicing fallows comprised two phases: the initial three-year tree phase followed by a seven-year tree-maize intercropped phase. While the initial tree density in the tree phase was 10000 trees ha^{-1}, it decreased by almost 30% during the seven-year tree-maize intercropped phase.

The experiments also included control treatments of continuously cropped maize monoculture with fertilizer (M+F) and without fertilizer (M-F), and natural fallows (NF).

At the end of two-year-old non-coppicing fallows, in October 2002, 18 randomly selected trees at Kalichero and Msekera, and 36 trees at Kalunga, were destructively harvested in each treatment for C analyses. The sampling procedure was derived from published methods (Kaonga & Bayliss-Smith, 2009; Kumar & Tewari, 1999). Data on litterfall, living stem, branch, twig and leaf, and root biomass from two-year old coppiced and non-coppiced fallows, and prunings from 10-year old coppiced trees were collected from improved fallows. Additional data on maize grain yields and crop residues, and weed biomass in four-year old non-coppicing fallows and 10-year old coppiced fallows, provided by the Zambia/ICRAF Project, were also collected from the same experiments. Carbon contents in weed, maize grain and stover, and root biomass were estimated using published conversion factors.

Soil samples for SOC analyses were collected at 0-30 depth in a grid pattern from 10 locations in the centre 49 m^2 of each plot of (i) coppicing fallows (2000/03 and 1992/03) and non-coppicing fallows (1999/02) at Msekera, (ii) coppicing fallows (2000/03) and non-coppicing fallows (2000/02) at Kalunga, and (iii) coppicing fallows at Kalichero from October 2002 to July 2003. Composite soil samples from each plot were air-dried, crushed, passed through a 2 mm sieve, and analyzed for SOC by the Walkley-Black method (Schumacher, 2002). The Zambia/ICRAF Agroforestry Project used the same procedure to collect soil samples in the same experiments from 1997 to 2000. Carbon densities (t ha^{-1}) were determined as a product of bulk density, C concentration, and horizon thickness. The Project also provided data on maize crop, weed, and tree residue inputs for the period 1995-2002.

The conceptual model identifies three major phases of improved fallows – tree, maize cropping, and tree-maize intercropping phases – depending on the spatial or temporal arrangement of trees and the maize crop in a fallow cycle. In non-coppicing fallows, two-three year tree phases alternated with maize monocropping phases of the same duration. However, in coppicing fallows with tree species that re-sprout after cutting, an initial three-year tree phase was followed by a continuous tree-maize intercropping phase, which ended when crop yields dropped below optimal levels (Mafongoya et al., 2006). Trees were pruned two-three times in a cropping season and leaf biomass was applied to the soil as organic

fertilizer. Detailed descriptions of management regimes of three-year old coppicing and non-coppicing fallows [Chintu et al., 2004; Kaonga & Coleman, 2008), four-year old non-coppicing fallows (Sileshi & Mafongoya, 2003) and 10-year old coppicing fallows (Sileshi & Mafongoya, 2006a) have been reported in earlier publications.

| Characteristic | Research sites | | |
	Msekera	Kalichelo	Kalunga
Longitude	13o39' E	13o29' E	13o51' S
Latitude	32o34' S	32o27' S	32o33' S
Altitude (m)	1030	1001	1101
Rainfall (mm)	900	800-1000	800-1000
Rain season	Nov – April	Nov-April	Nov-April
Temperature range	15 – 30oC	14 – 28oC	13 – 28oC
Soil classification			
USDA	Ustic Rhodustalf	Typic Kandiustalf	Aridic Kandiustalf
Soil properties			
pH	5.3	5.0	4.8
Organic C	10.0 g kg^{-1}	7.0 g kg^{-1}	4.0 g kg^{-1}
Total N	0.7 g Kg^{-1}	0.7 g Kg^{-1}	0.4 g Kg^{-1}
Clay	26.0 %	22.0 %	8.0 %
Sand	61.0 %	64.0 %	85.0 %

Table 1. Biophysical and climatic conditions, and characteristics of the surface soil (0-15 cm) of research sites in Chipata, eastern Zambia (Kaonga and Bayliss-Smith, 2010)

3. Results and discussion

3.1 Description of the conceptual model of carbon cycling in improved fallows

The model recognizes that C in improved fallows is recycled between the environment and organisms mainly through ecosystem C aggrading processes (e.g. photosynthesis, precipitation, and sediment deposition) and degrading processes (decomposition, respiration, soil erosion, leaching) regulated by drivers (e.g. climate, droughts, hydrology) and stressors (pests, fire, biomass harvesting) (Figure 1). This model, which specifies the boundaries and the scope of C dynamics in tropical improved fallows, comprises diagrams accompanied by detailed narratives. It is based on non-mechanized fallow systems where fauna and microorganisms play a major role in decomposition of SOM and C sequestration. In improved fallows, SOC stocks decrease considerably with depth and the model considers only the soil surface layer (0-30 cm) where vertical variability can be ignored to a reasonable approximation.

3.1.1 Ecosystem processes in improved fallows

Plant C pools represent the difference between primary production through photosynthesis and consumption by respiration, decomposition, and harvest processes (Brown, 1997). Net assimilation of C by plants in improved fallows can be modelled as a function of radiation interception (Q), conversion efficiency (net C fixed/unit radiation intercepted) (E), growth and maintenance respiration (R) (Aber & Melillo, 2001; Vose & Swank, 1990):

$$TPC = \sum_{i=1}^{t} (Q_i \times E_i) - \sum_{c=1}^{n} R_{i,c} \tag{1}$$

where TPC (t C ha^{-1} yr^{-1}) is the total plant C gain, the subscript $_c$ in $R_{i,c}$ is respiration rate for specific plant components (leaves, branches, stem, and roots) (Vose & Swank, 1990). However, net C assimilation is influenced by ecosystem drivers (climate, atmospheric deposition, resource availability) and stressors (drought, fire, nutrient deficiencies, herbivory, pests, biomass harvesting). Photosynthetic C intake rates of plants in improved fallows can be estimated as the sum of all plant C fractions expressed as:

$$PCI = C_{HB} + C_{PR} + C_R + C_{RD} \tag{2}$$

where PCI is photosynthetic C intake (t ha^{-1} yr^{-1}), C_{HB} represents C in harvested biomass, C_{PR} is C in post-harvest plant residues, surface litter, and fresh leaf biomass, C_R is C in root biomass, and C_{RD} depicts rhizodeposit C (Bolinder et al., 1997; Jenkinson et al., 1999). Photosynthetic C intake rates for trees in fallows are derived from NPP by the modified mean annual increment method (Art & Marks, 1971; Brown, 1997]. Data on underground plant C pools in improved fallows are scarce, but fractional allocation of photosynthetic C to different tree components can be approximated using the following formulae (Bolinder et al., 1997; Heal et al., 1997; IPCC, 2000; Young, 1989, 1997):

