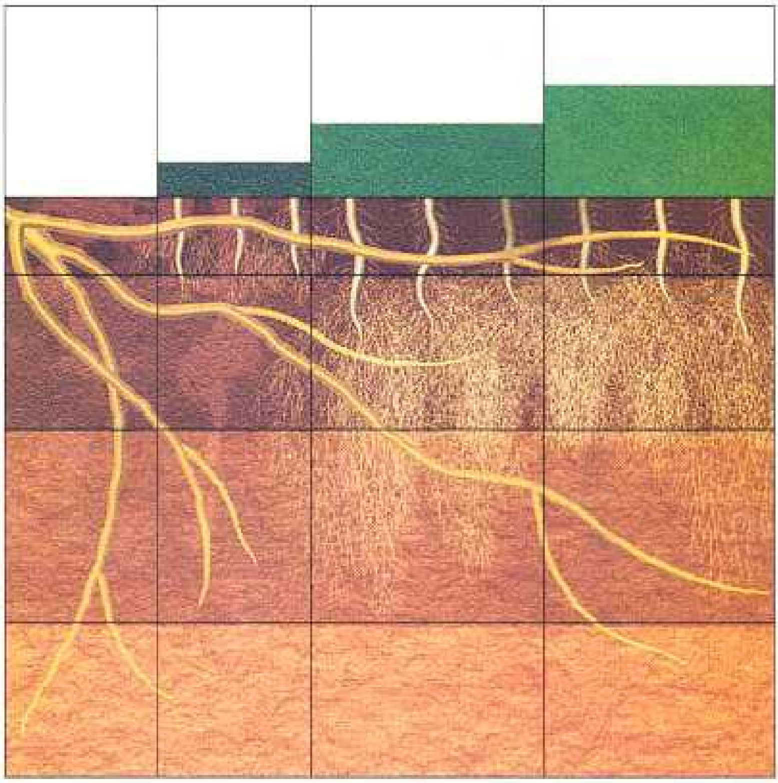
SEAMEOBIOTROP-GCTE IMPACTS CENTRE

FOR SOUTHEAST ASIA

GCTE WORKING DOCUMENT NO. 28



IC-SEA REPORT NO. 6

MODELLING GLOBAL CHANGE IMPACTS ON THE SOIL ENVIRONMENT

Bogor, Indonesia, 1999

The Impacts Centre for Southeast Asia (IC-SEA) was established by the Global Change and Terrestrial Ecosystems (GCTE) Core Project of the International Geosphere-Biosphere Programme (IGBP) in October 1995. It is hosted by SEAMEO BIOTROP, the Southeast Asian Regional Centre for Tropical Biology. The objective of IC-SEA is twofold:

- to assist developing countries in the Southeast Asian region to build their own capacity to analyse, interpret and predict global change impacts on terrestrial ecosystems, including agriculture, production forestry and nature reserve systems; and
- to promote planning for sustainable development and biodiversity conservation in rapidly changing global environment through the policy-makers and resource managers.

To achieve IC-SEA 's objectives the activities planned for the Impacts Centre include:

- offering technical training workshops on modelling the impacts of global change;
- supporting research fellowship and equipment grant programmes;
- undertaking collaborative impacts analyses with appropriate groups in the region; and
- providing expert advice (personal briefings, summaries, impact assessments) for policy-makers and resource managers about the potential impacts of global change in the region.

Based in Bogor, Indonesia, the Southeast Asian Regional Centre for Tropical Biology (BIOTROP) was established in 1968. It is one of the twelve centres under SEAMEO (Southeast Asian Ministers of Education Organisation). The organisation consists of ten member countries of Brunei, Cambodia, Indonesia, Lao PDR, Malaysia, Myanmar, Philippines, Singapore, Thailand and Vietnam. BIOTROP is aiming at becoming a leader in some general areas of tropical biology through quality research and training, as well as establishing and coordinating sustainable networks and linkages within the region and beyond. Its Programme Thrusts have been identified to address BIOTROP's concerns about environment, natural resources, and sustainable development. These are Tropical Ecosystems and Environmental Impacts, Biodiversity Conservation and Sustainable Management, and Environmental and Forest Biotechnology.

SEAMEO BIOTROP-GCTE/IC-SEA
IMPACTS CENTRE FOR SOUTHEAST ASIA

GCTE WORKING DOCUMENT NO. 28

IC-SEA REPORT NO. 6
MODELLING GLOBAL CHANGE IMPACTS ON THE SOIL ENVIRONMENT

Report of Training Workshop on
Modelling Global Change Impacts on the Soil Environment
at BIOTROP-GCTE/IC-SEA, Bogor, Indonesia

5-13 May 1998

Edited by:
Daniel Murdiyarso, Meine van Noordwijk, and Desi Ariyadhi Suyamto

Published by:
BIOTROP-GCTE/Impacts Centre for Southeast Asia (IC-SEA)
Bogor, Indonesia, 1999

Modelling Global Change Impacts on the Soil Environment

Edited by Daniel Murdiyarso, Meine van Noordwijk, and Desi Ariyadhi Suyamto

With contributions from Kurniatun Hairiah, Miko U.F. Kirschbaum, Betha Lusiana, Mario B. Manzano, Robert Simanungkalit, F.X. Susilo, S. M. Sitompul and Cheryl Palm.

GCTE Working Document No. 28/IC-SEA Report No. 6

1999, Bogor, Indonesia

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Acknowledgement
AusAID financed the training through CSIRO, Wildlife and Ecology Division. The workshop was also co-financed by SEAMEO BIOTROP through funds generated from SEAMES SEDF.

Original concept of cover design courtesy of ICRAF Southeast Asia: "General Lay-out of Zones and Layers in the WaNuLCAS Model". Cover redesigned by Desi Ariyadhi Suyamto.

Published 1999

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ISBN 979-95588-1-6

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PREFACE

This report is arranged to record the activities of the Training Workshops on Modelling Global Change Impacts on the Soil Environment, organised by IC-SEA on 5-13 May 1998.

The whole process of the workshop was highly interactive between participants and resource persons and among the participants themselves. Various case studies were shared and discussed. Measurement protocols were tested in fieldwork exercise and modelling tools were used, building on the expertise and experiences of the resource persons and the participants.

We would like to take this opportunity to thank all the resource persons. Our special thank is also due to Dr Louis Lebel for his interests during the preparation of the workshop.

The hard work of all IC-SEA staff that has made the workshop a success. Their support is highly appreciated. We hope that there will be a fruitful follow-up from this workshop through collaborative research involving projects that emerge from proposals developed during the workshop.

Editors

EXECUTIVE SUMMARY

In the recent period of dramatic economic growth of Southeast Asia, land-use change impacted on the environment often on a massive scale. Removal of carbon stocks, changes in biogeochemical cycles, and loss of biodiversity are always associated with the rapid change of the terrestrial landscape. The goal of achieving sustainable development in the context of global change requires a basic understanding of how terrestrial ecosystems respond to rapid environmental change. The challenge is particularly acute for developing countries, which are coming under increasing pressure to modify their development strategies to reduce the adverse impacts of climate change, due to the increase of greenhouse gas emissions, to reduce land and water degradation, and conserve the biodiversity of their natural ecosystems. This is in line with the international agreements, such as the climate change, biodiversity, and desertification conventions, which potentially constrain the development strategies of many countries.

The key issues related to the soil environment arise from the conversion of vegetative cover or land cover and the management of the soil itself. The direct and indirect environmental impacts of human activities on the soil environment begin when natural vegetation is removed and converted without proper measures to prevent the adverse consequences. One effect is soil degradation, causing changes in biogeochemical cycles, depleting soil fertility, and decreasing soil biodiversity. The objectives of the current workshop run from 5-13 May 1998 at IC-SEA, Bogor Indonesia, were to introduce the impacts of global change on the soil environment and to develop methods in assessing the impacts, including soil biodiversity, soil fertility and emissions of greenhouse gases. It was expected that by understanding the structure and development of models the participants would be able to further evaluate and validate them when models are applied into future impact assessment studies.

The course was organised in three themes: GHG emissions, Carbon-stock and Soil Fertility, and Modelling Tools. Hands-on exercises were conducted throughout the course. Data acquisition methods were applied in fieldwork and subsequent lab analysis during the workshop. The course covered various issues regarding the management of soil fertility to support agricultural productivity and its sustainability.

A number of modelling tools like CENTURY 4, CENW, and WaNuLCAS were used during the workshop. Firstly, CENTURY 4, which is a useful tool to understand and simulate carbon dynamics at ecosystem level over long time frames, was exercised using example from dynamically changing land-use in Sumatra. Secondly, CENW was explored a more recent modelling tool developed at CSIRO, Division of Forestry and partly based on the CENTURY Model. A water balance (loss and gain) by the system is included in this model. Thirdly, we tried the WaNuLCAS model of tree-crop interaction in agroforestry system, formulated in the STELLA Research modelling environment. Developed at ICRAF, WaNuLCAS gives emphasis to below-ground interactions, where competition for water and nutrients (nitrogen) depends on the effective root length densities of both plant components and current demands by tree and crop. The exercise was expected to give a general picture of how mixed cropping systems would benefit and compete with each other in utilising the resources available in their surroundings.

In addition, participants also practised a number of field techniques related to GHG sampling, below- and above-ground organic pools and soil biodiversity, including micro- and macro-fauna.

At the end of the session the participants prepared and presented research proposals for application in their own countries. These proposals are based on the current understanding of soil management problems and the possibility of applying the modelling tools exercised during the workshop.

SECTION

1

INTRODUCTION

1.1. BACKGROUND

1.1.1. RATIONALE

Global environmental change is widely accepted to have three main components: land-use change, changes in atmospheric chemistry and climate change. The extensive impacts on the soil environment may be categorised into physico-mechanical, biological and chemical consequences. An integrated assessment of these impacts and their feedback on agro-ecosystem functioning is needed to improve our understanding of the processes to better manage the systems.

Soil fertility is closely related to the productivity and sustainability of agro-ecosystems. Carbon stocks, therefore, become a key indicator in managing the soil in the globally changing environment. Changes in the soil ecosystem will affect biogeochemical cycles, including emissions and sequestration of greenhouse gases (GHGs) with significant effects on the climate of planet earth.

SEAMEO BIOTROP has collaborated with GCTE Impacts Centre for Southeast Asia (IC-SEA) and the International Centre for Research in Agroforestry (ICRAF) Southeast Asia Programme to run a Regional Training Workshop on Modelling Global Change Impacts on the Soil Environment. The workshop was designed to understand the relationship between land-use and land-cover change, above- and below-ground carbon stocks and GHG emissions.

Modelling is a tool to extrapolate and integrate extensive and long-term studies. Models offer some practicality in capturing issues like spatial variability and data inadequacy. In a sense, modelling simplifies complex processes and at the same time helps to integrate numerous experimental data with mechanistic understanding of the processes in the systems. Modelling tools were explored during the workshop to extrapolate fine-scale knowledge to large-scale problems for which measurements are difficult and where understanding is poor.

1.1.2. OBJECTIVES

The objectives of the training workshop were:

- to introduce the impacts of global change on the soil environment and to develop methods for assessing the impacts, including soil biodiversity, soil fertility and emissions of greenhouse gases;
- to understand the structure and development of models for further evaluation and validation when applied into future impact assessment studies; and

- to provide the participants with modelling tools to assess the impacts of global change on the soil environment.

This training workshop is part of a series of activities at IC-SEA as shown in Figure **1.1.** It was expected that the methods learnt during the workshop would be applicable for future impact assessment studies.

