

**Assessing carbon stocks and
modelling win-win scenarios
of carbon sequestration
through land-use changes**



**Assessing carbon stocks and
modelling win-win scenarios
of carbon sequestration
through land-use changes**

by **Raul Ponce-Hernandez**

with contributions from
Parviz Koohafkan
and **Jacques Antoine**

FOOD AND AGRICULTURE
ORGANIZATION OF THE
UNITED NATIONS

Rome, 2004

The designations employed and the presentation of material in this information product do not imply the expression of any opinion whatsoever on the part of the Food and Agriculture Organization of the United Nations concerning the legal or development status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.

All rights reserved. Reproduction and dissemination of material in this information product for educational or other non-commercial purposes are authorized without any prior written permission from the copyright holders provided the sources is fully acknowledged. Reproduction of material in this information product for resale or other commercial purposes is prohibited without written permission of the copyright holders. Applications for such permission should be addressed to the Chief, Publishing Management Service, Information Division, FAO, Viale delle Terme di Caracalla, 00100 Rome, Italy or by e-mail to copyright@fao.org

© FAO 2004

CONTENTS

<i>vii</i>	Foreword	
<i>viii</i>	Acknowledgements	
<i>ix</i>	Acronyms	
<i>xi</i>	Summary	
	Introduction	<i>1</i>
	Outline of the methodology	<i>5</i>
	Assessment of biomass and carbon stock in present land use	<i>9</i>
	Modelling carbon dynamics in soils	<i>29</i>
	Integrating the assessment of total carbon stocks to carbon sequestration potential with land-use change	<i>57</i>
	Biodiversity assessment	<i>69</i>
	Land degradation assessment	<i>81</i>
	Analysis of land-use change scenarios for decision-making	<i>105</i>
	Discussion	<i>115</i>
<i>143</i>	Conclusions and recommendations	
<i>149</i>	Bibliography	

1. Use of each nested quadrat site for sampling and measurement
2. Estimation of biomass of tropical forests using regression equations of biomass as a function of DBH
3. Estimation of crown or canopy volume as a function of the shape of the crown
4. Minimum data set for aboveground biomass estimation
5. Non-destructive methods for root biomass estimation
6. Summary description of the CENTURY model as per SOMNET
7. Summary description of the RothC-26.3 model as per SOMNET
8. Codes used in CENTURY to define each of the major land-use types
9. Specific information by major kind of land use for CENTURY
10. Variables describing irrigation in CENTURY
11. Parameters of file IRRI.100
12. Relationships between suitability classes and crop yields
13. Diversity indices for assessing plant diversity
14. Approaches to land degradation assessment
15. Physical degradation
16. Chemical degradation
17. Biological degradation
18. General information to be collected from the study area for land degradation assessment (e.g. Texcoco watershed, Mexico)
19. Data compilation table for physical land degradation by water
20. USLE results calculated from nomographs and by using GIS functions
21. Data compiled for the calculation of the crusting index (CI) and other factors pertaining to the assessment of degradation by compaction and crusting
22. Data compiled for the assessment of salinization and sodication of soils
23. Data collected on soil toxicity
24. Data and information collected on the biological degradation of soils
25. Relevant and useful data and information used in the assessment of land degradation per land cover class or LUT
26. Rating system for land degradation assessment (after FAO, 1979) – soil erosion by water
27. Rating system for land degradation assessment (after FAO, 1979) – degradation by wind erosion
28. Rating system for land degradation assessment (after FAO, 1979) – based on indicator variables of biological degradation
29. Ratings for evaluating physical land degradation – based on values of indicator variables for compaction and crusting
30. Calculated current risk for each type of degradation
31. Calculated state of present land degradation (e.g. Texcoco River Watershed, Mexico)
32. Degradation classes for Texcoco watershed by sampling quadrats
33. Land degradation process classification by land cover polygon
34. Results of applying the maximum limitation method on land degradation for the Texcoco watershed by land cover class polygon

1. Assessment of carbon stock in present land use
2. Estimation of biomass and carbon in aboveground pool of present land use
3. Procedures for generating a land cover class map from multispectral classification of satellite images
4. Quadrat sampling for biomass, biodiversity and land degradation assessments
5. Processes and activities in the sampling design of field surveys of biomass, biodiversity and land degradation
6. Allometric measurements in forest vegetation within the sampling quadrat, 10x10 m
7. Estimation of carbon stock in current land use and soils (belowground pool) through simulation modelling
8. Extraction of soil and climate parameters from agro-ecological cells or polygons for model parameterization
9. Partitioning of the basic components of organic matter in the soil in RothC-26.3 (after Coleman and Jenkinson, 1995a)
10. Structure of the SOM and carbon submodel in CENTURY (after Parton *et al.*, 1992)
11. Compartments of the CENTURY model
12. Relationship between programs and file structures in the CENTURY model
13. Scheduling input screen
14. Initial screen of the Soil-C interface
15. Input of site parameters in the Soil-C interface
16. Input of site parameters: climate variables in Soil-C
17. Organic matter initial parameters for specific ecosystems
18. Scheduling events and management with the Soil-C interface
19. Selection of output variables and output file specification for interface with GIS
20. Assessment of carbon sequestration in PLUTs
21. Land suitability assessment for PLUTs, including carbon sequestration potential
22. Estimation of carbon sequestration by PLUT
23. Assessment of species diversity and agrobiodiversity of actual land use
24. A field data form for recording biodiversity data
25. Graph of plant diversity indices against number of sampling quadrat sites to determine the number of sites needed
26. Customized biodiversity database (plants)
27. Physical degradation – soil erosion by wind
28. Maximum limitation classification of land degradation by land cover class for physical, chemical and biological degradation
29. Assessment of carbon sequestration potential, biodiversity and land degradation from LUC scenarios
30. Example of the optimization model for a single objective
31. Procedure for model building and its application in participatory decision-making using the AHP
32. Example of AHP model for gathering stakeholder preferences and participatory decision-making
33. Optimal LUC scenarios developed by linking the AHP and the optimization (goal programming) process to the GIS
34. Example of the implementation of a goal programming model with LINDO

1. Sampling a 10x10 m quadrat, concentrating on the tree layer and land degradation assessment.
2. Work in the 5x5 m quadrat concentrating on the shrub layer, deadwood and debris.
3. Work in the 1x1 m quadrat concentrating on the herbaceous layer, both of crops and of pastures and litter sampling.
4. Quadrat sampling concentrating on agro-ecosystems.

Contents of the CD-ROM

1. Report

2. Three case studies

TEXCOCO RIVER WATERSHED

Mexico State, Mexico

BACALAR

Quintana Roo State, Mexico

URBANO NORIS, RIO CAUTO WATERSHED

Holguin Province, Cuba

3. Soil-C program demo

4. Soil-C program

5. Soil-C user manual

System requirements to use the CD-ROM:

- PC with Intel Pentium® processor and Microsoft® Windows® 95 / 98 / 2000 / Me / NT / XP
- 64 MB of RAM
- 50 MB of available hard-disk space
- Internet browser such as Netscape® Navigator or Microsoft® Internet Explorer
- Adobe® Acrobat® Reader (included on CD-ROM)

This study was carried out within the framework of the normative programme of the FAO Land and Plant Nutrition Management Service (AGLL) in its role as the Task Manager of the Land Chapter of Agenda 21, *Integrated planning and management of land resources* for sustainable agriculture and rural development (SARD). It is a partnership between FAO, the International Fund for Agricultural Development (IFAD), the Global Mechanism (GM) of the United Nations Convention to Combat Desertification (UNCCD) and the Land Resource Laboratory of Trent University, Canada. The objective is to investigate the win-win options to address poverty alleviation, food security and sustainable management of natural resources by enhancing land productivity through diversification of agricultural systems, soil fertility management and carbon sequestration in poor rural areas, thereby creating synergies among the Convention to Combat Desertification (UNCCD), the Convention on Climate Change (CCC) and the Convention on Biodiversity (CBD).

The publication presents the methodology, models and software tools that were developed and tested in pilot field studies in Cuba and Mexico. The models and tools enable the analysis of land-use change scenarios in order to identify the land-use options and land management practices that would simultaneously maximize food and biomass production, soil carbon sequestration and biodiversity conservation and minimize land degradation in a given area (watershed or district). In these specific contexts, the objective is to implement a “win-win” scenario that would involve:

- ▶ viable alternatives to slash and burn agriculture;
- ▶ increased food security through increased yields;
- ▶ increased carbon sequestration in the soil;
- ▶ increased soil fertility through soil organic matter management;
- ▶ increased biodiversity.

This report provides a timely contribution to the debate on methods for land use, land-use change and forestry (LULUCF) as good practice guidance (GPG) for the above- and below-ground carbon sequestration assessment (biomass and soil) to support the preparation of national greenhouse gas inventories. A further enhancement of the methodology and field-testing of the tools are required before its wide application and dissemination in field biomass measurements and carbon sequestration estimations in different agro-ecological zones. It is hoped that the models and tools will be further tested in other areas and contribute towards developing comprehensive guidelines and procedures for projects assessing the current status and optimum options of land resource use and management.

This study was prepared by R. Ponce-Hernandez, Director of the GIS and Land Resource Laboratory, Trent University, in collaboration with P. Koohafkan and J. Antoine of FAO Land and Plant Nutrition Management Service (AGLL). The author was assisted by a research team at the Environmental Program and Department of Geography, Trent University.

The team included: T. Hutchinson (biodiversity and biomass assessment, J. Marsh (biodiversity conservation/protected areas), B. Pond (biomass assessment), J.L. Hernandez (biodiversity assessment), J. Galarza (biomass and carbon stock estimation), R.L. Dixon (biomass assessment and land degradation), L. Toose (soil organic matter modelling, land degradation and GIS), and D. McNairn (GIS technician).

Partners at case study sites included:
in Mexico – C. Chargoy Zamora, Head, Campo Ecotecnologico Chapingo, Universidad Autonoma Chapingo; H. Cuanalo de la Cerda, CINVESTAV, Instituto Politecnico Nacional, Merida, Yucatan; J.D. Gomez Diaz, Chair, Soils Department, Universidad Autonoma Chapingo; R. Gomez Rodriguez, J.C. Rivera, C. Martinez, I. Jimenez, J.L. Barranco, N.A. Salinas and F. Herrera of the Integrated Natural Resources Management Program, Soils Department, Universidad Autonoma Chapingo; P. Ponce Hernandez, Integrated Natural Resources Management Program, Soils Department, Universidad Autonoma Chapingo;
in Cuba – O. Lafita, Ministry of Natural Resources and Ecology, Holguin Province; D. Ponce de Leon, INICA, Havana; S. Segrera, INICA, Havana; R. Villegas, INICA, Havana.

This publication benefited from the editorial contributions of R. Brinkman and J. Plummer. Ms L. Chalk assisted in its preparation. The design and layout was prepared by Simone Morini, Rome.

AEZ	Agro-ecological zone
AEZWIN	FAO computerized decision-support system for multicriteria analysis applied to land resources appraisal
AGB	Aboveground biomass
ALES	Automated Land Evaluation System
AHP	Analytical hierarchy process
ANOVA	Analysis of variance
BGB	Belowground biomass
<i>b_{gm}</i>	Effective velocity of maximum production of total biomass
Bh	Aboveground biomass and carbon content of annual herbaceous species
BIO	Microbial biomass
<i>B_n</i>	Net biomass
<i>B_y</i>	Crop yield
C	Carbon
<i>C_{ci}</i>	Harvest coefficient
CDSS	Carbon decision-support system
CEC	Cation exchange capacity
CO₂	Carbon dioxide
CSP	Carbon sequestration potential
<i>C_t</i>	Coefficient of maintenance respiration of the crop
<i>D</i>	Diversity
DBH	Diameter of tree at breast height
DBMS	Database management system
DPM	Decomposable plant material
<i>D_{risk}</i>	Land degradation risk
DSSAT	Decision Support System for Agrotechnology Transfer
<i>E_{ai}</i>	Crop residues including roots, as percentage of total plant biomass
EPIC	Erosion/productivity impact calculator
F	Production of forage per hectare (including roots)
Fc	Percentage of foliage cover in tree crown or canopy
FYM	Farmyard manure
GIS	Geographical information systems
GPS	Global positioning system
GVI	Green Vegetation Index
H	Tree height
Hc	Height to base of tree crown
<i>H_i</i>	Harvest index
<i>H_i</i>	Moisture content in plant tissue by species
HUM	Humified organic matter
IBSNAT	International Benchmark Soils Network for Agrotechnology Transfer
<i>ICA_i</i>	Nutritional content of forage by species, or nutrition conversion index
IFAD	International Fund for Agricultural Development
INEGI	National Institute of Statistics, Geography and Information, Mexico
INICA	National Institute for Sugar Cane Research, Cuba
IOM	Inert organic matter
L	Length of canopy or crown

acronyms

LAI	Leaf area index
LD	Land degradation
LGP	Length of growing period
LUC	Land-use change
LULUCF	Land use, land-use change and forestry
LUT	Land utilization type
MCDM	Multicriteria decision-making
N	Nitrogen
N_{ci}	Number of livestock in the grazing or pasture management unit
NDVI	Normalized Differential Vegetation Index
P	Phosphorus
P_{ai}	Agricultural production by type of crop
PCC	Pedo-climatic cell
PE	Effective precipitation
PET	Potential evapotranspiration
PLUT	Potential land utilization type
PO	Pareto optimal
R	Index or coefficient of grazing
RPM	Resistant plant material
S	Sulphur
SABA	Slash-and-burn agriculture
SMD	Soil moisture deficit
SOC	Soil carbon
SOM	Soil organic matter
SOMNET	Soil Organic Matter Network
T	Average daily temperature within the growing period
TM	Thematic Mapper
TSMD	Topsoil moisture deficit
UN-FCC	False colour composite
USLE	Universal Soil Loss Equation
W	Width of canopy or crown
WD	Wood density

This report presents a methodology to assess the stocks of carbon pools both aboveground and belowground under various land-use systems, the status of their biodiversity and that of land degradation. The report also describes methods to analyse “win-win” land use and land management scenarios. These aim to reduce land degradation while enhancing soil fertility, land productivity and carbon sequestration. The report presents the related models and software tools and the test results of case studies in selected areas of Mexico and Cuba.

The methodology has been applied in the various watersheds of the case study areas. It can be summarized as follows:

- ▶ carbon stock assessment, involving computations of aboveground biomass (from field measurements and satellite image interpretation) and estimates of belowground biomass (derived from aboveground computations);
- ▶ carbon dynamics simulation and estimation of carbon sequestration considering actual land use, using the Roth C-26.3 and CENTURY (V.4.0) models;
- ▶ land suitability assessment for each land unit in the watershed for potential land utilization types, involving: pre-selection of crops, trees and grass mixes according to potential on the basis of high carbon photosynthetic assimilation (C3 and C4 pathways) and multicriteria climatic suitability, and suitability in terms of topography, wetness, soil fertility, physical and chemical characteristics (using decision-tree models in the Automated Land Evaluation System);
- ▶ carbon dynamics simulation and estimation of carbon sequestration considering potential land-use types, using the Roth C-26.3 and CENTURY (V.4.0) models;
- ▶ computation of carbon totals per land unit and per land-use type for current land use;
- ▶ estimation of carbon totals from potential land-use patterns;
- ▶ computation of biodiversity indices at the field sampling sites and their extrapolation to the watershed area;
- ▶ development of a customized database for biodiversity computations;
- ▶ computation of land degradation indices (physical, biological and chemical) at the sampled sites and extrapolation to all the watershed area;
- ▶ application of an analytical hierarchy process model for participatory decision-making regarding potential land-use scenarios including carbon sequestration.

The case studies involve three sites: Bacalar and Texcoco (Mexico) and Rio Cauto (Cuba). One Mexican site is located in a dry, poverty-stricken, degraded highland area in central Mexico with high population pressures on resources; the other in a tropical semi-deciduous forest area with very low population pressure, a high incidence of poverty and lower levels of environmental degradation. The Cuban site is located in the Province of Holguin in the Rio Cauto watershed. It is a dry, tropical area with various levels of resource degradation and a high incidence of resource constraints.

Data from each of the three sites were used to create georeferenced databases. Carbon simulation models (i.e. RothC-26.3 and CENTURY) were run using these databases.

The study also investigated the effect of alternatives to slash-and-burn agriculture on carbon dynamics in two locations in the Yucatan Peninsula (Quintana Roo), Mexico. Scenarios of land-use changes were generated through the models, and management approaches relating to soil organic matter and carbon dynamics necessary for stabilizing slash-and-burn agriculture were identified.

“Soil-C”, a customization of the CENTURY model (v. 4.0) including visual input and output interfaces and parameterization options for tropical and subtropical conditions, was implemented (beta version).

The CENTURY model was integrated fully with GIS via customization (i.e. software development with Visual Basic and scripts) in order to provide VISUAL CENTURY-GIS with map visualization capabilities as part of “Soil-C”. This enables non-expert users to run the carbon dynamics simulation model.

The study included comprehensive research on measurements of biomass and carbon stock estimation. A methodology for plant biodiversity estimation was also researched. Procedures were elaborated for assessing biomass and carbon stock of relatively large areas through field measurements and remote sensing.

A dedicated Internet-GIS system was developed to serve map and attribute data from the three case study sites, and to allow for remote spatial queries and basic GIS functionality on the Internet.

The software tools are designed to facilitate their customization and transferability to other areas.

CHAPTER 1

• **INTRODUCTION**

CO_2
carbon
dioxide

CHAPTER 1

Introduction

With the ratification of the Kyoto Protocol, several technical problems and policy issues have arisen that must be solved if practical implementations are to become a reality, in particular the implementation of projects under the Clean Development Mechanism. One of the main technical issues is the definition of a standard set of methods and procedures for the inventory and monitoring of stocks and sequestration of carbon (C) in current and potential land uses and management approaches. Deliberate land management actions that enhance the uptake of carbon dioxide (CO₂) or reduce its emissions have the potential to remove a significant amount of CO₂ from the atmosphere in the short and medium term. The quantities involved may be large enough to satisfy a portion of the Kyoto Protocol commitments for some countries, but are not large enough to stabilize atmospheric concentrations without major reductions in fossil fuel consumption.

Carbon sequestration options or sinks that include land-use changes (LUCs, or the acronym LULUCF, meaning land use, land-use change and forestry) can be deployed relatively rapidly at moderate cost. Thus, they could play a useful bridging role while new energy technologies are being developed. The challenge remains to find a commonly agreed and scientifically sound methodological framework and equitable ways of accounting for carbon sinks. These should encourage and reward activities that increase the amount of C stored in terrestrial ecosystems while at the same time avoiding rules that reward inappropriate activities or inaction. Collateral issues such as the effects of LUC on biodiversity and on

the status of land degradation need to be addressed simultaneously with the issue of carbon sequestration once economic incentives are perceived as rewards for sinks. The synergies between the UN conventions on biodiversity and desertification and the Kyoto Protocol can be exploited in order to promote LUC and land management practices that prevent land degradation, enhance carbon sequestration and enhance or conserve biodiversity in terrestrial ecosystems. Measures promoting such objectives are expected to improve local food security and alleviate rural poverty.

FAO and the International Fund for Agricultural Development (IFAD) have set out to develop and test a methodological framework of procedures for measuring, monitoring and accounting for carbon stocks in biomass and in soil, and for generating projections of carbon sequestration potential (CSP) resulting from LUCs. The framework aims to exploit the synergies between three major UN conventions, namely: climate change, biodiversity and desertification. The approach is to integrate procedures for developing LUC scenarios such that carbon sequestration, the prevention of land degradation and the conservation of biodiversity are optimized simultaneously. It is hoped that these actions will also result in added benefits such as increased crop yields, food security and rural income.

The methodological framework and the procedures described in chapters 1 to 8 were applied in the field in order to develop practical experience and knowledge of their suitability for application as standard procedures in routine

assessments. Three areas in Latin America and the Caribbean region were selected to develop these case studies:

- ▶ Texcoco River Watershed, Central Mexico (highland dry tropics),
- ▶ Bacalar, Yucatan Peninsula, Mexico (lowland moist tropics),
- ▶ Rio Cauto Watershed, Cuba (lowland dry tropics in the Caribbean).

The criteria used in selecting the sites encompassed the feasibility of implementation through contacts already made and the streamlining of logistics, as well as a broad sampling of ecological conditions.

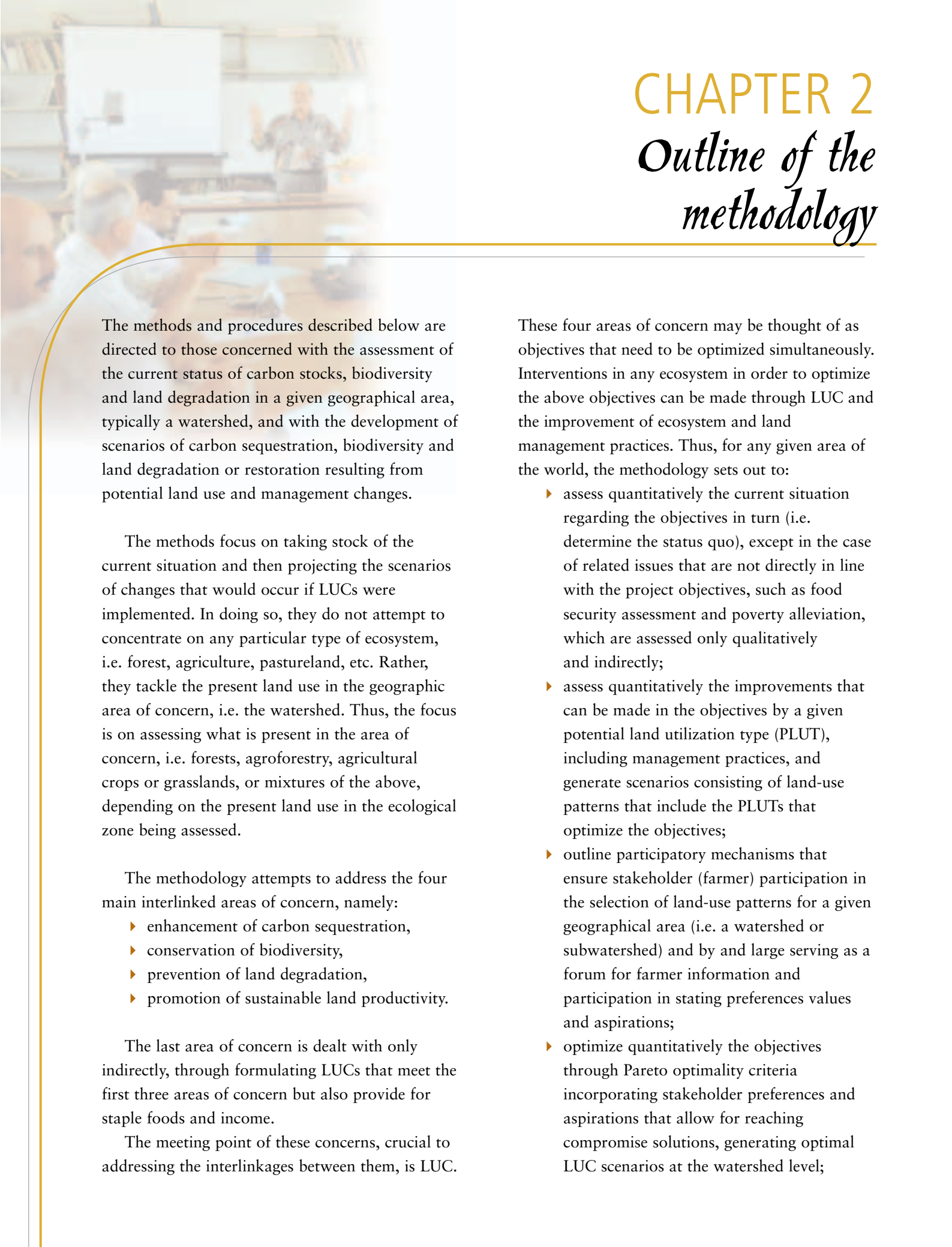
In view of the large volume of data and information of the case studies, these have been provided as an appendix to this report and in digital form on a CD-ROM accompanying this report. Chapter 9 discusses the most significant aspects of the methodology and the results obtained from applying the framework to each area, as far as methodological development is concerned. Chapter 10 presents conclusions and recommendations from this study.

The CD-ROM also contains the report, a demo version of the Soil-C software, the full Soil-C software and the user manual.

CHAPTER 2



OUTLINE OF THE METHODOLOGY



CHAPTER 2

Outline of the methodology

The methods and procedures described below are directed to those concerned with the assessment of the current status of carbon stocks, biodiversity and land degradation in a given geographical area, typically a watershed, and with the development of scenarios of carbon sequestration, biodiversity and land degradation or restoration resulting from potential land use and management changes.

The methods focus on taking stock of the current situation and then projecting the scenarios of changes that would occur if LUCs were implemented. In doing so, they do not attempt to concentrate on any particular type of ecosystem, i.e. forest, agriculture, pastureland, etc. Rather, they tackle the present land use in the geographic area of concern, i.e. the watershed. Thus, the focus is on assessing what is present in the area of concern, i.e. forests, agroforestry, agricultural crops or grasslands, or mixtures of the above, depending on the present land use in the ecological zone being assessed.

The methodology attempts to address the four main interlinked areas of concern, namely:

- ▶ enhancement of carbon sequestration,
- ▶ conservation of biodiversity,
- ▶ prevention of land degradation,
- ▶ promotion of sustainable land productivity.

The last area of concern is dealt with only indirectly, through formulating LUCs that meet the first three areas of concern but also provide for staple foods and income.

The meeting point of these concerns, crucial to addressing the interlinkages between them, is LUC.

These four areas of concern may be thought of as objectives that need to be optimized simultaneously. Interventions in any ecosystem in order to optimize the above objectives can be made through LUC and the improvement of ecosystem and land management practices. Thus, for any given area of the world, the methodology sets out to:

- ▶ assess quantitatively the current situation regarding the objectives in turn (i.e. determine the status quo), except in the case of related issues that are not directly in line with the project objectives, such as food security assessment and poverty alleviation, which are assessed only qualitatively and indirectly;
- ▶ assess quantitatively the improvements that can be made in the objectives by a given potential land utilization type (PLUT), including management practices, and generate scenarios consisting of land-use patterns that include the PLUTs that optimize the objectives;
- ▶ outline participatory mechanisms that ensure stakeholder (farmer) participation in the selection of land-use patterns for a given geographical area (i.e. a watershed or subwatershed) and by and large serving as a forum for farmer information and participation in stating preferences values and aspirations;
- ▶ optimize quantitatively the objectives through Pareto optimality criteria incorporating stakeholder preferences and aspirations that allow for reaching compromise solutions, generating optimal LUC scenarios at the watershed level;

- ▶ provide a mechanism for upscaling and generalization of computed estimates.

The methodology consists of four main sections or modules (one for each main area of concern). Within each module, it assesses the current situation and evaluates promising alternatives by creating scenarios. The sections are:

- ▶ the assessment of carbon stock and carbon sequestration potentials.
- ▶ the assessment of the status of biodiversity and its potential changes implicit in an LUC.
- ▶ the assessment of the current status of land degradation via its indicators, and the formulation of required land management practices for every suggested land utilization type (LUT) that would enhance the prevention of land degradation.
- ▶ the simultaneous optimization of the objectives above, including constraints for food security and minimum income by means of multicriteria programming models.

Details of procedures and activities in each of the modules are provided below. The methods described are part of a proposal advanced as a methodological framework. The procedures may require adaptation to the particular circumstances of the environment where the framework is being applied. It is not claimed that the framework is perfect or complete. In some instances, it may

require further elaboration for its implementation in practice. This report provides the technical details of the three main modular components of the methodology, namely:

- ▶ assessment of carbon stock and carbon sequestration in present and potential LUT. This component module, in turn, can be divided into: (i) assessment of present land use; and (ii) assessment of potential land use. In both, present and potential land use, two main submodules need to be considered: (i) estimation of biomass (aboveground and belowground) and its conversion to C; and (ii) estimation of carbon sequestration in soils through computer simulation modelling of soil organic matter (SOM) and carbon turnover dynamics.
- ▶ assessment of biodiversity status through the estimation of biodiversity indices from field data and geographical information systems (GISs).
- ▶ assessment of the status of chemical, physical and biological land degradation through a parametric semi-quantitative approach based on indicator variables.

For reasons of length and detail, issues pertaining to multicriteria optimization are only dealt with conceptually. Thus, the following is a detailed description of procedures and methods by modules in that order.

CHAPTER 3

***ASSESSMENT OF BIOMASS AND
CARBON STOCK IN PRESENT LAND USE***

CHAPTER 3

Assessment of biomass and carbon stock in present land use

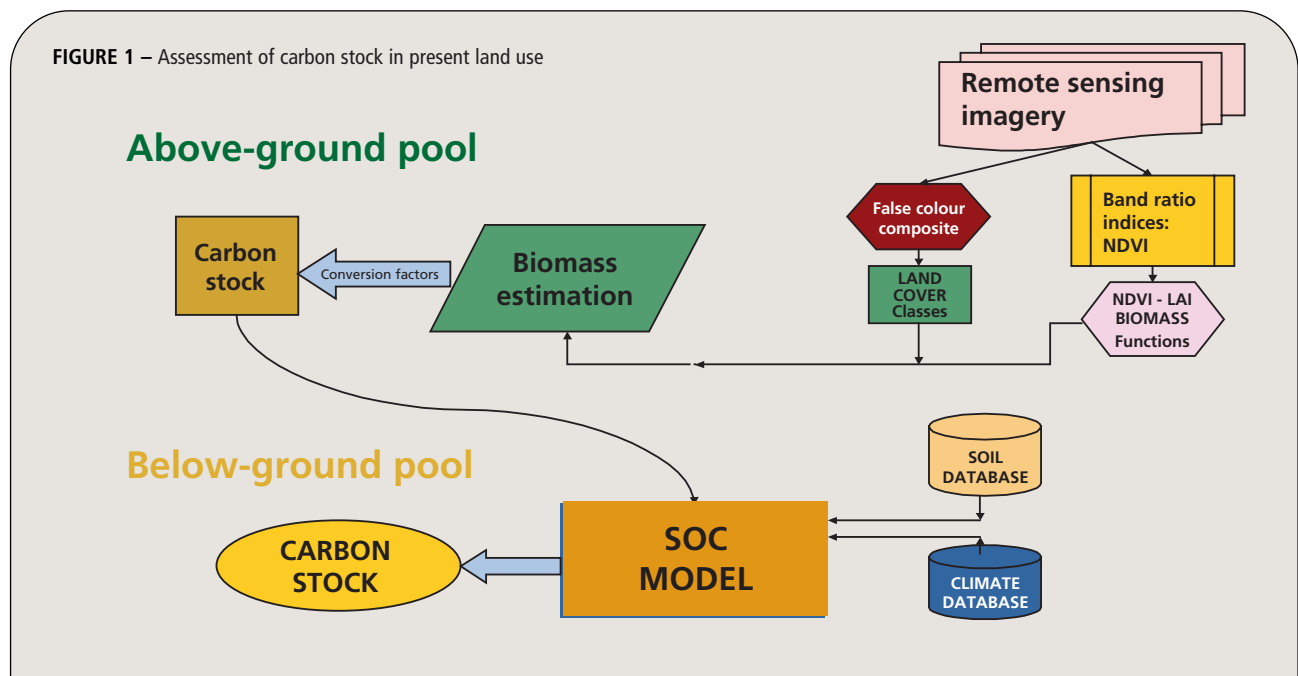
This module embraces the sequence of activities and procedures for assessing and estimating the carbon stock in both aboveground and belowground biomass (soil and biomass). It is broken down into stages for both pools. First, the assessment of the carbon stock in the current land-use pattern is carried out. Then, the generation of scenarios of potential land uses and their CSPs are formulated. It is assumed that the geographic area of concern (i.e. the watershed or administrative unit) has been identified and that its boundaries have been delineated in a topographic base map or corresponding cartographic materials, and that the method attempts to make full use of existing databases and analytical systems (e.g. FAO's AEZ, AEZWIN, SOTER and SDB).

Assessment of carbon stock and sequestration in present land use

The details of the methodological steps are explained in terms of the two main pools or compartments: aboveground and belowground.

Figure 1 illustrates the procedures involved and the relationships between them. The component procedures in Figure 1 are generalized conceptually to some extent so that they can be used here as a schematic guide to methods. Thus, they allow for some flexibility in substitution and replacement according to available resources and technology. For example, the remote-sensing component in Figure 1 can be substituted or complemented by a reliable field sampling and the use of air-photographs. Similarly, the use of band ratio indices, i.e. Normalized Differential Vegetation Index (NDVI), is not necessary and sufficient for the estimation of biomass. They could be replaced by another index, e.g. Green Vegetation Index (GVI) or a mechanism such as regression equations for biomass estimation, developed *in situ*. In this sense, the charts attempt to illustrate the methodology and procedures and they should be taken with that degree of flexibility. They indicate activities and their possibilities, rather than dogmatically strict methodological paths.