$$C_{HB} = Y_{HB} \times 0.48 \tag{3}$$

$$C_{PR} = (Y_{ABG} - Y_{HB}) \times 0.48 \tag{4}$$

$$C_R = Y_{ABG} \times 0.35 \times 0.48 \tag{5}$$

$$C_{RD} = C_R \tag{6}$$

where Y_{ABG} is aboveground biomass (t ha^{-1} yr^{-1}), Y_{HB} is the harvested plant biomass of economic use, 0.35 is tree root C expressed as fraction of aboveground C stock, and C_{RD} is the rhizodeposit C, and 0.48 represents a weighted C content of tree components (Kaonga, 2005):

$$\text{Weighted } \%C = (0.4C_{S+B} + 0.09C_T + 0.12C_L + 0.25C_R + 0.06C_{Lit} + 0.08C_{RD}) \times 100 \tag{7}$$

where $_S$ = stem, $_B$ = branches, $_L$ = leaves and twigs, $_R$ = root, and $_{Lit}$ = surface litter, and $_{RD}$ = rhizodeposit. Measured standing vegetal C must be adjusted for the dry weight of detached senesced tissues, leachates, herbivory, excreta, grazed or harvested biomass during the production period.

For maize sub-pools, plant C fractions can be estimated using the following formula derived from published methods (Bolinder et al., 1997):

$$C_{HB} = (Y_{ABG} - Y_{PR}) \times 0.45 \tag{8}$$

$$C_{PR} = Y_{HB} (1-HI)/HI \times 0.45 \tag{9}$$

$$C_R = Y_{ABG} \times 0.35 \times 0.45 \tag{10}$$

$$C_{RD} = 0.65 \times C_R \tag{11}$$
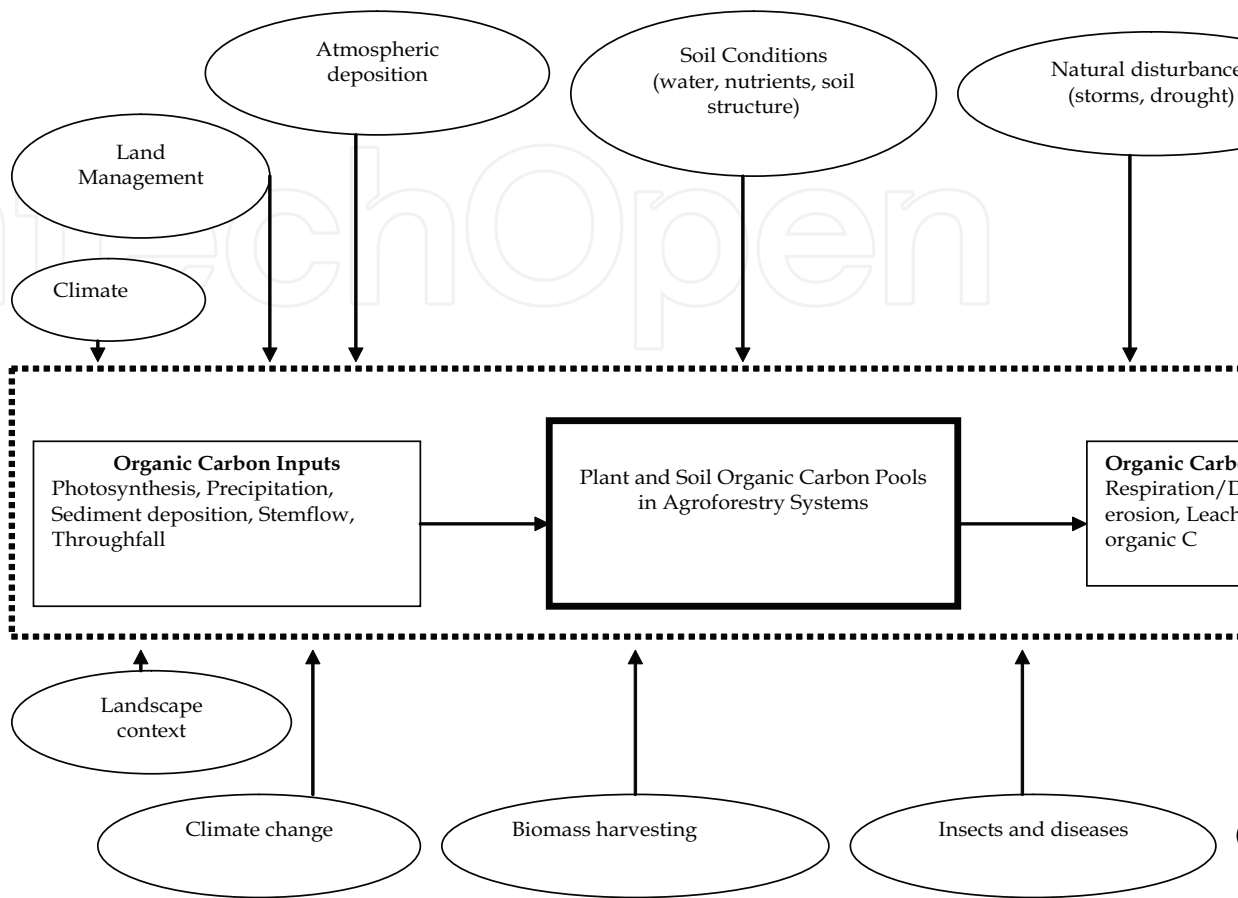
Fig. 1. A diagrammatic presentation of carbon pools and ecosystem drivers, disturbances, and stressors that influence carbon stocks and fluxes

where Y_{ABG} is the total dry matter yield (DM) of aboveground biomass (t ha^{-1} yr^{-1}), HI is the harvest index defined as DM yield of grain/total aboveground DM yield, and C_R = 31% of aboveground maize C stocks was root C (Buyanovsky & Wagner, 1986). Indices vary with maize variety, nutrient status of the soil, climate, pests and diseases, and agronomic practices. Root and rhizodeposit C inputs of weeds (grass) can be estimated by:

$$C_R = 0.31 \times C_{ABG} \tag{12}$$

$$C_{RD} = 0.65 \times C_R \tag{13}$$

Root and rhizodeposit C stocks are determined by various factors, including plant management practices, climate, soil conditions, pests and diseases, and herbivory. Stress factors that limit plant productivity reduce fractional allocation of photosynthesates to the root system and rhizodeposition.