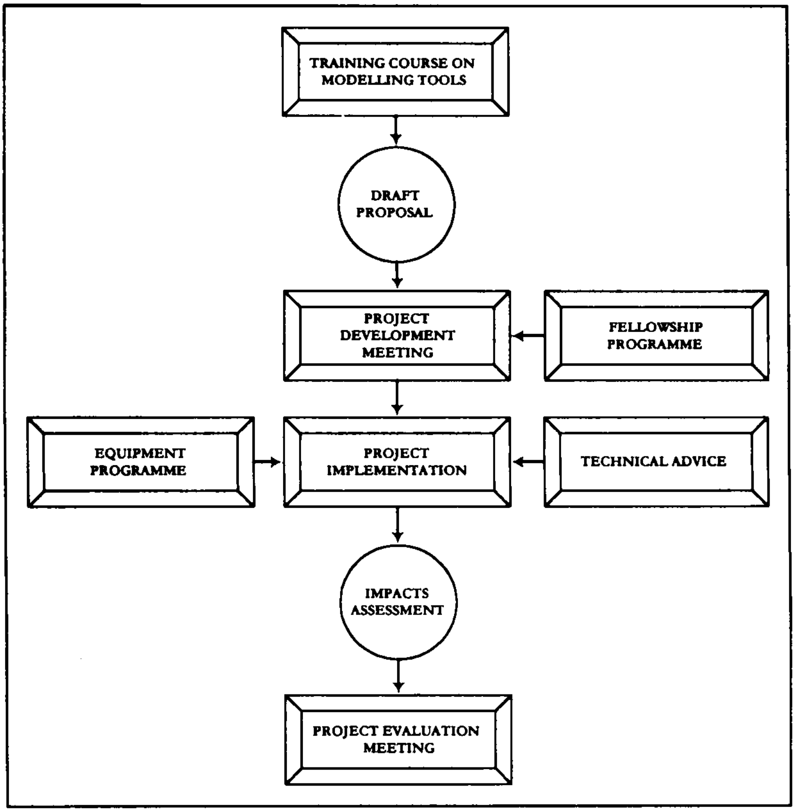

Figure 1.1. The Training Workshop is part of a series of integrated activities at IC-SEA. The final product will be state-of-the-science impact analyses.

1.2. CONTENTS

The course was organised in three themes: GHG emissions, Soil C-stock and Fertility, and Modelling Tools. Hands-on exercises on the use of various software and models, such as: GlobalC, FBA, ESCAPE, WaNuLCAS, CENTURY 4, and CENW were conducted to balance the lectures. Methods for data acquisition through fieldwork and analysis were tried out during the workshop. The course covered various issues regarding management of soil fertility to support agricultural productivity and its sustainability.

1.3. SCHEDULE

The course ran for eight days with a variety of activities and daily structures as shown in Table 1.1.

Table 1.1. Timetable of activities

DATE	MORNING	AFTERNOON	EVENING	RESPONSIBLE
Mon, 4 May	◑ Arrival	○ Arrival	● Arrival ● Welcome Dinner	IC-SEA + BIOTROP Staff
Tue, 5 May	◑ Opening session ◑ Introduction ◑ Workshop overview	○ What is Global Change? ○ Country Report	● Computer lab introduction ● Global C-balance	Staff, DM, MM, MN
Wed, 6 May	◑ Soil Macro-fauna (Introduction)	○ Soil Macro-fauna (Field methods)	● Land-use change and GHG emission (Field methods)	FS, DM
Thu, 7 May	◑ Soil C stock ◑ SOM dynamics	○ FBA ○ ESCAPE	● Introduction to Tree-crop interaction	KH, MN, DM
Fri, 8 May	◑ Soil Micro-fauna	○ Introduction to WaNuLCAS	● Proposal Development	RS, MN, FS, DM
Sat, 9 May	◑ Field work	○ Field work	● Free	All
Sun, 10 May	CENTURY: ◑ Introduction ◑ Event file ◑ Site file ◑ Crop file	CENTURY: ○ Growth and removal ○ Rotation experiment	CENTURY: ● Further applications	SS
Mon 11 May	CENW ◑ Introduction ◑ Soil module ◑ Water relations ◑ Growth module ◑ Allocation	CENW Applications ○ Sensitivity testing ○ Fertiliser experiment ○ Thinning experiment ○ Climate change experiment	CENW ● Further applications chosen by participants	MK
Tue, 12 May	◑ Report preparation	○ Report presentation	● Farewell dinner	All
Wed 13 May	◑ Departure	○ Departure		IC-SEA + BIOTROP Staff

Codes for trainers:

DM : Dr Daniel Murdiyarso, IC-SEA, Bogor, Indonesia
FS : Dr F.X. Susilo, Faculty of Agriculture, Lampung University, Bandar Lampung, Indonesia
KH : Dr Kurniatun Hairiah, Faculty of Agriculture, Department of Soil Science, Brawijaya University, Malang, Indonesia
MK : Dr Miko U.F. Kirschbaum, CSIRO Forestry and Forest Products, Australia
MM : Mr Mario B. Manzano IC-SEA, Bogor, Indonesia
MN : Dr Meine van Noordwijk, ICRAF Southeast Asia, Bogor, Indonesia
RS : Dr Robert Simanungkalit, Agency for Agricultural Research and Development, Ministry of Agriculture, Indonesia
ST : Dr S. M. Sitompul, Faculty of Agriculture, Department of Agronomy, Brawijaya University, Malang, Indonesia

SECTION

2

PROBLEMS OF DEGRADING SOIL ENVIRONMENT IN SOUTHEAST ASIA

Soil degradation in Southeast Asia is partly due to population pressure and a mismatch between land capability and land-use. Upland regions are the most affected areas where removal of vegetation cover is extensive and soil conservation measures often are not sufficient. Intensification and unbalanced inputs in a relatively harsh environment has worsened the soil environment resulting in low productivity.

This section deals with problems of soil degradation management identified by the participants and reported during the workshop. From here, the participants were expected to relate their understanding and the skills they learned during the workshop to develop a proposal to help solve some of the problems.

2.1. PROBLEMS OF SOIL RESOURCES MANAGEMENT IN CAMBODIA

By:

Keo Veasna - Ministry of Environment, Cambodia, Chhun Bunlong - Integrated Resource Information Centre, Sokphoun Sopheak - University of Agriculture, and Chheng Lyna - University of Agriculture

The land area of the Kingdom of Cambodia is 181,035 km^2. Among other environmental problems, deforestation has been one of the main causes of soil degradation. In the early 1970's, the forest cover was around 73 percent of the total land area. Within 20 years it was reduced to 49 percent mainly by commercial logging and shifting cultivation. Within this period, the civil war has left soil and forest resources unmanaged resulting in serious environmental degradation through increased soil erosion, river and lake siltation, hence decreasing soil fertility.

Although not directly related to environmental degradation, the extent of land mine areas restricts the optimum utilisation of land resource in Cambodia, especially in the plain regions where fertile soils are found. It was estimated that there are 2,326 mine fields covering an area of 394,300 ha.

Land-use planning for soil resource management should be based on the four ecological zones, namely coastal, floodplain/wetland, plateau and mountain zones. These plans should be in line with policies for coastal fishery, agriculture and inland fishery, forestry and biodiversity conservation, respectively.

Baseline up-to-date data is urgently needed for planning activities. These cover biophysical and socio-economic profiles of the country. There is so much to do, however, that priorities should be set. There is a serious lack of human resource and skilled personnel, that needs to be tackled as soon as possible before land degradation gets worse. Weak institutions and implementation of regulatory measures are among legal aspects that need to be strengthened.

2.2. LAND DEGRADATION AND SOIL CONSERVATION IN INDONESIA

By:

Aries Pramudia - Centre for Soil Research and Agroclimatic Centre, Rusnady Panjung - Hasanuddin University, Sobri Effendi - Bogor Agricultural University, Kamaluddin Syam - Lampung University, and A Kamir Brata - Bogor Agricultural University, Darmawan - Andalas University

In less populated areas, land degradation in Indonesia is largely associated with deforestation and conversion of tropical forests. On the other hand, in densely populated regions, the pressure of the population has caused degradation of upland soils, where conservation farming is not properly implemented, leading to the depletion of soil fertility and decline of crop productivity.

Soil and water conservation programmes in Indonesia are carried out in a watershed management approach, within which conservation farming is demonstrated. Institutionally the related agencies are strengthened and financial support was provided. A large number of soil conservation demonstration plots in various projects were discussed, included in the Integrated Watershed Management Plans. Almost all the 27 provinces in Indonesia were included in the strictly centralised plan. It is difficult, however, to measure the impacts of such large-scale undertaking. It is worth noting that most conservation farming research was carried out on-farm to ensure the adoption of the technologies. The research topics include the use of soil conditioner, application of organic matter, subsoil treatment, erosion control and land rehabilitation.

Deforestation, besides degrading soil organic matter and biodiversity, also leads to high emissions of greenhouse gases. Sustainable land management is expected to address poverty alleviation as well as improving environmental quality. The problem is that the majority of the conversions are associated with the development of mono-species plantations and managed by large-scale operators. Suggestions on how local people and small-holder farmers should be involved was made with regards to the trajectory of land-use, which can be grouped as follow:

LARGE-SCALE OPERATORS:						
Primary forests	⇒	Concessionaire	⇒	Forest plantation		
Primary forests	⇒	Planters	⇒	Estate (perennial) crops		
SMALL-SCALE OPERATORS:						
Primary forests	⇒	Local people	⇒	Perennial crops		
Secondary forests	⇒	Spontaneous migrants	⇒	Annual crops	⇒	Perennial crops
Agroforests	⇒	Local people	⇒	Annual crops	⇒	Perennial crops

It is obvious that in the upland regions, tree crop-based system are likely to be the best choice for both large- and small-scale operators in order to achieve sustainable management of soil resources. Although those trajectories are generally valid, it is realised that this exercise does not take into account the government-sponsored transmigration. With regards to their distribution and extent they should be treated separately.

2.3. SOIL DEGRADATION IN MALAYSIA: CAUSES, CONSEQUENCES, AND POSSIBLE SOLUTIONS

By:

Rosenani Abu Bakar - UPM, Abd Rahim Md Nor - UKM, Marzuki Ismail - UPM, and Dayang Amenozima Abang Ismail - UPM

Depletion of organic matter, loss of soil biodiversity, and soil acidification are among the major issues in land management in Malaysia. Activities in the upland are associated with tin mining and logging industries, while in the wetlands drainage of marine alluvial soil has major impacts. To a lesser extent, soil contamination by heavy metals and toxic organic compounds are also found due to mismanagement of industrial wastes.

Tin mining has been the main economic activity for quite a long time and provides important revenue in Malaysia. It has been reduced substantially in the last decade. Therefore, reclaiming the degraded land, with a low soil organic matter content is an important issue. It has been the national policy in Peninsular Malaysia that areas with high potential for mining are considered as Class I, followed by soils suitable for a wide range of agricultural crops, those suitable for a restricted range of agricultural crops, production forest, and conservation areas.

Forest conversion has been the main cause of the soil depletion as well as reducing above-ground biodiversity. In addition, when mono-species plantations were introduced, high inputs of inorganic nitrogen fertiliser have changed the biogeochemical cycles. Emissions of nitrous oxide and other nitrogen-related compounds are expected.

The newly logged-over forests also cause severe change in hydrological cycles by increasing the rainfall/runoff ratio, notably by the logging roads and skidding tracks causing up to 24 percent of the total runoff. It is expected that the associated erosion and sediment yields will also be increased.