FIGURE 1 – Assessment of carbon stock in present land use



Estimation of aboveground biomass

Detailed estimations of biomass of all land cover types are necessary for carbon accounting, although reliable estimations of biomass in the literature are few. Biomass and carbon content are generally high in tropical forests, reflecting their influence on the global carbon cycle. Tropical forests also have great potential for the mitigation of CO₂ through appropriate conservation and management (FAO, 1997). The biomass assessment methods described here are not restricted to forests, agriculture or pastures. They assess the present biomass regardless of cover type. Thus, they may be applied to areas where trees are a dominant part of the landscape, including closed and open forests, savannahs, plantations, gardens, live fences, etc., as well as to agricultural and pasture systems, including all kinds of crop rotations, mixes of crops, trees and pastures. The biomass of all the components of the ecosystem should be considered: the live mass aboveground and belowground of trees, shrubs, palms, saplings, etc., as well as the herbaceous layer on the forest floor, including the inert fraction in debris and litter. The greatest fraction of the total aboveground biomass in an ecosystem is represented by these components and, generally speaking, their estimation does not present many logistic problems.

Biomass is defined here as the total amount of live organic matter and inert organic matter (IOM) aboveground and belowground expressed in tonnes of dry matter per unit area (individual plant, hectare, region or country). Typically, the terms of measurement are density of biomass expressed as mass per unit area, e.g. tonnes per hectare. The total biomass for a region or a country is obtained by upscaling or aggregation of the density of the biomass at the minimum area measured.

BIOMASS is defined here as the total amount of live and inert organic matter above and below ground expressed in tons of dry matter per unit area.

Remote sensing for aboveground biomass estimation

Remotely sensed data are understood here as the data generated by sensors from a platform not directly touching or in close proximity to the forest biomass. Therefore, these data comprise images sensed from both aircraft and satellites. Remote-sensing imagery can be extremely useful, particularly where validated or verified with ground measurements and observations (i.e. “groundtruth”). Remote-sensing images can be used in the estimation of aboveground biomass in at least three ways:

- ▶ classification of vegetation cover and generation of a vegetation type map. This partitions the spatial variability of vegetation into relatively uniform zones or vegetation classes. These can be very useful in the identification of groups of species and in the spatial interpolation and extrapolation of biomass estimates.
- ▶ indirect estimation of biomass through some form of quantitative relationship (e.g. regression equations) between band ratio indices (NDVI, GVI, etc.) or other measures such as direct radiance values per pixel or digital numbers per pixel, with direct measures of biomass or with parameters related directly to biomass, e.g. leaf area index (LAI).
- ▶ partitioning the spatial variability of vegetation cover into relatively uniform zones or classes, which can be used as a sampling framework for the location of ground observations and measurements.

The use of band ratio indices such as the NDVI, GVI or other indices based on exploiting the discriminating power of infrared band ratios of chlorophyll activity in vegetation, requires relatively involved measurements of other morphological and physiognomic parameters of the vegetation canopy such as the LAI, and the presence of a strong relationship between the LAI and the NDVI, and the LAI and the biomass. The strength and the form of such relationships vary considerably with canopy type and structure, the state of health of the vegetation and

many other environmental parameters. Much of the work reported in the literature about such relationships is still a matter of research (Baret, Guyot and Major, 1989; Wiegand *et al.*, 1991; Daughtry *et al.*, 1992; Price, 1992; Gilabert, Gandia and Melia, 1996; Fazakas, Nilsson and Olsson, 1999; Gupta, Prasa and Vijayan, 2000). Therefore, remote-sensing products are suitable as a framework for providing upscaling mechanisms of detailed site measurements of aboveground biomass on the ground. However, their usefulness is circumstantial and depends on the strength of the relationships found for a given geographic area.

Classification of vegetation cover using multispectral satellite imagery

The procedures, techniques and algorithms for multispectral image classification are all well documented in the remote-sensing literature and are also beyond the scope of this report. In summary, the steps comprise:

- ▶ multispectral image acquisition (usually Landsat Thematic Mapper (TM) bands 1, 2, 3, 4, 5 and 7) and image enhancement (stretching

and filtering), corrections (geometric and radiometric) and georeferencing (registration).

- ▶ creation of false colour composite (FCC) images, typically TM3 (red), TM4 (short-wave infrared) and TM5 (near infrared).
- ▶ selection and sampling of “training sites” on the image, inspection of “clustering” of pixels of such training sites in the feature space and selection of a classificatory algorithm for the supervised classification.
- ▶ supervised classification consisting of using reflectance values from “training sites” and classes assigned to them in order to expand the classification to the rest of the FCC image, through the classificatory algorithms. An optional additional step is the conversion of the resulting classified image (in raster format) to vector format (raster-to-vector conversion) in order to create a polygon map of vegetation classes. Typically, the training sites should correspond to places on the ground where the vegetation cover type has been observed, recorded and validated.

FIGURE 2 – Estimation of biomass and carbon in aboveground pool of present land use

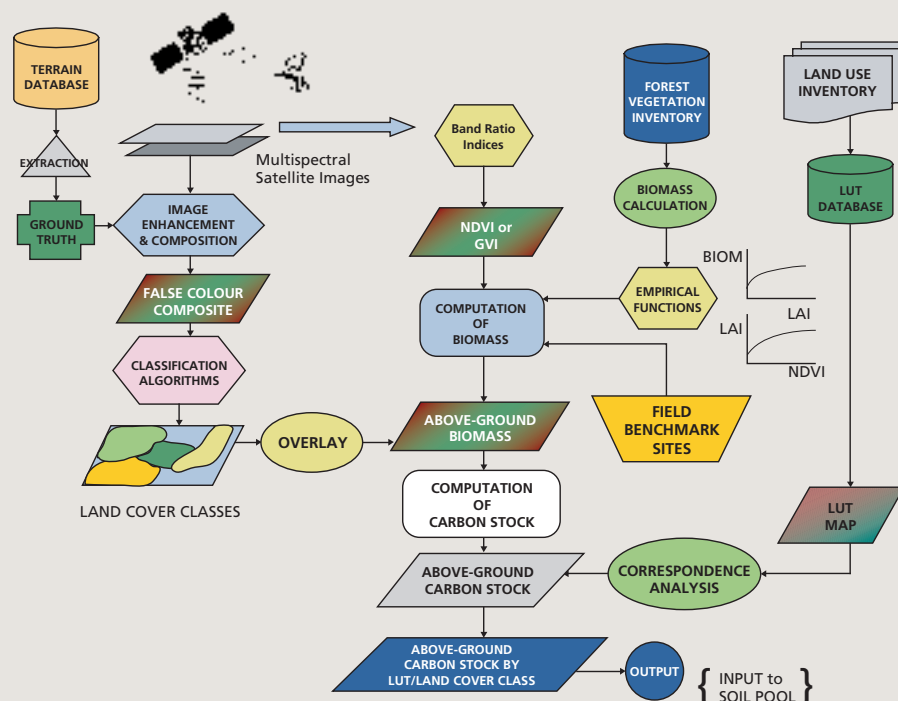
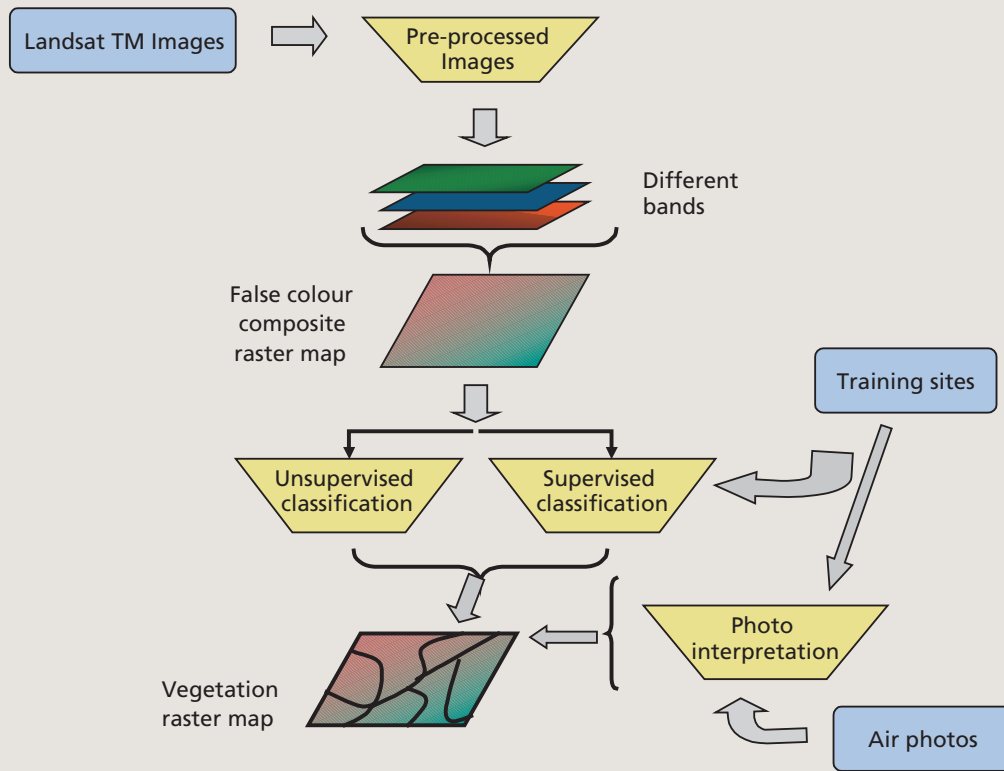


FIGURE 3 – Procedures for generating a land cover class map from multispectral classification of satellite images



The accuracy of the resulting vegetation map is a function of:

- ▶ the complexity of the mix of species in the crop, vegetation or forest cover and the complexity of the spatial variability of the cover in the area;
- ▶ the selection of the training sites and the degree to which they are representative of vegetation classes on the ground;
- ▶ the adequacy of selection of the classificatory algorithm as a function of the nature of the clusters formed by the training sites and the types of histograms of radiance values of each image band used in the classification.

The generated vegetation map should display the spatial variability of major vegetation or forest cover classes in the area of concern as classes in raster or grid-cell format, or as polygons in vector format. Figure 2 shows the methodological framework for aboveground biomass estimation. Figure 3 illustrates

the specific steps in the generation of a land cover vegetation map from multispectral satellite image interpretation.

Classification and mapping of vegetation cover from air-photograph interpretation

These techniques preceded the analysis and interpretation of satellite images. They have been standard procedures in the identification of vegetation classes and forest stands in conventional land cover mapping and forest inventory work in most countries. Therefore, this report does not describe them in detail. Together with field sampling and validation, air-photograph interpretation using photo-patterns, texture, tone and other photographic characteristics as well as the stereoscopic vision and the use of the parallax bar serves to delineate classes of crop or vegetation cover or forest stands. These boundaries of classes are later transferred to a map, creating mapping units, which in turn can be digitized into a GIS, so creating a vector polygon

map. The end result of this procedure is comparable with that obtained from the interpretation and classification of satellite images. The accuracies of one or the other vary depending on the expertise of the photo-interpreter, the density of field samples used for validation and on how representative they are of the variability of vegetation classes.

Both procedures, multispectral satellite image interpretation and air-photo interpretation, only lead indirectly to aboveground biomass estimation. The literature reports a range of variants to such procedures. These procedures range from conventional forest inventory based on ground measurements of the dimensions of individual trees (allometric measurements), to the use of yield tables, regression equations and to measurements derived from a range of sensor platforms (e.g. Foody *et al.*, 1996; Kimes *et al.*, 1998). All of them have in common the need for validation of estimates by means of ground measurements of tree geometries and volumes.

In this report, remote-sensing methods and ground-based methods are considered part of the same procedure. Therefore, they are used in combination. Remote-sensing techniques are regarded here, in combination with spatial interpolation and extrapolation techniques, as mechanisms for upscaling and downscaling estimates to areas of different sizes. They also provide a useful spatial framework for field sampling. For many practical and logistical reasons related to the availability and cost of remote-sensing materials in the developing world, the emphasis in this report is on the attainment of ground measurements, which serve as the basis for validation of all other estimation procedures, including remote sensing.

Multipurpose field surveys and sampling design

The sampling design for the collection of aboveground biomass data should be a multipurpose one in order to realize efficiencies in data collection and minimize costs. That is, the sites that are used to take measurements for aboveground biomass

estimation should also be used for biodiversity and land degradation assessments through the observation of its indicators. The multipurpose character of the sampling design demands that it should provide data for:

- ▶ aboveground biomass estimation: morphometric measurements of standing vegetation; stem and canopy of various strata of trees and shrubs, as well as debris, deadwood, saplings, and samples of herbs and litter fall;
- ▶ biodiversity assessment: plant species identification and quantification for calculation of plant diversity indices;
- ▶ land degradation assessment: site measurements and observations of relevant indicators of the status of land degradation.

Sampling quadrats of regular shape of dimensions 10 x 10 m, 5 x 5 m and 1 x 1 m, nested within each other, were defined as the units for sampling the landscape and measuring biomass, biodiversity and land degradation. The dimensions of the quadrats coincide with recommended practice in the ecological literature and represent a compromise between recommended practice, accuracy and practical considerations of time and effort. Figure 4 illustrates the nesting of the quadrats.

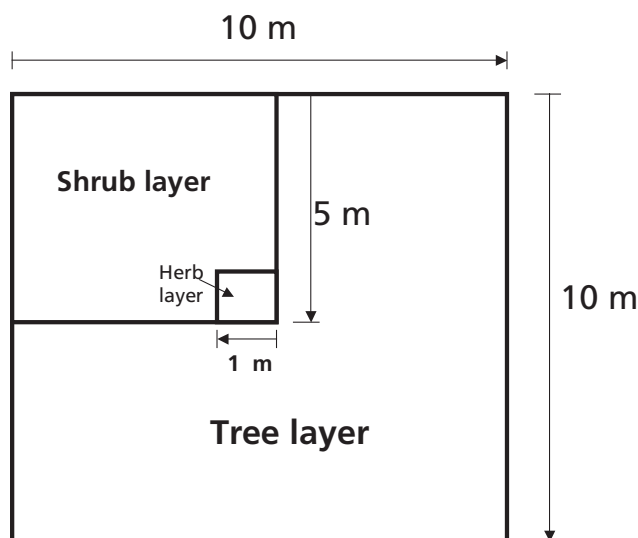


FIGURE 4 – Quadrat sampling for biomass, biodiversity and land degradation assessments

TABLE 1 – Use of each nested quadrat site for sampling and measurement

QUADRAT DIMENSIONS	USE OF QUADRAT IN MEASUREMENTS AND SAMPLING
10 x 10 m	Morphometric measurements of the tree layer. Measurements of trunk and canopy of trees and large deadwood. Identification of tree species and individual organisms within a species for biodiversity assessment. Site measurements and observations for land degradation assessment.
5 x 5 m	Study of the shrub layer. Morphometric measurements of the shrub layer. Measurements of stem and canopy and small deadwood. Identification of shrub species and individual shrub organisms within species for biodiversity assessment.
1 x 1 m	Sampling of biomass of herbaceous species and grasses, above-ground and roots, litterfall and debris for drying and weighing to determine live and dead biomass. Counting of herbaceous species and number of individuals within species.

The design of nested quadrats of different sizes (Figure 4) obeys requirements for measuring and counting vegetation of different sizes and strata, and for collecting debris and litter for estimation of biomass. Table 1 indicates the designated use for each quadrat.

Plates 1–4 illustrate the use of the nested quadrats by decreasing quadrat size.



PLATE 1 – Sampling a 10 x 10 m quadrat, concentrating on the tree layer and land degradation assessment



PLATE 2 – Work in the 5 x 5 m quadrat concentrating on the shrub layer, deadwood and debris



PLATE 3 – Work in the 1 x 1 m quadrat concentrating on the herbaceous layer, both of crops and of pastures and litter sampling



PLATE 4 – Quadrat sampling concentrating on agro-ecosystems

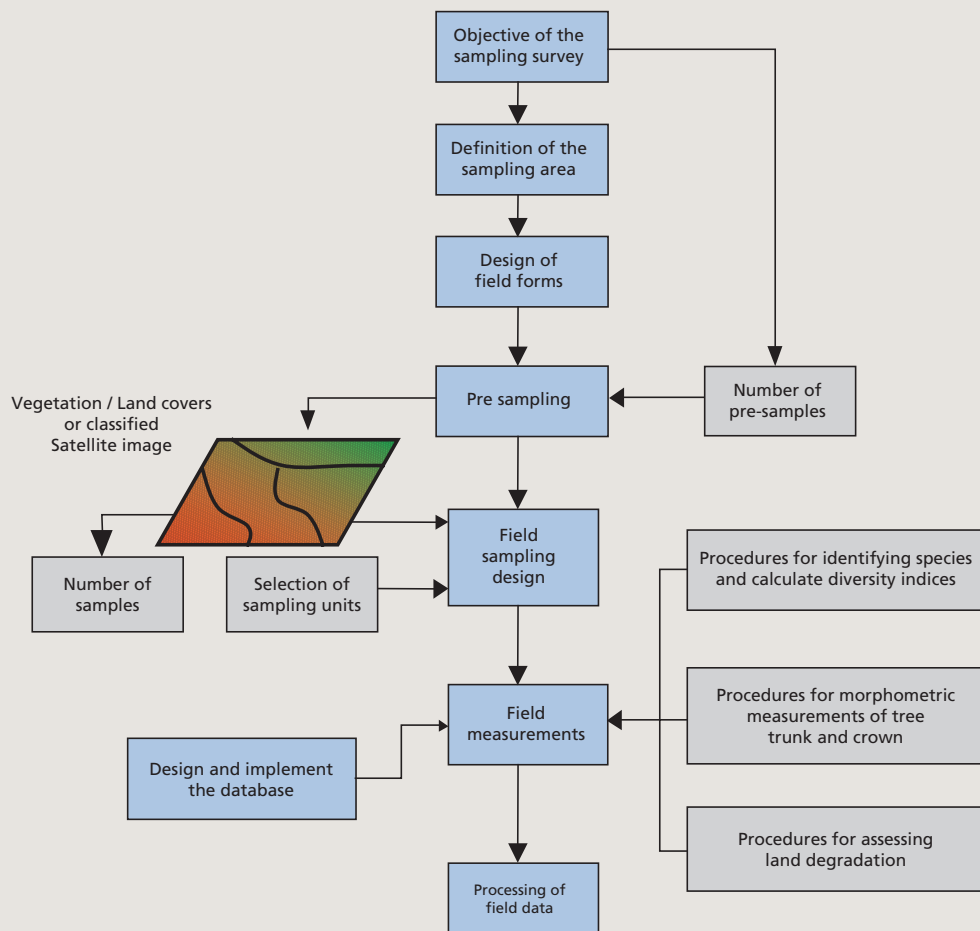
The sample sites and their location are selected through a number of activities. The goal is to obtain, at the lowest cost, a sample size and distribution that will provide data that are highly representative of the plant biodiversity, the spatial variability of aboveground biomass and the status of land degradation in the area studied. The process is complex because of the different spatial scales of variability of each variable of concern. Figure 5 illustrates a generalized flow chart of the sampling design.

Whether derived from multispectral satellite image interpretation or whether derived from air-photo interpretation and transformed into a raster or a vector map, the vegetation or land-cover classes map serves as the basis for stratification and

allocation of the sampling sites to land cover classes, also referred to here as strata. A stratified random sampling design with probability of sampling sites allocated to a polygon or class proportional to size of the area covered by each land cover class (stratum) is considered appropriate for the sampling framework and the location of sampling sites in the field survey. Each of the strata is defined by a land cover or vegetation type. The tools for defining strata include classification of satellite imagery, photo-interpretation of air-photographs as well as pre-survey ground observation and measurements (i.e. establishment of training sites) for supervising and verifying the goodness of the classification.

The definition of variables to be observed or measured is a central part of the survey design.

FIGURE 5 – Processes and activities in the sampling design of field surveys of biomass, biodiversity and land degradation



These variables are grouped in three classes:

- ▶ abiotic or site factors, including elevation, slope, aspect, local physiography, soil type and type of disturbance;
- ▶ biotic factors, including aspects of terrestrial flora, relevant to both biomass measurement and biodiversity (the latter include vegetation type, state of succession, number of species in different layers and the number of individuals for each species in different layers);
- ▶ land degradation factors, including the relevant indicator variables to be measured or observed for physical, chemical and biological land degradation.

Field data forms are designed and printed for each of the three areas of concern to the field sampling, namely: aboveground biomass (morphometric measurements), biodiversity indices and land degradation indicators. The field forms contain spaces for entry of data on the relevant variables in each of the three aspects of concern. Chapter 6 presents examples of these field data forms.

The morphometric measurements and the diversity of plants in two different landscape element types (strata) are discriminated. That is to say, dissimilarities within types of strata (polygons) should be significantly lower than those between them. The following statistical model depicts the partition of variability into sources and should be used for testing hypotheses during data processing using a one-factor analysis of variance (ANOVA) design. Normality and homogeneity of variance must also be tested:

$$Y_{ij} = \mu + \nu t_i + \varepsilon_{ij}$$

where, for example in the case of biodiversity indices: Y_{ij} is number of species or abundance in the j -th forest stand within the i -th type of vegetation (stratum); μ is the general mean of all strata; νt_i is the effect of i -th vegetation type on morphometric or plant diversity measurements; and ε_{ij} is the error in the j -th stand within the i -th type of vegetation (stratum).

The target level of accuracy for this sampling design should be set to 95 percent reliability and 5 percent error in the estimations.

The sample size must be determined for each stratum. However, typically, there is no prior information about the variance of the variables to be studied (i.e. morphometric measurements, number of species, abundance, etc.). Therefore, two steps should be taken to obtain the field information:

- ▶ pre-survey estimation of the prior-variance. This first step leads to a subjective determination of the pre-survey sample size.
- ▶ calculation of the number of samples for each stratum. The sample size is calculated by using the prior variance obtained from pre-survey and then using standard statistical formulae based on the prior variance of the variable of interest.

It is recognized that variables such as the total number of plant species would require the compilation and computation of “saturation curves” of species versus number of sampling quadrats in order to establish the total number of quadrats that would represent the variability of plant species population. This is a standard procedure in plant and landscape ecology work and the assessment team should aim at attaining such curves except where there are strong economic or logistical constraints.

The sampling sites (quadrats) are located in the field by selecting coordinate pairs randomly for each site with a random number generation device, after determining the number of sampling sites in each stratum or vegetation/land cover class. The number of samples for each stratum is selected proportional to its extent, using the vegetation map. The coordinate pairs of each site are located in the field with a global positioning system (GPS).

It is possible that more than one stratum of trees could be found within each vegetation type, particularly in tropical areas. This variability can be

recognized by recording the number of canopy layers present at each quadrat of 10 x 10 m. Within each layer defined by either height or state of succession, for all trees, the number of plants by species should be recorded for each of the layers considered. For example, in a tropical forest in which three canopy layers have been observed, in the first layer, trees of 20 m and higher should be measured; in the second layer, trees between 10 and 20 m, and in the third layer, trees less than 10 m high.

One of the most difficult tasks in practical fieldwork is the identification of the species on the ground. Owing to practical constraints, it is not possible to collect plants with all the morphological components needed for identification in a herbarium. Therefore, the knowledge of local people who have been working and living in or near the forest should play an important role in data collection. Local people can identify species accurately using local or even botanical names. This provides a useful alternative to the inclusion of a full-time botanist in the multidisciplinary team conducting the study. However, wherever possible, validation procedures should be set up in order to calibrate the validity of the method for identifying species, by collecting samples for botanical identification in the herbarium.

Finally, data should be collected in an organized and systematic fashion. A digital database system can be designed ahead of time and modified later in view of the realities in the field in order to facilitate data entry into the databases to be linked to data processing software, computer modelling and GIS. A commercially available database management system (DBMS) could serve for this purpose. This software should be customized to reflect the information needs of the project. Common DBMS software packages could be useful for storing and later processing the field data.

Calculation of aboveground biomass from allometric methods

The aboveground biomass is estimated from the field measurements at specific sites (quadrats) with which

the landscape was sampled in the area or watershed of concern. These are described above. Here, the procedural steps for the calculation of aboveground biomass from such field data are described.

In order to be able to calculate aboveground biomass in a watershed, the following steps concentrate on the forest layers. For methodological convenience, the calculations of trees and shrubs are divided in two sections according to tree morphology:

- ▶ calculation of biomass for trunk or stem;
- ▶ calculation of biomass for canopy or crown.

This distinction is necessary because different procedures and approaches for estimation are used in each case. In each quadrat of 10 x 10 m the following allometric measurements are obtained from field sampling of each tree within the quadrat boundaries (Figure 6):

- ▶ tree height (H),
- ▶ diameter at breast height (DBH),
- ▶ diameter of canopy or crown in two perpendicular directions, termed here for convenience “length” (L) and “width” (W),
- ▶ height to the base of the crown (Hc),
- ▶ percentage of foliage cover in the crown or canopy (Fc).

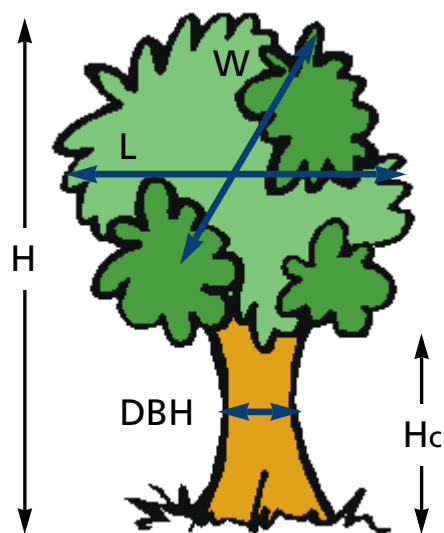


FIGURE 6 – Allometric measurements in forest vegetation within the sampling quadrat, 10 x 10 m

Here, two options are presented in terms of approaches to calculating trunk and canopy biomass. The selection of the approach depends to a large extent on the conditions and tools available during data collection, and therefore on the variables measured and the degree of accuracy required. The two approaches are:

- ▶ the allometric method,
- ▶ the linear regression equations method.

With the allometric method, consideration must be first given to the basal area (A_b) of the trunk. Where this has been recorded with conventional forest inventory equipment, the section below should be disregarded. Where the basal area has not been measured in the field, it can be estimated by:

$$A_b = \Pi \times r^2$$

where: $\Pi = 3.1415927$; and r is the radius of the tree at breast height (0.5 DBH).

With A_b , the volume (V) in cubic metres can be calculated from:

$$V = A_b \times H \times Kc$$

where: A_b is the basal area; H is the height; and Kc is a site-dependent constant in standard cubing practice used in forest inventory (e.g. in Texcoco, $Kc = 0.5463$).

Using the calculated volume of the trunk, total trunk biomass in kilograms may be calculated by multiplying by the wood density (WD) corresponding to each tree species measured:

$$\text{Biomass} = V \times WD \times 1\,000$$

The linear regression equation approach requires the selection of the regression equation that is best adapted to the conditions in the study area. Linear regression models have been fitted to data in various situations of variable site and ecological conditions globally. The work done by Brown, Gillespie and Lugo (1989) and FAO (1997) on estimation of biomass of tropical forests using regression equations of biomass as a function of DBH is central to the use of this approach. Some of the equations reported by Brown, Gillespie and Lugo (1989) have become standard practice because of their wide applicability. Table 2 presents a summary of the equations, as

TABLE 2 – Estimation of biomass of tropical forests using regression equations of biomass as a function of DBH

AUTHOR	EQUATION	Restrictions: DBH and climate based on annual rainfall
FAO	(FAO-1) $Y = \exp\{-1.996 + 2.32 \times \ln(\text{DBH})\}$ $R^2 = 0.89$	$5 < \text{DBH} < 40$ cm Dry transition to moist (rainfall > 900 mm)
FAO	(FAO-2) $Y = 10^{(-0.535 + \log_{10}(\pi \times r^2))}$ $R^2 = 0.94$	$3 < \text{DBH} < 30$ cm Dry (rainfall < 900 mm)
FAO	(FAO-3) $Y = \exp\{-2.134 + 2.530 \times \ln(\text{DBH})\}$ $R^2 = 0.97$	$\text{DBH} < 80$ cm Moist ($1\,500 < \text{rainfall} < 4\,000$ mm)
Winrock (from Brown, Gillespie and Lugo, 1989)	(Winrock-1) $Y = 34.4703 - 8.0671 \text{ DBH} + 0.6589 \text{ DBH}^2$ $R^2 = 0.67$	$\text{DBH} \geq 5$ cm Dry (rainfall $< 1\,500$ mm)
Winrock (from Brown, Gillespie and Lugo, 1989)	(Winrock-DH) $Y = \exp\{-3.1141 + 0.9719 \times \ln[(\text{DBH}^2)H]\}$ $R^2 = 0.97$	$\text{DBH} > 5$ cm Moist ($1\,500 < \text{rainfall} < 4\,000$ mm)
Winrock (from Brown Gillespie and Lugo, 1989)	(Winrock-DHS) $Y = \exp\{-2.4090 + 0.9522 \times \ln[(\text{DBH}^2)HS]\}$ $R^2 = 0.99$	$\text{DBH} > 5$ cm Moist ($1\,500 < \text{rainfall} < 4\,000$ mm)
Luckman	$Y = (0.0899 ((\text{DBH}^2)^{0.9522}) \times (H^{0.9522}) \times (S^{0.9522}))$	Not specified

Note:

$\pi = 3.1415927$; r = radius (cm); DBH = diameter at breast height (cm); H = height (m); $BA = \pi \times r^2$; and S = wood density (0.61).

found in the specialized literature, including the restrictions placed on each method.

Using any of these methods, tree biomass can be estimated by applying the corresponding regression equation. Plots of tree biomass estimates by DBH using the various regression equations for different types of cover type can be generated to illustrate the variations in predictions from each of the regression equations listed in Table 2.

Where only the biomass of the trunk has been estimated (e.g. by allometric calculations), the biomass of the crown (canopy) will need to be estimated and added to the biomass of the trunk. The first step is to estimate the volume occupied by the canopy. Given the variability of shapes of tree crowns from one species to another and even intraspecific variations from one individual tree to another, some generalizations need to be made for estimation purposes in regard to the variations in canopy density given by the aerial distribution of the branches and their foliage. The methods used represent reasonable approximations under the current practical circumstances of estimation. The crown or canopy volume can then be estimated by a function depending on the geometrical properties of the shape of the crown, as indicated in Table 3.

The volume of the crown estimated by the equations in Table 3 is the gross total volume. In reality, much of this volume is empty space. The

actual proportion of the volume occupied by branches and foliage is estimated by standing beneath the canopy or crown, beside the trunk, and obtaining a careful visual appreciation of the canopy structure. This proportion is then used to discount the air space in the crown volume: solid volume = $V(m^3) \times$ proportion of branches and foliage in crown volume.

Where possible, samples of branches and foliage should be taken to the laboratory in order to proceed with the determination of WD and dry matter in foliage. This ensures a more realistic approximation of biomass, leaving the estimation of foliage density as the only more subjective element in the estimation.

Literature pertaining to the calculation of WD of the crown is scarce. For the methodology presented here, a conservative approach is taken. Where the WD value of the tree is known, this value is divided in half to give an approximation of the density of leaves and small branches in the crown. Where the WD is unknown, then half the average for the WD values found for species in the quadrat plot or even in the same mapping unit or land cover polygon is applied.

Calculation of total aboveground biomass

Total biomass is calculated for each tree in the sample quadrat by the addition of the trunk and crown biomass estimates, then summing the results for all trees in the sample quadrat. This value can then be converted to tonnes per hectare. To the tree biomass estimate in the 10 x 10 m quadrat, the estimates from

TABLE 3 – Estimation of crown or canopy volume as a function of the shape of the crown

Approximate shape of the crown	Equation
Conical	$V (m^3) = \pi \times \frac{Db^2 \times Hc}{12}$
Parabolic	$V (m^3) = \pi \times \frac{Db^2 \times Hc}{8}$
Hemispherical	$V (m^3) = \frac{\pi \times Db^2}{12}$

Note:
 $\pi = 3.141592$; Db = diameter of the crown (to calculate Db, the average of the field measurements L and W is taken and used as the diameter of the crown: $Db = (L + W)/2$); Hc = height from the ground to the base of the crown.

shrubs, deadwood and debris measured in the nested 5 x 5 m quadrat need to be added. Shrub volume is estimated in a similar way to that of the trunk of trees, by calculating the volume of the stem.

However, considerable reductions in wood density are applied given the much larger moisture content in the green tissue of shrubs. Moreover, the contribution to volume due to foliage in the case of shrubs is considered negligible. Therefore, it is not considered in the overall estimation of total biomass.

The herbaceous layer, the litter and other organic debris collected in the field from the 1 x 1 m quadrat are taken to the laboratory, dried and weighed. The resulting value is the dry organic matter estimate per square metre. The resulting biomass calculation is then extrapolated to the 100 m² of the largest quadrat. This last figure can then be added to the estimates of biomass of tree trunk and crown (canopy) calculated earlier. The resulting calculation should yield a value of total aboveground biomass for each of the field sampling sites (10 x 10 m quadrats).

Minimum data sets for aboveground biomass estimation

Given the importance of aboveground biomass for carbon accounting, and as these estimations are used to derive inputs into the modelling of dynamics of soil carbon (SOC), the certain minimum data sets should be gathered during field surveys.

Both the allometric and the regression equation estimation methods require the data in Table 4.

In addition, some specific information is required about the tree species in order to complete the data sets, namely:

- ▶ wood density,
- ▶ volumetric coefficient,
- ▶ some method to readily calculate the density of wood plus foliage of the canopy with minimal field data.

These variables are the minimum data set for biomass estimation. They are easily obtainable and can be measured at low cost.

Estimation of belowground biomass

In any biological system, C is present in several known forms in pools and compartments. In terrestrial systems, it is convenient to divide these reserves into aboveground and belowground pools. This section is concerned with the belowground biomass pool.