Vegetation often modifies the intensity and distribution of precipitation falling on and through its leaves and woody structures, and chemistry of precipitation passing through agroforest canopies and down the stem. The canopies trap dust, aerosols, and gases in dry deposits and dissolved ions in precipitation and cloud droplets. Intercepted chemicals may be absorbed by plant foliage or microbes living on plant surfaces, or they may be washed off leaves and enter the soil system (Richter et al., 2000). Carbon is transferred to the soil in throughfall (precipitation that drips down through the forest canopy), and stemflow (intercepted precipitation that flows down the stem of a plant). The chemistry of throughfall and stem flow consists of C and nutrients in incident precipitation, soluble organic compounds and nutrients leached from vegetation, and those washed from surface of vegetation.

Products of decomposition and activities of phytophagous insects contribute to organic DOC in stemflow. The primary characteristics of a rainfall event that influence stemflow are rainfall continuity, rainfall intensity, and rain angle (Richter et al., 2000). Tree species determine stemflow through their morphological characteristics (crown size, leaf shape/orientation, flow path obstruction, and bark) and stand characteristics (individual tree species, structure of the forest, and species density). The two primary mechanisms influencing throughfall chemistry are wash-off of dry deposited elements from leaf surfaces, and canopy exchange through leaching of carbon and other organic compounds (Richter et al., 2000). Leaching can reduce soil C sequestration (Wise & Cacho, 1994) and contribute to transportation of C to marine ecosystems. In southern Africa, leaching is not intense because of low rainfall (Brown et al., 1994) and DOC leached below the topsoil is rarely lost from the system and the leaching front is arrested at less than 1m. However, leaching beyond the 0-30 cm depth was estimated using the formula,

$$L = C_i \times 0.05 \tag{14}$$

where C_i is the annual C inputs (t ha^{-1} yr^{-1}) to the soil and 0.05 represents a fraction of C_i that would be leached below the 30 cm depth.

Surface litter protects the soil against erosion, increases infiltration rates, regulates soil moisture, provides food and substrate for the decomposer community (Heal et al., 1997; Waring & Schlesinger, 1995), and cycles C and nutrients through decomposition, mineralization and leaching. The rate of litter decomposition in agroforestry systems (Young, 1989) is given by:

$$\frac{dL}{dt} = A_{Lit} - (K_{Lit} * P_{Lit}) \qquad (15)$$

where A_{Lit} = annual litter C input, K_{Lit} = litter decomposition constant, and P_{Lit} = accumulated litterfall. Litter decomposition rates in fallows functionally depend on quality (C:N ratio, polyphenols, and lignin content) and quantity of litter, climate and soil conditions, age and vegetation type, nutrients, and management practices.

Decomposition alters SOM through communition, leaching, and catabolism (Heal et al., 1997). When organic residues are added to the soil, they are enzymatically hydrolysed, mineral elements are released and or immobilized, and humic organic compounds differentially resistant to microbial oxidation are formed through biochemical transformation of SOM or microbial synthesis (Brady & Weil, 1996). Decomposition of SOM depends on soil moisture, soil temperature, clay content and type, soil nutrients, vegetation type, soil microbial activities, and management practices (Brady & Weil, 1996; Jenkinson et al., 1999). Although SOM exists as materials covering a wide range of decomposabilities (Falloon & Smith, 2002; Jenkinson et al., 1999), this model simply partitions SOM into labile, stable, and recalcitrant fractions. The split between humification and oxidation is taken as 15:85 for crop and weed residues and tree prunings, and 33:67 for root biomass (Young, 1989). Soil organic C accretion through decomposition of plant organic inputs is estimated by a method derived from published studies (Bolinder et al., 1997; Young, 1989):

$$C_i = [C_{HB} \times S_{HB}] + [C_{PR} \times S_{PR}] + [C_R \times S_R] + [C_{RD} + S_{RD}] \qquad (16)$$

where C_i is the annual C input to the soil, S describes the portion of C pool that is returned to the soil. Relative C input (R_i), expressing C input to the soil as proportion of PCI, is calculated as:

$$R_i = C_i / (C_{HB} + C_{PR} + C_R + C_{RD}) \qquad (17)$$

As humus in the soil is oxidized, annual humic C losses are estimated by:

$$C_1 = C_0 - KC_0 \qquad (18)$$

where C_0 = antecedent soil humus C, C_1 = C after one year, and K is humus decomposition constant – 3% for the tree phase, and 4% for cropping and tree-maize intercropped phases (Young, 1989).

Soil erosion preferentially removes the light organic fraction of low density SOC (<1.8 Mg m^{-3}), depleting C stocks in the topsoil (Lal, 2003). It alters C stocks and flows in agroforestry systems through removal or deposition of soil particles with humus (IPCC, 2000). Without quantitative data on erosion and the amount of eroded SOC, interpretation of the effects of different land-use systems on SOC dynamics is speculative (van Keulen, 2001). In fallows, erosion C losses are estimated by the formula:

$$E = E_A \times \%SOC \times CEF \qquad (19)$$

where E = erosion C losses (t C ha^{-1} yr^{-1}), E_A = achievable erosion rate, %SOC = SOC content in the topsoil, CEF = C enrichment factor (Young, 1989). This model takes E_A as 10 t C ha^{-1} yr^{-1} (Hudson, 1995; Young, 1989) and CEF as 2.0 (Young, 1989). Land-use change from

continuous monocropping to improved fallows induces changes in SOC stocks. Such changes can be calculated by a mass-balance equation (Lal, 2003):

$$\Delta SOC = (SOC_a + A) - (E + L + M) \tag{20}$$

where ΔSOC is the change in pool, SOC_a is the antecedent pool, A is accretion or input of C through organic additions, and losses due to erosion (E), leaching (L) and mineralisation (M) accentuated by anthropogenic perturbations.

3.1.2 Ecosystem drivers

The major ecosystem drivers of C cycling in improved fallows include climate, hydrology/geomorphology, and soil fauna and microbes. Climatic factors directly relevant to C cycling are rainfall, temperature, potential evaporation, and solar radiation. Climate regulates ecosystem processes and stressors. For example, in ecosystems with low vegetative cover, rainfall intensities may exceed infiltration capacity resulting in infiltration-excess and saturated overland flow, which may carry SOC (IPCC, 2000). The effect of hydrological processes on SOC dynamics depends on antecedent moisture conditions, soil conditions, biological activities, local gradients, and hydraulic conductivity (Brady & Weil, 1996).

Soil fauna, such as earthworms and termites, accelerate catabolism and leaching through communition of litter, mixing and incorporating fragmented products in the soil, changing porosity, and by increasing hydraulic conductivity and water infiltration (Mafongoya et al., 2006). Soil microbes degrade OM reduced by soil fauna. However, populations, activities, and distribution of soil fauna and microorganisms in ecosystems depend on site-specific variables like temperature, soil moisture, nutrients, pH, soil clay content and mineralogy, and vegetation type.