Malaysia is fortunate with the availability of Laws and Guidelines in place. They are implemented at both Federal and State Governments depending on the issues uniquely and commonly found in each state. Environmental Impact Assessment is widely practised and reported.

2.4. MANAGEMENT OF MARGINAL LAND IN THE PHILIPPINES

By:

Kent Gazal Apostol - UP Los Banos, Pieded Alviar Mendoza - UP Los Banos, Enrique P. Pacardo - UP Los Banos, and Epifania O. Agustin - Mariano Marcos University

Eroded soils in the Philippines are very extensive. In 13 provinces, more than 50 percent of land area is badly eroded. The main causes are population pressure and inefficient government policies.

Sloping areas are among the problematic ecoregions and may be considered as marginal lands for agricultural practices. They are characterised by low soil fertility, are prone to erosion, lack soil water available and hence have low productivity. High agricultural inputs are needed to meet the food demand. On the other hand, poverty is quite a problem in these areas. One cannot afford the extra spending needed for farm inputs.

Lack of land tenure security in deforested areas contributes to a careless management of land resources. Continuous cultivation is largely practised with minimum conservation measures. Consequently, the extent of marginal lands is ever increasing.

2.5. LAND DEGRADATION AND ITS CONSEQUENCES IN THAILAND

By:
Audthasit Wongmaneeroj - Kasetsart University, Pantip Klomjek - Kasetsart University, and Wunlert Wunpiyarat - Department of Land Development

The agricultural sector has been the backbone of Thailand's economy. More than 80 percent of the population is engaged in this sector, and more than 50 percent of the land area is classified as suitable for agricultural activities. Most of these lands, however, are cultivated under rainfed conditions and require high amounts of agricultural inputs. The government continues to push the agricultural production by providing generous subsidies for fertiliser and pesticides.

Efforts to implement sustainable farming have been started, such as organic farming, but they are limited in size compared with intensified production systems. In rice crops, one of the main export commodities, the attempts to reduce the use of agro-chemicals have shown promising results. This will eventually protect the soil environment.

Intensified agricultural activities have increased soil salinity, particularly in rainfed areas where water supply is often limited and variable. Whether land degradation due to intensive agriculture has brought adverse impacts or not, it is worth noting that for the sake of the agricultural sustainability, government and business sectors have to sit together to decide the priority. Some of the regulatory instruments need to be revisited.

2.6. THE PROBLEMS OF SOIL DEGRADATION IN VIETNAM

By:
Duong Thi Thanh Ha - Agroforestry College, Hoang Van Hung - Agroforestry College, Doan Huong Mai - Hanoi National University, and Ngo Ngoc Thanh - Vietnam National University

Out of the 33 million ha land area of Vietnam, 43 percent has problems related to the sustainability for production systems. These are caused either by land degradation due to intensive cultivation, or high chemical inputs. The misuse of chemical to boost agricultural production has resulted in several environmental problems, such as:

- depletion of micro-nutrients;
- erosion of soil biodiversity;
- change in soil physical characteristics leading to soil dependence on higher and higher fertiliser inputs; and
- top soil erosion due to less permanent vegetation cover.

There are several possible solution to reduce the expansion of problematic land and soil environment, such as:

- conservation farming which emphasise on erosion reduction and enhancing natural inputs;
- synchronising the input provided with the plant requirements; and
- establishment and expansion of agroforestry practices, which will accommodate more natural inputs rather than artificial ones to restore soil fertility and improve people's income.

SECTION 3

MODELLING GLOBAL CHANGE IMPACTS ON THE SOIL ENVIRONMENT

3.1. INTRODUCTION

The modelling exercises and tools, which are explored here, deal with various levels and scales of models. They begin with a very broad and global concept of carbon budget based on a common carbon input-output in the atmosphere driven by human activities. The aim is to give general implications for the carbon balance when humans alter natural ecosystems to meet their needs. It involves conversion of land and the use of fossil fuels as the main energy source.

Detailed process-based models involving ecophysiological parameters where the cycling of substances plays important role were also exercised. They do not only deal with carbon but also other components such as nitrogen, water and light when vegetation interacts with its physical environment including soil and the atmosphere.

3.2. GLOBALC – A BEGINNER'S MODEL OF GLOBAL CARBON STOCKS AND FLOWS

By:
Meine van Noordwijk

The GlobalC model accounts for carbon stocks in the atmosphere, in terrestrial ecosystems, the ocean and fossil form, and the major exchanges between these. CO_2 and some other gasses (held constant in this model) have a 'greenhouse' effect, reducing the amount of long-wave radiation that can leave the planet earth, thus increasing its temperature. A change in atmospheric CO_2 can by this mechanism lead to a change in global temperature (global warming or global cooling). Temperature itself has an impact on a range of biological processes in C sequestration by plant growth and C dissipation by decomposer activity. The oceans contain by far the largest C stocks, but only a small part of this, in the upper ocean layers, interacts with the atmosphere. Potentially the oceans can absorb CO_2 brought into the atmosphere by changes in terrestrial stocks or use of fossil fuel, but the rate, at which such absorption can occur, is limited by the equilibration processes. In the terrestrial systems, the model distinguishes two types of vegetation 'forest' and 'agriculture'. The rate of photosynthesis depends on temperature and atmospheric CO_2 but does not differ between these two land-cover types. The stocks maintained in above-ground biomass, however, do differ between the two vegetation types, as does the rate of litterfall, leading to differences in soil organic matter storage in soils. Figure 3.1 shows the diagram of processes in GlobalC.

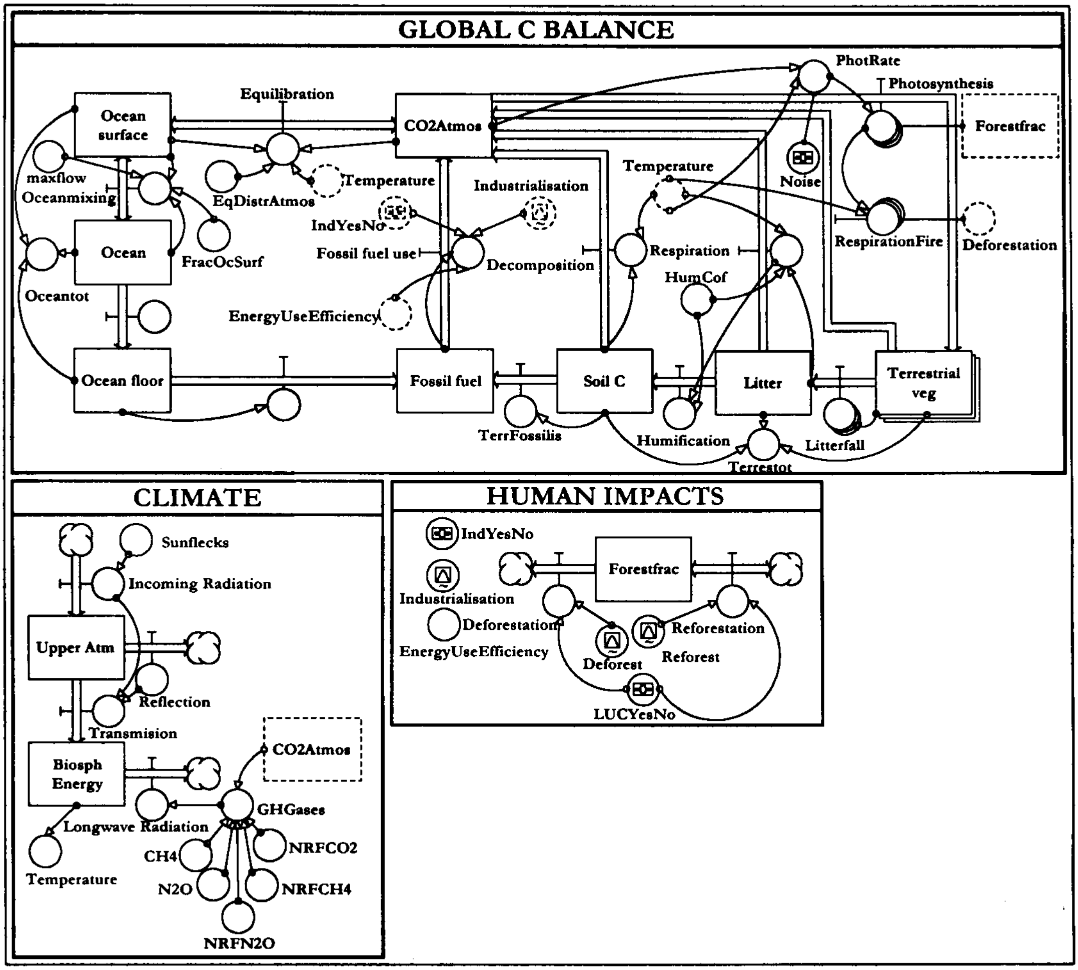

Figure 3.1. Model diagram of GlobalC

The model is obviously a strong simplification and does not incorporate many feedback loops and distinctions between climate zones and vegetation types (with the largest contrast between systems with below-ground storage in peat soils dominating in the subarctic and those with above-ground storage dominating in tropical forests on non-peat soils). Yet, for all its simplicity, the model suggests a number of conclusions (or hypotheses for further exploration):

- when left to itself, the very slow rate of fossil C production in oceans and terrestrial systems combined, leads to a gradual reduction of CO_2 in the atmosphere and cooling of the earth, but this trend is masked by 'natural' fluctuations;

- historical land-use change, leading to a gradual replacement of forests in the temperate zone and part of the tropics by agricultural land occurred at a speed that the oceans could dampen the effect; the fast deforestation of the second half of the 20th century leads to a recognisable increase in atmospheric CO_2, but not to dramatic impacts;

- fossil fuel use transfers CO_2 into the atmosphere at a rate beyond what the oceans can absorb and thus leads to global warming; if the globe remains forested, a small fraction of this atmospheric CO_2 can be stored in terrestrial stocks, but the effect is counteracted by increase in temperature and thus decomposition of soil C; and

- combined effects of fossil fuel use and land-use change lead to a marked increase of atmospheric CO_2 during the 20th century and into the third millennium.

The model presented here is in the STELLA modelling shell, which allows users to make runs, look at output, change parameters or scenario's (especially the time pattern of deforestation, reforestation and fossil fuel use) and add structural complexity to the model. Figure 3.2 shows example of simulation outputs resulted by GlobalC, in which global carbon balance and temperature in four different scenarios can be compared. Without human-induced changes, there is no significant temperature increase. It also shows that fossil fuel use will increase the temperature more drastically rather than deforestation.

The GlobalC model can help to see the relevance in a global perspective of the land-use questions discussed in this course:

- How do terrestrial C stocks differ between land-cover types?
- Which part of the total stock is in above-ground vegetation (biomass, litter, dead wood on the soil surface), and how much is below-ground (roots, soil organic matter, peat) and how can we measure the various stocks?
- What are the dynamics of these pools and how rapid is their response to change in land-use, temperature or atmospheric CO_2 concentration?
- What is the relationship between soil carbon pools and the functioning of agro-ecosystems from the farmers' perspective, via processes of mineralisation and functional aspects of below-ground biodiversity?
- What about the other greenhouse gasses (especially N_2O and CH_4) and their relations with land-use?