Estimation of root biomass

Roots play an important role in the carbon cycle as they transfer considerable amounts of C to the ground, where it may be stored for a relatively long period of time. The plant uses part of the C in the roots to increase the total tree biomass through photosynthesis, although C is also lost through the respiration, exudation and decomposition of the roots. Some roots can extend to great depths, but the greatest proportion of the total root mass is within the first 30 cm of the soil surface (Bohm, 1979; Jackson *et al.*, 1996). Carbon loss or accumulation

TABLE 4 – Minimum data set for aboveground biomass estimation

Variable / measurement	Unit
Tree height	m
Diameter at breast height	cm
Length of the crown	m
Width of the crown	m
Height to base of the crown	m
Proportion of branches and foliage in canopy volume	%

in the ground is intense in the top layer of soil profiles (0–20 cm.). Sampling should concentrate on this section of the soil profile (Richter *et al.*, 1999).

Non-destructive (conservation) methods rely on calculations of belowground biomass for similar types of vegetation and coefficients as reported in the literature. They are derived from the measurement of the aboveground biomass. Santantonio, Hermann and Overton (1977) suggest that the biomass is close to 20 percent of the total aboveground biomass and indicate that the majority of the underground biomass of the forest is contained in the heavy roots – generally defined as those exceeding 2 mm in diameter. However, it is recognized that most of the annual plant growth is dependent on fine or thin roots. The data available and recorded in the literature are limited, owing to the high costs involved in the collection and measurement of root biomass. According to MacDicken (1997), the ratio of belowground to aboveground biomass in forests is about 0.2, depending on species. A conservative estimate of root biomass in forests would not exceed 10–15 percent of the aboveground biomass. A reasonable estimate from the literature is: belowground biomass = aboveground forest biomass x 0.2.

Where a satisfactory estimate of volume and DBH of the aboveground component of plants is available, this information can be used to derive an estimate of the belowground biomass. The accuracy of the estimates depend noticeably on the size and selection of the sample, as suggested by Kittredge (1944) and Satoo (1955), who proposed the use of allometric regression equations of the weight of a given tree component on DBH, such as those of the form:

$$\log W = a + b \log \text{DBH}$$

where W represents the weight of a certain component of tree, DBH is the diameter at breast height (1.3 m), and a and b are regression coefficients. Although this type of regression has proved useful in several types of forests (Ovington and Madgwick, 1959; Nomoto, 1964; Ogino, Sabhasri and Shidei, 1964), a more exact estimation can be made using DBH^2h , where h is the height of the tree (Ogawa *et al.*, 1965). Nevertheless, Bunce (1968) showed that the inclusion of height improved the estimation of dry weight of the tree component marginally. In some cases, another expression was preferred: $\text{DBH}^2 + h + \text{DBH}^2h$. The knowledge of the

TABLE 5 – Non-destructive methods for root biomass estimation

METHOD	EQUATION	APPLICABILITY
Winrock (MacDicken, 1997; Bohm, 1979)	Species x 5:1 More loss than outlined in literature	Trees Shrubs
Santantonio, Hermann and Overton (1997)	BGB = Volume AGB x 0.2 BGB = Belowground biomass AGB = Aboveground biomass	Trees Shrubs
Kittredge (1944) Satoo (1955)	$\log W = a + b \log \text{DBH}$ W = dry weight of tree component (roots) DBH = Diameter breast height (1.3 m) a and b are regression coefficients	Trees Shrubs
Ogawa <i>et al.</i> (1965)	$\log W = a + b \log d^2h$ W = dry weight of tree component d = DBH h = height of tree a and b are regression coefficients	Trees Shrubs
Unattributed	$\log W = a + b \log (d^2 + h + d^2h)$ W = dry weight of tree component h = height of tree d = DBH a and b are regression coefficients	Trees Shrubs

weight of the trunk can generally increase the accuracy of the estimation by virtue of its correlation with root weight (Ogawa *et al.*, 1965). As for correlation with the weight of branches and leaves, the regression is consistent. However, it would vary with species and even between families of a single species. Age and density of stems has shown inconsistent associations with roots (Satoo, 1955).

The growth of roots in length can be considered similar to that of the branches using the radial increase of these when it is visible, although the thickness of the roots can change with age. Table 5 provides a summary of non-destructive methods.

Several methods exist to measure roots directly. These are essentially destructive methods that are used for measurements required in ecological and agronomic research. They are:

- ▶ excavation,
- ▶ auger cores,
- ▶ monolith method.

The Winrock International Institute of Agriculture (MacDicken, 1997) reports that the auger core sampling and the monolith methods of measurement of roots are economically more feasible than excavation. Therefore, these two methods are described briefly.

The sampling in these methods must be done when the biomass in the roots is at its highest, but avoiding the growing season. A correction factor of 1.25–2.0 can be applied to the mass of roots after the data have been collected. This factor is based on considerations of the losses due to sampling and processing.

The sampling of soil cores to determine the root biomass is usually carried out at a standard soil thickness of 0–30 cm. In contrast, monolith sampling is used to determine the relative distribution of roots below a depth of 30 cm. The choice of method depends on specific site conditions and includes

considerations on: the accuracy required; the availability of data about the expected distribution of roots in the soil for the species inventoried; soil depth; soil texture; and stoniness.

The soil auger core method uses a cylindrical tube 15 cm in length and 7–10 cm in diameter, with an extension of about 1 m. It removes or displaces a known volume of soil from a soil profile of known depth. A core of 50–80 mm in diameter is considered sufficient. The auger corer can be inserted manually or mechanically. Manual insertion of the auger corer is not practical for depths greater than 50 cm or for clayey or stony soils. In sandy dry soils, a small diameter core may be necessary in order to reduce soil losses while extracting the core. In very stony soils, and particularly where these have many woody roots, coring may not be possible. In these circumstances, it may be more practical to take a known volume of soil through a monolith taken from the face of a cut or cross section of soil corresponding to a cut, trench, hole or naturally occurring gully in the landscape.

Ideally, the sample of the profile should be to the limit of the depth of the root system. Rooting intensity changes with soil depth, but the spatial variability of root intensity is typically high. However, the limits of the sample can be based on initial observations of the walls of the soil profile. In some cases, the sample can be based on an exponential model that relates root distribution to the mass of the main stem of the root. This function could be used to extrapolate root density in the soil samples. As far as possible, soils must be sampled to a minimum depth of 30 cm.

The best manner to examine roots is to wash them immediately after extraction from the cores. The core samples can be stored in polyethylene bags in a refrigerator for a few days or in a freezer until examination and processing. Dry weight must be verified by weighing of dry biomass or by loss-on-ignition methods. The texture, the structure, degree

of compaction and the organic matter content have great influence on the precision and time required to extract the roots from the cores. The extraction involves a sieve or strainer of 0.3–0.5 mm mesh. The work can be simplified by a superficial washing and by combining strainers with 1.1 and 0.3 mm mesh. The first strainer will contain most roots, the second will contain the rest. The material taken from the strainers can also be mixed with water and the suspended material poured off (live roots of most species have a specific gravity near to 1.0). The remainder can be classified manually in a container under water (to remove fragments of organic matter and dead roots).

The fine roots are a small but important part of the system for the assimilation of water and nutrients. This functional distinction helps in classifying the root systems according to size. The class limits need to fall between 1 and 2 mm of root diameter. Roots larger than 10 mm in diameter are not sampled by the soil core. For herbaceous perennial vegetation, roots can be separated into classes of greater than and less than 2 mm. In mixed vegetation, the separation of roots of different species is difficult. Sampling in homogenous soils may not capture the spatial variability of root density, which is claimed to have weight variation coefficients commonly in excess of 40 percent. In heterogeneous soils, the variation coefficient can be much higher. This variability implies that many samples are required in order to estimate the weight of roots and the belowground biomass component. It is advisable to obtain experimental information from one or two sites on the nature of spatial variation of both soils and root distribution, where available.

The monolith method requires cutting a monolith of the soil, from which the roots are separated by washing. This method is frequently used for quantitative determinations of roots. Small monoliths can be sampled with simple tools such as a shovel. However, the use of machinery is required for the excavation of a trench front to be sampled.

The size of the monolith varies depending on the species of plant being investigated. Generally, the volume of a monolith varies between 1 and 50 dm³. The samples of the monolith can be obtained with a board of stainless steel pins nailed in wood. The size of the pinboard is determined by the type of pins, based on previous observations of depth and distribution of rooting. The soil collected with the pinboard is heavy (a sample of a block of 100 cm x 50 cm x 10 cm of soil can weigh almost 100 kg.). The soil is washed away, exposing the roots for observation. If rough soil fragments are shown in the mesh before putting the board in the ground, it will be of help to maintain the roots in the original location while the sample is washed. The washing of the sample can be facilitated through cold water soaking for clayey soils and soaking in oxalic acid for calcareous soils. Washed root samples can be stored in polyethylene bags for a short time in a refrigerator, but preferably they should be stored in a freezer. The samples are dried for 5 hours to 105 °C in an oven. The results can be expressed in dry matter per unit of volume of soil.

Choosing a belowground biomass estimation method

The methods presented thus far vary in their degree of rigour. There is an obvious trade-off between rigour and accuracy and cost and practical viability. In summary, it is felt that destructive sampling is not a feasible option owing to its high costs in terms of money, resources, effort and time. The data available from measurements obtained from any of the destructive methods that are reported in the literature are limited. This is so, again, because of the high cost of root sampling and measurement.

In summary, non-destructive methods should be preferred, particularly in situations where there may be an empirical function relating stem diameter or any other allometric measurement to root biomass. It is recommended that in situations where no empirical equation exists, the root volume and biomass should be estimated as a fraction of the aboveground biomass, as an interim measure, in

order to estimate total biomass. Later, if time, circumstances and budget allow, the assessor should aim at developing regression equations of root biomass as a function of easy or cheap-to-measure variables, such as DBH or simply diameter of the stem at the base of the trunk. Obtaining the data to develop such regression functions will require samples obtained by some of the destructive methods described above.

In the case studies described in this report, the following relationships were used to estimate belowground biomass:

- ▶ for coniferous vegetation: belowground biomass = 0.25 aboveground biomass,
- ▶ for broadleaf vegetation: belowground biomass = 0.30 aboveground biomass.

Mapping biomass in present land use

A single method for the quantification of biomass with universal application has not yet been developed or identified. This report presents three methods for biomass estimation, with differing requirements and results.

The spatial representation of variations in biomass across the study area can be achieved by first computing the total biomass (i.e. aboveground and belowground) for each quadrat site.

Mapping total biomass

The sum of the aboveground and belowground biomass, as calculated with the procedures described above, is total biomass of the vegetation in the actual land use sampled by the quadrat site. This is calculated for each quadrat sampling site (10 x 10 m) and is expressed in tonnes per hectare.

Each quadrat sampling site lies within a given polygon that represents a land cover or land-use class, which was mapped by multispectral satellite image classification or air-photo interpretation or digitized from an existing paper map. The areas within each polygon (vector) or class (raster) are

representative of homogenous vegetative cover types. The quadrat sites are also georeferenced from the GPS readings on the ground. The sampling design assured that all polygons received at least one quadrat site to represent them. For land cover polygons containing more than one quadrat site, total biomass for each polygon can be estimated by the following procedures.

Upscaling of biomass estimates from polygon or class averages

This procedure involves the calculation of the following:

- ▶ average of total biomass estimates for all quadrat sites within the polygon;
- ▶ upscaling by converting the total biomass averaged over the quadrat sites and their area to the total area covered by the polygon.

Procedures based on within-class averages carry the implicit assumption that the area of the polygon is sufficiently homogenous in vegetative cover to allow reliable spatial interpolation of data within the polygon boundaries. Issues of within-polygon spatial variability of total biomass may be a concern, particularly in situations of large differences between quadrat site biomass estimates within a given polygon.

Upscaling with spatial interpolation of biomass estimates using geostatistics

Geostatistics and regionalized variable theory provide a solid body of theory for the analysis of the structures of spatial variability and their estimation through spatial interpolation. Auto-covariance functions (e.g. the semi-variogram) allow for the elucidation of spatial dependence and of the structures of spatial variability in the biomass data from quadrat sites, which are considered as point data for the purpose of interpolation. The various forms of the technique called kriging use the information from the semi-variogram about the structures of spatial variability of biomass and can interpolate onto a fine grid of blocks (e.g. block

kriging) or cells, whose resolution can be defined by the analyst. Thus, this would create a continuous coverage of pixel values of biomass over the entire area. A corresponding map of estimation variance could accompany the former map, providing information on the reliability of estimates.

However, the power of kriging estimates comes at a price. This is in terms of the amount of point data available for the computation of reliable semi-variograms to model the spatial variability of biomass data, and for the spatial interpolation process itself. Kriging is very demanding on the amount of point data (i.e. the sampling support) available for interpolation. Typically, one could expect some limitations on the amount of quadrat sites that could be afforded from a field survey budget. Where the quadrat sites (point samples) are limited in number, the kriging interpolation may not be applicable.

Upscaling with interpolation of biomass estimates by bicubic splines or nearest neighbour methods

Spatial interpolation of biomass data can also be realized by means of techniques whose accuracy does not depend strongly on the number of quadrat sites sampled. Bicubic splines provide a coverage of grid cell values from the quadrat sites values by fitting, “patch-wise”, panels whose joins are created with continuity and smoothness conditions. This creates a continuous coverage of estimates over the entire area of study. Bicubic splines are not as accurate as kriging but they offer reasonably accurate interpolation estimates in exchange for the freedom from the sample size constraint that kriging imposes.

Other nearest neighbour techniques can also be used for upscaling the biomass estimates from the quadrat sites. In particular, distance-weighting functions are common practice in spatial interpolation procedures without the restrictions of any of the techniques described above.

In summary, a reasonable course of action regarding upscaling procedures of biomass estimates

would be, first, to decide on whether the quadrat sites are sufficient in number to compute reliable semi-variograms, and therefore interpolate with kriging. If the decision is that there are insufficient sites (point data) to estimate with this technique, then other interpolation algorithms (e.g. cubic splines) should be used. Class or polygon averages should be used in the event of having only a few quadrat sites in the total area and within each polygon.

The summation of the estimates per grid cell or pixel, polygon or biomass class results in a total of biomass for the entire watershed or study area.

Mapping carbon stock in present land use

Two main carbon pools are identifiable in a landscape:

- ▶ C in biomass,
- ▶ C in soils.

The first pool is the carbon stock in vegetation including living biomass and dead vegetation. The latter is the C present in SOM in its different forms and compartments, including litter in different degrees of decomposition. The remainder of this section focuses on simulation modelling and estimation procedures of SOM turnover in soils and carbon accumulation in the different SOC pools in present land use.

Carbon stock as biomass

The calculation of carbon stock as biomass consists of multiplying the total biomass by a conversion factor that represents the average carbon content in biomass. It is not practically possible to separate the different biomass components in order to account for variations in carbon content as a function of the biomass component. Therefore, the coefficient of 0.55 for the conversion biomass to C, offered by Winrock (1997), is generalized here to conversions from biomass to carbon stock: $C = 0.55 \times \text{biomass (total)}$. This coefficient is widely used internationally, thus it may be applied on a project basis. The results may be displayed in a similar fashion to total biomass.

Total carbon in present land use

The estimation of total C in present land use should include the carbon stock as biomass and the SOC present in the SOM. This estimation would consist of converting the SOM value reported for the soil mapping units in the study area to SOC. The content of SOC included in SOM may change depending of the type of organic residues present in the SOM. In turn, this changes with management and other factors. However, determining the composition of residues in SOM and the spatial variability of the different qualities of SOM in the soil is a difficult task. For estimation purposes, a generic coefficient can be assumed in order to transform SOM to SOC: $\text{SOC} = 0.57 \text{ SOM}$.

Multiplying the values of SOM by this coefficient and then transforming them from percentage values to tonnes per hectare can be done through computing a weighted average of SOM over the layers of the analysed soil profiles that represent each soil mapping unit. The weights correspond to the thickness of each horizon multiplied by its soil bulk density.

Where required, spatial interpolation and other procedures for upscaling estimates would help in mapping SOC for the entire area of concern. Adding these SOC values to the C present as biomass would yield the total carbon stock for the present land use, as follows: $\text{carbon stock}_{(\text{total})} = \text{C as biomass} + \text{SOC}$.

In interpreting results from carbon stock calculations, the rather dynamic nature of SOM should be borne in mind. The relatively fast turnover of SOM, particularly in agricultural lands and other managed soils, implies that a value of carbon stock calculated from SOC values derived from SOM can only be reliable for a relatively short period of time. The relatively large contribution of soils to total CO₂ emissions to the atmosphere (about 30 percent for agricultural soils) points to the need for a dynamic simulation of the turnover of SOM, with the consequent partition of C in the various pools within the soil. Land management has significant effects on the interannual and intra-annual variations in SOM and can make the difference in terms of the soil being an emitter or a sink. Thus, the need for dynamic simulation modelling of SOM turnover is linked strongly to the issue of stock permanence.



Mitigate CO₂ emissions



Increase soil organic matter



Control land degradation



Increase plant productivity



Increase soil biodiversity



Increase food security

Win-win options

CHAPTER

4

MODELLING CARBON DYNAMICS IN SOILS



CHAPTER 4

Modelling carbon dynamics in soils

The ability to simulate and predict over time the fate of organic materials added to the soil, whether by litter or by additions of crop residues and organic manures through crop and land management, is fundamental to carbon accounting and to the formulation of scenarios of land use and LUC that may increase carbon sequestration.

Methods for estimating and measuring changes and fluxes in SOC can be direct or indirect.

Direct methods include:

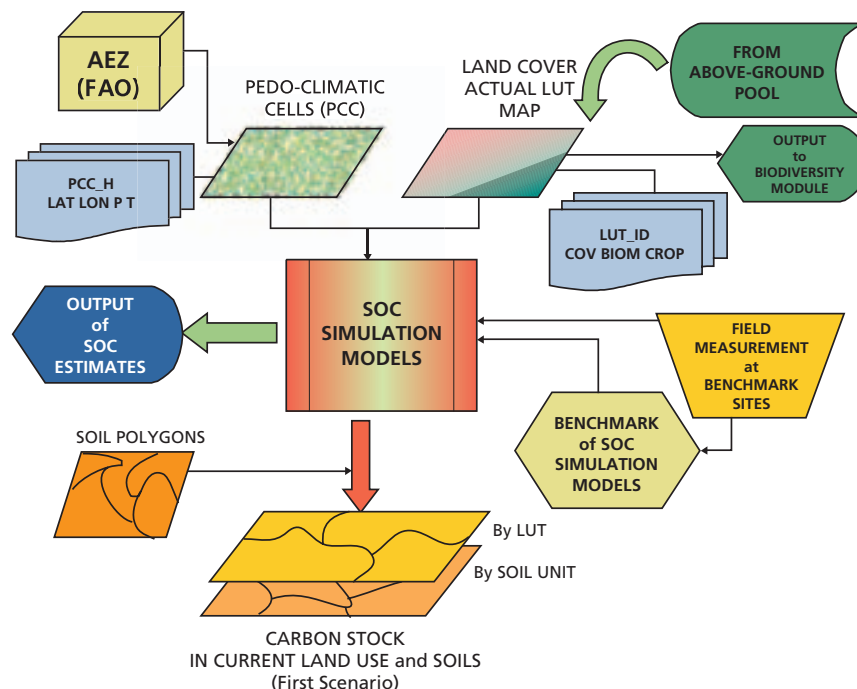
- ▶ field sampling and laboratory measurement,
- ▶ C (CO₂) flux monitoring.

Indirect methods are:

- ▶ accounting (including stratified accounting),
- ▶ modelling (simulation).

In the developing world, the costs, instrumentation requirements, labour intensity and technical knowledge involved in implementing direct methods for routine practice set them out of reach (aside from specific research projects). Therefore, they are not the concern of this report. Accounting methods are described at length throughout this document. Accounting also takes into consideration the strata generated by land cover classes derived from satellite imagery and air-photo interpretation. Modelling can be thought of as an indirect method for estimating changes in SOC. However, it is within reach of standard practice in the developing world, provided the data sets to feed into the model are available from resource inventories.

FIGURE 7 – Estimation of carbon stock in current land use and soils (belowground pool) through simulation modelling



Carbon stock in soils under present land use can be estimated through carbon dynamics simulation models. The prerequisites for model implementation are:

- ▶ the objects of modelling, i.e. the pedo-climatic cell (PCC) or soil polygon whose carbon dynamics are to be simulated. These units may be the result of zoning or partition of the environment into units.
- ▶ knowledge of the model, its structure and operation.
- ▶ the model data requirements. These determine the input data set and the difficulties in model parameterization.

Figure 7 illustrates the use of simulation models in the estimation of carbon stock under current land use.

The dynamics of C in the soil are complex. Accordingly, the models that simulate these dynamic processes can be complex too. Soil carbon simulation models are process-oriented multicompartment models. Typically, the models are mainly empirical in nature and all contain a slow or inert pool of organic C, which is not necessarily described in its nature or rate of formation. Some models treat the soil as homogeneous with respect to depth. Usually, the nature of litter is treated as being different to that of SOM. Many of these models reveal convergence in kinetic compartmentalization and a growing use of clay content and the inclusion of an IOM component.

As Figure 7 shows, the selection of the object of modelling (PCC, ecological zone or soil polygon) results from a process of partitioning the spatial variability of environmental parameters, soils, climate, landscape, etc. These procedures are discussed in later sections. Land cover classification and mapping, and the selection of quadrat sampling sites to serve as benchmarks to the model calibration, are discussed above. Thus, the following section focuses on model selection.

Simulation models vary in their degree of complexity and other attributes relevant for model selection by technical staff. Reports on the use of carbon simulation models are relatively abundant in the specialized literature (e.g. Smith *et al.*, 1997b; Coleman and Jenkinson, 1995b; Powlson, Smith and Smith, 1996; Li *et al.*, 1997; Izurralde *et al.*, 1996). The characteristics of such models vary in terms of their emphasis on some particular aspects of the carbon cycle, their degree of compartmentalization, the underlying assumptions made by the developers of the model, model performance, their required inputs, nature of outputs, accessibility and ease of use.

A number of comparative studies and evaluation of simulation models have been reported. Smith *et al.* (1997b) compared the performance of nine SOM models using data sets from long-term experiments. The models, referred to by their acronyms, were: RothC, CENTURY, CANDY, DNDC, DAISY, NCSOIL, SOMM, ITE and Verberne. Smith and co-workers observed that not all models could simulate all data sets, and that only four models attempted all. No one model performed better than all others across all data sets. The first six models (i.e. RothC, CENTURY, CANDY, DNDC, DAISY and NCSOIL) performed with no significant differences in accuracy between them. They predicted with significantly less error than the other models in the list.

Izurralde *et al.* (1996) evaluated five models (CENTURY, RothC, SOCRATES, EPIC and DNDC) in terms of their performance and a number of other parameters, at site-specific scale and at ecodistrict level in Alberta, Canada. SOCRATES appeared to be their choice because of its ease of operation and ability to mimic long-term trends. However, they concluded that for modelling regional carbon storage this model may be limited by the lack of detailed management options. CENTURY predicted long-term trends reasonably well and had more management options – management being a deciding factor in the nature of carbon fluxes in soils.

The European Soil Organic Matter Network (SOMNET) published a systematic review of simulation models (Smith *et al.*, 1997a). This can be consulted on line via the Internet (<http://saffron.rothamsted.bbsrc.ac.uk/cgi-bin/somnet-models>).

Selection of a carbon simulation model

The Internet resources of SOMNET offer a comprehensive list of models and a detailed description of the characteristics of each model, their required inputs, outputs and the conditions within which the model has performed best. It is beyond the scope of this report to offer a summary of such listings. In order to make a selection of the final model to be used for estimating changes in SOM and SOC over time, the reader is advised to: (i) access the Web site; (ii) decide on the criteria for selection of the model; (iii) narrow down, iteratively, to a short list of three or four models; and (iv) search for more detailed information about the model in the technical literature. Selection criteria could include:

- ▶ the required inputs for the model ought to match available data in the databases.
- ▶ the output variables generated by the model need to satisfy the objectives of the modelling exercise.
- ▶ the model should have been adapted to the particular conditions of soil, climate and land management of the site or region.
- ▶ the simulation model should offer the management options that need to be modelled.
- ▶ the level of accuracy of estimates from the model should be within the target accuracy required by the project.
- ▶ there is reported evidence that the model has performed well in ecological circumstances similar to those of the site of concern.
- ▶ accessibility and ease of use together with the implicit assumptions in the model about the user's technical background.

The models CENTURY and RothC-26.3 were selected in this project for simulating the dynamics of SOC and SOM turnover in the sites of the three case studies presented. The rationale for these choices was as follows. These models represent extremes of a gradient of accessibility, ease of use and complexity, CENTURY being the most complete. Although originally developed and tested in temperate conditions, both have been upgraded to encompass a wide range of ecosystemic variability, including tropical and subtropical conditions, which are present in a large part of Latin America and the Caribbean region. Moreover, both models are well documented and there is a sufficient volume of published work with the applications of both models to data. CENTURY is one of the most complete and frequently reported in studies of carbon dynamics simulation. Tables 6 and 7 show a summary description of the models as per SOMNET.

TABLE 6 – Summary description of the CENTURY model as per SOMNET**1. MODEL: CENTURY****2. MODEL NAME: CENTURY****3. SPATIAL SCALE OF THE MODEL**

Plot, field, regional, national, global

4. INTEGRATION TIME-STEP OF THE MODEL

Months

5. DATA USED TO RUN THE MODEL

a) Weather data used to run the model:

i) Data type:

rainfall – essential
 air temperature – essential
 evapotranspiration over grass – desirable

ii) Temporal resolution of weather data:

monthly – essential

b) Soil data used to run the model:

soil description – desirable
 waterholding capacity – essential
 clay content – essential
 particle size distribution – desirable
 organic matter content – essential
 soil pH – essential
 soil C content – essential
 soil C 13 content – desirable
 soil C 14 content – desirable
 soil N content – essential

c) Plant and animal inputs used to run the model:

plant production data useful for testing the plant model

d) Land use and management inputs used to run the model:

crop rotation – timing – essential
 crop rotation – amount – essential
 crop rotation – type – desirable
 tillage – timing – essential
 tillage – amount – essential
 tillage – type – desirable
 inorganic fertilizer – timing – essential
 inorganic fertilizer – amount – essential
 inorganic fertilizer – type – desirable
 organic manure – timing – essential
 organic manure – amount – essential
 organic manure – type – desirable
 residue incorporation – timing – essential
 residue incorporation – amount – essential
 residue incorporation – type – desirable
 irrigation – timing – essential
 irrigation – amount – essential
 irrigation – type – desirable
 ESSENTIAL: N input to the system

6. MODEL OUTPUTS

a) Soil outputs:

total C, biomass C, total C 13, biomass C 13
 total C 14
 biomass C 14
 CO₂
 total N
 biomass N
 total N 15
 total mineral N
 nitrate leaching
 soil water dynamics
 soil temperature dynamics

b) Plant outputs:

commercial crop yield
 C removed in agricultural products
 N removed in agricultural products
 total dry matter production
 N uptake by plants
 C input to soil in plant debris
 N input to soil in plant debris
 gaseous losses

c) Animal outputs:

C removed in animal products
 N uptake by animals
 C input to soil as animal products

N input to soil as animal products

gaseous losses from animals

d) Other outputs

7. MODEL DESCRIPTION

a) Description of the decomposition of plant and animal debris:

Decomposition of plant and animal debris described by multiple pools as follows:

1. structural defined by lignin to N ratio obtained by fitting
2. metabolic defined by lignin to N ratio obtained by fitting

b) Description of the decomposition of SOM:

decomposition of SOM described by multiple pools as follows:

1. microbe biomass defined by sand and abiotic decomposition rate obtained from measured data
2. slow SOM defined by sand and abiotic decomposition rate obtained from measured data
3. passive SOM defined by clay and abiotic decomposition rate obtained from measured data

c) Factors assumed to affect organic matter decomposition:

soil moisture
 soil temperature
 clay content

pH

N content

d) Soil layers used in the model:

the model divides the soil into one layer as follows:

SOM dynamics are only simulated in one layer – 0–20 cm.
 Soil layers for nitrate leaching model include 0–15, 15–30, 30–45, 45–60, 60–90, 90–120 cm (6 layers)

8. MODEL EVALUATION

Sensitivity analyses have been performed as follows:

impact of changing initial soil C levels and temperature effect on decomposition has been evaluated.

Model output has been compared to measured data that were independent of the data used in model development.

Model output has been compared to measured data quantitatively arbitrary criteria have been used to define good model performance as follows: 95 percent confidence limits (Parton and Rasmussen, 1994).

Good model performance has been defined by simulated results falling within the standard error or standard deviation of the measured data.

Statistical methods are used to determine good model performance. as follows: SOM levels and plant production were compared to predicted values from regression equations (Parton et al., 1987).

The model has met the criteria for good model performance in the following ecosystems / climate regions:

natural vegetation in a cold temperate boreal climate
 natural vegetation in a cool temperate climate
 natural vegetation in a warm temperate subtropical climate
 natural vegetation in a tropical climate
 grazed ecosystem in a cool temperate climate
 grazed ecosystem in a warm temperate subtropical climate
 grazed ecosystem in a tropical climate
 arable ecosystem in a cool temperate climate
 arable ecosystem in a warm temperate subtropical climate
 arable ecosystem in a tropical climate
 forestry ecosystem in a cool temperate climate
 forestry ecosystem in a warm temperate subtropical climate
 forestry ecosystem in a tropical climate

(Parton & Rasmussen, 1994; Paustian, Parton and Persson, 1992; Sanford *et al.*, 1991; Parton, Wooster and Martin, 1994; Schimel *et al.*, 1994)

9. USING THE MODEL

a) The model is intended for use by: users with the help of a manual

b) The following documentation is available: scientific documentation, user guide

c) The model has the following minimum hardware requirements: supercomputer, workstation, IBM compatible PC 286

d) The model has the following minimum software requirements: DOS 3, Windows, Unix

e) Model output format: model output is in ASCII file format, box ticked, no details given

f) Availability of the model: charge for model and documentation: US\$150 for user manual and copy of model

TABLE 7 – Summary description of the RothC-26.3 model as per SOMNET

1. MODEL: RothC-26.3

2. MODEL NAME: RothC-26.3

Most recent version 26.3

Date of most recent version: 1 May 1995

3. SPATIAL SCALE OF THE MODEL

Plot, field, catchment, regional, national, global.

4. INTEGRATION TIME-STEP OF THE MODEL

Months

5. DATA USED TO RUN THE MODEL

a) Weather data used to run the model:

i) data type:

rainfall – essential

air temperature – essential

evaporation over water – essential

ii) temporal resolution of weather data:

monthly – essential

b) Soil data used to run the model:

clay content – desirable

inert carbon composition – desirable

sampling depth, bulk density, percent C: all used to calculate total C in soil layer for input to model.

c) Plant and animal inputs used to run the model:

C in plant components desirable

crop yield – desirable

d) Land use and management inputs used to run the model:

crop rotation – timing – essential

crop rotation – type – essential

organic manure – timing – essential

organic manure – amount – essential

organic manure – type – essential

residue incorporation – timing – essential

residue incorporation – amount – essential

residue incorporation – type – essential

6. MODEL OUTPUTS

a) Soil outputs:

total C

biomass C

CO₂

As well as total C, also C content of individual fractions.

Radiocarbon content of individual fractions is expressed as a delta 14C value.

The radiocarbon content of the biomass C can also be derived.

b) Plant outputs

c) Animal outputs

d) Other outputs

7. MODEL DESCRIPTION

a) Description of the decomposition of plant and animal debris: decomposition of plant and animal debris described by multiple pools as follows:

1. DPM defined by fraction of input C; obtained by fitting

2. RPM defined by fraction of input C; obtained by fitting

b) Description of the decomposition of SOM:

Decomposition of SOM described by multiple pools as follows:

1. BIO defined by proportion of inputs entering compartment from decomposition

of the four active pools obtained from measured data

2. HUM defined by proportion of inputs entering from decomposition of the four active compartments;

obtained by fitting

c) Factors assumed to affect organic matter decomposition:

soil moisture

soil temperature

clay content

crop cover

d) Soil layers used in the model:

the model divides the soil into 1 layer as follows: topsoil;

normally 0–23 cm, other options available

8. MODEL EVALUATION

Model output has been compared to measured data which were independent of the data used in model development

Model output has been compared to measured data quantitatively

Good model performance has been defined by simulated results falling

within the standard error or standard deviation of the measured data

Statistical methods are used to determine good model performance.

as follows:

see references

The model has met the criteria for good model performance in the

following ecosystems / climate regions:

natural vegetation in a cool temperate climate

grazed ecosystem in a cold temperate boreal climate

grazed ecosystem in a cool temperate climate

grazed ecosystem in a warm temperate subtropical climate

grazed ecosystem in a tropical climate

arable ecosystem in a cold temperate boreal climate

arable ecosystem in a cool temperate climate

arable ecosystem in a warm temperate subtropical climate

arable ecosystem in a tropical climate

forestry ecosystem in a cool temperate climate

Possibly also cold and warm temperate and tropical forestry.