3.1.3 Ecosystem stressors

Productivity of tropical improved fallows is influenced by factors including climate change, air pollution, landscape context, management practices, biomass harvesting, herbivory, fires, and insect attack. Elevated atmospheric CO_2 concentration stimulates photosynthesis and inhibits respiration, increases water use efficiency, and affects feedbacks involving nutrient cycling (IPCC, 2000). By contrast (i) soil warming may increase C losses by accelerating respiration, (ii) increased productivity may deplete nitrogen concentrations leaving vegetation more susceptible to herbivory, (iii) actual plant productivity under field conditions may be constrained by nutrient limitations, and (iv) natural disturbances, insects, and diseases may become more intense and widespread (Sileshi et al., 2007). Droughts reduce ecosystem productivity due to low soil moisture contents and reduced nutrient uptake. However, data on the effect of increasing atmospheric C concentrations on C dynamics in agroforestry systems are scarce.

Carbon pools in improved fallows may be altered by the surrounding landscape depending on the nature of land-use. Widespread de-vegetation due to agricultural production results in a landscape that is windier, exposed to extreme temperatures, accessible to pests and diseases, vulnerable to loss of C through erosion, and favours increased microbial decomposition of SOC (Hudson, 1995; Watson et al., 2000). Management practices that

favour C storage in land-use systems also improve soil physical and chemical properties, reduce soil erosion, and increase biodiversity (Dixon, 1995; Sanchez, 1999).

When trees in improved fallows are harvested, photosynthesis ceases and C stored in woody biomass is released to the atmosphere as CO_2, if wood is burned or decays (Albrecht & Kandji, 2003). Similarly, harvesting of agricultural products, such as maize grain, represents a significant C export from the system. In addition, tillage enhances SOM losses through increased microbial decomposition because it destroys soil aggregates which physically protect SOC against decomposers, increases aeration, and it re-distributes bacterial and fungal hyphae in the plough layer thereby increasing contact between microbes and SOM (Paulstian et al., 2000). The effect of management practices on SOC depends on the extent of soil disturbance, quantity and fate of harvested biomass, soil nutrients, water regimes, plant species, and plant cover.

In southern Africa where crop-livestock production systems are common (Kwesiga et al., 1999) grazing reduces green area index (GAI) and NPP, changes fractional C allocation to different plant tissues, and drastically reduces annual C inputs to the soil (Aber & Melillo, 2001). Similarly, insect attack can reduce NPP in agroforestry systems. For example, root nematodes and termites reduced growth and productivity of *Sesbania* and *Cajanus* in eastern Zambia (Mafongoya et al., 2006). Thus, herbivory can reduce overall plant productivity.

3.2 Estimation of major carbon pools using the model

3.2.1 Quantitative estimates of PCI and carbon pools in improved fallows

To illustrate how the conceptual model estimated major C pools using experimental data from improved fallow experiments, the model calculated PCI, and aboveground tree biomass, root and extra root C based on the following assumptions:

a. Trees and the maize crop in improved fallows produce optimal yields in a sub-humid climate with a unimodal rainfall pattern,
b. Fast growing tree legumes in improved fallows produce biomass yields close to those obtainable in other agroforestry systems in similar environments,
c. Carbon inputs and exports in both spatially mixed and rotational tree-crop systems are evenly distributed over a period, but the curve of SOC against time has toothed pattern for rotational fallows (Young, 1989; Sanchez, 1999),
d. Root C in the 0 to 30 cm soil layer is taken as 95% for crops (Buyanovsky & Wagner, 1986) and weeds and 70% for tree legumes (Dhyani & Tripathi, 2000).

Using Eqs. (2) – (6), PCI for *L. collinsii* (Table 2) was calculated based on measured harvested aboveground biomass C as follows

$$C_{HB} = \left(Y_{HB} \times 0.48\right) / \text{Age of fallow (yrs)} = 5.2 / 2 = 2.6 \text{ t ha}^{-1}\text{yr}^{-1}$$

$$C_{PR} = \left(Y_{Lit} \times 0.48\right) = 1.0 \text{ t ha}^{-1}\text{yr}^{-1}$$

$$C_R = C_{HB} \times 0.35 \times 0.7 = 1.1 \text{t ha}^{-1}\text{yr}^{-1}$$

$$C_{RD} = CR = 1.1 \text{t ha}^{-1}\text{yr}^{-1}$$

Using Eq. (2),

$$\text{PCI for whole tree biomass} = (4.5 + 1.0 + 1.1 + 1.1) = 7.7 \text{t ha}^{-1}\text{yr}^{-1}$$

$$\text{PCI for aboveground tree biomass} = (4.5 + 1.0) = 5.5 \text{t ha}^{-1}\text{yr}^{-1}$$

Using Eqs. (7) and (16), annual C inputs to the soil in the tree phase were calculated as follows,

$$C_i = [C_{HB} x\, S_{HB}] + [C_{PR} x\, S_{PR}] + [C_R x\, S_R] + [C_{RD} + S_{RD}]$$
$$= [4.5 \times 0.21) + [1.0 \times 1.0] + [1.1 \times 1.0] + [1.1 \times 1.0] = 4.2 \text{ t ha}^{-1}\text{yr}^{-1}$$

The relative C input (R_i) to the soil, calculated using Eq. (17) is given as

$$R_i = 4.2/(2.6 + 1.0 + 1.1 + 1.1) = 0.54$$

Based on Eq. (19), soil erosion C losses were calculated as

$$E = E_A \times \%SOC \times CEF = 10 \times 0.01 \times 2 = 0.2 \text{ t ha}^{-1} \text{ yr}^{-1}$$

Changes in SOC stocks as a result of a shift from maize monoculture to *L. collinsii* improved fallows were quantified by a mass-balance equation Eq. (20) as follows:

$$\Delta SOC = (SOC_a + A) - (E + L + M)$$
$$= (35.6 + 4.2) - [0.2 + (4.2 \times .05) + (2.0 \times .85) + (2.2 \times 0.67)]$$
$$= 0.6 \text{ t ha}^{-1}\text{yr}^{-1}$$

Variables for each species were used to model representative PCI rates and tree C pools in fallows.

3.2.2 Modelled above and belowground carbon pools and fluxes in the tree phase

Figure 2 shows modelled PCI rates, and above- and below- ground C pools, derived from measured and modelled variables in Table 2. Modelled PCI rates (4.1 - 8.1 t ha-1 yr-1) for nine tree species in the two-year-old tree phase in eastern Zambia (Table 2) were consistent with those (4.0-8.0 t ha-1 yr-1) published for tropical agroforestry systems (Dixon, 1995). Similarly, modelled C stocks in aboveground tree biomass in two-year-old improved fallows (3.4 - 9.4 t ha-1) were within the published range (1.5-12.5 t ha-1) for agroforestry systems in Latin America (Kursten & Burschel, 1993) but lower than those (9.9-21.7 t ha-1) published for 18-22-month old fallows in Kenya (Abrecht & Kandji, 2003). Differences between C stocks in this study and that in Kenya could be attributed to variations in soil and climatic conditions. However, the conceptual model reasonably estimated the PCI rates for, and C stocks in, tree biomass. The quantity of C in tree biomass and the PCI rate differ with tree species. In eastern Zambia, *Gliricidia*, *L. collinsii*, *Senna*, and *T. candida* fixed more C in above- and below-ground biomass than other species presumably because of differences between species and their adaptability to site characteristics (Table 2). Carbon sequestration in the tree phase could be increased by selecting superior tree species that are adapted to production sites.