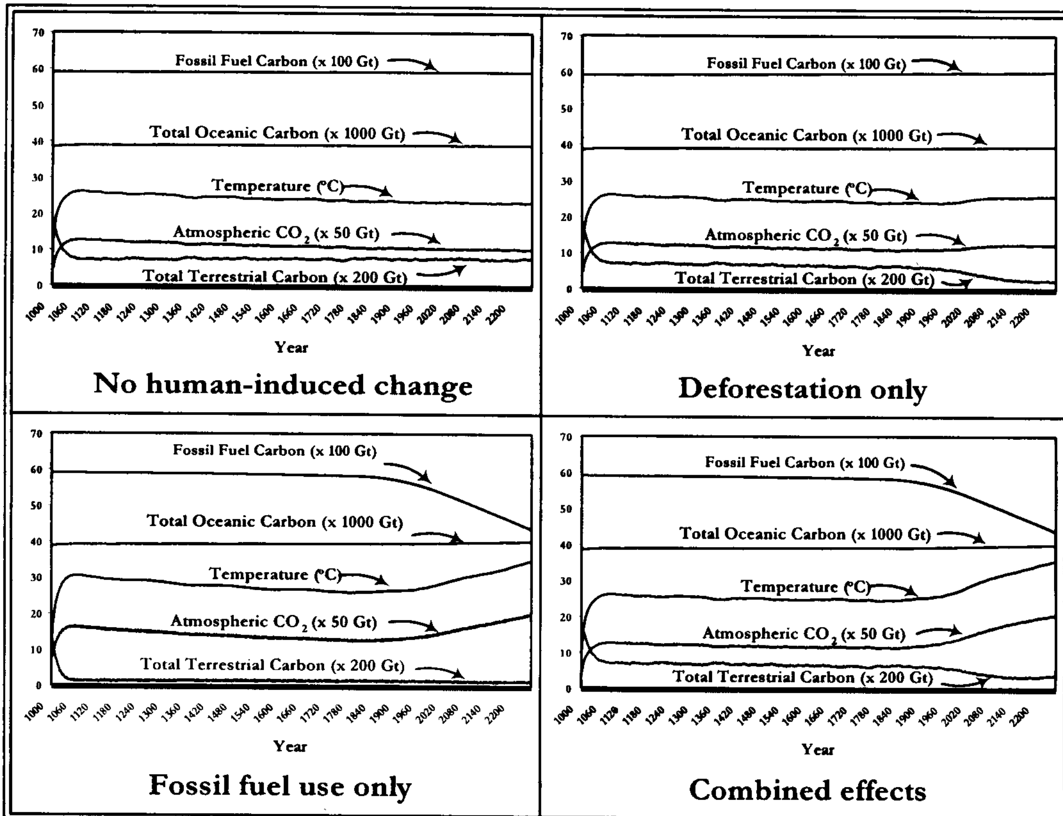

Figure 3.2. Simulation outputs resulted by GlobalC that compares global carbon balance and temperature in four different scenarios.

3.3. CENTURY

By:
S.M. Sitompul

3.3.1. INTRODUCTION

The first widely used Soil Organic Matter (SOM) model was developed by Jenkinson and Reyners (1977) who divided soil C into active, slow and passive pools with different turnover times (1 y, 30 y, and 1,500 y respectively). Van Veen and Paul (1981) then improved this model by including concepts of physical and chemical protection, and factors such as soil erosion and soil cultivation. Parton *et al.* (1987) added the impact of soil texture on SOM dynamics and eventually developed a relatively complete model called Century Model.

In the Century Model, the fractionation of soil organic matter is based on the rate of decomposition or turnover time and results in three fractions or pools (Figure 3.3). The fraction of SOM with a short turnover time (1-5 y) is called active SOM (SOM1C), which consists of live microbes and microbial products along with soil organic matter. The fraction with an intermediate turnover time (20-40 y) is called slow SOM (SOM2C), which is physically and/or chemically protected and more biological resistant to decomposition. The third fraction has the longest turnover time (200-1500 y) and is called passive SOM (SOM3C), which is chemically recalcitrant and may be also physically protected. The source of soil organic matter is confined to plant residue, which is divided into components based on lignin to nitrogen ratio. The component with a high lignin/nitrogen ratio is considered to be the structural part with 1-5 y turnover time, and the one with a low ratio is considered to be the metabolic part with 0.1-1 y turnover time. The lignin/nitrogen ratio is used to split plant residue into structural and metabolic components and to allocate all plant residue lignin flows into the structural component.

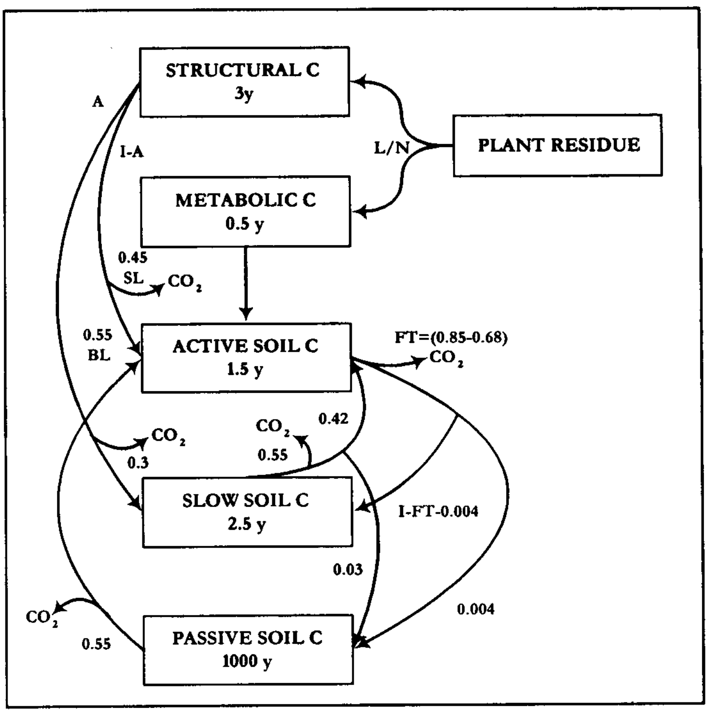

Figure 3.3. Flow diagram for the carbon flow model (SL = Surface Litter, BL = Soil Litter, L/N = Lignin to Nitrogen ratio, A = Lignin fraction, FT = Fraction of Soil Silt + Clay content.

It is also assumed that the rate of structural material decomposition is controlled by its lignin content and that the lignin fraction is directly incorporated into slow SOM. The critical point of the Century Model is that the decomposition of each pool is a result of microbial activity, and hence some organic matter will be lost in every step through respiration.

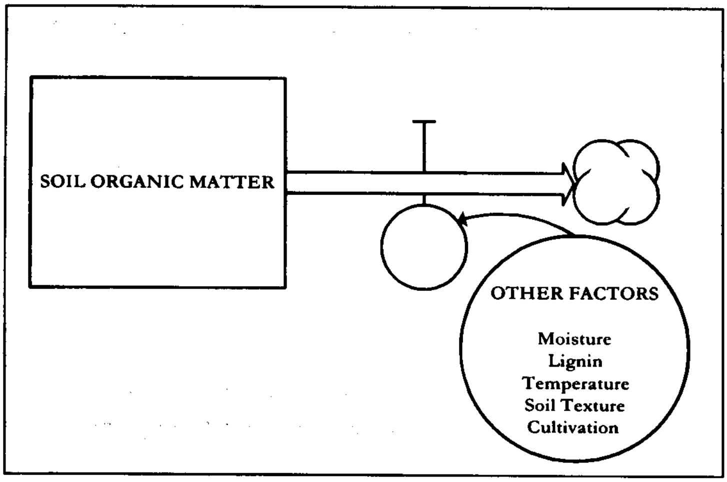

Figure 3.4. The model of SOM decomposition following first order equation.

The rate of decomposition is calculated using first order equation as shown in Figure 3.4, which means that the change of SOM with time, or the amount of organic matter loss through decomposition, is not constant, but dependent upon the amount of SOM and other factors. It can be written in the form of a differential equation as follows:

$$\frac{\delta(SOM)}{\delta t} = k.SOM.f$$

This equation can be easily solved with analytical means as shown below

$$\frac{\delta(SOM)}{SOM} = k.f.\delta t$$

$$\int_{SOMo}^{SOMt} \frac{\delta(SOM)}{SOM} = kf\int_{0}^{t}\delta t$$

ln (SOMt/SOMo) = kft

SOMt = SOMo.e^{kft}

However, complex differential equations cannot be always easily solved analytically, so that the numerical integration, such as Euler's Method and Second Order Method (Runge-Kutta), will be used. Equations used to calculate a change in each component of organic matter in the Century Model are shown below:

$$\frac{\delta C_i}{\delta t} = K_i.Lc.A.C_i \qquad i = 1, 3$$

$$\frac{\delta C_i}{\delta t} = K_i.A.Tm.C_i \qquad i = 5$$

$$\frac{\delta C_i}{\delta t} = K_i.A.C_i \qquad i = 2, 4, 6, 7, 8$$

where

i = POOL	K_i	i = POOL	K_i
1. Structural Surface Litter	3.90	5. Active SOM (Microbial Biomass, SOM1)	7.30
2. Metabolic Surface Litter	14.80	6. Slow SOM (Particulate Fraction, SOM2)	0.20
3. Structural Soil Litter	4.90	7. Surface Microbial Biomass	6.00
4. Metabolic Soil Litter	18.50	8. Passive SOM Fraction (SOM3)	0.0068

and

K_i = maximum decomposition rate (yr^{-1}) for fraction-i
A = the combined effect of abiotic impact of soil moisture and soil temperature on decomposition
Tm = is the effect of soil texture (T) on active SOM turnover
= 1 - 0.75(T) where T = silt + clay
Lc = impact of lignin content of structural material (Ls) on structural decomposition
= $e^{(-3.Ls)}$

3.3.2. MAJOR VARIABLES

The model runs using a monthly time step and the major input variables for the model include:

- monthly average maximum and minimum air temperature;
- monthly precipitation;

- lignin content of plant material;
- plant N, P and S content;
- soil texture;
- atmospheric and soil N inputs; and
- initial soil C, N, P and S level.

The model can be run for C and N only by setting NELEM = 1, otherwise set NELEM = 2 or 3 to simulate C, N and P or C, N, P and S respectively. In addition to these elements, numerous outputs can be obtained from the model (Metherell, 1993).

3.3.3. AN EXAMPLE OF CENTURY APPLICATION

Century Model version 4.0 was used to simulate SOM dynamics after forest conversion into plantations, such as oil palm and sugarcane. This type of land-use change is considered to be major cause of deforestation. In Lampung, secondary forest having grown for about 30 years is the available area of forest converted to plantations. The outputs of simulation model show that this forest may accumulate >11,6 kg $C.m^{-2}$ equivalent to a total biomass (TBM) of >255 $Mg.ha^{-1}$, and >80% of which (208 $Mg.ha^{-1}$) is large wood component. The above-ground biomass of this forest is about 226 $Mg.ha^{-1}$, which agrees with field estimates of secondary forest at the same site, based on tree diameter at breast height (dbh), that vary between 115.9 and 355.3 Mg. ha^{-1} of above-ground biomass (Sitompul *et al.*, 1996; Hairiah, 1997).

Sugarcane cultivated after forest removal without external application of fertiliser has a TBM of 2,3 kg $C.m^{-2}$ in the first year which then declines rapidly in the following years. A parallel trend is exhibited by sugarcane yield which is 40 $Mg.ha^{-1}$ in the first year and then falls to less the half after 5 years. The effect of fertiliser application of 150, 250 and 350 kg $Urea.ha^{-1}$ successively in the first, second and following years in addition to 350 TSP $ha^{-1}.year^{-1}$ may maintain a sufficiently high yield. This yield is close to that observed in the field and comparable with the average productivity of upland sugarcane in Indonesia during the period of 1981-1991 (*Anonymous*, 1992).