Undisturbed natural vegetation in Broadbalk and Geescroft wilderness

The model failed to meet the criteria for good model performance

in the following ecosystems / climate regions:

wetlands, all climate zones

9) USING THE MODEL

a) The model is intended for use by: model developers, users with

less than one weeks' training, users with the help of a manual

b) The following documentation is available: scientific documentation, user guide, technical documentation

c) The model has the following minimum hardware requirements:

IBM compatible PC 286

d) The model has the following minimum software requirements:

DOS 3

e) Model output format: model output is in ASCII file format

Most graphics packages: Sigmplot, Harvard Graphics, Excel have all been used successfully

f) Availability of the model: Freely available with documentation

and release form from K. Coleman

Model parameterization – preparation of soil and climate parameters

The models require three sets of data:

- ▶ soil data,
- ▶ climate data,
- ▶ management data, including crop and land management and additions of organic materials in quantities and over time.

In order to derive the specific sets of variables to parameterize the models, the suggested methodology describes a set of procedures for the definition of agro-ecological zones (AEZs). These are essentially relatively homogeneous areas with unique combinations of soil and climate. They are referred to as PCCs. The characterization of the area is made in terms of AEZs following the FAO approach as described below.

Biophysical characterization of the area

The biophysical characterization of the area is to be done in terms of thematic layers of information on soils, climate and land cover or land use. The cartographic representation of these data is at a scale adapted to the size of the study area or river basin. Typically, most countries within the Latin America and Caribbean region would have thematic coverages from past surveys and resource inventories. An appropriate scale for working at the level of a medium-sized watershed or basin would be between 1:20 000 and 1:50 000. At this range of scales, there is adequate detail on terrain conditions of the study area. The use of maps at this scale in countries such as in Mexico, for example, has an added advantage in that the official mapping agency, the National Institute of Statistics, Geography and Information (INEGI), provides coverage for 70 percent of the country at this scale. Application of these methods in other Latin American countries will require the use of similar map products that typically should include information on:

- ▶ soil texture (clay and sand contents),
- ▶ soil bulk density,
- ▶ soil depth,
- ▶ present land use.

In the process of biophysical characterization, two possible situations may occur:

- ▶ the necessary information is present in digital format. Relevant information can be processed using a GIS. In this case, the GIS can help in generating the PCCs.
- ▶ data are in analogue (non-digital) format, e.g. paper, plastic or other material. The PCCs need to be defined.

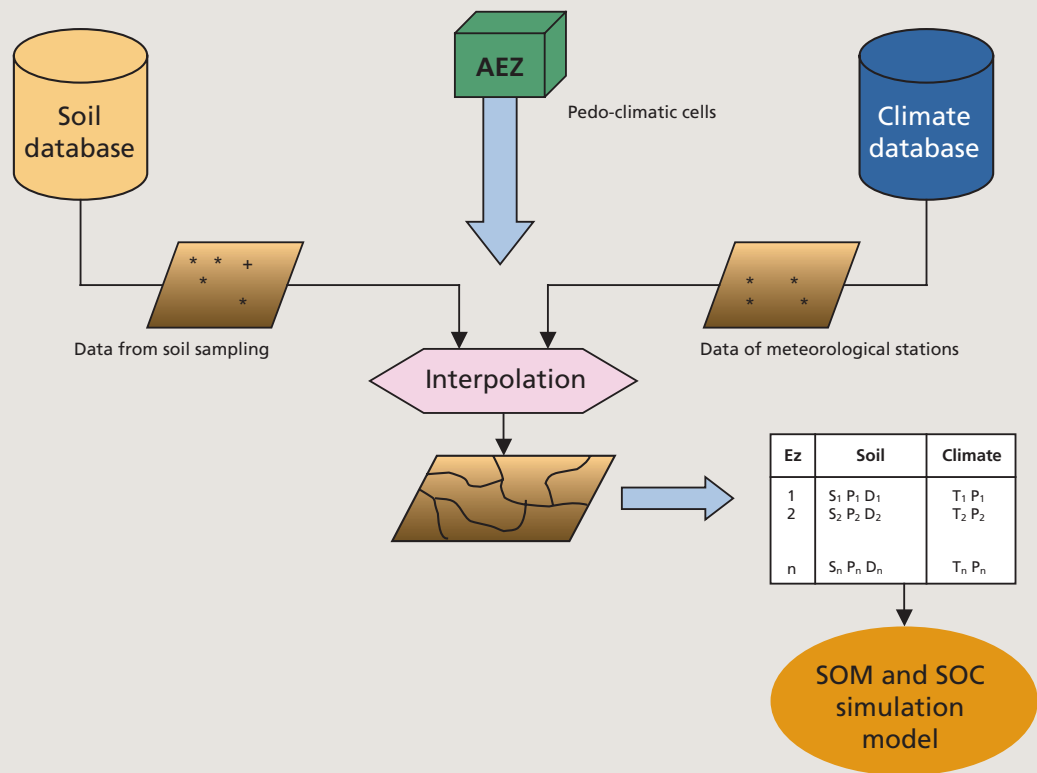
The latter situation will require a process of boundary definition through thematic overlay. Where this is achieved manually, some advantages can be taken of the situation in order to enhance data preparation of data for modelling. The following are some activities in the manual preparation of data:

1. definition of basin boundaries on a transparent or translucent surface – in such a

way that when comparing it to the thematic maps the boundaries can be generated as required.

2. overlay of the map of present land-use classes on the map of vegetation cover (where these are two different maps) in order to eliminate sites without possibilities of carbon sequestration (i.e. urban, peri-urban and industrial areas). The map generated is to be considered the base map.
3. soil map. When overlaying the base map (Step 2) on soil boundaries, information such as the textural classes (i.e. the percentage of clay and sand), soil depth and soil bulk density can be extracted.
4. topographic map and its slope classes. The overlay of the topographic map on the base map allows the delineation of zones with slopes whose ranges determine the feasibility of certain activities. For example, the interval from 0 to 8 percent shows areas of the landscape where intensive agriculture can take place. From 8 to 30 percent slope, rainfed agriculture and the production of fruit trees is possible, and slopes greater than 30 percent would indicate areas suitable for forest systems. The resulting map provides a reclassification of slope ranges related to possible use.
5. the overlay of all of the maps produced in this fashion (i.e. Steps 2, 3, and 4) would generate a preliminary map of AEZs or ecozones or regions, as internally homogenous as possible in terms of relief, present land use and soil characteristics.
6. definition of AEZs or PCCs. Meteorological station values of climate parameters relevant to land use, such as length of growing period (LGP), moisture available in the soil, air temperature and radiation should then be upscaled in the same map base. Given that their position on the landscape is known through their coordinate pairs, it would be possible to identify areas of influence or

FIGURE 8 – Extraction of soil and climate parameters from agro-ecological cells or polygons for model parameterization



“domains” of each meteorological station (e.g. Thiessen polygons). In these domains, it should be possible to obtain or extract values of climate parameters necessary for modelling. Where spatial data have been digitized and the spatial databases of resources are available in digital form, spatial interpolation techniques, such as kriging, bicubic splines or distance functions, can be applied. Interpolation or tessellation will be achieved automatically in GIS, such as indicated in Figure 8. The end of this stage achieves the definition of agro-ecological (i.e. pedo-climatic) cells that can be grouped into zones.

Preparation of soil and climate parameter data

This section explains procedures for preparing data to parameterize the simulation models (where databases of soil and climate are present).

In any given watershed, a database of soil characteristics may be present from past surveys and databases. Such databases may include records of soil samples and analytical data in any given zone, with the parameters required by the models (specified for each model). However, part of this information is often missing. In such circumstances, estimates of the values of the missing data have to be generated. A climate database may be generated with information from the meteorological stations that influence each zone, and whose location is nearest to the zone. The pooled values from such stations, although not strictly within the study area, may have to suffice for modelling purposes where insufficient stations fall within it.

Figure 8 illustrates how the PCCs or zones are to be characterized with data as accurate as possible, from soil profiles and from meteorological stations. For interpolation of these data, tables of attributes by each ecozone serve as the source of inputs to the SOM simulation models.

Model parameterization and calibration with site information

In order to parameterize the models, once PCCs or zones have been defined and identified, it is important to ensure that the data extracted from the databases of the PCCs provide the necessary variables to run the models. Therefore, before running the models an intensive data preparation stage should be planned and implemented carefully.

Data on the amount of organic matter, clay content (percent), bulk density and depth with regard to the soil profiles must be included. The contributions of the aboveground biomass to the soil according to the LUT and its management, in the form of crop residues, organic manures and litter, should be recorded and prepared for input into the models. The amounts of inputs of organic materials must be quantified in terms of tonnes of C per hectare per year.

Other important information needed for full model parameterization includes:

- ▶ identification of areas where there are additions of crop residues, organic manures or any other organic material.
- ▶ agricultural production by type of crop (Pa_i).
- ▶ harvest coefficients (the percentage of the total biomass that is harvested) (Cc_i).
- ▶ carbon–nitrogen ratio by species present in the crop mix.
- ▶ moisture content in plant tissue by species (percentage of water in plant) (H_i).
- ▶ production of forage per hectare (including roots) (F).
- ▶ number of head of livestock in the grazing or pasture management unit, by species by hectare (Nc_i).
- ▶ crop residues including roots, as percentage of total plant biomass (Ea_i). (The percentage of the plant that is removed as crop residues including roots if any. Where this information is not available, methods used in the calculation of the belowground biomass in this

report can be used to derive an estimate.)

- ▶ nutritional content of forage by species, or nutrition conversion index, which is a measure of the nutritional quality of forage (ICA_i).
- ▶ index or coefficient of grazing (R).
- ▶ aboveground biomass and carbon content of annual herbaceous species (these data are obtained from the quadrat (1 x 1 m) sampling sites during the multipurpose field surveys) (Bh).

Simulation modelling of carbon dynamics in soils

This section outlines the specific procedures for running each of the SOC models selected. It discusses the requirements, characteristics and data for model input.

Modelling with RothC-26.3

Model characteristics

RothC-26.3 is a model of the turnover of organic C in non-waterlogged soils that allows for the effects of soil type, temperature, moisture content and plant cover on the turnover process. It uses a monthly time step to calculate total organic C (tonnes per hectare), microbial biomass C (tonnes per hectare) and $\Delta^{14}C$ (from which the radiocarbon age of the soil can be calculated) on a time scale of years to centuries (Jenkinson *et al.*, 1987; Jenkinson, 1990; Jenkinson, Adams and Wild, 1991; Jenkinson *et al.*, 1992; Jenkinson and Coleman, 1994). It needs few inputs and these are easily obtainable. It is an extension of the earlier model described by Jenkinson and Rayner (1977) and by Hart (1984).

RothC-26.3 computes the changes in organic C as it is partitioned into five basic compartments: inert organic matter (IOM), decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (BIO) and humified organic matter (HUM).

Input variables required to run the model

Table 7 indicates the data required to run the model. In particular:

- ▶ rainfall and open pan evaporation are used to calculate topsoil moisture deficit (TSMD), as it is easier to obtain rainfall and pan evaporation data, from which the TSMD is calculated, than monthly measurements of the actual topsoil water deficit.
- ▶ the air temperature (in degrees Celsius) is used rather than soil temperature because it is more easily obtainable for most sites.
- ▶ the clay content (in percent) is used to calculate how much plant available water the topsoil can hold; it also affects the way organic matter decomposes.
- ▶ the DPM/RPM ratio provides an estimate of the decomposability of the incoming plant material.
- ▶ it is necessary to indicate whether or not the soil is vegetated because decomposition has been found to be faster in fallow soil than in cropped soil, even where the cropped soil is not allowed to dry out (Jenkinson *et al* 1987; Sommers *et al.*, 1981; Sparling, Cheshire and Mundie, 1982).
- ▶ the plant residue input is the amount of C (tonnes per hectare) that is put into the soil per month, including C released from roots

during crop growth. As this input is rarely known, the model is most often run “in reverse”, generating input from known soil, site and weather data.

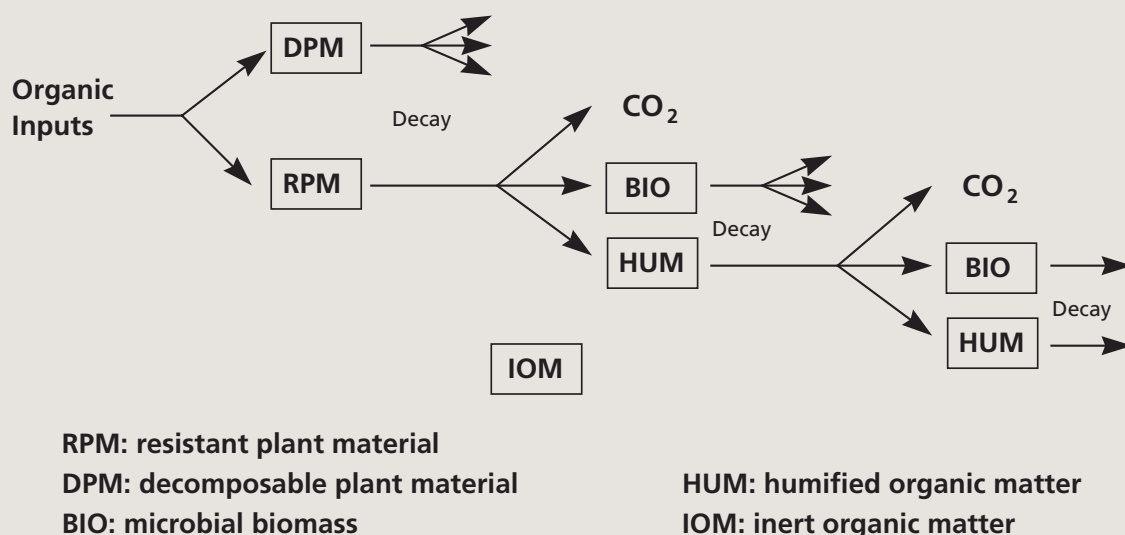
- ▶ the amount of farmyard manure (FYM) (tonnes of C per hectare) is input separately, because FYM is treated slightly differently from inputs of fresh plant residues.
- ▶ depth of soil (cm).
- ▶ apparent density of the soil.

Model structure

Soil organic C is split into four active compartments and a small amount of IOM. The four active compartments are: DPM, RPM, BIO and HUM. Each compartment decomposes by a first-order process at its own characteristic rate. The IOM compartment is resistant to decomposition. Figure 9 shows the structure of the model.

Incoming plant C is split between DPM and RPM, depending on the DPM/RPM ratio of the particular incoming plant material. For example, for most agricultural and improved grassland, a DPM/RPM ratio of 1.44 is used, i.e. 59 percent of the plant material is DPM and 41 percent is RPM.

FIGURE 9 – Partitioning of the basic components of organic matter in the soil in RothC-26.3 (after Coleman and Jenkinson, 1995a)



For a deciduous or tropical woodland, a DPM/RPM ratio of 0.25 is used, so 20 percent is DPM and 80 percent is RPM. All incoming plant material passes through these two compartments, but only once. Both DPM and RPM decompose to form CO₂ (lost from the system), BIO and HUM. The proportion that goes to CO₂ and to BIO + HUM is determined by the clay content of the soil. The BIO+ HUM is then split into 46 percent BIO and 54 percent HUM. BIO and HUM both decompose to form more CO₂, BIO and HUM. FYM is assumed to be more decomposed than normal plant material. It is split in the following way: DPM 49 percent, RPM 49 percent and HUM 2 percent.

If an active compartment contains Y tonnes of C per hectare, this declines to $Y e^{-abckt}$ tonnes of C per hectare at the end of the month, where: a is the rate modifying factor for temperature; b is the rate modifying factor for moisture; c is the plant retainment rate modifying factor; k is the decomposition rate constant for that compartment; and t is 1/12, as k is based on a yearly decomposition rate. Thus, $Y(1 - e^{-abckt})$ is the amount of the material in a compartment that decomposes in a particular month.

According to Coleman and Jenkinson (1995a), the decomposition rate constants (k) in per year values for each compartment are set in RothC at: DPM = 10.0, RPM = 0.3, BIO = 0.66, and HUM = 0.02.

Variations in soil and climate conditions become modifying factors of the default decomposition rates suggested by the model. In order to use the model in different conditions of soil and climate, the decomposition rates need modification. These are illustrated here to allow for a view of the internal workings of the model.

The rate modifying factor (a) for temperature is given by:

$$a = \frac{47.9}{1 + e^{\frac{106}{tm + 18.3}}}$$

where tm is the average monthly air temperature (degrees Celsius).

The soil moisture deficit (SMD) rate modifying factor (b) is calculated as follows. The maximum SMD for the 0–23-cm layer of a particular soil is first calculated from:

$$\text{maximum SMD} = -(20.0 + 1.3 (\% \text{ clay}) - 0.01 (\% \text{ clay})^2)$$

Thus, the maximum SMD obtained is that under actively growing vegetation. Where the soil is bare during a particular month, this maximum is divided by 1.8 to allow for the reduced evaporation from a bare soil. Next, the accumulated SMD is calculated from the first month when evaporation exceeds rainfall until it reaches the maximum SMD, where it stays until the rainfall starts to exceed evaporation and the soil wets up again. The factor 0.75 is conventional for converting open pan evaporation to evapotranspiration from a growing crop.

Finally, the rate modifying factor (b) used each month is calculated from the following rule:

$$\text{if } acc. SMD < 0.444 \text{ max. SMD,}$$

$$b = 1.0$$

$$\text{otherwise,}$$

$$b = 0.2 + (1.0 - 0.2) * \frac{(\text{max. SMD} - acc. SMD)}{(\text{max. SMD} - 0.444 \text{ max. SMD})}$$

The plant retainment factor (c) slows decomposition where growing plants are present. Where soil is vegetated, $c = 0.6$. Where soil is bare, $c = 1.0$.

In order to adapt the model to soil conditions other than those at Rothamsted, the model adjusts for soil texture by altering the partitioning between CO₂ evolved and BIO + HUM formed during decomposition, rather than by using a rate modifying

factor, such as that used for temperature. These calculations are provided here to show how the model allows for soil textural changes. The ratio $\text{CO}_2/(\text{BIO} + \text{HUM})$ is calculated from the clay content of the soil using the equation:

$$x = 1.67 (1.85 + 1.60 \exp(-0.0786 \% \text{ clay}))$$

where x is the ratio $\text{CO}_2/(\text{BIO} + \text{HUM})$.

Then, $x/(x + 1)$ is evolved as CO_2 and $1/(x + 1)$ is formed as $\text{BIO} + \text{HUM}$.

The scaling factor 1.67 is used to set the $\text{CO}_2/(\text{BIO} + \text{HUM})$ ratio in Rothamsted soils (23.4 percent clay) to 3.51; the same scaling factor is used for all other soils.

Radiocarbon measurements are commonly expressed in one of two ways:

- ▶ as percent modern, i.e. 100 (specific activity of the sample) / (specific activity of the standard);
- ▶ as the $\Delta^{14}\text{C}$ value, i.e. 1 000 (specific activity of the sample - specific activity of the standard) / (specific activity of the standard).

Thus, $\Delta^{14}\text{C} = 10 (\text{percent modern}) - 1\ 000$.

Radiocarbon age is related to $\Delta^{14}\text{C}$ in the model by the equation:

$$\Delta^{14}\text{C} = 1\ 000 \exp(-\text{radiocarbon age}/8\ 035) - 1\ 000$$

using the conventional half-life for ^{14}C (5 568 years).

The radiocarbon content of each year's input of plant C is taken to be the same as that of atmospheric CO_2 for the same year. The "radiocarbon activity scaling factor" in the model printout is the radiocarbon activity of the input for a particular year, expressed as either: (percent modern)/100, or $(\Delta^{14}\text{C} + 1\ 000)/1\ 000$, taking the value for the starting year of the Rothamsted long-term experiment (1859) as 1.

The age of the IOM fraction is set by default to 50 000 years, implying that it contains virtually no ^{14}C ($\Delta^{14}\text{C} = -998.0$) and that it is of geological age rather than pedological age. Coleman and Jenkinson (1995a) provide a detailed explanation of radiocarbon age calculations.

Preparation of input files for the model

In order to run the RothC model, it is necessary to prepare a series of input files that contain climate and soil information as well as land management information with and without the addition of FYM.

RothC-26.3 has been updated with a graphic user interface designed by Coleman and Jenkinson (1995a). This interface allows for the creation of climate and land management input files through a set of boxes and screens. It is useful in the preparation of input files to run the model. The climate files require the input of monthly average temperature, total monthly precipitation and total monthly open pan evaporation, as well as an input for both percentage clay in the soil and the soil depth. It is necessary to create a climate input file for each PCC. In practical situations, the extent of the area of influence (domain) of any meteorological station could cover several PCCs. Thus, the number of input files is reduced to the number of combinations of spatial domains of meteorological stations and soils.

The land management input files require the gathering and input of detailed data on management activities, particularly those related to carbon simulation, namely, the monthly inputs of organic matter to the soil. These must be defined in order to run the model. These values differ depending on the land cover type and the land use, which brings different amounts of C to the soil either in the form of litter or crop residues and organic manures. Non-tilled areas such as forests and natural grasslands or cropland and areas with cultivated grasses can be modelled by allowing the user to incorporate both litter inputs as well as any special applications of

FYM. These data may not be readily available for any given area. Thus, they may have to be generated. A simple method for the calculations of these inputs of organic matter into the soil system, applicable in the Latin American context, is described below.

The following calculations allow the user to estimate the monthly contribution of organic matter to the soil from the current LUT, without accounting here for additions of FYM. Typically, data on monthly contributions of organic matter by crops are not available in common records, hence the need for these calculations. The calculations require information related to the LUT and the crop mixes part of such LUT. Assuming that such variables are known, the calculations can proceed as follows:

- ▶ incorporation of dry organic matter from agricultural crops by crop type: $ms = [(Pa_i \times Cc_i) - H_i] \times Ea_i$. The results of this calculation need to be distributed among the months that the crop (i) stays in the field. Pa_i are the crop yields, Cc_i is the harvest intensity ratio (percent of total biomass that is harvested and removed), H_i is the moisture content in plant tissue of that species, and Ea_i is the crop residues including roots, as a percentage of total plant biomass.
- ▶ total additions of organic matter from herbaceous species (Bh) according to LUT: $Bh = \text{dry weight of collected biomass in } 1 \text{ m}^2 \times 10\,000 \times 0.55$. Bh is the aboveground total carbon content from herbaceous species sampled from the 1 x 1 m quadrat in the field. The value of 0.55 refers to the fraction, in grams of C per square metre, contained in the sample collected from the 1 x 1 m quadrat in the field. This latter value can be modified if the carbon content has been analysed.
- ▶ organic matter additions from summer pastures: $B_i = (F \times R)$, where B_i is the residual biomass after grazing by the herd, R is the grazing coefficient (the proportion of aboveground biomass not eaten by the herd), and F is the production of forage per hectare,

including roots. The residual animal manures incorporated into the soil due to pasturing can be estimated from: $Ep = [(F - (F \times R))/Nc_i] \times (1 - ICA_i)$, where Ep is the amount of animal manure left from grazing activities that is incorporated into the soil, ICA_i is the nutrition conversion index of forage, and Nc_i is the number head of livestock of a given species per grazing unit per hectare. Both partial results must be added and prorated over the 12 months of the year. In the existing case of several animal species present in the summer pasture, the same procedure must be applied for each one of the animal species present and the result summed into the total.

RothC-26.3 model parameterization

The RothC model requires initial parameter values of DPM, RPM, BIO, HUM and IOM, whose initial state is not known. The value of SOC present in the soil is the only parameter available. In order to obtain an estimate of the values on the compartments of SOM (i.e. DPM, RPM, BIO and HUM) that generated the present value of IOM in the current value of SOM, the model can be run backwards in time, setting the parameters DPM, RPM, BIO and HUM and their radiocarbon ages to zero and IOM to the current value implicit in the actual known value of SOM. By running the model backwards to “equilibrium” (10 000 years), it is possible to determine the values of the other compartments that generated the actual value of IOM in the current SOM. Typically, trial runs with varied additions of organic residues are performed backwards to equilibrium until the amounts of C left in the partitioned compartments are within narrow bounds of the present amount of SOM. This would indicate the values of the parameters of DPM, RPM, BIO, and HUM that generated the present value of IOM and SOM from 10 000 years ago. The model is thus parameterized. The values of DPM, RPM, BIO, HUM that are left in the final run (where the total SOM is within a reasonable bound of accuracy, i.e. within about 0.2 tonnes/ha of the present value of

SOM and IOM), are the starting values of the model to be run forward over the period for which simulation is wanted.

Calculation of the amount of organic matter in the soil for each site for which the model will run

Values of SOM and IOM for each instance (i.e. PCC or polygon) for which the model needs to be run should be calculated in advance of the runs for the period for which predictions are required. The reported values of SOM (percent) for each soil polygon of a soil map in the study area are obtained from a typical or representative soil profile, and converted to tonnes per hectare.

Runs to parameterize the RothC-26.3 model

The following steps describe the sequence of actions to run the model backwards in time to equilibrium so that it can be parameterized through trial runs using similar sequences of steps.

To run the RothC model, it is necessary to ensure that the input files are located in the same subdirectory as the executable program of the RothC model. The program runs interactively in an MS-DOS environment by typing the command “model26” and responding to the questions and prompts interactively as follows:

- ▶ a four-character name for the output file needs to be entered. The extension “out” is assigned automatically by the program to this output file.
- ▶ the name of the climate input file, with a “.dat” extension, is requested by the program and needs to be entered together with the extension.
- ▶ the user is asked to select whether to run the model as “short term” (when the model has already been parameterized and the amounts of C within each compartment are known), or to run the model to equilibrium (i.e. run it backwards to define the amount of C within each compartment according to the current climate, soil and management characteristics).
- ▶ the next step asks the user to define, in tonnes of C per hectare, the amount of C stored in each compartment of the model. To run the model to equilibrium, all compartments are initially set to zero, except for IOM, which reflects the amount of organic matter in the soil (from soil profile data).
- ▶ selection of the value of the DPM/RPM ratio as either predefined by land use, i.e. model-suggested default values for agricultural land (1.44), unimproved grassland and shrubs (0.67), deciduous and tropical woodland, or as defined by the user.
- ▶ the land management input file is requested next, the user must select a previously created land management file, including its “.dat” extension.
- ▶ selection of period and output parameters, such as returning results for every year, or just the last year (for the equilibrium model, only the results for the last year of the model should be requested to avoid excessive unnecessary output) and the starting month for the model, which, typically, can be set to January.

The model runs to equilibrium and yields initial model parameters. Trials are carried out recurrently by changing the values of inputs of organic residues slightly until the resulting total level of SOC is very close to that of the current value of SOC in the SOM. This procedure is repeated for each PCC or each soil polygon, land cover polygon or land facet polygon for which the model is to be run to generate predictions.

Soil carbon dynamics modelling and scenario generation for specific time periods

Once parameterized, the model is run under current conditions of soil climate and management for a given time period. This time period could be, for example, the first commitment period (as established in the Kyoto Protocol). The first set of runs is without any inputs of FYM as management. This generates a set of scenarios of carbon dynamics without FYM. Then, the model is run with the

inputs of FYM equivalent to likely or desirable changes in crop and land management. This second set of runs produces a set of scenarios with improved management, which the analyst can compare with the scenarios without management (FYM) for the same time periods. These scenarios provide for the possibility of establishing comparisons and observing the effects of management in SOC dynamics. Given the frequent shortage of quantitative information about additions of FYM in Latin American countries, two alternatives may be pertinent:

- ▶ the deliberate, planned gathering of this type of information from field surveys and interviews with farmers and local researchers in the study area.
- ▶ the use of assumed “educated” values of FYM that may be as realistic as possible, given background knowledge and information about the management in the study area.

As the model has already been parameterized for current conditions, running the model in “short term” mode will produce estimations of the amount and distribution of C in soil, and that released to the atmosphere as CO₂ by component, for a defined period of time in the future. The case studies reported in this document used model runs with and without FYM additions for each cell and present land use for a projected period of 50 years. The final results of these simulations appear in the case studies reported in this report.

Modelling with the CENTURY model

The CENTURY model simulates the long-term dynamics of C, nitrogen (N), phosphorus (P), and sulphur (S) for different plant–soil systems. The model can simulate the dynamics of grassland systems, agricultural crop systems, forest systems, and savannah systems. The grassland/crop and forest systems, have different plant production submodels that are linked to a common SOM submodel. The savannah submodel uses the grassland/crop and forest subsystems and allows for the two subsystems to interact through shading effects and nitrogen

competition. The SOM submodel simulates the flow of C, N, P and S through plant litter and the different inorganic and organic pools in the soil. The model runs using a monthly time step. A detailed description of the model (CENTURY 4) used in this study and other important information is available at <http://www.nrel.colostate.edu/projects/century/nrel.htm>. Model documentation is available in Parton *et al.* (1992).

A new release of the model (CENTURY 5) is available for downloading at <http://www.nrel.colostate.edu/projects/century5/>

Input variables

The major input variables for CENTURY include:

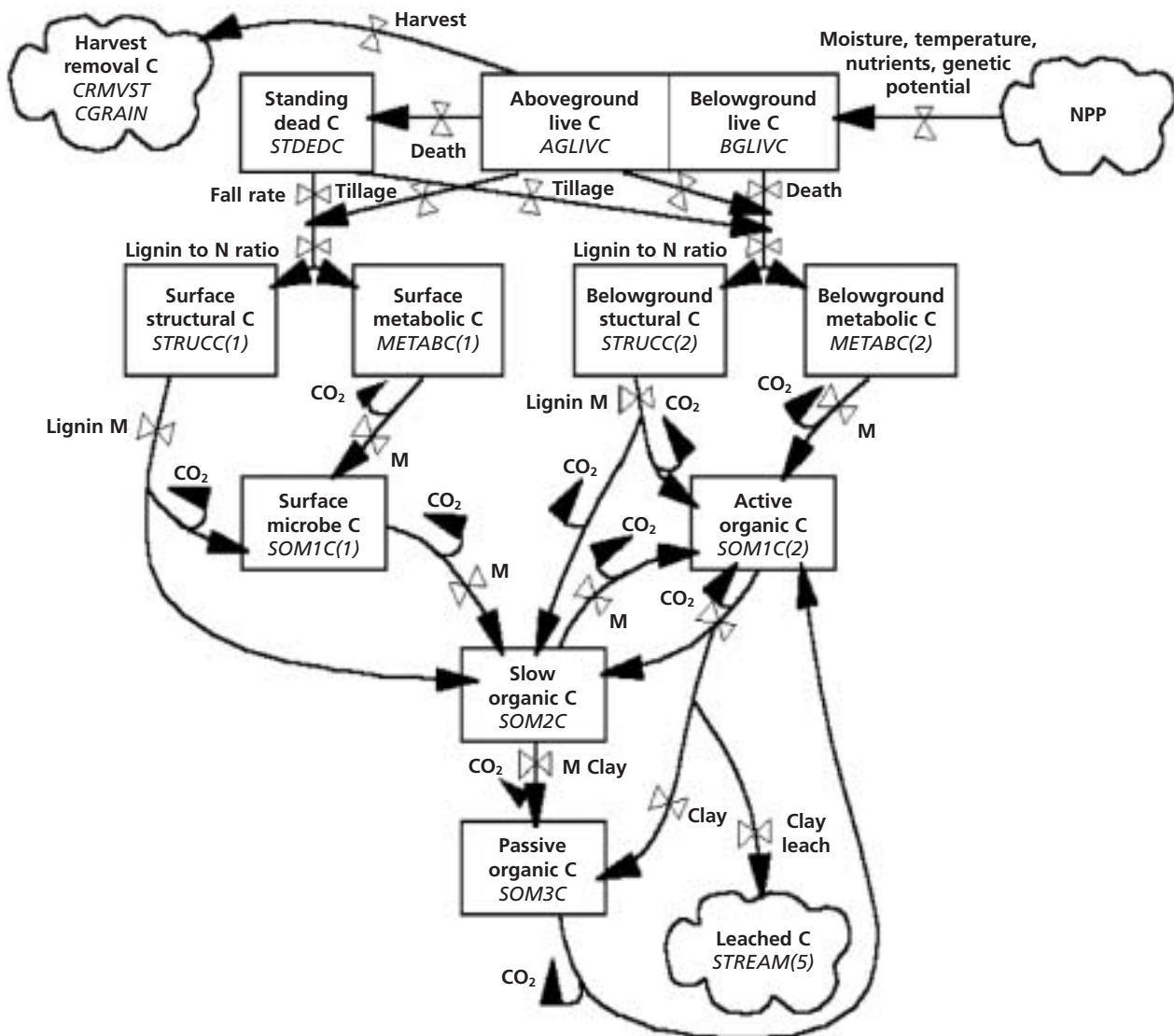
- ▶ monthly average maximum and minimum air temperature,
- ▶ monthly precipitation,
- ▶ lignin content of plant material,
- ▶ plant N, P and S content,
- ▶ soil texture,
- ▶ atmospheric and soil N inputs,
- ▶ initial soil C, N, P and S levels.

These input variables are available for most natural and agricultural ecosystems and can generally be estimated from existing literature. Most of the parameters that control the flow of C in the system are in the fix.100 file that is part of the system files. The user can choose to run the model considering only C and N dynamics (NELEM = 1), or C, N and P (NELEM = 2), or C, N, P and S (NELEM = 3).