With a modelled PCI rate of 0.7 t ha-1 yr-1, weeds in the tree phase stored 0.8 t C ha-1 in aboveground biomass, while belowground sub-pools comprised root (0.3 t ha-1) and extra root C (0.2 t ha-1 yr-1) (Figure 2). The contribution of weeds to C cycling in improved fallows

depended on the species and age of the trees. During the early stages of the tree phase, when the green area index of trees was low, weed density was high. However, after the tree canopy closed and litterfall commenced, the weed population declined probably because of the mulching effect of litter, increased competition for resources, and allellopathic effects of tree-derived organic residues (Sileshi et al., 2007).

Measured total SOC stocks in the soil surface layer (0-30 cm) in two-year-old tree fallows were estimated to be 36.5 t ha^{-1} (Figure 2). With modelled annual humic and erosion C losses estimated at 0.4 and 0.2 t ha^{-1} yr^{-1}, respectively, the modelled net annual assimilation rates of SOC stocks in the topsoil in two-year-old tree fallows was 0.7 t ha^{-1} yr^{-1} compared to 0.7-1.1 t ha^{-1} yr^{-1} in four-year-old non-coppicing fallows at Msekera (Kaonga and Coleman, 2008) and 0.6 t ha^{-1} yr^{-1} in a 10-year-old *Erythrina poeppigiana* alley cropping system in Costa Rica (Oelbermann et al., 2004), suggesting a close fit between modelled and published SOC accretion rates.

3.2.3 Modelled and measured carbon pools and fluxes in the cropping phase

Carbon pools and flows in the cropping phase are influenced mainly by the previous tree phase, and maize and weed biomass inputs. Based on harvest index and rhizodeposit fraction, and C stocks in maize crop residues and root biomass, the calculated PCI for maize in four-year old *Cajanus, Sesbania* and *Tephrosia* rotational fallows (Table 3) ranged from 4.7 to 7.2 t ha^{-1} yr^{-1}. The modelled rate for these fallows (5.4 t ha^{-1} yr^{-1}, Figure 3) was comparable to that (6.6 t ha^{-1} yr^{-1}) calculated for a 10-year-old *Erythrina poeppigiana* alley cropping in Costa Rica (Oelbermann et al., 2004). Differences between the modelled and measured PCI rates may be attributable to differences in age, climate, crop varieties, and approaches to crop biomass measurement.

| | | | Modelled C (t ha^{-1} yr^{-1}) | | |
| | Aboveground biomass C | Surface litter | Root biomass | Extra root | PCI* |
Treatment	(C_{AB}) (t ha^{-1})	(C_{lit}) (t ha^{-1} yr^{-1})	(C_R)	(C_{RD})	
A. angustissima	5.2	0.7	0.6	0.6	4.5
C. callothyrsus	4.8	0.6	0.5	0.5	4.0
G. sepium	8.2	1.0	1.0	1.0	7.1
L. collinsii	9.0	1.0	1.1	1.1	7.7
S. sesban	5.5	0.7	0.6	0.6	4.8
S. siamea	9.4	1.1	1.1	1.3	8.1
T. candida	7.2	0.9	0.9	0.9	6.2
T. candida 02971	8.9	0.8	1.1	1.1	7.4
T. vogelli	4.5	0.7	0.6	0.6	4.1
Mean	7.0	0.8	0.9	0.9	6.0

Table 2. Modelled tree legume C stocks and photosynthetic C intake (PCI) of the tree phase of fallows (2002/02) in Chipata, Zambia; PCI* = [(C_{AB}/2) + [(C_{AB}/2) x 0.35 x0.7)] + C_{lit} + C_{RD}; C_R (0-30 cm depth) = 0.35 x C_{AB} x 0.70; C_{RD} = C_R

The plant C pool in the cropping phase in eastern Zambia depends on mainly annual plants and the fate of aboveground biomass. Modelled annual C inputs to the soil consisted of maize crop residues (4.1 t ha^{-1} yr^{-1}) and weed biomass (1.4 t ha^{-1} yr^{-1}). The inputs increased
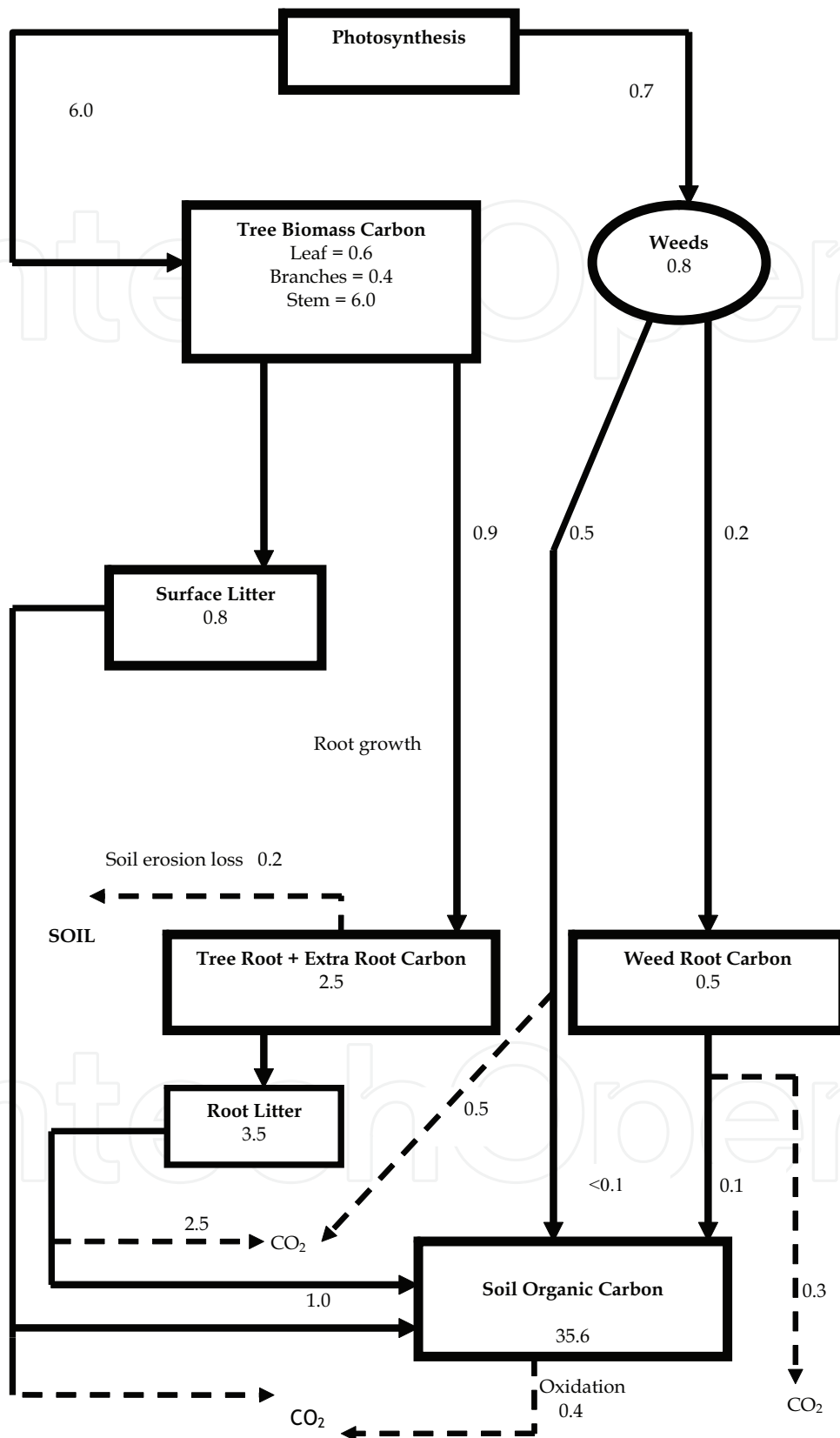
Fig. 2. A conceptual model of the carbon cycle in the tree phase of an improved fallow. Values are in kg C ha^{-1} and kg ha^{-1} yr^{-1}