The dynamic of soil organic matter alters with changes in land-cover from forest to sugarcane. Under forest, the active pool of SOM either at soil surface (SOM1C1) or in soil (SOM1C2) reaches a level which fluctuates around 30 and < 50 g $C.m^{-2}$ respectively after 10 years old (Figure 3.5). The slow pool of SOM (SOM2C) tends to increase slightly which is the opposite of passive pool (SOM3C) trend. As a whole, the total organic matter (SOMTC) increases slightly with time and reaches 5281 g $C.m^{-2}$ (2%) in the last month before forest removal. This SOMT level is around the common values observed in the field at 0-20 cm depth under secondary forest of about 30 years old in Lampung (Van der Heide, 1992; *Anonymous*, 1995). This also assumed to be the level required for maintaining favourable soil physical conditions in the humid tropics (Young, 1989).

When forest is removed and replaced by sugarcane, SOM1C1 drops immediately to a very low level, then fluctuates slightly around a constant level. In turn, SOM1C2 characterised by high fluctuation increases initially then tends to decline after a few years. An immediate and a slow decrease with time following forest removal is exhibited by SOM2C, while SOM3C declining very slowly with time has no response to the land-cover change.

The SOM outputs of simulation model indicate the depletion of soil organic matter as forest is replaced by sugarcane and a low-input management causes a larger drop than a high-input management does. This trend is comparable with that of yields, which suggests the significant role of SOM in soil fertility and hence crop productivity. Century Model may give good estimates of SOM.

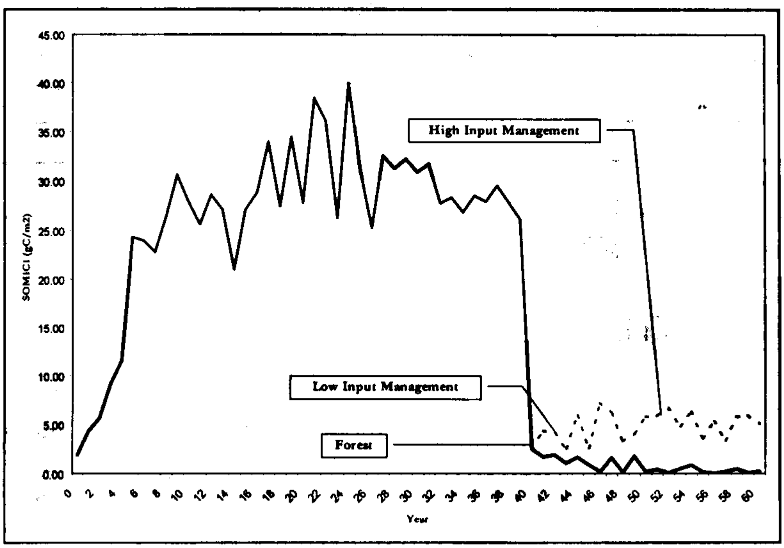

Figure 3.5. The dynamics of active SOM at soil surface (SOM1C1) under forest and sugarcane with low-input management or high-input management.

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3.4. CENW

By:
Miko Kirschbaum

3.4.1. INTRODUCTION

The Carbon, Energy, Nutrients and Water (CENW) model combines and links fluxes of soil carbon, nutrients, atmospheric CO_2 and water. Plants grow by fixing CO_2 from the atmosphere. However, the need to open a diffusion path for CO_2 inevitably leads to water loss in the diffusive exchange of CO_2 and water through stomatal pores. Water can be replenished from the soil provided adequate soil water is available. Otherwise, further plant CO_2 fixation is prevented by stomatal closure.

As shown in Figure 3.6, to meet their nitrogen requirements, plants must take up nitrogen from the mineral nitrogen pool. Nitrogen can be supplied by external sources or from the decomposition of organic matter. Plants utilise part of their carbon and nitrogen in new growth, and some carbon and nitrogen is lost in death or senescence of plant components. This returns carbon and nitrogen to the soil to form organic matter. Organic matter is decomposed by organisms in the soil, releasing CO_2 to the atmosphere. Any excess nitrogen can enter the pool of mineral nitrogen from where it can be taken up by plants.

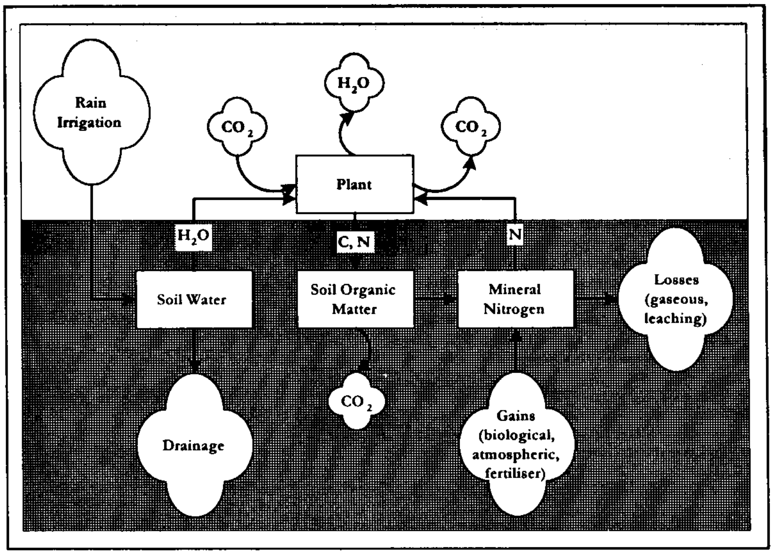

Figure 3.6. Carbon, nutrients, CO_2, and water fluxes in CENW.

The model runs on a daily time step. Photosynthetic carbon gain depends on light absorption, temperature, soil water status, foliar nitrogen concentration and any foliage damage due to frost or scorching temperatures during preceding days.

Some photosynthetically fixed carbon is lost in respiration and the remainder is utilised for growth, with allocation to different plant organs determined by plant nutrient status, tree height and species-specific allocation factors. Water use is calculated with the Penman-Monteith equation, with canopy resistance given by stomatal conductance, which, in turn, is linked to calculated carbon gain. Water loss by transpiration and soil evaporation and water gain by rainfall or irrigation then determine the soil water status for the following day.

3.4.2. NITROGEN DYNAMICS

Nitrogen is taken up after it has been added by atmospheric deposition, fertiliser addition, biological fixation or mineralisation during the decomposition of soil organic matter. Decomposition rate is determined by temperature, soil water status and soil organic matter quality in a modified formulation based on the CENTURY model (see Section 3.3).

The nutrient cycle is closed through litter production by the death of trees, or by shedding of plant parts, such as roots, bark, branches and, most importantly, foliage. Litter then adds to the organic matter pools from where carbon is eventually lost and nitrogen becomes available again as inorganic mineral nitrogen.

The amount of nitrogen mineralised is calculated with a variant of the CENTURY. The key modifications are:

1) nitrogen can only exchange between the organic matter pools and the mineral nitrogen pool via the active pool of soil organic matter;
2) the critical C:N ratio for immobilisation/mineralisation is expressed as a function of the relative amounts of organic matter passing through the metabolic and structural litter pools, respectively;
3) the C:N ratio of all pools may vary; the effective C:N ratios of pools other than the active one are determined solely by the C:N ratios of the pools from where organic matter is received;
4) three additional litter pools are included, corresponding to branch, stem and coarse root litter;
5) nitrogen flows between pools are calculated from the carbon flow between pools divided by the C:N ratio in the source pool;
6) the flow of the lignin fraction of organic matter from structural litter to the slow pool is accompanied by additional (shielded) non-lignin organic matter;
7) the C:N ratio of material entering the structural litter pool is set to be some multiple of that in the metabolic litter pool; hence, both are variables as a function of the C:N ratio in the incoming litter;
8) there is a direct flux of nitrogen from the mineral nitrogen pool to the slow pool; this flux is small and of little relevance unless large amounts of mineral nitrogen are available such as during fertilisation; and
9) there is direct uptake of nitrogen from the active pool via mycorhizal associations.

3.4.3. WATER FLOWS

Water is received by rainfall of which a fraction is intercepted by the canopy from where it evaporates without benefit to the stand (Figure 3.7). Irrigation water may then also be added. Some further water may be lost by litter interception, again without benefit to the stand.

Water is then added to the soil which in the model is divided into an arbitrary number of layers. Water is always added to the top-most layer from where it drains to the next lower layer and so on provided the soil water content of that layer exceeds the layers maximum water holding capacity. If water content of the lowest soil layer exceeds its water holding capacity, deep drainage results and the water is lost from the site.

Trees have access to water from all layers. Transpiration is calculated with the Penman-Monteith equation, based on intercepted net radiation, temperature, VPD, constant (user-input) aerodynamic resistance and canopy resistance that is calculated based on CO_2 concentration and previously calculated CO_2 assimilation rate. Canopy resistance is assumed to be proportional to CO_2 assimilation rate.

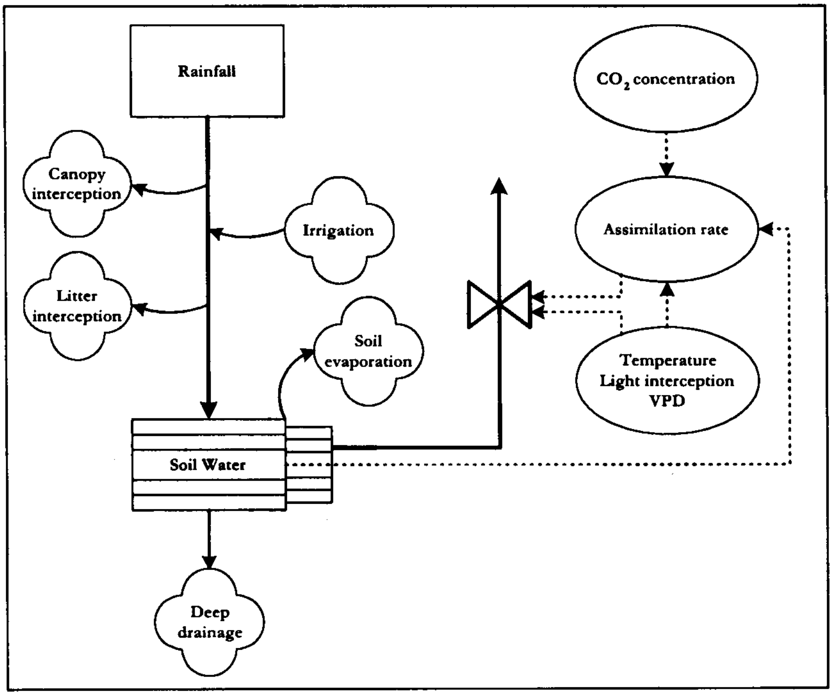

Figure 3.7. Water flows in CENW.

Water is assumed to also evaporate directly from the soil surface, but only the top soil layer is assumed to be able to support soil evaporation rates.

3.4.4. CARBON FLOWS

In the model, carbon enters the system through photosynthesis, which is calculated as a function of soil water content, foliar, nitrogen concentration, environmental conditions (temperature, VPD, CO_2 concentration and light interception), inherent plant characteristics and possibly reduced capacity due to prior temperature damage.

Some fixed carbon is lost in maintenance respiration and the remainder is available for growth, with a fraction of carbon during growth being lost in growth respiration. Growth occurs in various biomass pools that differ greatly from one another through their turn over times, nitrogen concentrations and whether they are found above or below-ground.

Allocation to these different biomass pools follows a number of simple rules that control the allocation to respective pools.