Structure of the SOM submodel in CENTURY

The SOM submodel is based on multiple compartments for SOM and is similar to other models of SOM dynamics (Jenkinson and Rayner, 1977; Jenkinson, 1990; van Veen and Paul, 1981). Figure 10 illustrates the pools and flows of C. The model includes three SOM pools (active, slow and passive) with different potential decomposition rates, aboveground and belowground litter pools, and a surface microbial pool, which is associated with decomposing surface litter.

FIGURE 10 – Structure of the SOM and carbon submodel in CENTURY (after Parton *et al.*, 1992)



With increased N in the residue in the ratio, more of the residue is partitioned to the structural pools, which have much slower decay rates than the metabolic pools. The structural pools contain all of the plant lignin (STRLIG(*)).

The decomposition of both plant residues and SOM are assumed to be microbially mediated with an associated loss of CO₂ (RESP(*)) as a result of microbial respiration. The loss of CO₂ on decomposition of the active pool increases with increasing soil sand content. Decomposition products flow into a surface microbe pool (SOM1C(1)) or one

of three SOM pools, each characterized by different maximum decomposition rates. The potential decomposition rate is reduced by multiplicative functions (DEFAC) of soil moisture and soil temperature and may be increased as an effect of cultivation (CLTEFF(*), cult.100). Average monthly soil temperature near the soil surface (STEMP) is the input for the temperature function while the moisture function uses the ratio of stored soil water (0–30 cm depth, AVH2O(3)) plus current month precipitation (RAIN) to potential evapotranspiration (PET). The decomposition rate of the structural material (STRUCC(*)) is a function of the fraction of the

structural material that is lignin. The lignin fraction of the plant material does not go through the surface microbe (SOM1C(1)) or active pools (SOM1C(2)) but is assumed to go directly to the slow carbon pool (SOM2C) as the structural plant material decomposes.

Aboveground and belowground plant residues and organic animal excreta are partitioned into structural (STRUCC(*)) and metabolic (METABC(*)) pools as a function of the lignin to no lignin ratio.

The active pool (SOM1C(2)) represents soil microbes and microbial products (total active pool is ~2 to 3 times the live BIO level) and has a turnover time of months to a few years depending on the environment and sand content. The soil texture influences the turnover rate of the active soil SOM (higher rates for sandy soils) and the efficiency of stabilizing active SOM into slow SOM (higher stabilization rates for clay soils). The surface microbial pool (SOM1C(1)) turnover rate is independent of soil texture, and it transfers material directly into the slow SOM pool (SOM2C). The slow pool includes RPM derived from the structural pool and soil-stabilized microbial products derived from the active and surface microbe pools. It has a turnover time of 20–50 years. The passive pool (SOM3C) is very resistant to decomposition and includes physically and chemically stabilized SOM and has a turnover time of 400–2 000 years. The proportions of the decomposition products that enter the passive pool from the slow and active pools increase with increasing soil clay content. A fraction of the products from the decomposition of the active pool is lost as leached organic matter (STREAM(5)). Leaching of organic matter is a function of the decay rate for active SOM and the clay content of the soil (less loss for clay soils), and only occurs where there is drainage of water below the 30-cm soil depth (leaching loss increases with increasing water flow up to a critical level – OMLECH(3), fix.100).

Anaerobic conditions (high soil water content) cause decomposition to decrease. The soil drainage

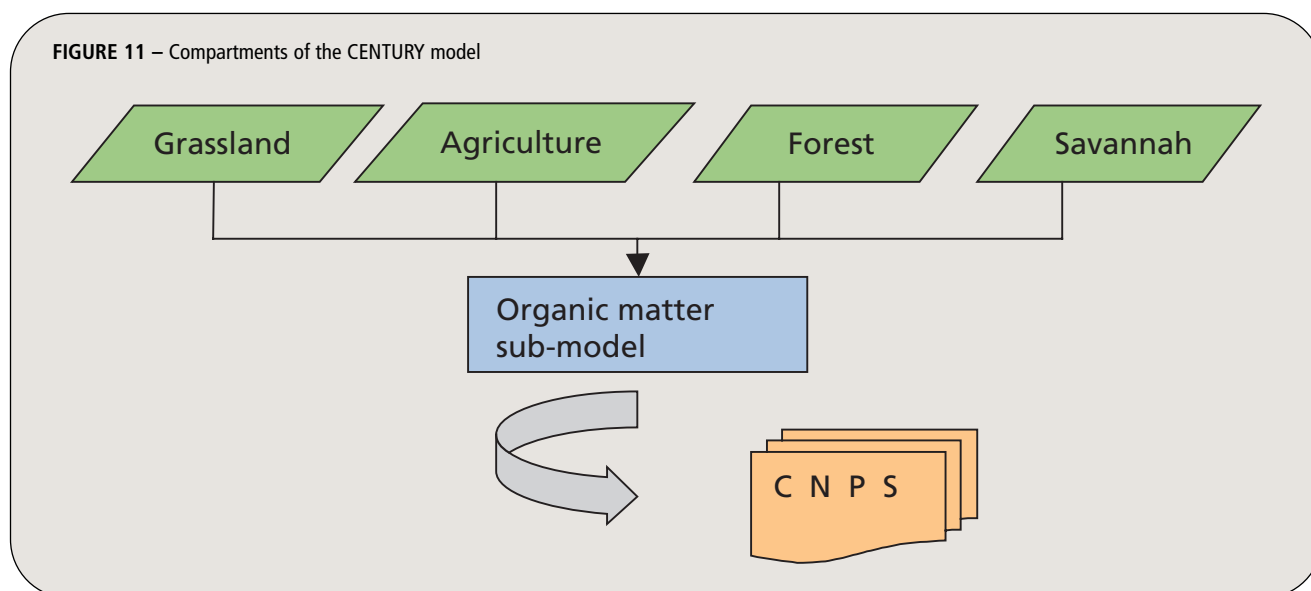
factor (DRAIN, <site>.100) allows a soil to have differing degrees of wetness (e.g., DRAIN = 1 for well drained sandy soils, and DRAIN = 0 for a poorly drained clay soil). A detailed description of the structure of an earlier version of the model and the way in which model parameters were estimated is given in Parton *et al.* (1987).

The model has N, P and S pools analogous to all of the carbon pools. Each SOM pool has an allowable range of C to element ratios based on the conceptual model of McGill and Cole (1981). Reflecting the concept that N is stabilized in direct association with C, C/N ratios are constrained within narrow ranges, while the bonds of P and S allow C/P and C/S ratios to vary widely. The ratios in the structural pool are fixed at high values, while the ratio in the metabolic pool is allowed to float in concert with the nutrient content of the plant residues. The actual ratios for material entering each SOM pool are linear functions of the quantities of each element in the labile inorganic mineral pools in the surface soil layers (MINERL(1,*)). Low nutrient levels in the labile pools result in high C to element ratios in the various SOM pools. The N, P and S flows between SOM pools are related to the carbon flows. The quantity of each element flowing out of a particular pool equals the product of the carbon flow and the element to C ratio of the pool. Mineralization or immobilization of N, P and S occurs as is necessary to maintain the ratios discussed above. Thus, mineralization of N, P and S occurs as C is lost in the form of CO₂ and as C flows from pools with low ratios, such as the active pool, to those with higher ratios, such as the slow pool. Immobilization occurs when C flows from pools with high ratios, such as the structural pool, to those with lower ratios, such as the active pool. The decomposition rate is reduced if the quantity of any element is insufficient to meet the immobilization demand.

Functional structure of CENTURY

The CENTURY model simulates the dynamics of C, N, P and long-term S in agricultural, forest,

FIGURE 11 – Compartments of the CENTURY model



grassland and savannah systems. Figure 11 shows the subdivision of modules in these four categories and their input to the SOM submodel.

The model requires inputs of variables related to the status of C, N, P and S in the soil. The complexity and completeness of the CENTURY model is commensurate with the relatively large amounts of detailed data required to run the model of organic matter, or any of the other submodels. If the focus of study is the dynamics of C, the subset of variables required to run the model decreases in size, variables do not need to be initialized for submodels other than the SOM submodel. Information and data about all of the variables requested by CENTURY on input is not absolutely required. Data collection can be limited to only the necessary variables to obtain single carbon calculations.

As indicated earlier, the CENTURY model recognizes three types of organic materials in soils depending on their decomposition rates: resistant, slow and fast. Single calculations will require variables related to these partitions.

Information required by CENTURY per mapping unit, PCC or site

The information required by CENTURY can be divided into two types:

- ▶ site characteristics data, that is, data related to the type of land mapping unit or land facet and the type of ecosystem sustained by such unit;
- ▶ data on variables necessary for the parameterization of the model in the context of the particular ecosystem to be analysed.

For site variables, the information required by mapping unit, PCC or site is:

- ▶ precipitation, monthly averages (from the climate station of influence);
- ▶ maximum air temperature (monthly maximum temperature from the climate station of influence);
- ▶ minimum air temperature (monthly minimum temperature from the climate station of influence);
- ▶ content of lignin in the plant material;
- ▶ content of N, P and S in the plant material;
- ▶ texture of the soil;
- ▶ initial contents of total S, C, N and P in the soil;
- ▶ schedule of agricultural, livestock or forestry activities;
- ▶ levels and amounts of agricultural inputs used during the management cycle;
- ▶ production by LUT (crop yields or other units of LUT output in tonnes per hectare);

- ▶ soil erosion (as soil losses in kilograms per square metre);
- ▶ date of disturbances (e.g. incidence of fire, clearings or other disturbing phenomena during the study period).

Regarding specific data and information on the LUT or ecosystem under study, CENTURY models SOC on the basis of three major kinds of land use: agricultural, grassland and forest. These are selected in the model with the variable “ivauto”. Table 8

shows the codes used in CENTURY to define each of these three land-use types.

Table 9 shows the specific information needed to parameterize the model for each ecosystem or major kind of land use (as states of “ivauto”) in three columns, each containing the required information for the land-use identifier ivauto. The table is subdivided vertically in three blocks that correspond to three thematic modules of parameterization.

TABLE 8 – Codes used in CENTURY to define each of the major land-use types

ivauto	Major kind of land use
0	Forest
1	Grassland
2	Agricultural

TABLE 9 – Specific information by major kind of land use for CENTURY

CONCEPT	0	ivauto 1	2
Module 1			
Bulk density	x	x	x
Number of soil layers or soil profile horizons	x	x	x
Drainage pattern	x	x	x
Permanent wilting point of the soil (soil moisture)	x	x	x
Field capacity of the soil (soil moisture)	x	x	x
pH	x	x	x
Module 2			
Labile organic C (g/m ²)	x		
Non-labile organic C (g/m ²)	x		
C/N ratio per soil layer	x	x	x
Initial inputs of plant residues (g/m ²)	x		
C/N ratio of litter on soil	x	x	x
C/N ratio of the soil organic horizon	x	x	x
Value of the C isotope in land cover (litter) (g/cm ²) ¹	x		x
Initial value of belowground active C ²	x		x
Initial value of belowground active N ³	x		x
Module 3			
Amount of C in foliage in the forest system	x		
Amount of N in foliage in the forest system	x		
Amount of C in fine and coarse branches	x		
Amount of N in fine and coarse branches	x		
Amount of C in fine and coarse roots	x		
Amount of N in fine and coarse roots	x		
Initial amount of C in dead material	x		

¹ Values of DPM and RPM generated by RothC may be used as non-labile and labile C, respectively.

² Values may be derived from data from other models (e.g. IOM, RPM and DPM of RothC-26.3, which can be identified as labile and non-labile fractions).

³ A value of N must be assigned; although this study does not require nitrogen simulation, the system models C and N simultaneously.

FIGURE 12 – Relationship between programs and file structures in the CENTURY model

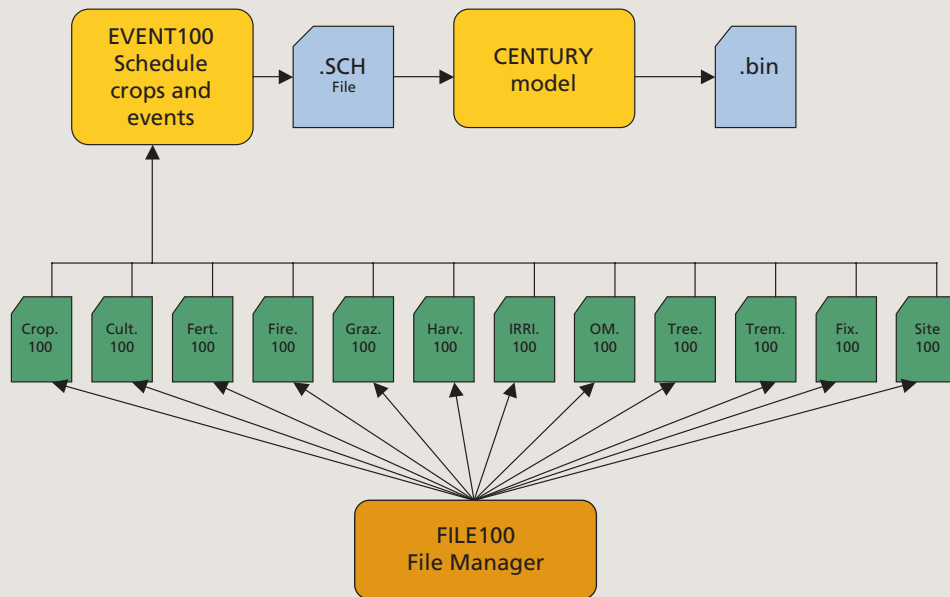


Figure 12 shows the relationship between the program modules and the file structures in the CENTURY model.

The files shown in the lower part of the chart in Figure 12 correspond to the 12 variants or components of management. Each one of these variants accounts for a large number of variables. These variant components are files within the “FILE100” structure. The large number of variables and management parameters implicit in the variants of the FILE100 structure is excessive for practical situations, particularly in conditions in the developing world. The CENTURY model may be driven by as many as nearly 650 different variables with an abundant number of variants in each of them.

It would be practically impossible to use this model if initial values for most of those parameters did not exist and had to be initialized from no values at all. In most practical situations, it is almost impossible to record so many variables in such detail. However, the CENTURY research team has generated values and tested them experimentally in a range of ecosystems. These values of parameters for

the major kinds of land use (variable “ivauto”) can be used reliably as standard default values where field data are not available in any given situation. The important issue here is the good selection of the ecosystem type for which files of those standard parameters exist, and which ought to be similar or resemble the ecosystem to be modelled. The resemblance between the modelled ecosystem and the standard ecosystem files for which the model can be parameterized should be as close as possible.

It is not known with certainty, and for all situations, how robust the model is to changes in these parameters and their approximations in terms of model results with experimental data and controlled comparisons. However, the model developers (Parton *et al.*, 1994) recommend that for reliable simulations it is best to use parameters from standard tried ecosystems suggested by the CENTURY research group, rather than to manipulate nearly 650 variables individually for which no data may be available, and for which only guesses could be made, as unpredictably wild results could be obtained in the latter situation. For example, file IRRI.100 stores four variables, the values of which have been determined through

TABLE 10 – Variables describing irrigation in CENTURY

IRRI.100 variable	DESCRIPTION
Auirri	Controls application of automatic irrigation = 0 automatic irrigation is off = 1 irrigate to field capacity = 2 irrigate with a specified amount of water applied = 3 irrigate to field capacity plus PET
Fawhc	Fraction of available water holding capacity below which automatic irrigation will be used when auirri = 1 or 2
Irraut	Amount of water to apply automatically when auirri = 2 (cm)
Irramt	Amount of water to apply regardless of soil water status (cm)

TABLE 11 – Parameters of file IRRI.100

Parameters	A50	A25	A15	A75	A95	AF	F5	Flood
Auirri	1.0	1.0	1.0	1.0	1.0	2.0	0.0	0.0
Fawhc	0.75	0.25	0.15	0.75	0.95	0.25	0.0	0.0
Irraut	0.0	0.0	0.0	0.0	0.0	10.0	0.0	0.0
Irramt	0.0	0.0	0.0	0.0	0.0	0.0	5.0	15.0

experimental analysis of several levels of irrigation (Table 10). Experimental values with different levels of irrigation have been assigned for each variable (Table 11).

Thus, when irrigation is applied at 50 percent of soil field capacity, the system will assign automatically the values corresponding to the column A50, and respectively for each level of irrigation. Because of this format, CENTURY has the possibility of being driven by nearly 650 different variables with an abundant number of variants.

The upper part of Figure 12 shows the scheduling of crops and events. These schedules require information pertaining to the SITE.100 files (site characteristics) to create a schedule file (*.sch). The schedule file is created through running the executable program “event100.exe”. Once created, this schedule file will contain all the necessary information by the model to describe crop and soil management activities for each LUT.

In order to run the CENTURY model successfully, it is necessary to generate the schedule file (*.sch) recording all management information. This in turn requires the information stored in the specific FILE100 file corresponding to the particular ecosystem that resembles the site under study. For this reason, detailed descriptions are provided below of the processes to generate both the FILE100 – including the modifications that made for modelling each site – and the schedule file through the EVENT100 routine.

Input of initial parameters through the FILE100 routine

The executable FILE100.exe is run in CENTURY as an MS-DOS command: <c:\century\file100>. A menu of options appears in the main window where the 12 types of FILE100 are listed (Figure 12). On selecting one of the first 11 options, the following menu appears:

What action would you like to take?

0. Return to main menu
1. Review all options
2. Add a new option

3. *Change an option*

4. *Delete an option*

5. *Compare options*

Enter selection:

With this menu it is possible to modify the FILE100 created by the developers of the model (University of Colorado, the United States of America), used as default for each ecosystem type. The developers do not recommend attempting to modify the default file corresponding to the ecosystem of interest in its entirety because of the hundreds of variables involved. Some of the variables required to complete the site parameterization of the model are extremely specific. In most practical circumstances, data for all such variables will not be available. Thus, the CENTURY team recommends, as the most pertinent method for entering site variables, the selection of the option (“standard” ecosystem file) that is most similar to the site to be modelled.

Returning to the initial FILE100 menu, the selection of the Site.100 option where the specific information for each site will be entered, a Site.100 file that most closely reflects the characteristics of the study site should be modified. In this option, the menu that appears is:

Which subheading do you want to work with?

0. *Return to main menu*

1. *Climate parameters*

2. *Site and control parameters*

3. *External nutrient input parameters*

4. *Organic matter initial parameters*

5. *Forest organic matter initial parameters*

6. *Mineral initial parameters*

7. *Water initial parameters*

Enter selection:

In this menu, the variables that describe the site can be input. Option 1 allows the input of data corresponding to the precipitation per month, the standard deviation of the precipitation and its skewness per month, as well as the minimum and maximum temperatures per month. Option 2 allows

for the selection of site and control parameters. Here, the variable “ivauto” determines the LUT or ecosystem to be analysed. This parameter is pivotal and crucial to the choice of many other subsequent parameters. Based on its value, all other variables referred to in Module 1 (Table 9) are determined. The remaining variables retain the values in the standard Site.100 reference file.

As the objective of the methodology is the simulation of the SOC dynamics, and as the dynamic processes of C in SOM turnover are related closely to those of N, the option to simulate C and N together is justified. In CENTURY, the option to simulate only C does not exist. As far as the input of parameters of external nutrients is concerned, the variables are specific for the modelling of N and S. They should not be modified unless accurate measurements of such parameters are available, provided the default values are similar to those of the conditions of the studied site.

In Option 4, variables that are part of Module 2 (Table 9) are input. Variables in this module correspond to the specifics of C and N fractions in different morphological constituents of organic matter sources. Once these values have been input, the remaining variables are set to the default values or are assigned a value of 0, except for those that correspond to the initial N contents in the subsoil for live and inert materials. These values are assigned according to the C/N ratio of plant materials incorporated into the soil.

The variables in Module 3 (Table 9) are essentially the C and N in foliage, branches and roots. These data are input into the model in Option 5, for the simulation of forest ecosystems.

The two last options in the CENTURY menu listed above do not need to be modified. This is because the values in the standard default file containing this information satisfy the requirements of the model and its variants to obtain output values of N, P and S.

Scheduling land management options through the EVENT100 routine

The file EVENT100 was designed to include the information referring to crop and land management and other human influence on the sites being modelled. In this file, all the management activities are registered, such as the anthropogenic input of nutrients, disturbances, the specification of the periods of simulation and soil use.

The program EVENT100.exe will produce files with the extension *.sch that record the events to occur during the simulation. The schedule file becomes the basis for running the CENTURY model. Within the schedule file (*.sch), it is possible to provide detailed information to the model about the human activities that could affect the dynamics of C, such as agricultural practices and the use of chemicals, as well as the possibility of inserting the proposed standard or default variables used by the CENTURY research team, through the files Crop.100 and Tree.100. This executable program offers the possibility of changing the management regime monthly as well as by year.

The schedule (*.sch) files are created in the same subdirectory as the CENTURY model, and run with the executable program EVENT100.exe <c:\century\event100>. On execution of such command in the MS-DOS environment, the program requests the name of the FILE100 for which a schedule is to be created. The option whether or not to label C is then requested. The program also requires information as to whether or not a microcosm is to be simulated. This refers to simulation under laboratory experimental conditions. For studies on carbon stock and sequestration implicit in LUCs, it is not necessary to simulate a microcosm in lab conditions. These last two options can be set to the defaults. The user continues selecting the alternatives that reflect the conditions of the area to be evaluated, as well as the recommendation of the stochastic handling of the climate values of Site.100.

The scheduling is set up by blocks of time (years) for which activities are planned in the DOS environment through a combination of commands (bottom row of screen) and management activities to be scheduled (left column) over the months (remaining columns) in a screen similar to that depicted in Figure 13.

FIGURE 13 – Scheduling input screen

Block # 1 Year: 1 of 2 Start: 1920 End: 1950 Comment: W-F

Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

CROP
PLTM
HARV
FRST
LAST
ENM
FERT
CULT
OMAD
IRRI
GRAZ
EROD
FIRE
TREE
TREM
TFST
TLST

System commands: FILL NEXT NXTA GOMT NXYS GOYR CPYR NBLK GBLK
ABLK DBLK CBLK TIME PREV DRAW DRWA HELP SAVE QUIT

Current dates: January of Year 1

User command: _

While the keys in the left-hand column refer to anthropogenic activities, the commands for manipulation of the screen are in the lower part. These are used to specify all the crop and land management activities, disturbances, as well as other events during the year or the block of time being analysed. For a full description of each of the management options listed in the left-hand column of the screen, the reader is referred to the CENTURY model operations manual. This step concludes the parameterization and data input into the model.

Running the CENTURY model

Once the site and control parameters have been input, and the crop and land management activities scheduled through the EVENT100 program, the model can be run. In the MS-DOS environment, the CENTURY subdirectory is accessed, and the model is run by providing a command which contains the name of the schedule file as well as the name of the output file on which the results of the run will be placed. This last file will have the results in binary format. The command has the following structure: `<c:\century\ century -s schedule filename -n output filename>` (both filenames without extension).

Given the fact that the volume of output data from the CENTURY model could be an enormous amount of information (almost 600 variables for each time block specified over the entire study period), the output is stored as a binary file (*.bin extension). The output refers to the multiple details of variables C, N, P and S. To access the results of interest to any given project, specific variables for specific years are selected from within the assembly of variables stored in the binary file. These selected variables can then be imported into spreadsheets and databases for manipulation and linkage into the GIS. The CENTURY model offers a utility for conversion from binary to ASCII formats. The LIST100 program is an executable file that creates output in ASCII format (*.lis extension) from the binary file (*.bin). The command and interactive dialogue are:

```
<C:\century\list100>
Enter name of binary input filename (not bin):
Enter ASCII output filename (not .lis):
Enter the starting Time, press < return >
for beginning of time:
Enter ending Time, press < return >
for ending time:
Enter variable, (one to per line), press < return >
to enter or after blank to quit:
```

The variables that are deemed relevant for carbon sequestration projects are those related to the fluxes of C in soil and CO₂ release. Relevant variables include: som1c(1), som2c, som3c and totc for SOC dynamics, and amt1co2, amt2co2, as11c2, as21c2, as2c2 and as3c2 for C lost to the atmosphere as CO₂. The resulting ASCII file with extension “lis” contains the list of the selected variables for output. From this file, the results can be entered in a spreadsheet program and manipulated and graphed. They can also be placed in database format for linkage to GIS databases for spatial representation of results.

The case studies in this report include scenarios of carbon dynamics with different levels of inputs of crop and organic residues. These range from no management at all to realistic levels of inputs of crop residues for the areas studied. These scenarios were generated with both the RothC-26.3 and CENTURY models.

Software customization of the input/output interface of the CENTURY model – “Soil-C”

Given the complexity and the degree of difficulty involved in inputting data, creating management scenarios, parameterizing and running the CENTURY model by non-experts, it became clear that a more user-friendly graphic user interface was needed. This interface would enable non-expert users to access and run the model and to obtain useful results in situations of routine assessment of carbon stock and sequestration. During the customization of the software, it became apparent that a facility for selecting output parameters and a

link to a GIS for spatial representation of modelling results were desirable.

The project generating this report undertook the customization of the CENTURY model input/output interface and GIS link. The full documentation of the customization effort can be found in Ponce-Hernandez *et al.* (2001). A summary description of the customization is presented in this report.

The graphical user interface (named “Soil-C”) was created as a GIS training project between Trent University and Sir Sanford Fleming College, Canada, and sponsored by FAO. Soil-C consists of a suite of programs written in Visual Basic computer language that interface with the model CENTURY (version 4.0) (available at <http://www.nrel.colostate.edu/projects/century/nrel.htm>).

To run the Soil-C interface programs, it is necessary to have installed:

- ▶ ESRI ArcView GIS version 3.2 or above,
- ▶ Microsoft Excel (version 97 or 2000),
- ▶ CENTURY (version 4.0).

The options on the main screen (Figure 14) introduce the user to a hierarchy of menus:

- ▶ input site data (equivalent to input data through “FILE100”).
- ▶ input management data (equivalent to input “EVENT100” parameters and creation of the schedule files).
- ▶ select output variables (equivalent to choose output variables through “LIST100”).
- ▶ GIS output definition.
- ▶ run CENTURY.

Figures 14–19 show the initial sequence of screens for data input (Visual Basic forms). The CD-ROM accompanying this report contains a demo of the Soil-C interface program, the Soil-C program and the user manual.

The experience gained by running the model for the generation of several land-use scenarios through case studies was an important factor in the decision to customize the interface to the CENTURY model. It is believed that users of the model can save considerably on learning time by using the interface, provided the results they need are simple enough to be within the capabilities included in the customization.