		Annual C inputs and harvests (t C ha^{-1} yr^{-1})		
		C. cajanus	*S. sesban*	*T. vogelli*
Maize				
	Measured stover (C$_{PR}$)	1.2	1.9	1.5
	Measured grain (C$_{HB}$)	1.1	2.2	1.5
	Modelled root (C$_R$)	0.7	1.2	0.9
	Modelled rhozodeposit (C$_{RD}$)	0.5	0.8	0.6
Weeds				
	Aboveground biomass (C$_{AB}$)	0.8	0.8	1.1
	Modelled roots (C$_R$)	0.2	0.2	0.3
	Modelled rhizodeposit (C$_{RD}$)	0.2	0.2	0.2
	Modelled PCI	4.7	7.2	6.1

Table 3. Measured and modelled annual plant C inputs to the soil, photosynthetic C uptake, and biomass C harvests from cropping phase of improved fallows in eastern Zambia

with C and nutrient supply to the soil. An increase of one tonne of SOC in degraded agricultural soils may increase maize crop yield by 10-20 kg ha^{-1} (Lal, 2004). Similarly, restoration of soil fertility using fertilizer trees increases maize biomass production (Mafongoya et al., 2006; Oelbermann et al., 2004). Considering modelled annual humic C inputs and losses, eroded C, and total SOC stocks estimated at 28.0 t ha^{-1} (Figure 3), the net annual SOC assimilation rate in the cropped phase was 0.3 t C ha^{-1} yr^{-1}. Carbon losses through harvested maize grain, estimated at 1.3 t C ha^{-1} yr^{-1} (Figure 3), have a profound effect on ecosystem C pools. In eastern Zambia, where livestock constitute a major component of improved fallows, the existing sequential land tenure system allows livestock to feed on maize stover in the fields. Farmers may also harvest crop residues for fuel or burn them to clear the fields during land preparation to reduce disease and pest infestation, and to return nutrients to the soil. The amount of crop residues returned to the soil depends on the maize variety, climate, soil conditions, agricultural practices, and land tenure.

3.2.4 Modelled and measured carbon pools and fluxes in intercropped phases

Figure 4 shows C pools and flows in intercropped fallows and PCI rates derived from measured and modelled variables in Table 4. In tree-maize intercropping, re-sprouting trees, maize crops and weeds constitute the plant C pool. Trees are periodically pruned and materials are incorporated into the soil as C and nutrient sources. Modelled PCI rates (1.5-3.7 t ha^{-1} yr^{-1}) for 10-year-old *L. leucocephala*, *G. sepium*, and *S. siamea* coppicing trees (Table 4) were consistent with those published for smallholder agroforestry systems (1.5-3.5 t ha^{-1} yr^{-1}) in the tropics [6,9] and tree fallows (1.4 – 4.3 t ha^{-1} yr^{-1}) in eastern Zambia (Sileshi et al., 2007). Modelled PCI rate for maize in coppicing fallows (5.0 t ha^{-1} yr^{-1}, Figure 4) was similar to that (6.6 t ha^{-1} yr^{-1}) calculated for maize in a 10-year-old *Erythrina poeppigiana* alley crop in Costa Rica.