Carbon is eventually lost in the senescence of plants parts, the death of entire trees or during tree pruning, thinning or harvesting. Carbon (and nitrogen) are then added to litter pools from where carbon is lost in soil respiration and nitrogen can reenter the active plant pools after mineralisation (Figure 3.6).

Allocation is worked out based on a number of related considerations. Firstly, for plants that have reached the age of sexual reproduction, it is assumed that a constant fraction of carbon is allocated to the production of male and female reproductive organs.

The remaining carbon is allocated to vegetative growth, with the allocation ratios stem:branch, bark:stem and coarse roots:stem assumed to be constant and species specific.

Allocation to stems (and by implication to branches) is assumed to vary in proportion to tree height so that the allocation ratio of branches (and stems): foliage is proportional to tree height. The underlying assumption is that to produce a new leaf, the plant also constructs a new xylem element, which has to extend from the leaf to the ground. Its length thereby is proportional to tree height and so is the required carbon allocation.

For the allocation to fine roots and foliage, it is assumed that they are in a dynamic equilibrium controlled by the relative ease of the uptake of carbon and nitrogen. If nitrogen is very freely available, fine-root growth can be at a minimum and plant resources can be given to enhanced foliage growth; if nitrogen is poorly available, greater root growth is necessary to obtain more nitrogen whereas foliage growth is necessary as carbon is already excessive relative to the availability of nitrogen. Hence, the ratio of fine-roots:foliage is variable as a function of plant nutrient status, which specifically is determined as a function of foliar nitrogen concentration.

The allocation of nitrogen to different biomass components is firstly proportional to the calculated carbon allocation ratios, but it is further modified by the consideration that different biomass components have very different nitrogen concentrations.

3.4.5. VALIDATION

The model has been developed, parameterised and validated against a very comprehensive data set obtained at a thoroughly studied site near Canberra, Australia. Tests have been performed on nitrogen dynamics (Figure 3.8), water dynamics and total biomass production, and the model was generally able to replicate all observed responses fairly reliably.

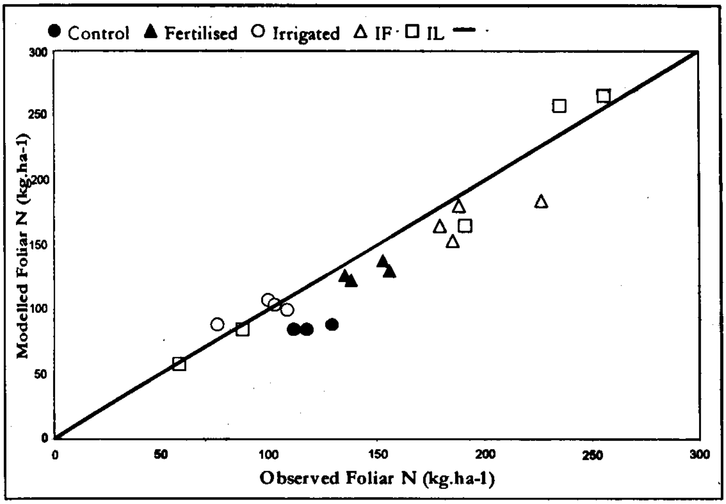

Figure 3.8. Comparison between observed and simulated foliar nitrogen as validation test of CENW at study site in Canberra, Australia.

3.4.6. SENSITIVITY TEST

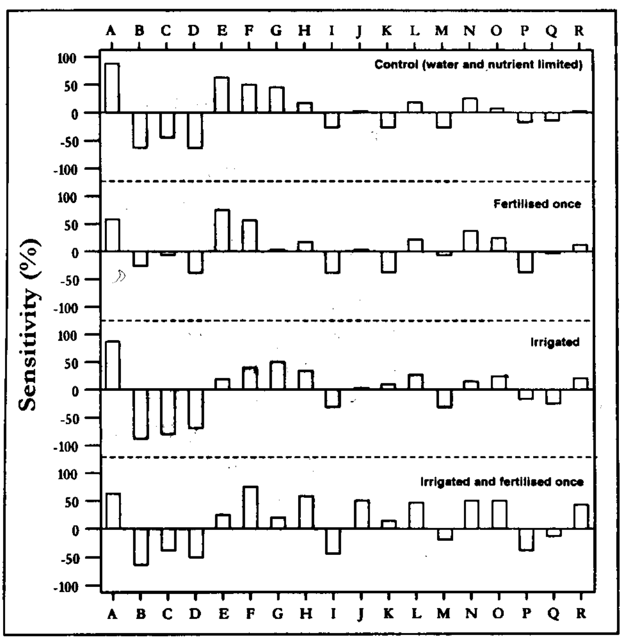

Figure 3.9. Sensitivity of stem wood production to change in wood:branch ratio (A), foliar N to saturate photosynthesis (B), crown N ratio (C), foliage:branch ratio (D), CO_2 concentration (E), maximum assimilation rate (F), fertility (G), high-temperature damage (H), light extinction coefficient (I), maximum foliar N (J), stomatal constant (K), maximum temperature for photosynthesis (L), root:foliage ratio (M), curvature term in photosynthesis (N), upper optimum temperature (O), lower optimum temperature (P), treshold foliar N for photosynthesis (Q), and specific leaf area (R), under four treatments.

Figure 3.9 shows the sensitivity of stem wood production to change in various parameters under four different conditions. Greatest growth response is observed to the ratio of stem wood to branch (A) and foliage to branch allocation (D), the nitrogen concentration that saturates photosynthesis (B), the nitrogen gradient within the crown (C), and the maximum assimilation rate (F). Lesser, but still significant sensitivity is also observed to the light extinction coefficient (I) and the parameters that define the temperature response of photosynthesis (L, O, P).

Other parameters show different sensitivity under different conditions. For example, growth is highly responsive to CO_2 concentration (E) in the Control and Fertilised treatments but much less important for the two irrigated treatments. Maximum possible foliar nitrogen concentration (J) is of great significance in the irrigated and fertilised treatment but of no significance at all in the other treatments.

The nitrogen gradient in the crown (C) is very significant in the irrigated treatment, unimportant in the fertilised treatment and of moderate importance in the other treatments.

A very interesting parameter is the stomatal parameter (K), which is of reasonable significance in the unirrigated treatments, with growth negatively correlated with the stomatal parameter. In the two irrigated treatments, the correlation is small and positive. That is because under irrigated conditions, higher stomatal conductance is an advantage, because higher intercellular CO_2 concentration allows higher photosynthetic carbon gain. Under unirrigated conditions, transpiration efficiency is critical in determining total possible wood production, and reduced stomatal conductance makes that possible.

The comparison of sensitivities to different parameters under different experimental treatments is revealing as it shows how control over growth shifts with external conditions to different aspects of plant performance. Under unfertilised conditions, growth is highly sensitive to parameters that control nutrient dynamics, such as the nitrogen concentration that saturates photosynthesis (B) and the nitrogen ratio within the crown (C).

Under unirrigated conditions, it is factors related to water economy, such as CO_2 concentration (E) and the stomatal parameter that are of great importance. In treatments receiving adequate supplies of both water and nutrients, the control is shifted over several parameters, and growth is more sensitive to parameters such as the maximum possible nitrogen concentration (J), the photosynthetic temperature terms (H, L, O, P) and specific leaf area than it is for the other treatments. Terms primarily related to the ultimate utilisation of carbon, expressed in carbon allocation coefficients (A, D, M) are of similar importance in all treatments.

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3.5. WANULCAS

By:
Meine van Noordwijk and Betha Lusiana

3.5.1. AGROFORESTRY SYSTEMS

WaNuLCAS (Water, Nutrient, and Light Capture in Agroforestry System) is a model of tree-crop interaction in agroforestry system. The model is formulated in the STELLA Research modelling environment. Emphasis was given to below-ground interactions, where competition for water and nutrients (nitrogen) depends on the effective root length densities of both plant components and current demands by tree and crop. An up-to-date version can be obtained from *http://www.cgiar.org/icraf/sea/wanulcas/* (operational per June 1999).

The key feature of the model is the description of uptake of water and nutrients (at the recent stage only N) on the basis of root length densities of both the tree and the crop, plant demand factors and the effective supply by diffusion at a given soil water content.

The model represents a four-layer soil profile (vertical), with four spatial zones (horizontal), a water and nitrogen balance and uptake by a crop and a tree (Figure 3.10).

The user can define the width and depth of each zone and adjust it to the type of system simulated. The model can be used both for simultaneous and sequential agroforestry systems and may help to understand the continuum of options ranging from improved fallow via relay planting of tree fallow to rotational and simultaneous forms of hedgerow intercropping. The model explicitly incorporates management options such as tree spacing, pruning regime and choice of species or provenance. The model includes various tree characteristics, such as (dynamic) root distribution (over 16 cells, 4 layers x 4 zones), canopy shape (above 4 spatial zones), litter quality, maximum growth rate and speed of recovery after pruning.

If applied to hedgerow intercropping, the model allows for the evaluation of crop growth at different distance from the hedgerow for different pruning regimes and hedgerow tree spacing or fertiliser application rates. When applied to rotational fallow systems, the edge effects between currently cropped parts of a field and the areas where a tree fallow is growing can be simulated, by letting the first zone represent a fallow plot and zone 2, 3 and 4 represent three zones in a neighbouring cropped field. For isolated trees in parkland systems, equidistant zones around individual trees can be pooled (Table 3.1).