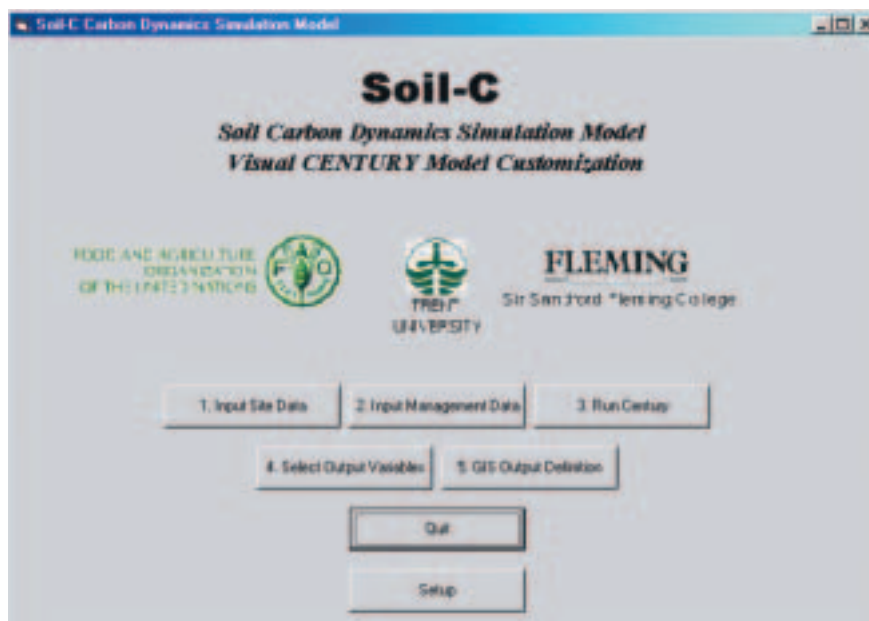


FIGURE 14
Initial screen of the Soil-C interface

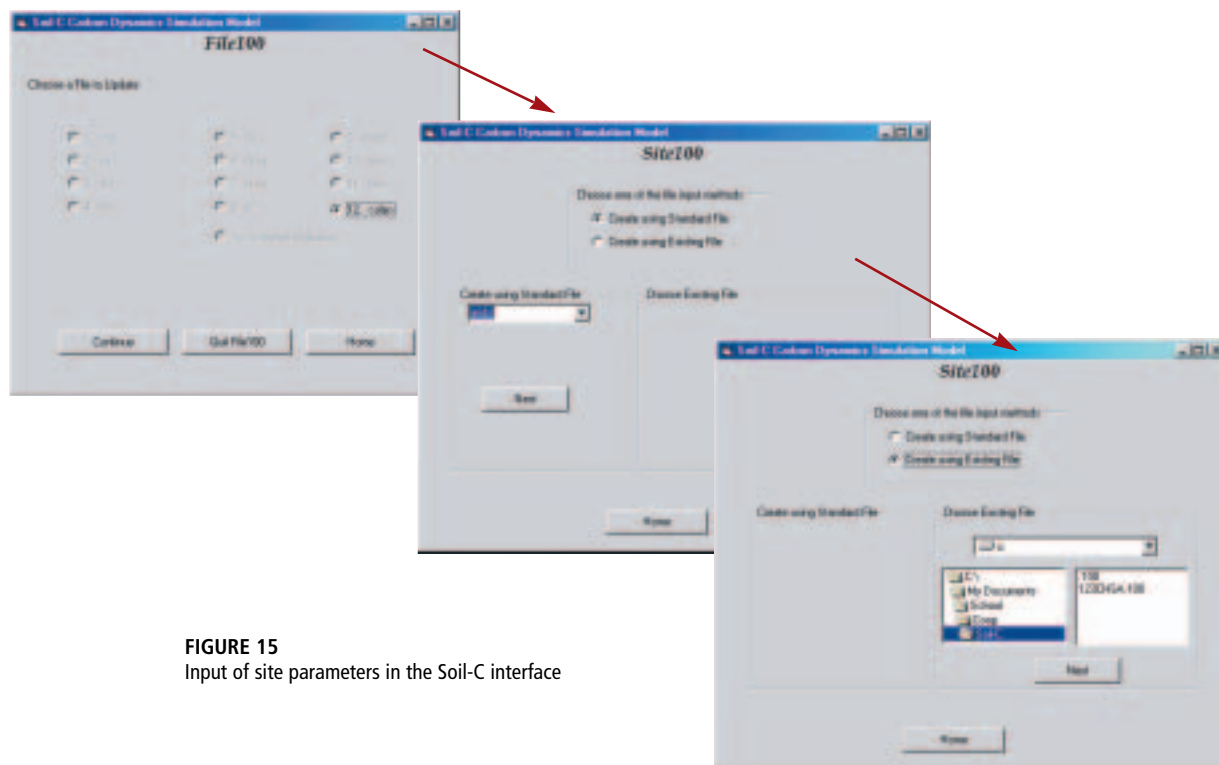


FIGURE 15
Input of site parameters in the Soil-C interface

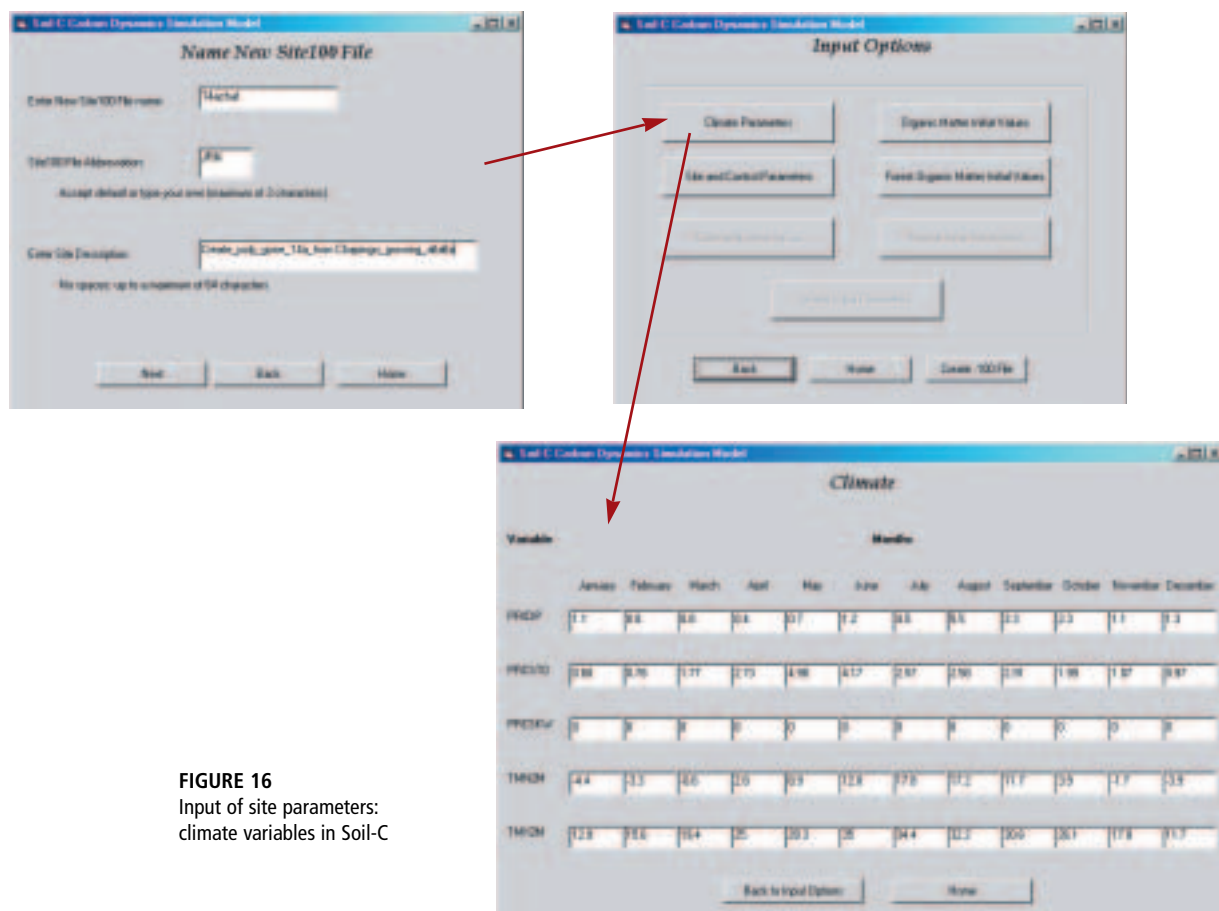


FIGURE 16
Input of site parameters:
climate variables in Soil-C

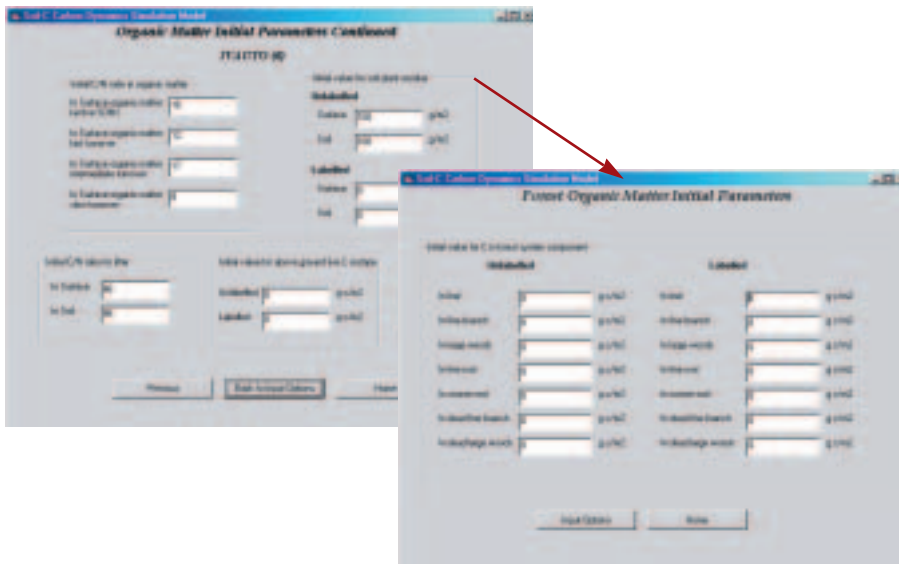


FIGURE 17
Organic matter initial parameters
for specific ecosystems

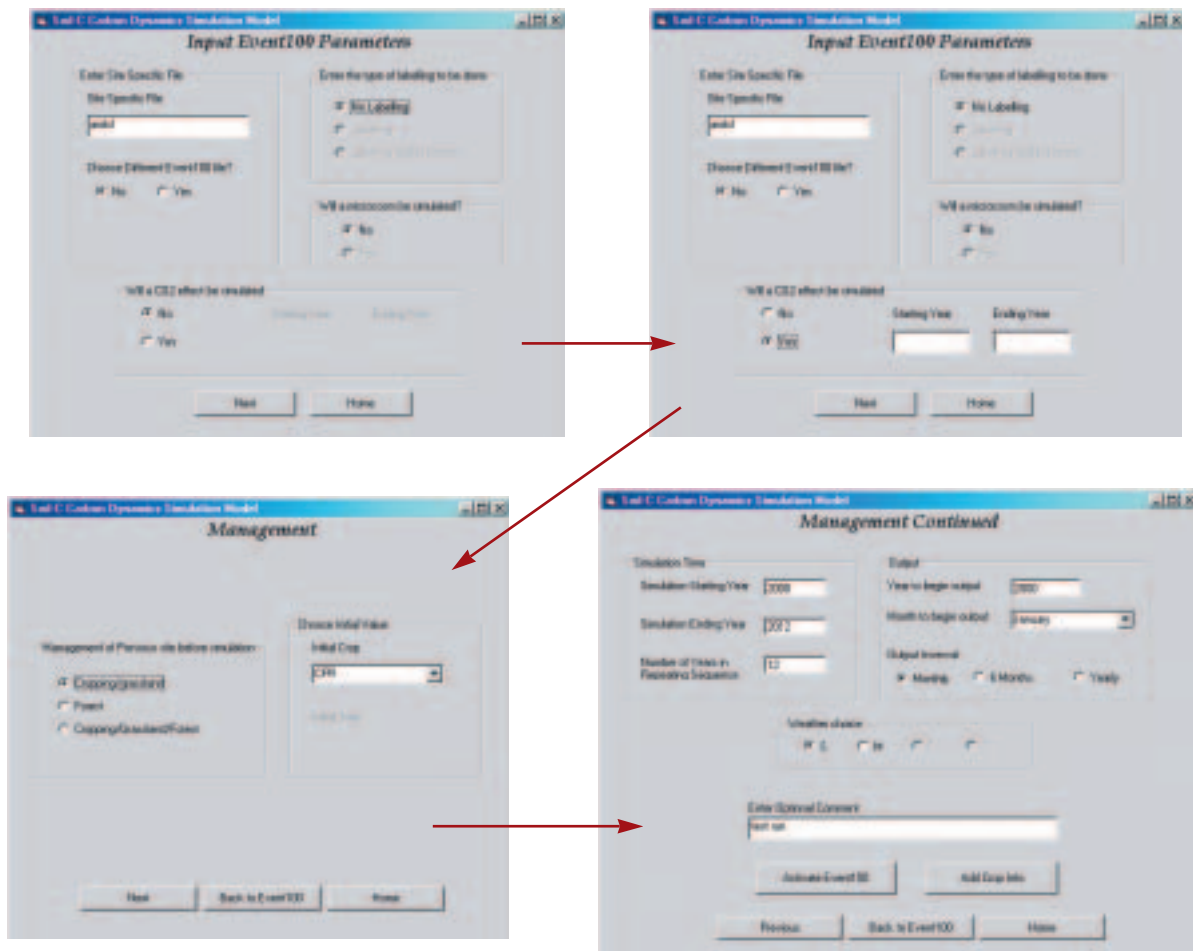


FIGURE 18
Scheduling events and management
with the Soil-C interface

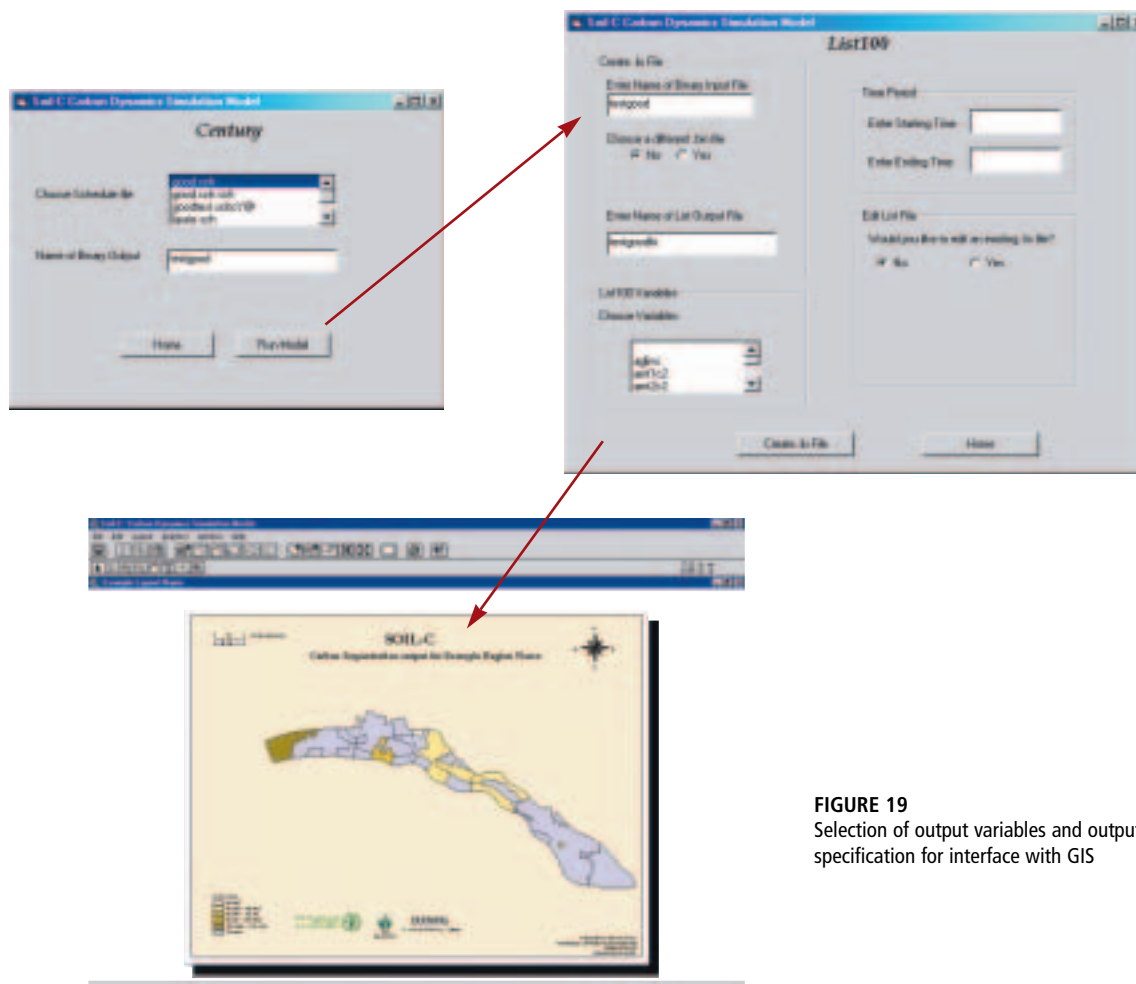
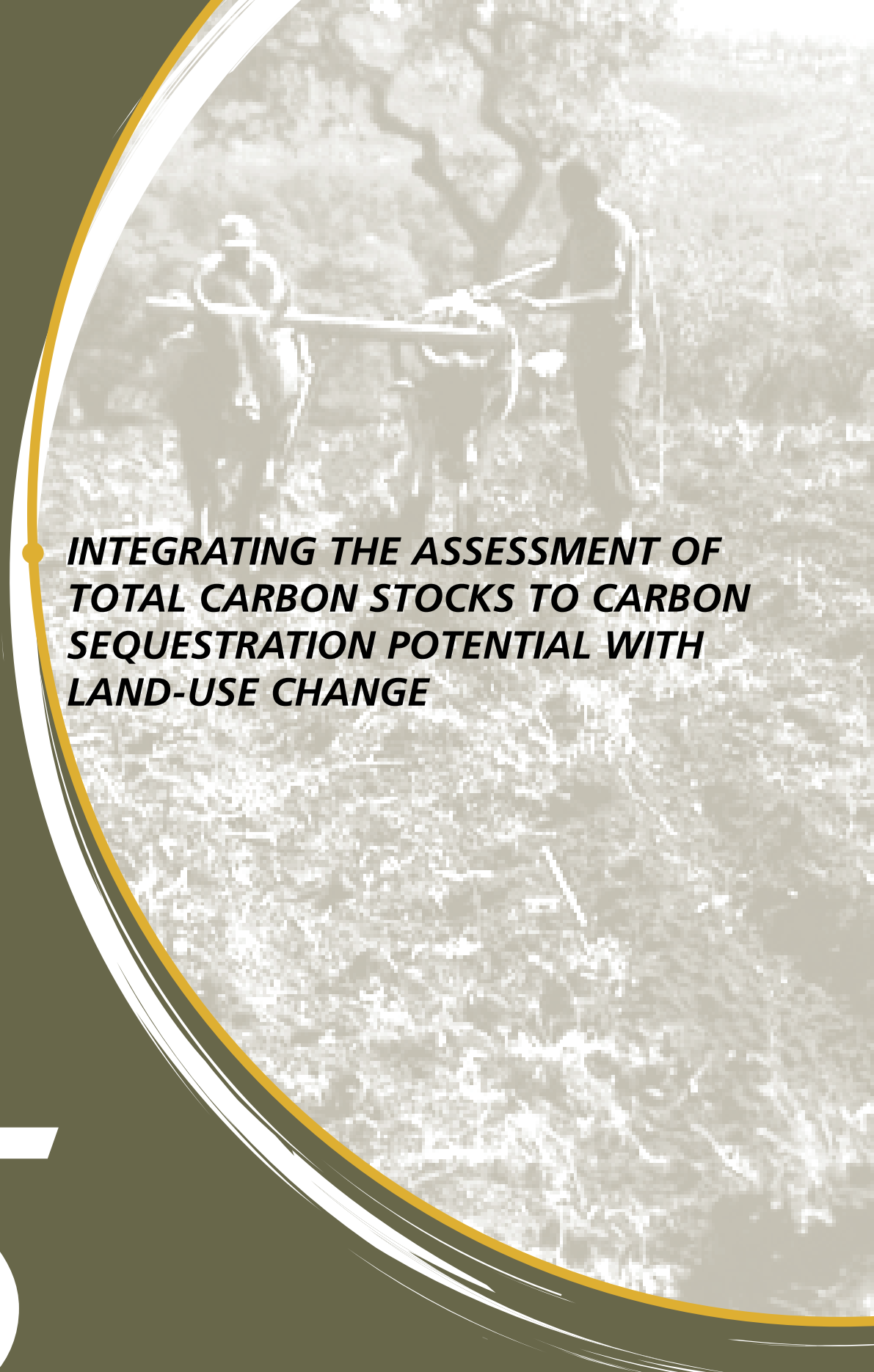


FIGURE 19
Selection of output variables and output file
specification for interface with GIS

CHAPTER 5



***INTEGRATING THE ASSESSMENT OF
TOTAL CARBON STOCKS TO CARBON
SEQUESTRATION POTENTIAL WITH
LAND-USE CHANGE***

CHAPTER 5

Integrating the assessment of total carbon stocks to carbon sequestration potential with land-use change

The procedures described in the preceding chapters relate to the assessment of carbon stock aboveground and belowground. Simulation models were used to predict the turnover of SOC in SOM at different time periods. Having computed values for carbon stock in each of the carbon pools, attention can turn to the completion of the carbon accounting process.

Total carbon stock for present land use

For carbon accounting purposes, the total carbon stock for a given area, which may be a soil or LUT polygon, or a PCC, present in the current land-use pattern, can be calculated from:

$$\begin{aligned}C_{\text{stock total}} &= C_{\text{ag}} + C_{\text{bg}} \\C_{\text{bg}} &= C_{\text{bg-biom}} + C_{\text{soil}} \\C_{\text{stock total}} &= C_{\text{ag}} + (C_{\text{bg-biom}} + C_{\text{soil}})\end{aligned}$$

where $C_{\text{stock total}}$ is the total stock of C in the ecosystem, including aboveground (C_{ag}) and belowground (C_{bg}) pools. The constituents of the belowground pool are the carbon content in roots and all belowground biomass ($C_{\text{bg-biom}}$) and the C in the soil (C_{soil}) as organic C in SOM.

The values of $C_{\text{stock total}}$ after the estimation of aboveground biomass, its conversion to C, the estimation of C in belowground biomass (roots, etc.), and the modelling of SOM turnover to establish SOC are calculated for particular sites where the biomass measurements have taken place, in this case the 10 x 10 m quadrats.

The calculated carbon stock values implicitly assume permanence of the present land-use pattern

in the area of study. This is important given that the SOM starting parameters for the simulation models required rates of addition of organic materials to the soil. However, the land-use pattern in a watershed is subject to year-to-year changes, even though they may be minor.

Upscaling and mapping total carbon stocks

Methods for upscaling from values measured, estimated or modelled for sites, polygons or PCCs are discussed in Chapter 3.

Assessment of carbon stock and sequestration in PLUTs

The methodological details considered so far in this chapter involve the determination of the stocks of C under present land use. However, for many practical and strategic reasons it may be pertinent to know what the implications would be, in terms of carbon stock and sequestration, biodiversity, land degradation and food security, of alternative scenarios of LUC.

The assessment of PLUTs is fundamental to the creation of LUC scenarios, which may represent advantageous options for farmers and land users in terms not only of the production of food, fodder and fibre, but also of the potential accrual of carbon stock and sequestration credits. Thus, in order to be considered realistically for implementation in a LUC scenario, any PLUT should:

- ▶ represent advantages in terms of increases of carbon stock and sequestration potential;
- ▶ represent gains in food production and food security;

- ▶ not affect biodiversity adversely;
- ▶ not promote or increase the degradation of the land;
- ▶ be biophysically and economically suitable for the characteristics of the area where it would be implemented.

Later sections of this report deal with the conditions on biodiversity, food production and security, and land degradation. This section concentrates on the other two criteria. Thus, the selection of a PLUT to become part of a land-use pattern in a potential LUC scenario, as far as C is concerned, is based on two criteria:

- ▶ the enhanced carbon sequestration criterion: the PLUT should represent potential increases in total carbon stock and sequestration potential over the time involved in the planning horizon.
- ▶ the biophysical land suitability criterion: the land where the PLUT is to be implemented should be biophysically suitable. That is, the biophysical requirements of the PLUT should be met entirely or to a large extent by the biophysical conditions of the land to which it is intended. The PLUT must also be economically viable.

A land evaluation scheme can include both criteria. The criteria of land suitability for a given crop can be supplemented by additional criteria that reflect enhancement of carbon sequestration. Thus, the land evaluation exercise will accomplish both: selecting LUTs that are biophysically suitable and enhancing carbon sequestration. The selection of PLUTs for a given area of interest rests on a series of procedures. The following section describes these in more detail. Figure 20 summarizes the overall methodological framework for the assessment of carbon sequestration in PLUTs.

Land evaluation for PLUTs – with carbon sequestration criteria

This procedure is one of the central components of the overall methodological framework shown in Figure 20. The land evaluation process follows the methodological framework proposed by FAO (1986) and adopted almost globally as the standard method for land evaluation for rainfed and irrigated agriculture. Land evaluation is crucial to ensure that PLUTs are suitable for the area by meeting the biophysical characteristics and qualities of the local environment, in addition to having high CSP.

FIGURE 20 – Assessment of carbon sequestration in PLUTs

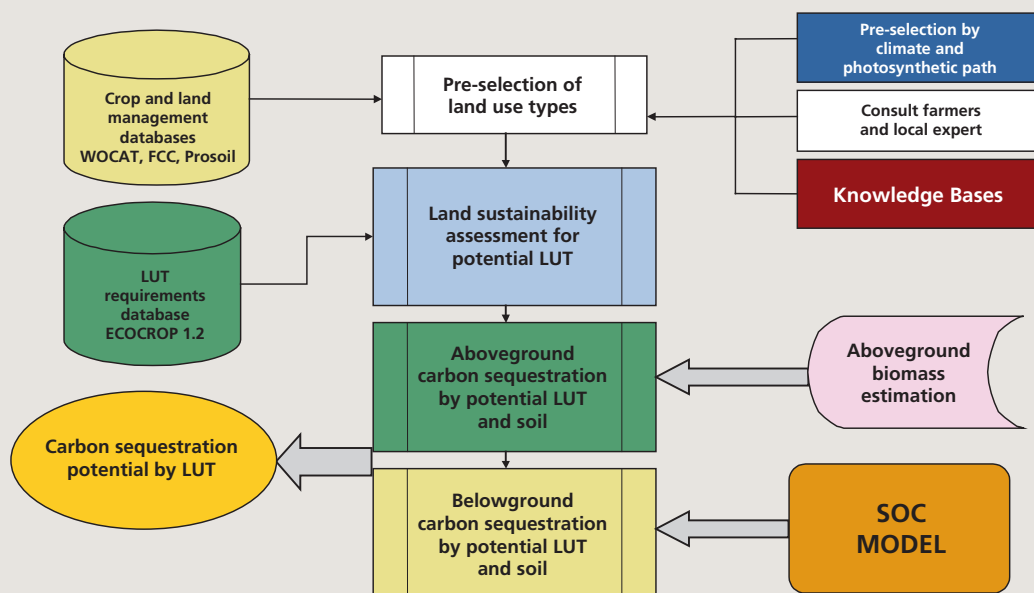
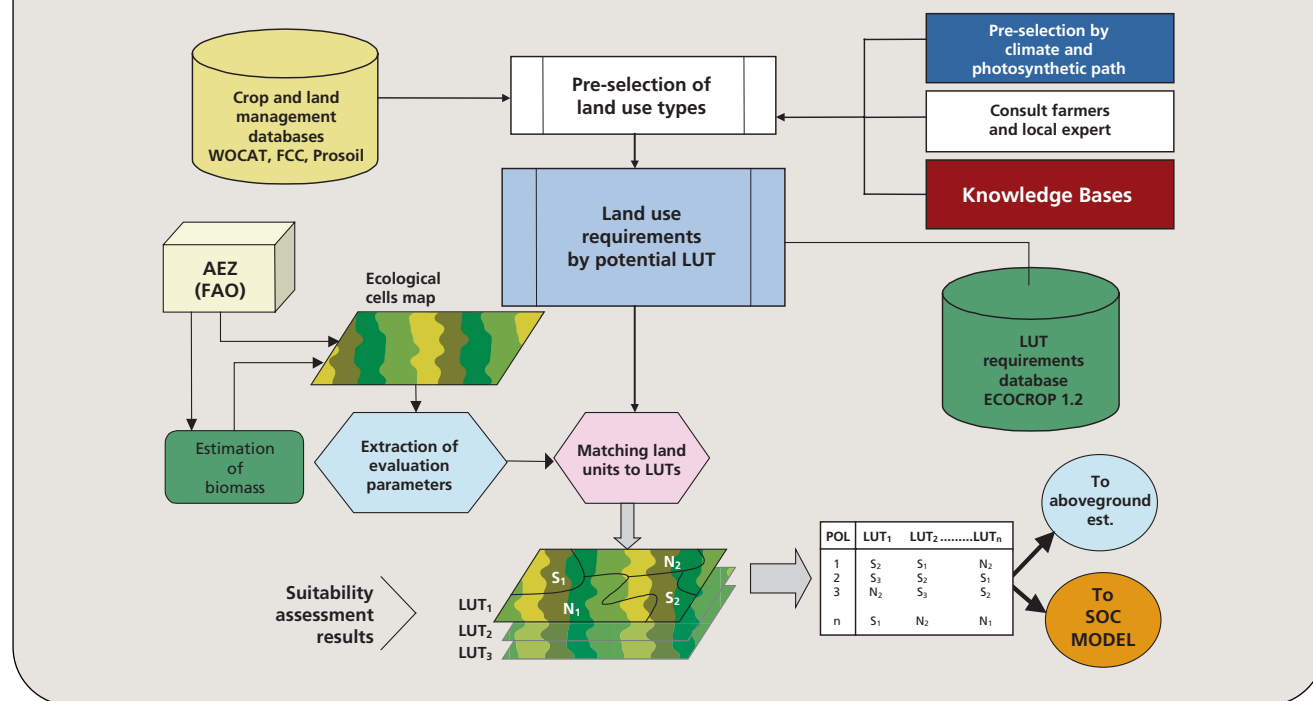


FIGURE 21 – Land suitability assessment for PLUTs, including carbon sequestration potential



The procedural stages for evaluating the suitability of PLUTs are standard practice in land evaluation. Figure 21 illustrates the stages in land suitability assessment incorporating criteria for carbon sequestration. The key aspects of the procedures in land suitability assessment can be consulted in FAO (1986). Such procedures, some of which are charted in Figure 21, are described in some detail in later sections of this report.

Pre-selection of land utilization type by climate suitability and photosynthetic pathway

The initial step in the land suitability assessment involves the compilation of a preliminary list of PLUT by climate suitability (temperature, radiation and soil moisture regimes) and photosynthetic pathway. This starts with the identification and compilation of a list of plant species that are actually grown or can be found in the area of study that meet two requirements: (i) there are official records or anecdotal evidence indicating that they have adapted to, and have been grown in the area of study; and (ii) such species possess advantageous photosynthetic characteristics, particularly as they relate to CO₂ assimilation

efficiency, including variations under different management and growing periods in the study area.

Of particular interest are certain agricultural, agroforestry or forestry species that: (i) can accumulate biomass rapidly; (ii) are well adapted climatically, in addition to producing food, fibre and fodder for the local populations; and (iii) are economically viable. Two types of databases and knowledge bases need to be examined:

- ▶ crop requirements databases. The adaptability requirements to climate and soil.
- ▶ physiological and phenological databases for selection of crops, trees and grass species based on photosynthetic pathway (efficiency).

Each species has different photosynthetic pathways, which determine the speed of biomass accumulation. The types of plant species of interest, according to their photosynthetic efficiency and speed of biomass accumulation, are groups C₄ (typically, 70–100 mg CO₂/dm²/h; Group III and IV crops) and C₃ (40–50 mg CO₂/dm²/h; Group II and V crops). Photosynthetic efficiency refers to the net

speed of CO₂ interchange in saturation by light, and to the terminal velocity of growth (accumulated biomass) of each plant species. Tables of data on photosynthetic efficiency by species can be found in topical and specialized sources (e.g. Hall and Rao, 1999; FAO, 1978b).

The activities described above correspond to conducting research for the selection of LUT with maximum CSP. At this stage, it is important to conduct intensive consultation with farmers and local experts regarding the initial list of LUTs and then, on the basis of their feedback, refine the list of promising LUTs. Once the initial list has been compiled, the selected PLUTs must be characterized in terms of their infrastructural setting, socio-economic conditions, level of inputs, cropping system and land management, particularly as it pertains to SOM. Comprehensive FAO guidelines for LUT description have been published to aid in this process (FAO, 1986).

The identification of LUT requirements is of central importance in the suitability assessment. Knowledge bases containing specific information on plant species requirements are not common. Ecocrop (FAO, 1999) is one of the few resources available. It is a crop environmental requirements database developed in the Land and Water Development Division of FAO, pooling information from its many projects around the world. This database provides a large list of climate and soil requirements for crop, tree and grass species (about 1 700). The database is generic in terms of the nature of the requirements listed. Knowledge of specific crop requirements is not abundant as it is usually derived from long-term field experience and research. However, there is some very useful published work including knowledge bases of this kind, e.g. Sys (1985). Sys's database is really a knowledge base in that it includes threshold values and their ranking into suitability classes. Both threshold values and designated suitability classes are expressions of long-term experience and accumulated knowledge.

The final list of promising plant species is compiled following the criteria indicated above. Climate and soil requirements per species are identified and listed with the species identity. The requirements can be considered pointers to the type of data on land characteristics that need to be collected in order to assess the suitability (climate and soil) of land polygons for each of the species in the list.

Land suitability assessment

The requirements of each plant species in the list should be matched to the status of equivalent land qualities. The matching process takes a variety of approaches to its implementation with data from the soil and climate databases. FAO (1986) has prepared detailed guidelines on the topic for a variety of infrastructural, management and ecological conditions. A description of a methodology of that kind is beyond the scope of this report. It should suffice to indicate the stages of the process for the suitability assessment and to describe in brief one of the approaches to carrying out the assessment.

Once the biophysical characterization of the area and the definition and mapping of ecological or PCCs have been completed, the land suitability assessment can proceed. This consists of the matching of requirements to qualities. Two contrasting approaches can be adopted:

- ▶ manual matching of LUT requirements to land qualities through their characteristics and allocation to suitability classes through the use of tabular knowledge bases (e.g. Sys, 1985; Ponce-Hernandez and Beernaert, 1991). The actual value of a given climate or soil characteristic is allocated to a suitability class on the basis of the ranges of each class in the table. The characteristics are evaluated one by one.
- ▶ development of an automated suitability assessment model. This is an automated procedure, which requires the development of a multicriteria assessment model. Software shells for automation, based on the construction of decision trees, such as the Automated Land

Evaluation System (ALES), can be very useful for achieving these aims. Detailed explanation of the process of construction of decision trees in ALES is beyond the scope of this report. The reader is referred to Rossiter (1995).

The manual approach is labour intensive and only recommended where the data sets to be matched are not large (i.e. the number of land units and LUTs), or the assessment is straightforward, involving only a few land qualities. Conversely, the need for automation becomes clear where the process may become a routine operation in an organization or the volumes of data are sufficiently large to make manual matching prohibitive. In this report, a combination of manual and automated methods was applied to the case studies presented, depending on considerations of: volume of data to be processed, viability of decision-tree model development, effort involved and time.

The matching process results in the generation of potential land-use information, which consists of a suitability matrix with LUT and land unit polygons or PCCs as columns and rows, respectively.

Mapping potential land use

Transfer of the land suitability assessment ratings (suitability classes) to the soil/land/ecological zone polygon map (vector), or to the pedo-climatic raster map in the GIS, allows for the generation of a series of map coverages or thematic layers in the GIS. Each layer represents the spatial variability of suitability ratings for a given PLUT. Therefore, there are as many thematic map layers as there are PLUTs.

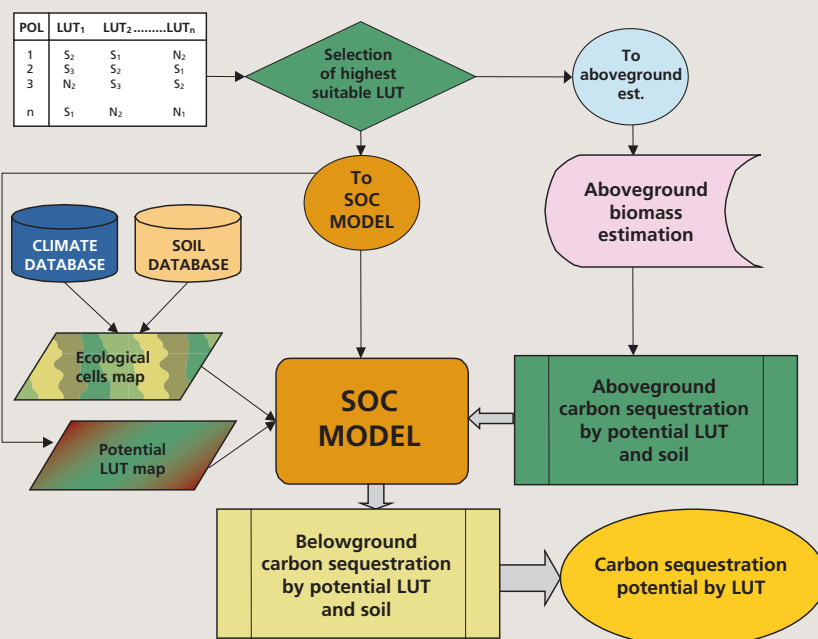
Selection criteria for mapping PLUTs

Not all the land units evaluated are biophysically suitable for all the PLUTs considered. Therefore, to create the first viable scenario of potential land use, selection criteria need to be identified in order to build the first suitability assessment scenario. The selection rule used was:

- ▶ select only the LUTs with the two highest suitability classes for each land unit polygon/cell, and attribute such ratings to the corresponding polygons or grid cells.

Thus, only PLUTs with “highly suitable” (S1–0) and “suitable” (S1–1) classes were selected. Hence,

FIGURE 22 – Estimation of carbon sequestration by PLUT



the final LUC scenario consisted of those PLUTs that attained such ratings, making it possible to generate one map showing the spatial variability of “highly suitable” PLUTs in the area, and another map with the “suitable” PLUTs in the area. These two maps are the scenarios for LUC.

Although very useful, these scenarios only establish whether the PLUTs are ecologically suited and feasible in the area of concern. The fluxes, balances and the stock and sequestration of C in all its pools, which are implicit in each PLUT, are yet to be determined for carbon accounting purposes, should the LUT be implemented on the ground.

The main difficulty with the estimation of carbon stock and sequestration in PLUTs is the fact that these LUTs are conceptual and yet to materialize. Thus, physical measurements for the estimation of aboveground and belowground biomass, which were the main instrument for estimation in present land use, are not yet possible. Estimation processes based on theoretical constructs, state-of-the-art knowledge and simulation modelling, in this case, will determine whether or not there are advantages in implementing the potential LUC scenarios.

Estimation of carbon stock and sequestration in PLUTs – aboveground and belowground pools

Figure 22 provides an outline of the procedural stages for the generation of these estimates.

The estimation of biomass of potential crops not yet grown poses a methodological problem: the lack of physical presence of those plant species on the ground, which would allow measuring or physically estimating their biomass. Three solutions can be envisaged to this problem. In order of accuracy and intricacy, from the most simple and least accurate to the most complex and most accurate, these are:

- ▶ inference from the suitability classes and expected yields. Biomass can be estimated through knowledge of the genetic potential of

the species involved in the LUT, and knowledge of the range of the potential yields from the range of yield values equivalent to the suitability class of that LUT in the land polygon of concern.