Modelled PCI rates for the whole intercropped phase (7.4-9.4 t ha^{-1} yr^{-1}) were also comparable to published range (4.0-8.0 t ha^{-1} yr^{-1}) for other agroforestry systems (Dixon, 1995). Rates for individual plant species in intercropped phases were not as high as those of pure stands of trees and maize, but the rate for the whole system was either superior or comparable to those of sole cropped phases. Carbon uptake in intercropped phases can be very high because of sequestration by trees and crops (2.0 - 9 t ha^{-1} yr^{-1}) depending on tree rotation (Robert, 2001).
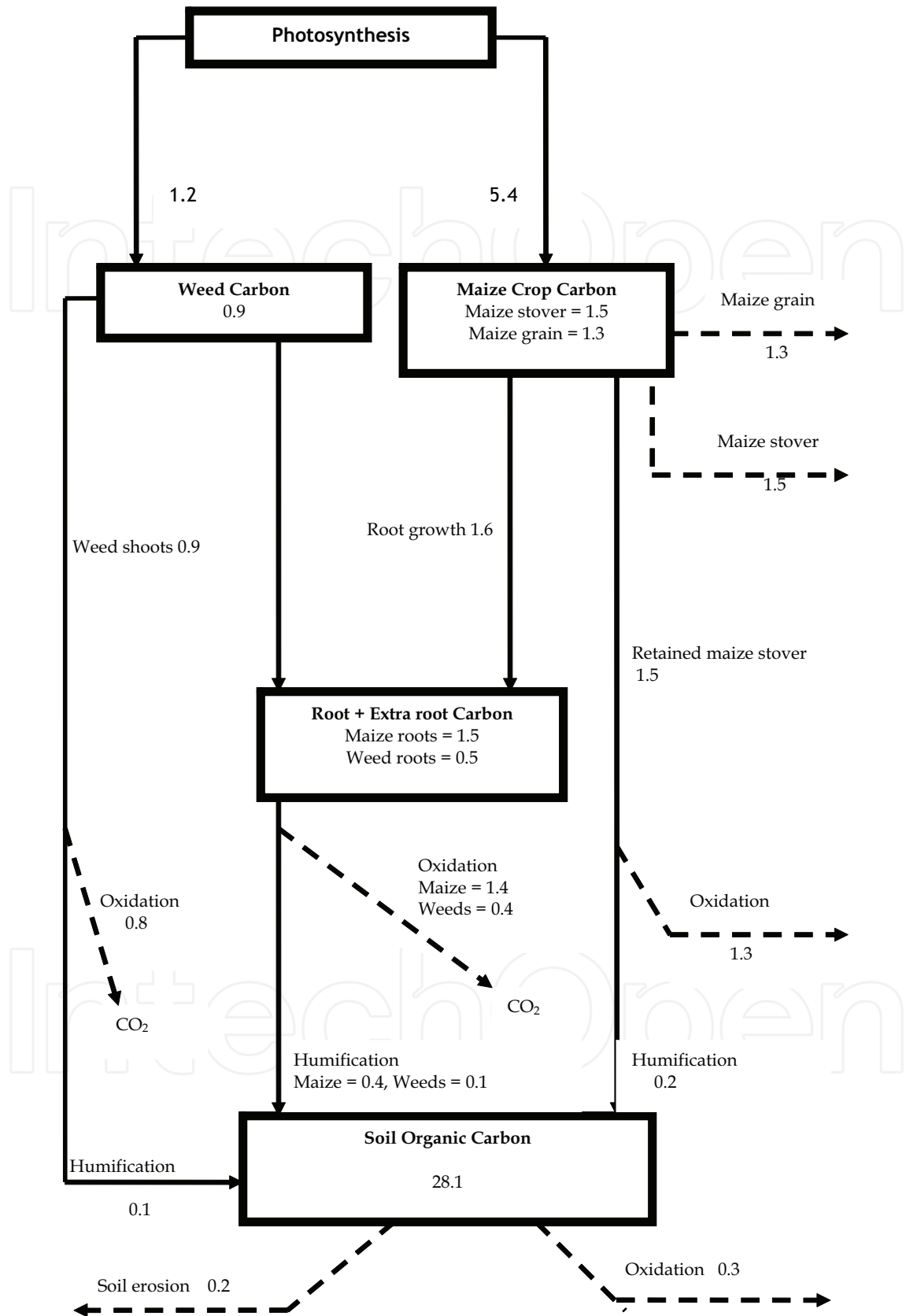
Fig. 3. A conceptual model of carbon cycling in the cropping phase of rotational improved fallows. Values are in kg C ha^{-1} and kg ha^{-1} yr^{-1}.

The maize crop in the intercropped phase in eastern Zambia had the highest PCI rate among plant C sub-pools possibly because high tree pruning intensity, two-three times in a cropping season, reduced total tree DM production. High pruning frequency reduces nodulation efficiency in N_2-fixing species and hence limits overall tree productivity (Chesney, 2000). Pruning intervals of one, two, or three months progressively reduced NPP compared with six monthly pruning (Duguma et al., 1988). In addition, competition for resources between trees and maize, and tree mortality with time can also contribute to reduced tree productivity. However, tree species significantly regulate the productivity of intercropped fallows through the quality and quantity of biomass produced. For example, *Senna* produced almost twice as much biomass as *Gliricidia*, but maize biomass production was still higher in *Gliricidia* than in *Senna* fallows, suggesting that *Gliricidia* produced high quality prunings that readily decomposed releasing nutrients for the maize crop.

	Annual C inputs and harvests (t C ha^{-1} yr^{-1})		
	G. sepium	*L. leucocephala*	*S. siamea*
Maize biomass C			
Measured stover (C_{PR})	1.5	1. 8	1.5
Measured grain (C_{HB})	1.8	1.9	1.6
Modelled root (C_R)	1.0	1.2	1.0
Modelled rhizodeposit (C_{RD})	0.7	0.7	0.6
Weed biomass C			
Aboveground biomass (C_{AB})	1.2	1.3	1.1
Modelled roots (C_R)	0.4	0.3	0.3
Modelled rhizodeposit (C_{RD})	0.2	0.3	0.2
Trees			
Measured prunings (C_{AB})	1.3	1.7	2.1
Modelled Root litter (C_{RD})	0.3	0.3	0.3
Modelled PCI	8.4	9.5	8.7

Table 4. Annual plant C inputs to the soil, photosynthetic C uptake, and biomass C harvests from the Tree-maize intercropped fallow in eastern Zambia

Trees, maize, and weeds constitute the principal sources of annual plant C inputs to the soil. Measured SOC stocks in intercropped fallows in eastern Zambia were estimated at 35 t ha^{-1}, with annual humic C loss of 0.4 t ha^{-1} yr^{-1}. Considering estimates of total SOC, humic C inputs and losses, and eroded C, the net C gain was 1.0 ha^{-1} yr^{-1}. Understanding of long-term C sequestration potential of the intercropped fallows requires studying tree biomass production patterns (as tree population decreases with increasing tree rotation) and biomass removal from the system. Substantial aboveground vegetal C stocks are harvested either as food, fuelwood, or fodder. The intercropped fallow loses C through harvested grain (1.8 t C ha^{-1} yr^{-1}) and tree stems (0.2 kg C ha^{-1} yr^{-1}), and through maize crop residues (1.6 t C ha^{-1} yr^{-1}), if they are removed from the field. In the long-term, SOC stocks in fallows depend on the quantity and quality of above- and below-ground plant residues added to the soil over many rotations.