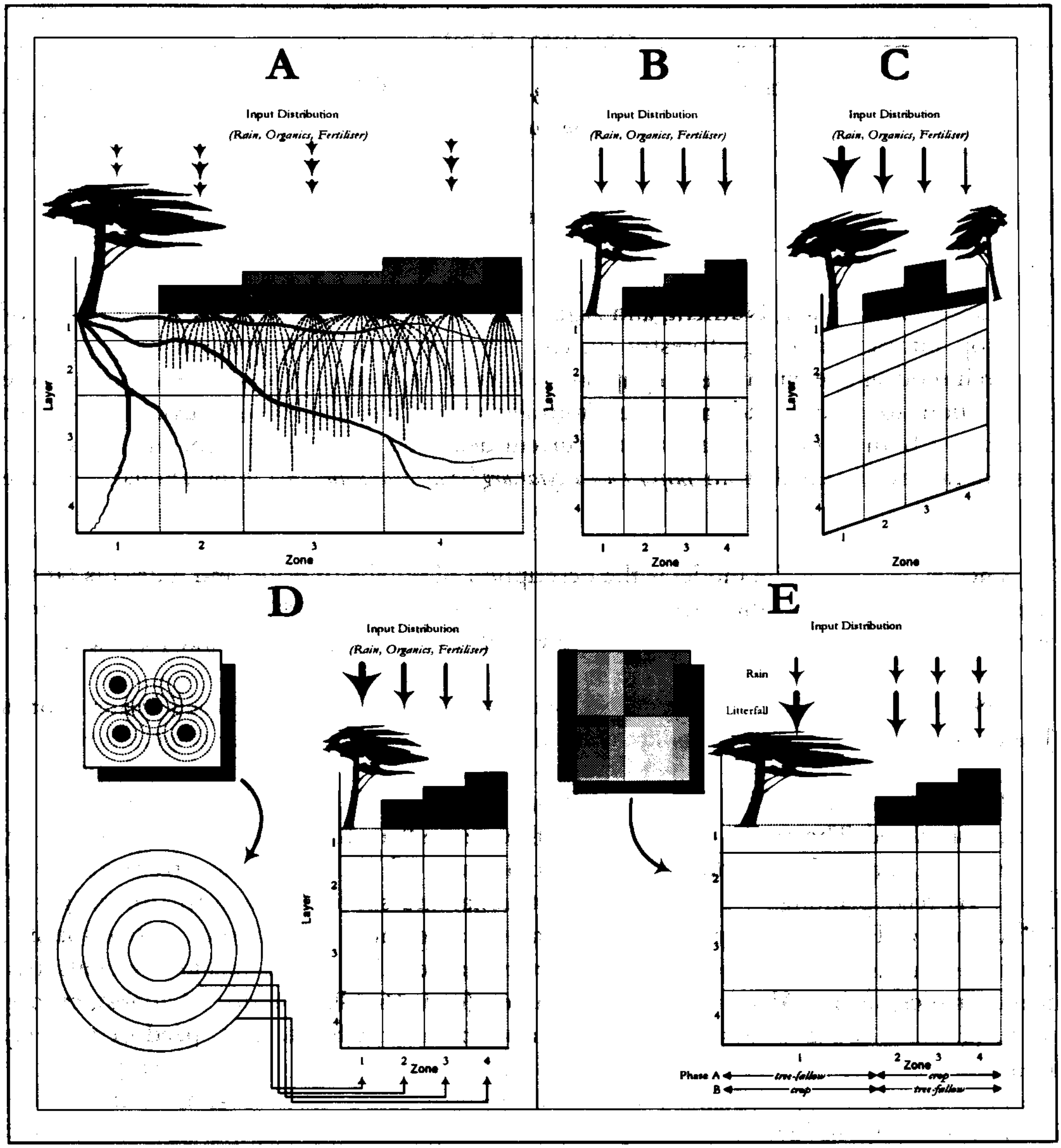

Figure 3.10. General lay out of zones and layers in the WaNuLCAS model (A) and applications to four types of agroforestry system: (B) Alley cropping, (C) Contour hedgerows on slopes, with variable topsoil depth, (D) Parkland systems, with a circular geometry around individual trees, (E) Fallow-crop mosaics with border effects

Table 3.1. Characteristic settings for four types of agroforestry system.

Type of Agroforestry System	Geometry	Tree canopy	Topsoil Depth	Water Infiltration	Time Sequence
Alley cropping on flat land	Linear	Zone 1-4	Homogeneous	Homogeneous	Continuous
Alley cropping on slopes	Linear	Zone 1-4 + symmetrical canopy 4-1	Gradient	Heterogeneous (runoff + runon)	Continuous (soil redistribution can be simulated)
Parkland trees	Circle	Zone 1-4	Homogeneous	Heterogeneous	Continuous
Tree fallow/ mosaic	Linear	Zone 1 (fallow plot size)	Homogeneous	Homogeneous	Switching between fallow and crop stage

A number of inputs to the soil surface can be distributed proportional to the relative surface areas or heterogeneously. This way, it for example account for surface runoff of rainfall in one zone and its infiltration in another. Separately, patch-level net run-on or run-off can be implemented. Similar weighting factors are used for allocating litterfall, tree pruning, fertilisers and crop residues to the various zones, while conserving their overall mass balance.

The model assumes the same crop to be grown in all three zones, simultaneously. Sequencing of crops is possible by specifying the crop type, planting year and day of year for each subsequent crop. The vegetative and generative duration of that crop (at standard temperature) is used as input, and modification of phenological development by actual temperature can be accommodated. Each crop should be specified on the basis of its maximum dry matter production rate per day, expressed in kg m^{-2} day^{-1}, and a graphic or tabulated input of its relative light use efficiency (dry matter production per unit light intercepted) and its leaf weight ratio as a function of crop stage. These parameters may be derived for a given location from more specific models, such as the DSSAT family of crop growth models.

Trees can be pruned in the model to a specified degree, on the basis of two criteria: concurrence with a crop on the field and tree biomass above a prune limit. Alternatively, calendar dates for pruning events can be given as input. Prunings can be returned to the soil as organic input (in the standard case with regular distribution over the zones).

3.5.2. SOIL AND CLIMATE INPUT DATA

Climate effects are mainly included via daily rainfall data, which can be either read from a spreadsheet or generated on the basis of a daily probability of rainfall and an expected monthly rainfall total. Average temperature and radiation are reflected in potential growth rates, which are used as input, but thermal time (temperature sum) is reflected in the speed of phenological development inside the model. Temperature effects on organic matter decomposition are incorporated according to the Century model. Parameters influencing potential evapotranspiration (wind speed, VPD) are not explicitly required, only the resulting potential-soil-evaporation-rate.

Soil is represented in four layers, the depth of which can be chosen, with specified soil physical properties and initial water and nitrogen contents, for all sixteen cells. For calculating water infiltration to the soil, a layer-specific estimate of the field capacity (soil water content one-day after heavy rain) is needed. No capillary rise or abiotic water redistribution other than during rainfall events is included in the model in its current form. For calculating potential water uptake a table of the soil's matrix flux potential is needed, which integrates unsaturated hydraulic conductivity over soil water content (De Willigen and Van Noordwijk, 1994). The model also needs the relationship between water potential and soil water content, to derive the soil water content equivalent to certain root water potential. As these relationships are not generally measured for all soils where we may want to apply the WaNuLCAS model, pedotransfer functions are used (Arah and Hodnett, 1997). WaNuLCAS derives parameters of the Van Genuchten equations of soil physical properties via a pedotransfer function from soil texture, bulk density and soil organic matter content. The function selected was developed by Wösten *et al.* (1995). As this pedotransfer function is based on soils from temperate regions, one should be aware of its possible poor performance on soils with a low silt content, as the combination of clay + sand at low silt contents is much more common in the tropics than in temperate regions.

3.5.3. WATER BALANCE

The water balance of the system includes rainfall, with the option of exchange between the three zones by run-on and run-off, surface evaporation, uptake by the crop and tree and leaching. Only vertical transport of water is included (so far). For the description of the soil water balance in soil-plant models a number of processes should be combined which act on different time scales. The WaNuLCAS model currently incorporates some of the processes, but aggregates them to a daily time step:

1) rainfall or irrigation (with additional run-on) and its allocation to infiltration and surface run-off (and/or pounding), on a seconds-to-minutes time scale,

2) infiltration into and drainage from the soil via a cascade of soil layers, and/or via bypass flow, on a minutes-to-hours time scale,
3) subsequent drainage and gradual approach to hydrostatic equilibrium on a hour-to-days time scale,
4) transfers of solutes between soil layers with mass flow,
5) evaporation from surface soil layers on a hour-to-day time scale, as modified by soil water content and vegetative cover,
6) water uptake on a hour-to-days time scale, but mostly during day time when stomata are open,
7) hydrostatic equilibration (hydraulic lift and sink) via root systems on a hour-to-days time scale, but mostly at night when plant transpiration is negligible,

Drainage to lower layers is effectuated on the same day as a rainfall event occurred. An empirical infiltration fraction (as a function of rainfall intensity, slope and soil water deficit) can be implemented at patch scale. Between the zones of the WaNuLCAS model, surface run-off and run-on resulting in redistribution among zones can be simulated on the basis of a user-specified weighing function for effective rainfall in the in the various zones. Upon infiltration a tipping bucket model is followed for wetting subsequent layers of soil, filling a cascade of soil layers up till their effective field capacity. Field capacity is estimated from the water retention curve. Soil evaporation from the surface layer depends on ground cover (based on LAI of trees and crops) and soil water content of the topsoil.

An option exist to simulate hydraulic lift and hydraulic sink phenomena in tree roots, transferring water from relatively wet to relatively dry layers. Hydraulic continuity via root systems can lead to transfers of water between soil layers, on the basis of water potential and resistance. If the subsoil is wet and the surface layers are dry, this process is called hydraulic lift (Dawson, 1993). The reverse process, transfers from wet surface layers to dry subsoil is possible as well and has recently been observed in Machakos (Kenya) (Smith *et al.*, 1998; Burgess *et al.*, 1998). Although the total quantities involved in these water transfers may be relatively small, it can be important in the competition between shallow and deep-rooted plants. Hydraulic lift can re-wet nutrient-rich dry topsoil layers and thus facilitate nutrient uptake. The reverse process, deep water storage by deep rooted plants after moderate rainfall which only infiltrate into the topsoil, can increase their overall resource capture vis-à-vis shallow rooted plants.

3.5.4. NITROGEN BALANCE

The nitrogen balance of the model includes inputs from fertiliser (up to four applications, specified by amount and time of application), atmospheric N fixation and mineralisation of soil organic matter and fresh residues. Uptake by crop and tree is allocated over yields (exported from the field/patch) and recycled residues. Leaching of mineral N (nitrate) is driven by the water balance, the N concentrations and the apparent adsorption constant for nitrate in each layer (thus allowing for a chemical safety net by subsoil nitrate adsorption). Decomposition of soil organic matter is represented by a three-pool model, following the terminology and concepts of the Century model (Parton *et al.*, 1994).

3.5.5. GROWTH

Growth of both plants (crop and tree) is calculated on a daily basis by multiplying potential growth (which depends on climate and current plant size) with the minimum of four stress factors, one for shading, one for water limitation, one for nitrogen and one for stress history. The latter factor ensures for example that plants will not directly resume their maximum growth rates the day after they have been exposed to full sunlight after pruning the trees. The half-life time of the stress can be chosen by the model user, but experimental data for this parameter are scarce; a value of a few days appeared to be adequate.

The model assumes that under N deficiency crops keep their potential transpiration rate, but have a reduced actual water use efficiency (WUE, dry matter production per unit water use). The reduction in WUE under nitrogen stress may be overstated by this approach. N uptake will be reduced as biomass accumulation slows down and thus demand is decreasing.

A number of the allocation functions depend on the physiological age of the crop. A basic length of the vegetative and generative stage is given as model input for each crop. These values are used to re-scale time into crop-age; for environments where temperature is a major variable, crop development can be driven by a temperature sum (thermal time) rather than by time.

WaNuLCAS uses a simple description of tree canopy shape, above-ground biomass production and litterfall. In the model, the calculated above-ground tree biomass increment is first of all allocated to a buffer of carbohydrate reserves and is allocated from there to make (a) a canopy, consisting of leaves and small branches (<2 cm diameter), (b) a support structure, consisting of supporting branches and a trunk, and (c) replacement of leaves and branches transferred to litterfall.

The allocation over canopy and support structures depends on the size of the tree while litterfall is related to the development of bare branches in the support structure.

Within the canopy, the increment in leaf biomass is calculated from (a) LWR (leaf weight as fraction of total biomass in the canopy); (b) SLA (specific leaf area, or leaf area per unit leaf weight).

Tree canopy shapes are approximated by a half ellipse on a stick (forming an umbrella), with as parameters (a) R, radius (half of the width); (b) H, height (measured above the bare stem section); the canopy height consists of a green part and, above a certain total height, a bare section; (c) S, shape, or ratio of radius and height of the half ellipse (or of width and total height of a full ellipse; S = R/H; S = 1 indicates a circle); and (d) LAI-canopy (leaf area index within the canopy), which can vary between LAImin and LAImax.

Growth of the canopy in a lateral or vertical direction can be continuous, but for light capture the canopy is at any point in time discretisised on the basis of the zones it covers under a vertical projection, with even distribution within each zone.

3.5.6. UPTAKE AND COMPETITION

Uptake, U, of both water and nitrogen by the tree and the crop is driven by demand, D, but within limits set by a zero-sink uptake model (De Willigen and Van Noordwijk, 1987 1991, 1994) on the basis of root length density and effective diffusion constants in each cell where the plant has roots.

For water the potential uptake is based on the matrix flux potential (De Willigen and Van Noordwijk 1987, 1991, 1994). If potential uptake (at plant level), PU, exceeds demand, actual uptake from each cell is reduced proportionally.