- ▶ calculation from standard phenological equations of net biomass as a function of climate parameters and LAI. Net biomass for a given crop can be calculated from standard crop growth (phenological) equations, where it is set as a function of the maximum velocity of biomass production and respiration. This is in effect a simplified model of plant growth based on certain assumptions about the shape of the curve of biomass accumulation as a function of effective LGP (time), the maximum slope of such curve (first derivative), and its relation to LAI and main climate parameters influencing the speed of biomass accumulation and plant respiration, such as temperature and radiation (FAO, 1978b, 1981; De Wit *et al.*, 1978).
- ▶ computation from crop and forest growth simulation models. Plant growth and biomass accumulation models allow for the simulation of biomass accumulation in crops and tree species. Aboveground biomass estimation is also a compartment of some organic matter turnover models (e.g. CENTURY). There is a relatively long list of simulation models that could provide estimates of biomass in crops. It would seem logical that universal crop simulation models, e.g. the erosion/productivity impact calculator, known as EPIC (Sharpley and Williams, 1990) and WOFOST (van Diepen *et al.*, 1989), should be more complex than single-crop simulation models, e.g. CERES (Jones and Kiniry, 1986) and SOYGRO (Jones *et al.*, 1989). However, this does not seem to be the case. Several researchers have attempted a detailed review of these types of models. Such discussion is beyond the scope of this report. However, these types of models can be very useful in predicting total biomass accumulation of

TABLE 12 – Relationships between suitability classes and crop yields

Suitability classes and crop performance as a percentage of maximum potential yields			
S1-0 Highly suitable	S1-1 Suitable	S2 Moderately suitable	S3 Marginally suitable
95–100	85–95	60–85	50–60

potential crops, shrubs and trees in a PLUT mix. The Decision Support System for Agrotechnology Transfer (DSSAT) from the International Benchmark Soils Network for Agrotechnology Transfer (IBSNAT, 1989) is considered of particular interest to users in the developing world. The DSSAT includes CERES, CROPGRO and other models with different degrees of sophistication and detail.

Biomass estimation by the AEZ approach and through suitability class and expected potential yields

Biomass estimation has attracted considerable research effort. There is a relative wealth of published work on the subject. This section focuses only on the readily applicable approaches to biomass estimation.

In its AEZs Project, FAO (1978b) defined a method for estimating the biomass of cropping systems. The method is based on calculations supported by knowledge of the relationships of climate parameters and phenological stages of crop growth. The AEZ method has been expanded substantially through the incorporation of many capabilities for land resources assessment. This was demonstrated particularly clearly in the very complete case study of Kenya (FAO, 1993a). The AEZ methodology has evolved to become part of a computerized decision-support system (known as AEZWIN) for multicriteria analysis applied to land resources appraisal (FAO, 1999). The AEZ approach and methodology have been advanced by FAO through land resources assessments in the developing world. The method for biomass estimation used by the FAO's AEZ team is the basis of the calculations suggested below.

On the other hand, in situations where the method, the software or the data for the AEZ method are not available, a simple method consists of converting the suitability class pertaining to each LUT to a range of crop yields. In turn, these could be transformed to biomass through using a ratio of grain–fruit to aboveground biomass (grain–fruit/biomass), specific for each species. As an example, Table 12 provides an indication of how the ranges of suitability classes can be related to crop yields (Sys, 1985). Such relationships could be useful for estimating crop yields from a simple suitability rating as a measure of crop performance.

An investigation into historical records of potential, constraint-free yields and potential constrained yields (usual constraints are climate, soil and pests) attained in the study area would produce valuable data to aid in biomass estimation without the use of models. Information may be obtained from local research stations, agriculture statistics agencies or, better, from the local farmers in each of the ecozones in the study area. A combination of data on potential crop yields, both constrained and constraint-free (high levels of inputs), will provide the reference yields from which to calculate a fraction according to the suitability class assigned to the LUT and crop or crops for a given land unit. In this case, as the PLUTs have already been selected, only the two highest suitability classes are considered. The figures derived in this way will provide a range of yields. A conservative approach would be to adopt the lower limit of the percentage range of the potential yields, converted into kilograms per hectare. For example, an LUT with a crop (e.g. maize) given a suitability class S1–1 would consist of 85 percent of potential yields attained in the area.

The harvest index (H_i) relates crop yields (B_y) as a fraction of net biomass (B_n):

$$B_y = H_i \times B_n$$

Thus, the net biomass can be approximated by:

$$B_n = B_y / H_i$$

FAO (1981) has reported values of H_i for a relatively wide range of crops for Latin America and the Caribbean region. The report also contains tables of net biomass estimates for selected constraint-free crops, grouped by photosynthetic pathway and climate suitability. Then, with imposed constraints (climate, soils, topography and pests), the report also gives expected yields at two levels of inputs. These data provide a starting point to the initial values of net biomass and crop yields. Such values can be fine-tuned with local information from farmers and agencies about maximum attained yields and potential yields in the area of concern. This approach provides an alternative to using crop growth models or similar tools.

The estimates of net biomass lead to two useful calculations:

- ▶ the fraction of net biomass that corresponds to roots and belowground biomass;
- ▶ the fraction of aboveground net biomass that is left in the field as crop residues and later incorporated into the soil as input into the SOM turnover processes.

The latter is a fraction that is site dependent. It needs to be investigated locally with farmers and agricultural agencies and research stations as it depends exclusively on the local crop and land management. In many areas of the developing world, stalks and crop residues are a valuable resource for backyard and extensive livestock feed. However, in most instances, most or all of the crop residues (and their carbon content) are removed from the system. These leakages cannot be accounted for accurately

even where they become animal tissue. Their fate is not certain, and they constitute a removal from the soil of the field from where they were extracted.

Net biomass estimation from standard phenological equations as a function of climate parameters and LAI

The net biomass production of a crop with N days of growing period in the field can be calculated (FAO, 1981) from:

$$B_n = 0.36b_{gm} / (1/N + 0.25C_t)$$

where B_n is the net biomass (kilograms per hectare), b_{gm} is the effective velocity of maximum production of total biomass (kilograms per hectare), which is reached with an LAI = 5. Where LAI is not five, then proportions of b_{gm} can be calculated depending on the value of LAI at the moment of b_{gm} . C_t is the coefficient of maintenance respiration of the crop. It is a function of temperature such as:

$$C_t = C_{30}(0.44 + 0.00019T + 0.0010T^2)$$

where C_{30} is the value of C at 30 °C, 0.02283 for a grain and 0.0108 for a legume; and T is the average daily temperature within the growing period.

The following data sets are necessary for calculating B_n by this procedure:

- ▶ climate data: latitude; altitude; growing period (days); beginning and end of the growing period (date); mean solar radiation within the growing period (calories per square centimetre per day); mean temperature (diurnal) within the growing period (degrees Celsius); and mean temperature (24 h) within the growing period (degrees Celsius).
- ▶ crop data: crop species; time to maturity (days); LAI at the point of maximum growth in the crop growth curve or at the time of maximum velocity of growth (usually five); H_i (adimensional); climate suitability group of the crop (see FAO, 1981).

Once the net biomass has been estimated, it is possible to estimate crop yields from it through standard harvest indices. Then, it is possible to estimate the fraction corresponding to crop residues returned to the soil. This is site dependent and should be ascertained from local sources (farmers or local agricultural agencies).

Biomass estimation from crop growth simulation models

Plant growth and biomass accumulation models allow for the simulation of biomass accumulation in crops and tree species. Models of this type, categorized by their degree of complexity and specificity, produce a relatively long list. Among the most commonly available models are: EPIC (Jones *et al.*, 1991), WOFOST (van Diepen *et al.*, 1989) and CERES (Jones and Kiniry, 1986).

Of particular interest to modellers in the developing world could be the DSSAT mentioned above. The DSSAT is a shell that allows the user: (i) to organize and manipulate crop, soils and weather data; (ii) to access and run a collection of crop growth models in various ways; and (iii) to analyse their outputs, rather than running single models.

Biomass estimates for belowground biomass (BGB), i.e. roots, can be estimated as a fraction of aboveground biomass (AGB) by applying the same coefficients as in the estimation for present land use:

- ▶ BGB = 0.25 AGB for coniferous vegetation;
- ▶ BGB = 0.30 AGB for broadleaf vegetation and crops.

In the case of crops, the coefficient 0.3 should be used. Then, for a given site or polygon:

$$\text{Biomass}_{(\text{total})} = \text{AGB} + \text{BGB}$$

The value of total biomass can be estimated from the equation above. Independently of the choice of model, the biomass estimates obtained, by necessity, will be referenced spatially to either a pixel or a

polygon representing the land unit or ecozone or pedo-climatic unit from which the climate, soil and site data were extracted to run the model. Therefore, biomass estimate values must be interpolated spatially by any of the procedures described in the preceding sections.

Upscaling and mapping total biomass implicit in potential land use

Upscaling the estimates of biomass of PLUTs is a relatively straightforward procedure as suitability map layers have already been created for the “highly suitable” and “suitable” PLUTs. In this report, these were mapped out by assigning these two suitability ratings from the matching process to each one of the map objects, i.e. land unit polygons or PCCs evaluated.

The procedures for upscaling estimates of biomass consist of assigning the calculated value of $\text{Biomass}_{(\text{total})}$ calculated for a given LUT to the land unit polygon or PCC where this PLUT is assigned in the two scenarios of potential land use, either the “highly suitable” scenario or the “suitable” scenario. This will provide at least two mapping scenarios of biomass estimated by each of the estimation procedures above. The upscaling procedure based on spatial interpolation or drawing average means per polygon was not necessary in this case. This is because the objects on which the biomass was estimated were already polygons and not the sampling quadrats used to estimate actual land use.

Estimation of carbon stock implicit in potential land use

Independently of the biomass estimation procedure, carbon values can be derived by using a similar approach for the estimation of C in biomass of current land use (described in preceding sections of this chapter). Therefore, carbon stock in total biomass of PLUT can be estimated from:

$$\text{Carbon}_{(\text{in biomass})} = 0.55 \text{Biomass}_{(\text{total} = \text{AGB} + \text{BGB})}$$

Mapping carbon stock implicit in potential land use

A simple GIS scalar operation can generate the spatial distribution of the potential carbon stock that would materialize if the PLUT were implemented. This operation consists essentially of multiplying all the values of the pixels containing the total biomass of the corresponding PLUT by a scalar or constant (0.55). It is a straightforward operation. In the case of polygons, the attribute tables of the polygons containing the values of total biomass are multiplied by the constant coefficient and assigned to a new coverage or thematic layer. These operations allow for the creation of maps depicting the spatial variability of total carbon stock under “highly suitable” or “suitable” land use.

Modelling potential carbon sequestration by potential land use – generation of carbon scenarios

Thus far, the procedures for estimating C have considered accounting for belowground and aboveground biomass. Accounting for SOC present in SOM calls for the use of SOM turnover simulation models, as SOC is part of the overall carbon balance: potential carbon stock_(total) = C as potential biomass + SOC, where SOC in this case is the organic C that would accumulate or decrease in the soil following the introduction of a PLUT through a LUC from the current land use. Thus, in order to estimate the value of SOC left after turnover of SOM from additions of crop residues incoming from the PLUT to be implemented, it is necessary to model the dynamics of organic matter turnover. The simulation models of SOM turnover should be run under the hypothetical implementation of a PLUT and its crop and land management parameters. Chapter 2 outlines the procedural stages involved in these operations.

The methodological stages for the simulation of SOC dynamics in the “belowground” pool for PLUT have been outlined in preceding sections in this chapter. The main steps are:

- ▶ input of organic matter contributions from PLUT (crop residues, manures, litter and any other organic residues).

- ▶ selection of the carbon dynamics simulation model. In this case, RothC-26.3 or CENTURY is used.
- ▶ extraction of soil and climate model parameters from each PCC/soil or land polygon, for input into the carbon simulation model.
- ▶ model simulation execution.
- ▶ model output and generation of SOC stock scenarios for PLUT.
- ▶ carbon sequestration calculations and database development.

The generation of carbon scenarios over time and space is achieved by adhering to the following sequence of steps:

- ▶ linking the SOC simulation model output to a GIS;
- ▶ preparation, with the aid of GIS functions, of scenarios of carbon stock by LUT and by soil type/land unit or PCC, over different periods of time meaningful to the assessment;
- ▶ computation of statistics, maps of total carbon stock by both pools for the scenarios desired, legends and output tables.

The analytical steps to link the output from the carbon simulation models to the GIS are not difficult but involved and laborious. They are also GIS software specific and may depend on idiosyncratic architectures and functions whose degree of laboriousness changes with the software package used. For example, in the GIS software ArcView, a series of manipulations of tables and pivots in spreadsheet format allows for the transfer of the carbon simulation model outputs to ArcView tables and their assignment to polygons of soil or land cover.

On the other hand, a customized interface (e.g. “Soil-C”) could be used to link the model results to their spatial distribution mapped out in the GIS. These steps provide estimates of carbon stock for PLUTs that are to be compared with the stock in present land use.

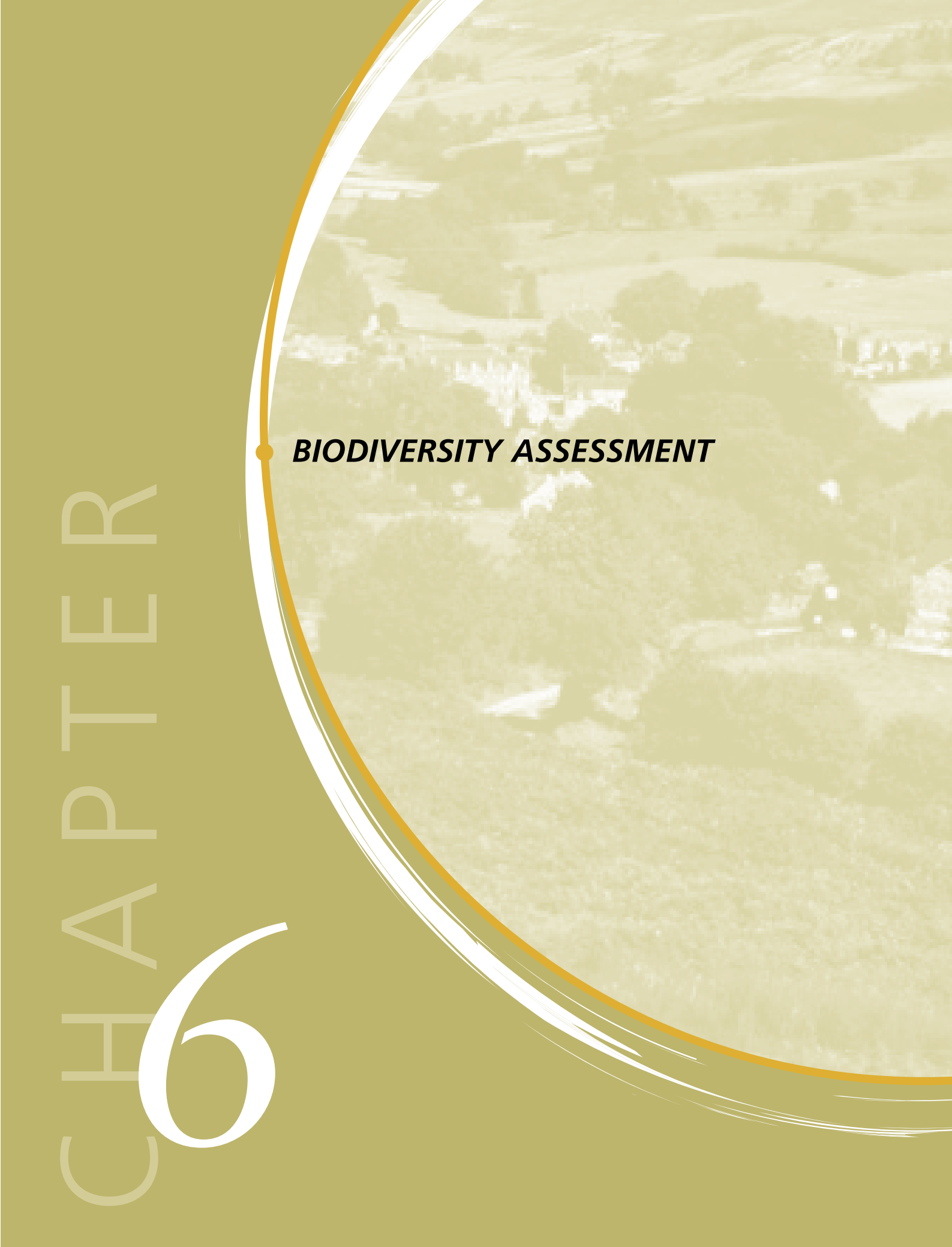
Carbon sequestration attributable to land-use changes

The preceding sections have assessed the estimates of carbon stock for the actual LUTs and the carbon sequestration implicit in PLUTs. A comparison of estimates between current and potential LUT per each land polygon or PCC should be made. The simple balance could be established in algebraic terms by:

$$\text{Carbon sequestered} = \text{potential carbon stock}_{(\text{total})} - \text{actual carbon stock}_{(\text{total})}$$

where the potential carbon stock corresponds to the C in PLUTs, and the actual carbon stock is the carbon stock in present LUTs for a given plot of land or area of the landscape. This comparison would yield the gains or losses in carbon stock resulting from implementing the PLUT in that land polygon or PCC.

CHAPTER 6



BIODIVERSITY ASSESSMENT

CHAPTER 6

Biodiversity assessment

In the context of this report, biodiversity refers to the plant diversity that can be observed by conventional means and without significant investment of effort for extended periods of time before the assessment. Essentially, it is understood here as the diversity that can be determined while undertaking simultaneously the morphometric measurements for biomass estimation and the field observations for land degradation assessment at the nested quadrat sites used for field sampling.

Measures of biodiversity at the level of species or populations are directed towards the attainment of an index of the number of species and their relative abundances within a given landscape. These indices are some of the most useful measures of biodiversity because species are more tangible and easier to study than communities or entire landscapes.

Typically, strategies for measuring biodiversity at this level involve protecting a single species. Nevertheless, this protection could help other species in different ways, such as species with similar habitat requirements, species with a large number of other species depending on it, or species with large area requirements (Noss, 1990). Therefore, ecologists use measures of the number of species or their relative abundances in order to address biodiversity from species diversity to the ecosystem level (Noss, 1999). The approach consists of broad habitat protection to benefit a wide range of species as ecosystems consist of the population of all species coexisting at a site. They also include the abiotic factors, which are interdependent with the biotic community.

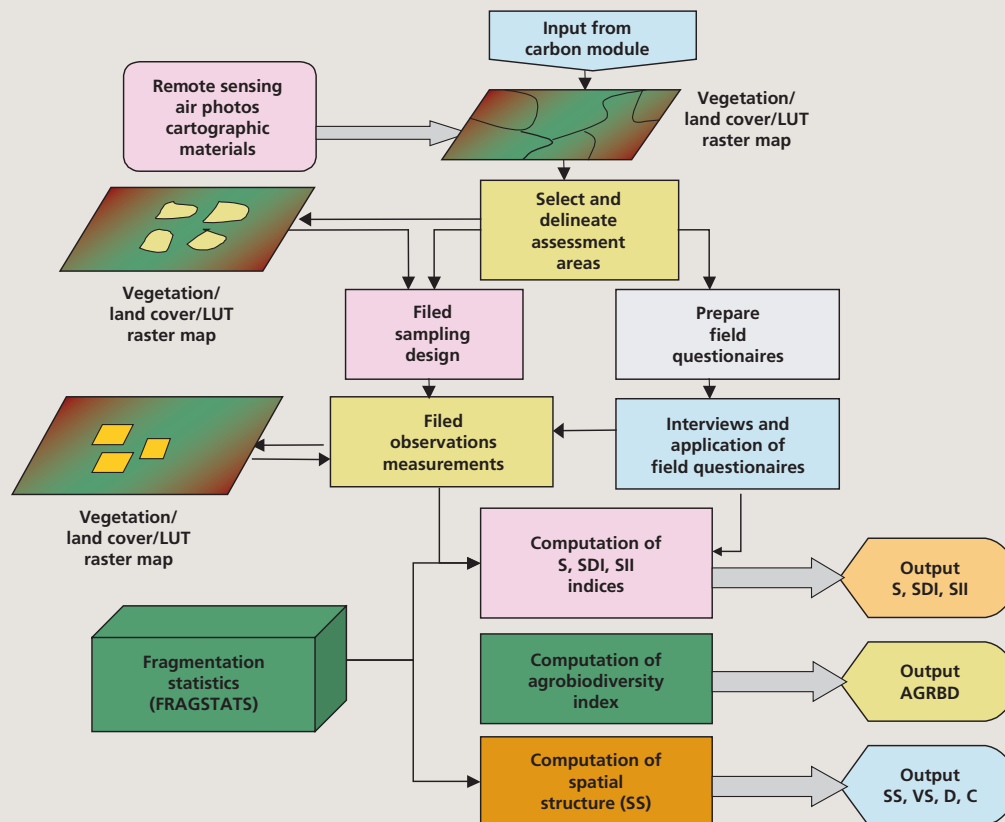
Consequently, ecosystem diversity attempts to protect several species by preserving the habitat in which they live.

The relationship between the structure of the landscape and the diversity of the ecosystems present can be used to design mechanisms for the assessment of biodiversity at the landscape level. This could be of particular benefit to those assessment methods that employ remote-sensing techniques. Satellite image classification could then provide a useful spatial framework tool for collecting data at this level.

Classification of the landscape into vegetation types or landscape element types can also be used in order to provide a geographical framework for predicting the status of biodiversity of the landscape, provided that the variation of biodiversity measurements (e.g. species numbers, richness and abundance) within such units is much smaller than those between them. This is a pre-condition for the validity of any mapping units. Figure 23 illustrates the methodological steps for assessing biodiversity.

Remote sensing in the assessment of biodiversity

Satellite images provide almost the only source of reasonably continuous data on the reflectance properties of the ground and the ground cover. Such products can be used for the upscaling or interpolation of estimates or measures of diversity at specific sampling sites.

FIGURE 23 – Assessment of species diversity and agrobiodiversity of actual land use

Classification and mapping of land cover or vegetation types

A satellite image can help in interpreting differences in land cover and land use by exploiting the differences in reflectance of multiple spectral wavebands. For example, an FCC image, typically created using band 5: 1.55–1.75 nm (middle infrared), band 4: 0.76–0.90 nm (near infrared) and band 3: 0.63–0.69 nm (red) of Landsat TM7 imagery, could help in classifying land cover and land use. Every pixel of the FCC image is assigned a class of land cover or land feature, depending on the internal algorithms of the software for classification. This classification should be supervised by defining locations in the image where there is certainty of the corresponding land cover class. The classification from these training sites is expanded to the total of pixels in the image, creating a supervised classification and a map showing the spatial extent of land cover classes.

Indigenous knowledge of the local vegetation and its successional stages can prove invaluable in identifying vegetation types and suitable training sites for supervised classification. Exact location of the training sites on the ground can be achieved using a hand-held GPS unit. Training sites are identified and located for all identified vegetation types and subtypes. After trial and error, removing some unusable or redundant training areas, a total number that seems to achieve the best results in the classification should be determined.

In addition to the training areas, the six bands (TM 1, 2, 3, 4, 5 and 7) of Landsat TM7 imagery are used in the supervised classification in order to produce a vegetation raster map with several landscape element types (vegetation classes). The maximum likelihood algorithm is recommended for a supervised classification and for mapping the vegetation classes. The system calculates the

statistical properties of the reflectance values for each cover type within each selected band, in this case for the six bands. The system then extrapolates the results, allocating each pixel of the image to the most appropriate class. After several trials to remove some of the bands, a final vegetation raster map is produced using red, near-infrared and middle-infrared bands (TM 3, 4 and 5), which achieve best results. In order to remove the speckle in the classified image, filters may have to be applied.

A supervised classification to produce a vegetation raster map is a relatively expensive exercise owing to the fieldwork component. Therefore, the use of an unsupervised classification can be explored as a less expensive option. The unsupervised classification does not require field support, it is used where there is minimal information about the classes to be recognized and separated in the image. Typically, the unsupervised classification can be considered as a preliminary classification, providing a first approximation to expected classes in the field. The classificatory algorithm used in the unsupervised classification groups data automatically, recalculating class means, and merging and splitting classes as required. The unsupervised classification assigns pixels to a specific number of classes in order to maximize their discrimination on the basis of reflectance values alone,

in the number of bands used for classification. Therefore, the most difficult task in this type of classification is to determine the features corresponding to the resulting classes present on the ground.

The generated vegetation/land cover map from the multispectral classification of the satellite images can then be used as a geospatial framework for designing the sampling scheme and the distribution of quadrat sampling sites in the field. The mapping units provide the strata for reference in sampling.

Biodiversity indices

Several quantitative indices have been designed to provide information on the various aspects of plant diversity in landscapes. Table 13 lists some of those most widely used. However, it was necessary to introduce an ad-hoc designed index for agricultural diversity: the Agrobiodiversity Index (AgrBD). This can be calculated from: $\text{AgrBD} = (S_D/S)T \Delta t$, where S_D is the number of domesticated species in the total number of species S identified; Δt is the elapsed time between the beginning and end of the cropping cycle; and T is the number of consecutive years that the crop mix has been on a particular field or area. For $0 < \text{AgrBD} < 365$, if $T = 365$ days. Thus, if $\text{AgrBD} = 365$, all biodiversity is agrobiodiversity.

TABLE 13 – Diversity indices for assessing plant diversity

Index*	Formula
Number of species	S
Margalef	$D_M = (S - 1)/\ln(N)$
Shannon	$H = -\sum p_i \ln p_i$
Evenness	$E = H/\ln(S)$
Simpson	$D = \sum p_i^2$
Reciprocal Simpson	$1/D$
Simpson (1-D)	$1 - \sum p_i^2$
Reciprocal Berger Parker	$d = (N_{\max}/N)^{-1}$

* The Indices are cited in Magurran (1988).

Where: S = number of species; N = number of individuals; p_i = the proportion of individuals found in the i -th species; $N_{\max}$ = number of individuals in the most abundance species.

The various biodiversity indices (i.e. plant diversity in this context) can be used depending on the circumstances of the area under study and the incorporation of the nature of the diversity information required to monitor changes with changes in land use. For example, measures of plant diversity that are useful in cropland may not be so useful in the Amazon context. The indices from the list in Table 13 that were used for the case studies reported in this document were:

- ▶ species richness: number of species (S);
- ▶ Simpson Diversity Index;
- ▶ Shannon Diversity Index;
- ▶ agrobiodiversity (AgrBD).

The diversity inside a community is also known as “ α diversity”. To measure α diversity, species richness, Shannon Diversity Index and Simpson Diversity Index were used. Species richness is estimated with the total number of observed species. The Shannon Diversity Index is calculated by multiplying a species proportional abundance by the natural log of that number:

$$H' = -\sum p_i \ln p_i$$

where p_i is the proportion of individuals found in the species “i”. This index assumes that individuals are sampled randomly from an infinite or very large population. Similarly, it supposes that all species are represented in the sample. The value of the Shannon Diversity Index usually falls between 1.5 and 3.5 and only rarely exceeds 4.5.

The Simpson Diversity Index is defined as the sum of squares of proportion abundance of each species:

$$D = \sum p_i^2$$

As D increases, diversity decreases. Therefore, the Simpson Diversity Index is usually expressed as $1 - D$ or $1/D$. Where $1 - D$ is used as the index, it ranges

from 0 to 1, with values close to 1 showing a community of many species with equally low abundances while numbers close to 0 express fewer species with one of them clearly dominant.

The computation of the so-called spatial structure index makes sense in situations where there are significant levels of vegetation canopy, and where these vertical structures appear to influence directly the diversity of other species, whether plants or animals (e.g. Amazon rainforest). In the case studies used to illustrate this method, the spatial structure index was not computed.

Field sampling, measurement and data processing for biodiversity

Field survey and sampling need to be undertaken in order to estimate the biological composition (plant diversity) of several landscape element types (vegetation types). As this survey is conducted simultaneously with the biomass measurements and the land degradation assessments, the sampling units are essentially the same. The sampling design and the distribution of the sampling sites on the ground are also identical.

The sample unit on the ground consists of a quadrat of 10 x 10 m in which the number of trees by species must be recorded. Where there are clearly distinguishable canopy layers, these can be sampled separately to facilitate the identification of species. For every canopy layer considered, the identification of species should proceed. For example, in a first canopy layer, trees that are 20 m or higher can be identified and counted. A second layer should consider trees between 10 and 20 m high. A third layer should consider trees of less than 10 m, and so on. Every 10 x 10 m quadrat contains a nested subquadrat of 5 x 5 m for sampling shrubs taller than 1 m. A further nested subquadrat of 1 x 1 m is used for sampling the dominant herbs, and all the tree regrowth and shrub species less than 1 m high. Therefore, trees, shrubs and dominant herbs that fall

FIGURE 24 – A field data form for recording biodiversity data

BIODIVERSITY DATA FORM

IDENTIFICATION

STUDY AREA:		QUADRAT NUMBER:	
SELECTED STRATA:		FIELD STRATA:	
UTM LOCATION	MAP:	GPS:	EASTING
			NORTHING

GENERAL VARIABLES

		CODE		CODE	
LAND COVER			LOCAL PHYSIOGRAPHY		
STATE OF SUCCESSION			SOIL TYPE		
TYPE OF DISTURBANCE					
ELEVATION		SLOPE		ASPECT	

TREE LAYER (> 20 m)

SPECIES	COD	FREQUENCY	TOTALS

SPECIES	COD	FREQUENCY	TOTALS

NUMBER OF SPECIES:

TREE LAYER (> 10 m AND <= 20 m)

SPECIES	COD	FREQUENCY	TOTALS

SPECIES	COD	FREQUENCY	TOTALS

NUMBER OF SPECIES:

within the sampling quadrats characterize the biological composition of plants in the study area. Sampling sites should be georeferenced using a GPS. This will allow the digitizing of all sample site locations, after being validated, for entry into a spreadsheet or a database. At each of the sampling quadrats, plant species are identified and counted using special field forms. These forms should be designed ahead of the fieldwork and should be used

for recording field data in the event of having no means of direct digital recording (i.e. digital data logger). The example in Figure 24 illustrates a field data form for recording biodiversity data.

Identification of species

One of the most difficult tasks during fieldwork could be the identification of species on the ground.

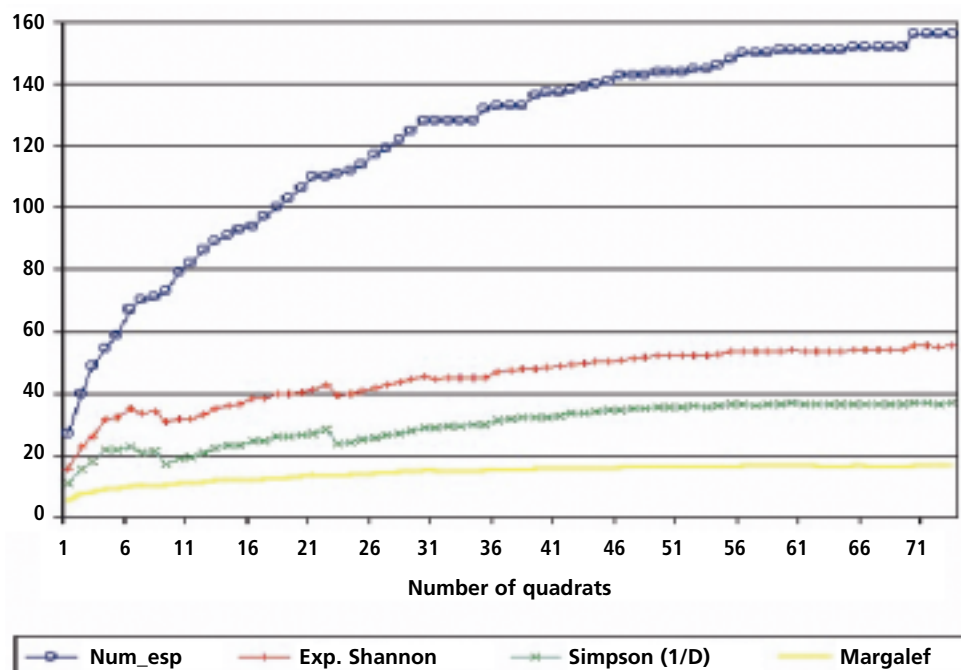
A major constraint in practice is the impossibility to collect plants with all the plant morphology components needed for identification in a herbarium, and to have available the time and effort that this requires. It is highly recommended that a member of the field team be a botanist, plant taxonomist or forest taxonomist, who could at least make an approximate identification of difficult species, thereby minimizing the amount of plant collection required for later identification in the herbarium or laboratory.

On the other hand, where no member of the field team has the required expertise for plant identification, a useful strategy is to benefit from indigenous knowledge by engaging the help of knowledgeable local people. These are people who are plant experts or have been working in the area long enough to have the ability to identify species using local names. Published work describing the vegetation of the study area should be reviewed as it may also prove extremely valuable.

Estimating sample size

For the purposes of identifying the optimal sample size, an interactive approach can be followed. Pielou's pooled quadrat method (Magurran, 1988) can be used to calculate the number of samples needed in the landscape in order to produce reliable estimates of the status of biodiversity in the area. The method consists of taking a sample of one quadrat at a time, and calculating incrementally and iteratively the diversity values (indices) in the quadrats entered. The number of samples is then increased to 2, 3 and 4 quadrats, and so on, until all the quadrats sampled so far are accounted for. A fresh set of diversity values is calculated with the pooled data each time. The calculated biodiversity indices should be plotted as they emerge from calculations from the current field samples against the total number of samples used in the calculation. This should allow for monitoring the number of samples after which gains in the values of the indices are negligible or nil (i.e. the curve of the index becomes asymptotic to the axis of the number of samples). Figure 25 illustrates this procedure.