Modelled PCI rates in improved fallows declined in the order: intercropped phase > cropped phase > tree phase, presumably because of differences in tree species and rotation. Re-sprouting trees in the intercropped phase increased maize biomass production. Net
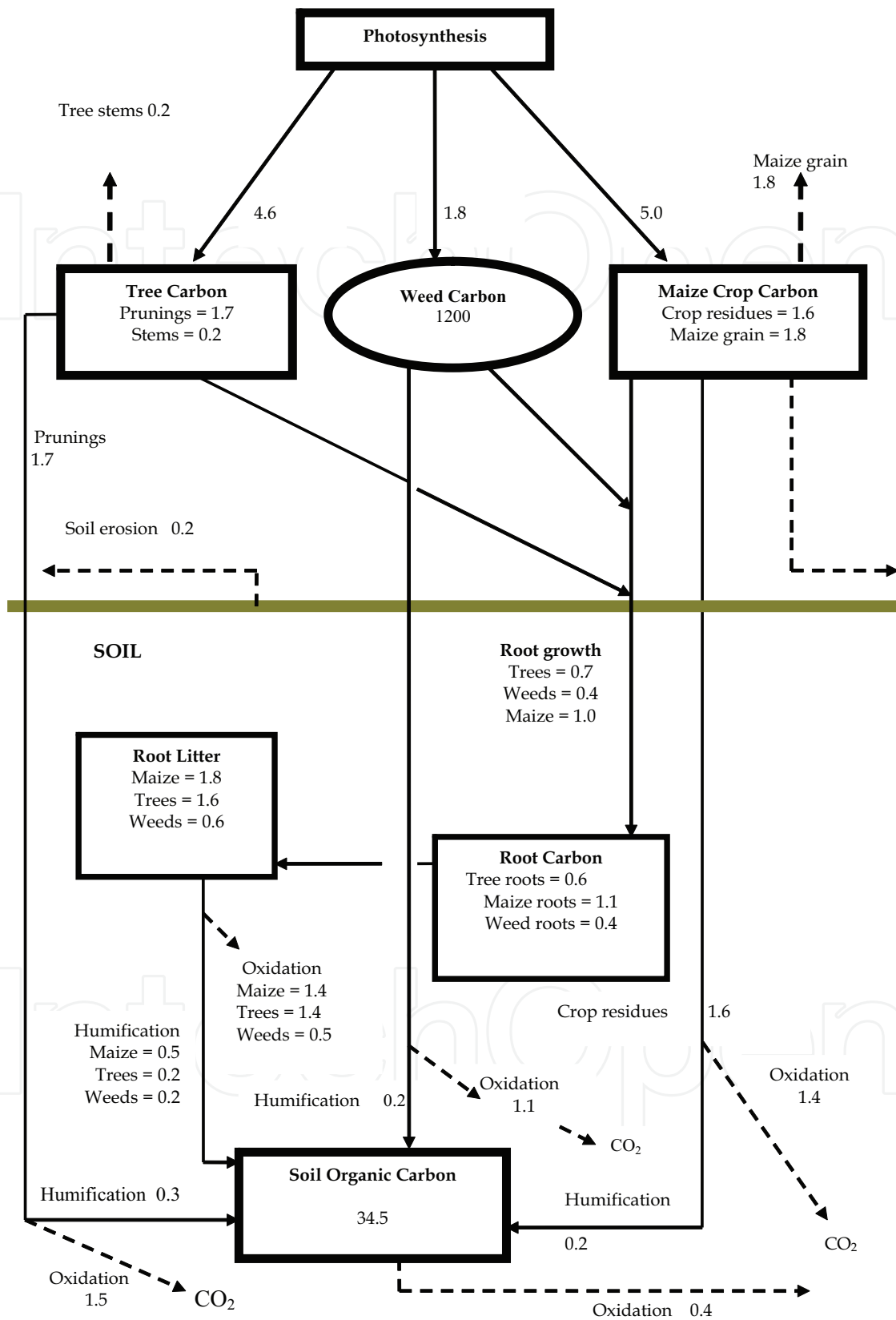
Fig. 4. A conceptual model of the carbon cycle in the tree-maize intercropping phase of a coppicing improved fallow. Values are in kg C ha^{-1} and kg ha^{-1} yr^{-1}

primary production of agroforestry systems is likely to be higher than those of crop-based, tree-based, and animal-based systems (Lal, 1995). However, the long-term sustainability of the system should be investigated.

Land-use change resulted in increased SOC stocks in tree-maize intercropping, tree, and cropping phases by 1.0, 0.7, and 0.3 t ha^{-1} yr^{-1}, respectively. Considering that these changes occur in the top soil, phases with more deeply rooted tree species are likely to deposit more C in the subsoil because of their deep root system (Jobaggy & Jackson, 2000). However, tree roots in the intercropped phase may be shallower than those in the tree phase because of pruning stress and the tendency of roots to be concentrated in the top soil as soil fertility improves. Further research into underground C dynamics in fallows is needed.

4. Conclusion

A conceptual model of carbon dynamics in improved fallows in the tropics is presented. It describes the major C pools and fluxes, ecosystem processes underpinning carbon dynamics, and ecosystem drivers and stressors. It represents a simplified approach to what is a complex biogeochemical cycle, but accounts for major ecosystem processes that determine C turnover in improved fallows to the extent that it can be used to develop practical C management strategies. This model provides a framework for describing the relationships between the various components of the C cycle, exploring possibilities for modification of organic C pools and for examining the consequences of various measures of C management options.

The model, using empirical and published plant and soil C data, estimated major plant and soil C pools in improved fallows, which were used to develop simplified carbon budgets of tree, cropped and intercropped phases of improved fallows. Modelled carbon pools were comparable to measured pools. The model has also revealed gaps in our understanding of C dynamics in improved fallows. Ecosystems stressors and drivers including climate change, atmospheric deposition (C and N fertilization), pest and diseases, natural disturbances, and herbivory, which ultimately reduce plant productivity, are not clearly understood. Similarly, data on soil erosion, underground plant C stocks, and DOC, the longevity of various C pools, and their response to regional climatic changes are needed. This model presents estimates as an initial approximation, recognizing that more reliable estimates emerging from further research can easily be incorporated in the model to improve its accuracy. However, this model provides a useful framework for designing agroforestry systems with a C sequestration function.

5. Acknowledgements

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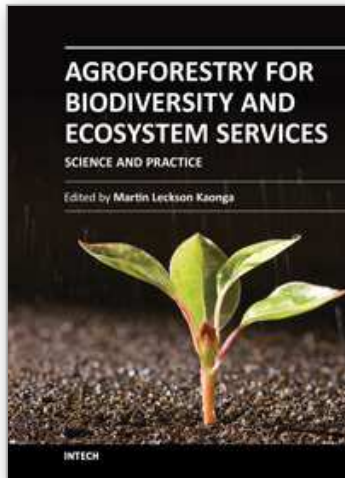
Agroforestry for Biodiversity and Ecosystem Services - Science and Practice

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Agroforestry has great potential for reducing deforestation and forest degradation, providing rural livelihoods and habitats for species outside formally protected land, and alleviating resource-use pressure on conservation areas. However, widespread adoption of agroforestry innovations is still constrained by a myriad of factors including design features of candidate agroforestry innovations, perceived needs, policies, availability and distribution of factors of production, and perception of risks. Understanding the science, and factors that regulate the adoption, of agroforestry and how they impact the implementation of agroforestry is vitally important. Agroforestry for Biodiversity and Ecosystem Services: Science and Practice examines design features and management practices of some agroforestry practices and their impact on biodiversity and the ecosystem services it delivers. It also identifies policy issues for facilitating adoption of desirable agroforestry practices and gradual diminution of undesirable policies.