Demand for nitrogen uptake is calculated from empirical relationships of maximum N uptake and dry matter production under non-limiting conditions (5% N in dry matter up to a closed crop canopy is reached at an above-ground biomass of 2 Mg ha-1, 1%N in new dry matter after that point; De Willigen and Van Noordwijk, 1987), a luxury uptake (stating that growth will not be reduced until N content falls below 80% of the above defined maximum uptake which is used as demand), a possibility for compensation of past uptake deficits and an option for N fixation (driven by the Ndfa parameter, indicating the part of the N demand which can be met from atmospheric fixation).

Competition is based on sharing the potential uptake rate for both (based on the combined root length densities) on the basis of relative root length multiplied by relative demand, D.

Water uptake from any cell is shared between all components having roots in a given cell, with the share based on effective root length density (corrected for root diameter), plant demand and the degree to which plant demand can be met from other cells in which a plant is rooted.

3.5.7. ROOT GROWTH

Root growth is represented for the crop by a logistic increase of root length density in each layer up till flowering time and gradual decline of roots after that time. A maximum root length density per layer is given as input. The model thus does not (yet) incorporate functional equilibrium responses on shoot/root allocation of growth, nor does it allow for a local response to shift root growth to favourable zones. These elements can however, be incorporated in a later stage. The tree root length density in all zones and layers is assumed to be constant, thus representing an established tree root system with equilibrium of root growth and root decay. The model can be modified to make tree root length density in each cell a function of time or dependent on tree size or age.

3.5.8. LIGHT CAPTURE

Light capture is treated on the basis of the leaf area index (LAI) of both components and their relative heights, in each zone. Potential growth rates for conditions where water and nutrient supply are non-limiting are used as inputs (potentially derived from other models), and actual growth is determined by the minimum of shade, water and nutrient stress. Three strata can be distinguished: an upper canopy (with only one type of leaves), a mixed one (with both types of leaves present) and a lower one (with one only). Total LAI for each plant in each zone is fractionated according to the relative heights of tree and crop, thus ensuring symmetry in the relations and the possibility of crops shading trees depending on relative heights. Light capture is calculated from the LAI in each canopy layer and a plant-specific light extinction coefficient. These equations should give a reasonable approximation for any canopy geometry (Kropff and Van Laar, 1993).

3.5.9. MANAGEMENT OPTIONS

The WaNuLCAS model can evaluate a number of farmer management options. These can be grouped in strategic decisions, to be made by a farmer before crops are planted and by a modeller at the start of a simulation and tactic management during a growing season, in response to actual crop performance.

Strategic options include (a) plot size and tree spacing; (b) choice of tree species as reflected in their functional parameters of canopy shape and branch allocation, root distribution under given soil conditions); and (c) cropping cycle: crop types and planting dates.

Tactical options represented in the model are (a) tree pruning: predetermined dates or based on a prune-limit; (b) use of fertiliser and organic inputs and their distribution over the zones; and (c) crop residue removal.

At this stage only two types of plants are considered and thus it is implied that there are no weeds. The equations for resource sharing and competition are set up in such a way that the model can be extended to an N-plant interaction and different plants can share a zone in the model, above as well as below-ground.

3.5.10. EXAMPLE OF MODEL APPLICATION: TREE-SOIL-CROP INTERACTIONS ACROSS A RAINFALL GRADIENT

To further explore the sensitivity of the model a series of calculations was made for an agroforestry system with scattered trees and crops growing on all land except for a circle directly around each tree (Figure 3.10).

The soil profile consisted of four layers (15, 15, 50 and 30 cm thick, respectively) and had a sandy texture (61% sand, 11% silt, 28% clay) and a bulk density of 1.3 $Mg.m^{-3}$ and thus had a rather low water-holding-capacity according to the pedotransfer function. Calculations were made for five climate zones, based on random daily rain events with a set monthly average and daily rainfall probability of about 20%.

As the same starting value was used for the random generator, all runs for different agroforestry systems in a given climate were made with the same daily rainfall pattern. The simulation run was 2 years, and two crops were grown per year for the 1500 and 2400-mm rainfall zone. Simulations for pure crops (covering the whole field) were compared with those of trees only (unrestricted tree growth) or agroforestry systems were tree occupied the inner circle and crops the remainder of the land. The trees were pruned at sowing time for each crop and a second time during the crop if their biomass exceeded a set value of 0.2-kg m^{-2} (averaged over the whole field). For comparison a set of simulations was included where the tree was pruned in the same way as in the agroforestry system, but where no crop was grown. Four variants were considered for the agroforestry system, indicated by 'narrow', 'medium', 'broad' and 'very broad' tree canopies with a crown diameter of 1, 2, 3 or 4 quarts of the diameter of the whole system. Note that all zoning is relative to tree size and no absolute distances have to be specified. Tree root length density was 2, 1.5, 0.6 and 0.2 cm cm^{-3} for the four depth layers directly under the tree, respectively, and 0.6, 0.36, 0 times that value in the three other zones, respectively; thus tree roots were confined to a circle of 3/4 the total diameter. The tree was able to derive 40% of its daily N demand by atmospheric nitrogen fixation and tree N could be transferred to the crop via litterfall and tree pruning, based on a gradual N mineralisation. The crop was supposed to have a 98-day duration and a rather shallow root system, with a harvest index under non-limiting conditions of 41%. No N fertiliser was used.

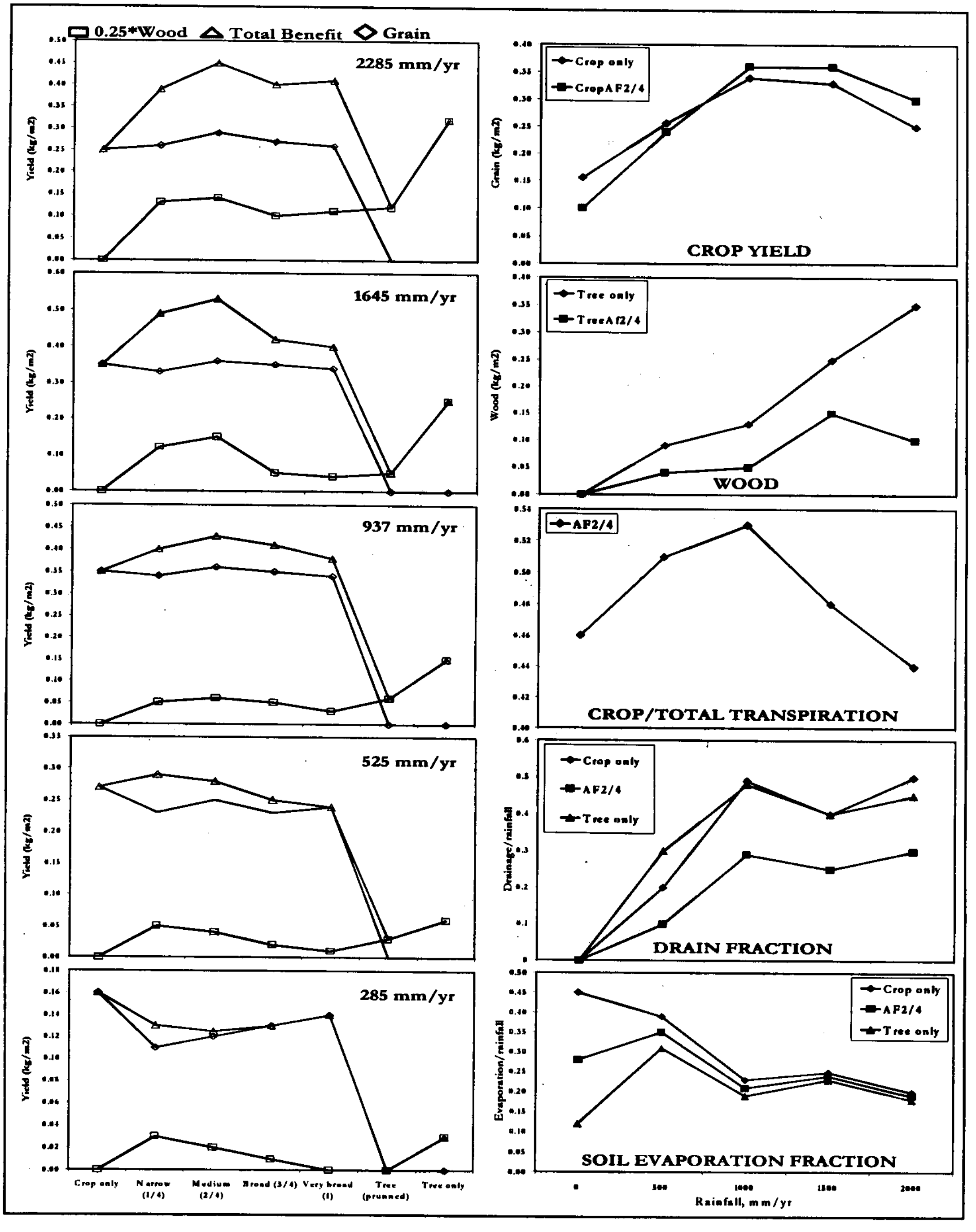

Figure 3.11. Calculations with the WaNuLCAS model of grain and wood production and water use for a range of annual rainfall conditions in an agroforestry system with isolated trees which are pruned when a crop is sown, resembling an early stage of a parkland system; production is accumulated over 2 years, involving 4 (at 2285 and 1645 mm/year) or 2 crops of 98 days duration, on a sandy soil with limited N mineralisation from soil organic matter.

From the simulation results we focus here on grain production (actual harvest index was between 36 and 41%), stem wood production for the tree (treating crop residues, litterfall, pruning and current tree canopy as intermediate components of the system) and the water balance (Figure 3.11). The simulation involved a gradual shift from water to nitrogen as the major factor limiting crop production. At high rainfall the total N supply in the soil was effectively exhausted by the first crop in the pure crop control and the three following crop yields were low. Under these conditions the agroforestry system could increase crop yield (by up to 8%), by supplying at least some N for the later crops, thus compensating for the area without a crop and competition effects on crop growth. The medium tree canopy shape (2/4) gave the highest crop yield of all agroforestry systems in the three wettest climates. For the simulations at 450 and 240 mm rainfall, crop yields were reduced in agroforestry by 11 and 35% respectively, as competition for water dominated over positive effects on N supply; at 450 mm the four agroforestry systems gave equal grain yields, while at the 240 mm run, the narrow tree morphology was best. In contrast to grain yield, wood production was always higher in the pure tree system than in the agroforestry system. The narrow tree morphology produced more wood, as it invested less resources in a leaf + fine branch canopy. Total yield for the agroforestry system can be calculated if the value of wood can be expressed relative to that of grain. In Figure 3.11 a 1:4 ratio is used. In the driest simulations there is agroforestry system will reduce total yield, while the curve for the 450-mm zone is nearly flat (and a slightly higher or lower relative value of wood (or other tree products) could shift the balance). For the three wettest climates the positive effects of agroforestry on grain yield are accompanied by additional wood production and agroforestry is superior, unless the relative value of wood is at least 50% higher than we assumed here. The additional production of agroforestry is based on a more complete use of water: the fraction of rainfall draining from the profile is substantially (about 15-20% of rainfall) reduced by the tree - crop combination, while model results for soil evaporation losses are intermediate between pure crop and pure tree systems. The share of the crop in total transpiration was always around 50% and peaked in the 1000-mm rainfall situation. Crop water use efficiency was highest at the driest site, as N limitations reduced it in wetter zones. For the tree water use efficiency was not effected by climate, as its N fixation was not limited by drought.

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