FIGURE 25 – Graph of plant diversity indices against number of sampling quadrat sites to determine the number of sites needed



In practice, as the sampling sites are multipurpose sites, the final number of sampling sites will be a compromise between the factors mentioned above and considerations related to biomass estimation and land degradation assessment.

Biodiversity database development

For the purpose of systematically storing and processing the field data in an almost simultaneous fashion as they are entered, in addition to retrieving diversity data, a dedicated database system was developed and implemented by customizing a commercially available DBMS (ACCESS). All field data were input, processed and validated into the customized program. Although the system was implemented to recover all indices presented in Table 13, which can be calculated by quadrat as well as by trees and shrub layers, a user able to manipulate standard query language could make any query and

consultation to the database. The customized program also allows users to enter, delete and update information on quadrats and species. Figure 26 illustrates the data entry screen of the database.

Three standard biodiversity indices, namely: species richness, Shannon Diversity Index, and Simpson Diversity Index (Magurran, 1988; Whittaker, 1972), as well as Margalef, species evenness, Reciprocal Simpson and Reciprocal Berger-Parker indices, can be computed almost instantaneously by using the customized database.

Geospatial framework for upscaling and interpolating diversity indices

The raster map of land cover or vegetation classes, which results in the so-called “landscape element types” after the satellite image multispectral classification, provides strata useful as a frame for

FIGURE 26 – Customized biodiversity database (plants)

BIODIVERSITY DATA FORM

IDENTIFICATION

Study area: GPS: Easting: Nothing:

Quadrat number:

Strata type:

GENERAL VARIABLES

Land cover: Local physiography:

State of succession: Soil type:

Disturbance:

Elevation: Slope: Aspect:

TREE LAYER (< 20 m)

Study area	Quadrat number	Layer	Species code	Number of ind.
1	4	1	49	1
1	4	2	6	1
1	4	2	7	1

Record: of 49

Records: of 70

sampling. It can also be useful for upscaling and the interpolation of diversity indices. The distinct classes of pixels that can form clusters and mapping units, or can be converted to polygons in vector format, are the units for upscaling. Both polygons and raster mapping units can be used as a geospatial framework to upscale and interpolate the computed indices of plant biodiversity. The properties of internal homogeneity or uniformity of such mapping units can be exploited to serve in the upscaling or spatial extrapolation or interpolation of plant diversity indices computed at specific locations (point data).

Uniformity index to assess the homogeneity of mapping units

As the usefulness of the mapping units for upscaling will depend directly on their internal homogeneity, this needs to be tested. In order to provide an indicator of the degree of internal uniformity of each of the classes on the plant diversity indices that are calculated from quadrat sampling data, a uniformity index can be computed as a measure of the goodness of the classification in partitioning spatial variability and creating strata (classes) that can be used for interpolation. The uniformity index is calculated by subtracting the relative variance from 1. The relative variance is a ratio of the within-class variance to total sample variance. When the value of the index is close to 1, the mapped class boundaries are very meaningful in terms of partitioning the variability of plant diversity indices across the landscape. The within-class variance is considerably smaller than the total variance, indicating that the classes are relatively homogeneous. This could also be viewed as a strong relationship between the spatial distribution of plant diversity indices and the boundaries of the mapped classes. The species composition of the vegetation classes can be separated by such boundaries of the vegetation classes identified in the field. Therefore, the classes are useful for discriminating plant composition of each landscape element type. The equation for calculating the uniformity index (U) is:

$$U = 1 - \left(\frac{\sigma_w^2}{\sigma_t^2} \right)$$

where: σ_w^2 is the within-class variance, and σ_t^2 is the total variance.

Assessing map accuracy of the vegetation map produced

The randomly selected field samples of vegetation from quadrat sites can be used for assessing the accuracy of the landscape classification. These samples can be used to estimate plant diversity at field level and to test the accuracy of the classes derived from satellite image interpretation. The assessment of the accuracy of the classification can be based on two procedures: (i) overall accuracy; and (ii) Cohen's Kappa statistic. These are the most common techniques for assessing the agreement between classes in the map and classes on the ground. The overall accuracy of the classified image can be computed by dividing the total number of correctly classified sampling quadrats by the total number of sampling quadrats. The overall accuracy (AC_o) can be written as:

$$AC_o = (SQ_{cc} / SQ_{tot})$$

where: SQ_{cc} is the total number of sampling quadrats classified correctly, and SQ_{tot} is the total number of reference sampling quadrats placed in the field.

The Cohen's Kappa statistic (Campbell, 1987) measures the excess of agreement between map and reality over the level of agreement that would have been obtained by chance alone. The Kappa (K) coefficient will equal 1 if there is perfect agreement, whereas 0 is what would be expected by total chance alone. The equation of the Kappa statistic can be written as:

$$K = (d - q) / (N - q)$$

where: d is the overall value for percentage correct; q is the estimate of the chance agreement to the observed percentage correct (these values are calculated using number of cases expected in diagonal cells by chance, and are drawn from some form of contingency table); and N is the total of number of cases.

A value of the Kappa statistic of 0.5 would imply that the mapping units predict reality with 50 percent reliability. Thus, the map is not very much better than chance.

Assessments of both internal homogeneity of mapping units (uniformity index) and map accuracy (Cohen's Kappa) are essential to determine the usefulness of the mapped classes for upscaling and interpolation of diversity indices.

Relating multispectral vegetation classes to biodiversity indices

The main practical objective of linking field quadrat measurements of plant diversity to vegetation classes, as derived from multispectral satellite image classification, is to explore the relationships between mapped boundaries of classes on the image and the spatial distribution of indices of plant diversity. Finding a strong association between them would allow for exploiting the map of vegetation classes as a mechanism for upscaling measurements on the ground to an entire landscape. This process can be considered as a typical case of spatial interpolation of point data (quadrat sites). The approach adopted in this report for the upscaling process uses the multispectral class boundaries as domain limits within which the diversity indices values are interpolated. Hernandez-Stefanoni and Ponce-Hernandez (2003) provide a description of the procedure.

It is recognized that other important techniques for spatial interpolation (e.g. geostatistical techniques, distance functions, and bicubic splines) are available and should be attempted, provided favourable conditions of number of samples (point data) and

spatial structure in the diversity indices exist. However, this section concentrates on exploring the virtues of mapped vegetation classes to indirectly stratify and map plant diversity indices, and on how to use such a spatial framework for upscaling biodiversity measurements to the landscape scale.

Thus, in order to estimate the biological composition of the entire studied area based on the classification derived from the multispectral satellite image, two steps need to be considered. First, several diversity indices can be calculated by vegetation type (mapping unit) by pooling all the field quadrats of every vegetation class, as derived from the multispectral classification. Second, this report adopted the approach suggested by Burrough and McDonnell (1998) to spatial prediction based on classes. This approach essentially makes use of the classes as the mechanism for interpolating values of the class attributes to the entire area covered by each class. The approach assumes, in this case, that diversity values within vegetation classes are significantly lower than those between them. That is to say, that the within-class variability of the attribute needs to be confirmed as substantially smaller (i.e. internal homogeneity) than the variability across classes before a class can be used as a mechanism for extending the values of its attributes to all locations within the class.

A standard ANOVA can compute the variances required for testing the contributions of quadrats, vegetation types and the residual error to the total variability of the calculated diversity indices in the area. The ANOVA to be undertaken could use the model:

$$Y_{ij} = \mu + \nu t_i + \varepsilon_{ij}$$

where: Y_{ij} is the number of species or abundance in the j -th quadrat within the i -th vegetation type; μ is the general mean of all vegetation types; νt_i is the effect of i -th vegetation type; and ε_{ij} is the error in the j -th quadrat within the i -th vegetation type or subtype.

The one-factor ANOVA model can test for significant differences in the diversity of plants across vegetation classes. Thus, through the ANOVA, a comparison can be made between the mean of the number of species by quadrat (that is the species richness in 100 m²), and the mean values of the exponential Shannon Diversity Index and Reciprocal Simpson Index (1/D) by quadrat, among the vegetation types. The Least Significant Difference test (Tabachnick and Fidell, 1996) can be used to determine whether there are significant differences among classes.

As described by Hernandez-Stefanoni and Ponce-Hernandez (2001), a number of assumptions are necessary in order to use vegetation classes and their mapped spatial extents as a reliable mechanism for making predictions of biodiversity values. First, the values of diversity data should be random and not spatially continuous. This means that the value of the diversity indices should be independent of the location inside each polygon (landscape element type). Second, the variance of diversity data within vegetation classes should be small if not homogeneous. Third, all diversity values should be distributed normally, in the probabilistic sense. Finally, all spatial changes should take place at boundaries in a relatively sharp manner (Burrough and McDonnell, 1998). For testing the assumptions of normality of the data, the Komolgorov-Smirnov test can be used. Levene's test could be used for testing the homogeneity of variance among vegetation classes. Thus, randomness and independence can be dealt with only indirectly through the tests indicated above and through the ANOVA tests. It is presumed that the plant diversity indices are quasi-stationary over space, which is characteristic of transition phenomena, accounting for small within-class variations.

Mapping biodiversity indices

The procedures discussed above provide a range of techniques that can be used under different circumstances of data and variability to map out the

spatial extent of plant diversity indices and to obtain a display of the spatial distribution of the diversity of plants in the area of concern.

Using mapping unit polygons as interpolants is the simplest mapping method. This method enables use of GIS functionality. The process would consist essentially of calculating a particular diversity index from within-class pooled data on, and attributing that value to, the polygon from which the quadrat data were pooled. Polygon attribute assignment functions that are used in this situation are a standard function in any GIS software.

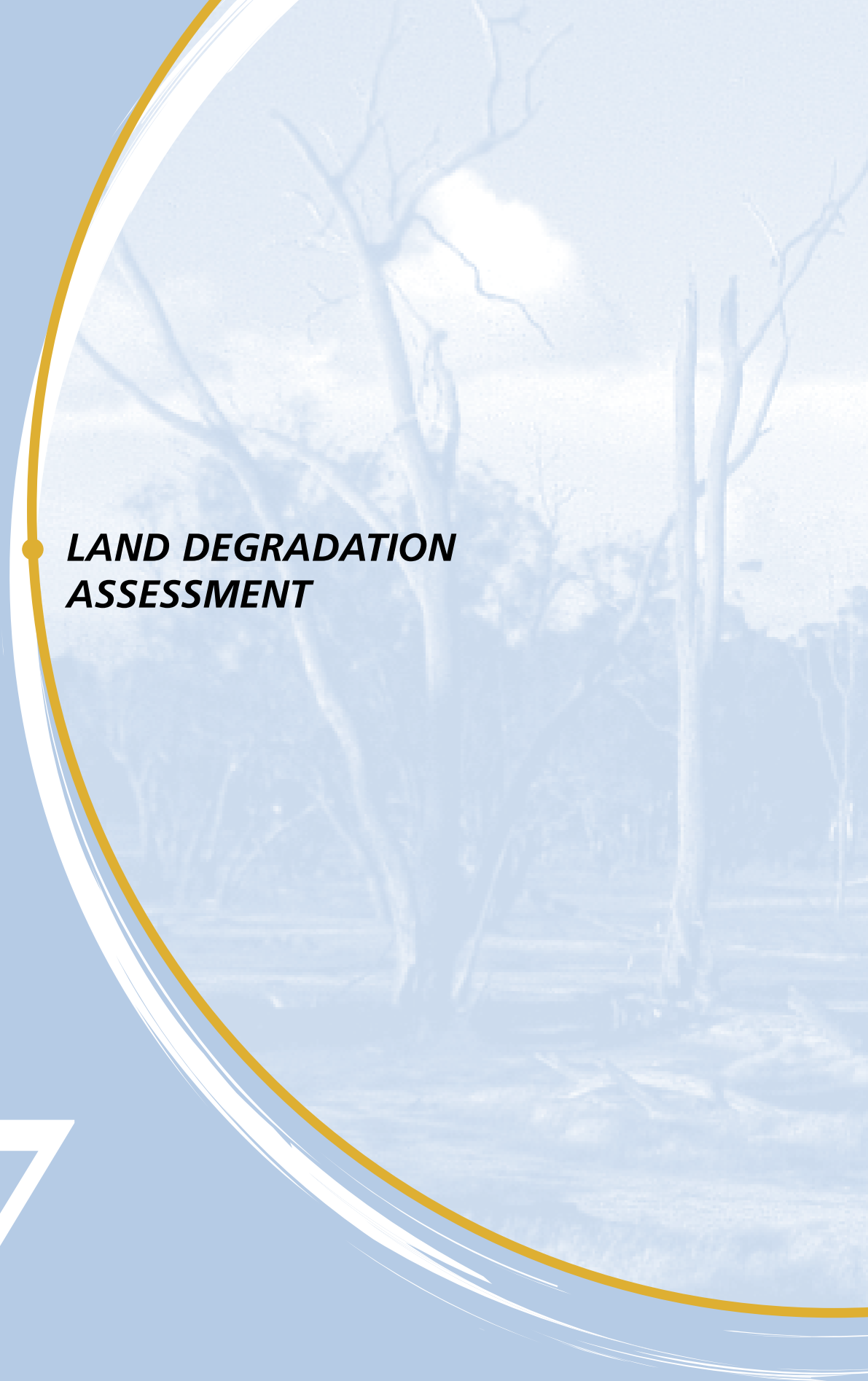
Spatial interpolation with block kriging requires that a clear spatial structure be found in the semi-variogram of the diversity index, and that anisotropies are accounted for. Typically, this technique would be demanding in terms of the number of sample sites (point data) required for an optimal interpolation, but it would not use the vegetation classes mapped out with the multispectral classification. The map resulting from block kriging would be a raster map of the diversity index.

Other spatial interpolation methods, such as bicubic splines (an exact interpolator), would make fewer demands on the number of sampling sites but would create a smoothing effect. This method does not use the vegetation classes from the multispectral classification. A "gridding" method has to be chosen where other interpolation packages that do not use block kriging or bicubic splines are used. Typically, this "gridding" or interpolation method is some form of distance function moving average.

CHAPTER

7

LAND DEGRADATION ASSESSMENT



CHAPTER 7

Land degradation assessment

Land degradation has been defined as the set of processes that lower the current and potential capability of the land to produce (quantitatively or qualitatively) goods and services. Degradation processes cause a decrease in the quality of land. For the purposes of this methodological development, and for the sake of comparing current land use with potential land use involved in LUCs, two concepts in land degradation are useful: present land degradation, and the risk of land degradation. The former is assessed for current or actual land-use patterns, while the latter can only be predicted as risk incurred if potential scenarios of land use were implemented.

The methods to assess present land degradation depend on the type of land degradation: physical, chemical or biological. The assessment of land degradation necessitates the assessment of each of the component processes. This section concentrates on the methodological details of land degradation assessment. The approaches to land degradation range from simple qualitative observations in the field to elaborate computer simulation modelling of complex processes. Table 14 summarizes the approaches.

Parametric semi-quantitative approach

A parametric semi-quantitative approach to the assessment of land degradation was adopted. The rationale for this:

- ▶ it is a relatively fast and inexpensive method and less involved than either setting up medium to long-term field experimental plots or calibrating and running data-demanding and expertise-based computer simulation models of degrading processes.
- ▶ the main aim of the assessment was to obtain a picture of the current “status” of degradation of the land in a rapid, low-cost and useful manner with little demand for either specific expertise in modelling or processes, or very specific data.

The fundamental premise of the approach is that land degradation (D) is a function of: “climate aggressivity” (C), soil resistance to that aggressivity (S), topographic factors (T), natural vegetation (V), land use (L), and land management (M). Thus, for current or actual land use, $D = f(C, S, T, V, L, M)$.

For operating conditions of implementing a given LUC, V, L and M would remain constant, which would be the case of a given PLUT.

TABLE 14 – Approaches to land degradation assessment

Direct field observations using diagnostic criteria or simple visual indices (subjective)
Landscape units assessment (land systems and facets) and subjective rating
Parametric semi-quantitative method (computation of indices on factors)
Rating system and decision trees (computer automation)
Simulation modelling (computer modelling)

Land degradation can be estimated as a function of four factors:

- ▶ climate,
- ▶ soil,
- ▶ topography,
- ▶ a human factor, which expresses itself directly as the choice of land cover and its management.

These four factors can be readily observed in any field situation and become the main groups of data for the assessment. The diagnostic parameters or indicators to observe, calculate or measure for each factor of a given process and type of degradation are indicated in Tables 15, 16 and 17.

TABLE 15 – Physical degradation

Process	Factors			
	Climate	Soils	Topography	Human factor
Soil erosion by water	Erosivity of rainfall (R) factor (USLE) or $\sum_{i=1}^{12} (p^2/P)$	K erodibility factor (USLE) from Weichmeir's nomographs or from textural classes and parent material	Slope (S) and slope length (L) factors (USLE)	Crop (C) and conservation (P) factors from USLE (tables or nomographs)
Soil erosion by wind	Wind erosivity index: $C = V^3 / (2.9PE^2)$ or $C = \sum_{i=1}^{12} (V^3/100)(P-PET/PET) n$	CEC or pF15	N.A.	Coefficient of natural vegetation per LUT
Compaction, crusting, sealing	Erosivity of rainfall (R) factor (USLE) or $\sum_{i=1}^{12} (p^2/P)$	Crusting index: $CI = (Z_f + Z_c)/A$ $CI > 2.5$ intense crusting $CI < 1.5$ non-crusting	Flat lands are more susceptible	Heavy machinery, no cover crops, puddling

TABLE 16 – Chemical degradation

Process	Factors			
	Climate	Soils	Topography	Human factor
Salinization	$P/PET < 1$ and salt in the landscape	$P/PET < 0.75$ and presence of some saline soils in the area	Assessed by landform: closed basin, lacustrine beds	No levelling of irrigated land, excess irrigation, quality of groundwater
Sodication	$P/PET < 1$, but with higher values for Sodication	$P/PET < 0.75$ and presence of some saline soils in the area	Assessed by landform: closed basin, lacustrine beds	No levelling of irrigated land, excess irrigation, quality of groundwater
Acidification	$\sum_{i=1}^{12} (P-PET)$; $P > PET$ or $[\sum (P-PET)]$ - Moist R	Low CEC and presence of kaolinitic clay	Flat lands are more vulnerable	Deforestation increases leaching, excess fertilizers, excess irrigation
Toxic comps.	$P/PET < 1$, dry climate	Preponderant geologic material with substance as part of composition	Low, flat and depositional	Proximity to factories & mines, irrigation with sewer water, excess of pesticides and chemicals Toxics > threshold value

TABLE 17 – Biological degradation

Process	Factors			
	Climate	Soils	Topography	Human factor
Decline in SOM	$K_2 = 1/2 \sum e^{0.1065t}(P/PET)$ $(P < PET)$ K_2 is the rate of humus decay (%/year) for $P > PET$ $P/PET = 1$ for $t < 0$, $t = 0$ Coefficient of humification (B) $B = m(K_1/K_2)$ K_1 is the coefficient of humification	Texture: sandy > clay $K_2 = 1\ 200/(A + 200)(C + 200)$ $A = \text{clay (\%)}$ $C = \text{CaCO}_3 (\%)$ $5 < \text{pH} < 7.5$ little effect	N.A.	Land cover and shade affect soil temperature C/N ratio of crops in the LUT Additions of organic matter If OM decreases and SOM is mineralized more slowly than it is added, then there is biological degradation

A comparison between the compound index for actual land degradation (D) for a given tract of land and the land degradation risk estimated by such parameters for each PLUT (D_{risk}) will indicate whether the rates of degradation would increase or decrease with the potential LUC. Thus: change in land degradation rate = ($D_{\text{risk}} - D$).

The type of degradation affecting the land and the factors responsible for such degradation under the actual or any potential land use will also be clear from these systematic observations.

Land degradation assessment and databases

The parameters in Tables 15, 16 and 17 are indicators of degradation processes in the three types of land degradation. They are not direct assessments themselves. However, being indicators or “proxy” variables, they are included in most databases on climate and land resources. The following list comprises the minimum data sets that need to be assembled in order to calculate such degradation indices:

► Climate:

- mean monthly precipitation (p),
- annual precipitation (P),
- effective precipitation (Thornthwaite) (PE),
- potential evapotranspiration (PET) estimated with current methods (e.g. Penman, Penman-Monteith, Thornthwaite),
- wind velocity (average) (V),

- rainfall erosivity (factor “R” from the universal Soil Loss Equation (USLE)), estimated as a function of its intensity from nomographs (Wischmeier and Smith, 1965; FAO, 1978a),
- mean monthly temperature (t).

► Soil/landscape:

- soil erodibility (factor “K” from the USLE), estimated as a function of other soil parameters (texture, organic matter, depth, etc.) from nomographs (Wischmeier and Smith, 1965; FAO, 1978a),
- cation exchange capacity (CEC) of the soil (weighted average over the soil depth considered),
- soil moisture constant (pF = moisture content in the soil at 15 bars of tension),
- fine silt content in the soil (Zf) in percent (2–20 mm),
- coarse silt content in the soil (Zc) in percent (20–50 mm),
- clay content of the soil (A percent) in percent, and clay type (e.g. kaolinitic),
- organic matter (OM percent) content in the soil, in percent,
- humus content of the soil (B) in equilibrium (percent),
- calcium carbonate (CaCO_3) in the soil, in percent (C),
- slope (S) in percent (percent),

- slope length (L) in metres,
- landform (descriptive).
- ▶ Management and human factors:
 - crop factor (factor “C” from USLE tables; Wischmeier and Smith, 1965; FAO, 1978a),
 - soil conservation practices (factor “P” from USLE tables; Wischmeier and Smith, 1965; FAO, 1978a),
 - land cover (percent of area covered and percent of shade, types of crops and vegetation,
 - annual additions of DPMs including crop residues and manures (tonnes/ha/year),
 - land use (description in terms of LUTs).

The variables in the minimum data set can be obtained readily. Common sources of these types of data are:

- ▶ soil survey reports,
- ▶ soil databases,
- ▶ meteorological databases,
- ▶ land use/land cover maps and reports.

Soil, land resources, meteorological and land use or land cover databases are common sources of digital data for compiling the variables of the minimum data sets to calculate the indices of the three types of land degradation.

Field surveys for land degradation assessment

In order to produce estimates of the indices or indicators of the three types of land degradation, computed at specific sites, it is necessary to obtain the input variables for the calculation at such sites, as part of the minimum data sets. For the purpose of data gathering, a set of quadrat sampling sites of 10 x 10 m was defined. These quadrat sites were the same sites as the ones used for the biomass and plant diversity estimations.

The quadrat sites are located using a stratified random sampling scheme, where the strata

correspond to land cover classes derived from a satellite image interpretation or from air-photo interpretation. The number of samples in each class is a compromise between maximizing data collection for representation, and time, effort and cost.

The data collection takes place through gathering data from existing databases (i.e. climate, soil and land use and management) before the start of the field survey and complementing, confirming and validating these data with field observations and measurements where necessary. Field forms were used to gather necessary information on the three types of land degradation.

Data gathering and the completion of the land degradation field forms were performed simultaneously as the biomass and biodiversity measurements were completed in the field. This requires a multidisciplinary field team and the division of tasks while in the field in order to achieve efficiency. The technical aspects regarding the sampling scheme and distribution of samples in the studied area are dealt with above in the sections on biomass and biodiversity estimation.

The field data gathering is followed by a data processing phase where data are input into digital spreadsheets. The calculations are then made in order to yield the indices for each process and type of land degradation.

Data processing for land degradation assessment

Field data were collected for assessing: erosion by water and wind; degradation by compaction and crusting; and chemical degradation including observations on acidification, salinity, sodication and toxicity, as well as information on biological degradation. Observations were made on climate, soil state, microtopography, macrotopography, vegetation cover and human impacts (positive and negative).

Data compilation

The data collected on the forms were compiled into spreadsheet format where data from climate stations (i.e. temperature, precipitation and potential evapotranspiration) and detailed soils data could be added. Using these data, the processes affecting land degradation could be modelled. Tables 18–24 illustrate the details of data compiled from each field form.

Data modelling and calculation of degradation status and risk

Based on the data provided at each quadrat site, indices for each of the modes of degradation were calculated. The results were assessed according to FAO (1979) methodology. Table 25 outlines the basic elements needed in order to assess land degradation.

With the relevant information and data sets compiled and organized, the calculations of each of the indicator variables per each of the types of land degradation were set up and performed in

spreadsheets. According to the values calculated per each of the indicator variables or indices, a rating system was set up according to FAO (1979) procedures for each type of land degradation. The ratings were derived depending on the ranges of values of each of the indicator variables of the type of land degradation evaluated. Tables 26–29 show the rating systems for four of the types of degradation processes (i.e. erosion by water, wind, biological degradation, and compaction and crusting) that were used in the case studies accompanying this report.

Using these rating systems and classes, examples of these types of the indicator or index measures were rated with respect to the different factors affecting land degradation. The climate, soil, topography and human influence ratings were then multiplied together to assess the current state and risk of each type of degradation. Tables 30 and 31 present examples of the calculations. The case studies provide full examples of data and calculations.

TABLE 18 – General information to be collected from the study area for land degradation assessment (e.g. Texcoco watershed, Mexico)

Site	Geographical given		Terrenos planos suceptibles	Evaluada por geoforma: cuenca cerrada planicie de inundación	Plana y deposicional	Cambio en la CIC ó PFI5	Baja CIC y presencia de arcilla Kaolinitica	Material geológico: con materiales toxicos abundantes
	Lat. N(19°)	Long. W(98°)						
01 – 01	30.331'	54.698'	Plana	Plano vegetación gramineas	Planicie suceptible a inundación, alta sodicidad	Plana	Solonchak contiene sodio Pss>15 percent	Rocas igneas, contaminación por basura, radioactivos y materiales pesados
01 – 02	30.418'	54.438'	*	*	*	*	*	***
01 – 03	30.354'	55.650'	Plana	*	Zona de deposición	Plana	Vertisol haplico	Rocas igneas, sedimentarias
02 – 01	30.113'	56.613'	Plana	Plana, alfalfa	Planicie suceptible a inundación, alta sodicidad	Plana	Eutric planosol	***
02 – 02	30.860'	56.758'	Plana	*	Planicie	*	Solonchak	Rocas igneas, sedimentarias
03 – 01	29.985'	53.418'	*	*	*	*	*	***
04 – 01 x	27.671'	48.800'	Lomerio abrupto	Pendiente concava, posible acumulación en microcuencas	Lomerio abrupto	No afecta	Baja CIC suelos de ando	No
05 – 01	30.355'	50.914'	Plana	*	Planicie ligera inundación, cuenca abierta	Plana	Mediana	Rocas igneas, fertilizantes y pesticidas
07 – 01	29.800'	51.367'	*	*	*	*	*	***
07 – 02	30.628'	53.402'	*	*	*	*	*	***
07 – 03	29.972'	52.352'	Plana	*	Planicie, zona de deposición	Plana	Alta	Rocas igneas, fertilizantes y pesticidas
08 – 01	26.906'	46.272'	Lomerio suave	Si es suceptible	Lomerio suave	*	*	Igneo
08 – 02	26.694'	46.218'	Lomerio suave	No por ser lomerio suave	Lomerio suave	*	*	Igneo no materiales toxico

TABLE 18 – General information to be collected from the study area for land degradation assessment (e.g. Texcoco watershed, Mexico) – *continued*

Site	Geographical given		Terrenos planos susceptibles	Evaluada por geoforma: cuenca cerrada planicie de inundación	Plana y deposicional	Cambio en la CIC ó Pf15	Baja CIC y presencia de arcilla Kaolinitica	Material geológico: con materiales tóxicos abundantes
	Lat. N(19°)	Long. W(98°)						
08 – 03	29.800'	31.387'	Minima	*	*	*	*	***
08 – 04 (a)	30.152'	58.475'	Terrenos ligeramente plano	Planicie de inundación, a cuenca abierta	Plana	Entisol cantidad moderata de limo	Presencia de arcilla Kaolinita	Rocas igneas, fertilizantes y pesticidas
08 – 04 (b)	29.942'	49.972'	*	Cuenca abierta susceptible a lavado	Plana	Entisol regosol	Mediana	Rocas igneas, fertilizantes y pesticidas
08 – 04 (c)	29.170'	50.580'	*	*	*	*	*	***
08 – 05	30.610'	51.343'	*	Planicie cuenca abierta	Plana	Entisol	Mediana	Rocas igneas, fertilizantes y pesticidas
12 – 01	26.324'	44.933'	No son terrenos planos	Serrania (lomerio-abrupto)	No es plana	*	*	Ignco no materiales toxico
12 – 02	26.790'	45.495'	Acumulación de M.O. y residuos organicos	No	No	*	Andosol muy arcilloso	Presencia de Al, Fe y Mn (suelos de andosol)
12 – 03	25.353'	44.813'	No influye (cañada)	Parte baja acumulación de agua y sales	No	*	Andosol arcilloso	Presencia de Al, Fe y Mn

TABLE 19 – Data compilation table for physical land degradation by water

Strat/ plot_ID	SOILS				TOPOGRAPHY				COVER			CONSERVATION	
	Soil group	% silt	% clay	% sand	% OM	Soil structure	Permeability	Slope (%)	Slope <	Slope length (m)	% cover		Type of cover
01 – 01	Vc + Vp/3 (89)	48	20	32	0.6	1	5	0.5	0.225	200	100.00	maize	"blind basin??" terraces and "coverturas" with measures of conservation
01 – 02													
01 – 03	Zg + Vc - n/3							1	0.45	500	100.00	pasture	
02 – 01	Zg + Vc - n/3	44	22	34	1.1	1	5	0.5	0.225	200	95.00	fallow	
04 – 01								14	6.3	50	80.00	young forest	Reforestation ~ 10-year old trees
05 – 01	Hh/2							3	1.35	100	40.00	maize, oats	
07 – 03	Hh/2							2	0.9	200	95.00	maize	
												legume residue	
08 – 01								5	2.25	50	70.00	(husks/pods)	linear furrows, divided plots
08 – 02								4	1.8	100	100.00	maize	
08 – 04 (a)	Hh/2							5	2.25	1 000	60.00	maize	
08 – 04 (b)	Vp/3							2	0.9	100	35.00	maize	
08 – 04 (c)	Hh + Be/2								0		100.00	(crops)	furrowed
08 – 04 (d)	Hh/2								0		100.00	(crops)	
08 – 05	Vp/3							2	0.9	200	80.00	maize	
12 – 01	Bh + Tm/1							80	36	20	100.00	forested	
12 – 02	Bh + Tm/1								0		100.00	forested	resid treebits
12 – 03	Be + I + Bh/2								0		100.00	forested	resid treebits
12 – 04									0		100.00	forested	

TABLE 20 – USLE results calculated from nomographs and by using GIS functions

X	Y	Site	Elev	R	K	LS	C	P	AGIS
508840.2	2156664	01-01	2242.66	2118.96	0.04	0.00	0.19	1.00	0.00
509722.2	2156881	01-02	2242.06	2120.96	0.04	0.00	0.19	1.00	0.00
507755.8	2156519	01-03	2243.40	2116.88	0.04	0.00	0.19	1.00	0.00
515057.4	2156765	05-01	2282.99	2159.53	0.02	1.20	0.19	1.00	9.80
515245.4	2155449	07-01	2321.82	2180.96	0.02	1.30	0.19	0.55	5.90
510951.2	2156476	07-02	2240.20	2125.70	0.04	0.00	0.19	1.00	0.00
512425.9	2155767	07-03	2248.17	2136.10	0.00	0.00			
524094.1	2150128	08-01	2969.23	1745.54	0.02	3.90	0.09	1.00	12.30
523674.8	2150273	08-02	2944.00	1751.19	0.02	3.50	0.19	1.00	23.30
516272	2156158	08-03	2320.00	2189.05	0.02	2.30	0.19	0.55	10.50
516431	2154538	08-04a	2366.99	2144.70	0.02	1.00	0.19	0.55	4.50
516431	2156967	08-04b	2309.80	2173.06	0.02	1.90	0.19	0.55	8.60

TABLE 21 – Data compiled for the calculation of the crusting index (CI) and other factors pertaining to the assessment of degradation by compaction and crusting

Strat/ plot_ID	CLIMATE Rainfall erosivity factor (R)	SOILS							Class
		1.- Crusting index CI = (Zf + Zc)/Zc Classification(?)	(Zf + Zc)/Zc	2.- CI = (1.5 x Zf + 0.75Zc)/(C+ 10* %OM)	% OM	% Clay	Zf	Zc	
01 – 01	2118.962	36	1.938169985	1.841	33.830	35.000	65.000	SOFT CRUSTING	
01 – 02	2120.956	51	1.769814052	2.488	38.686	50.000	50.000	SOFT CRUSTING	
01 – 03	2116.884	51	1.769814052	2.488	38.686	50.000	50.000	SOFT CRUSTING	
02 – 01		51	1.769814052	2.488	38.686	50.000	50.000	SOFT CRUSTING	
02 – 02		51	1.769814052	2.488	38.686	50.000	50.000	SOFT CRUSTING	
03 – 01	2129.104	36	2.978817299	1.045	23.540	35.000	65.000	INTENSE CRUSTING	
04 – 01		36	3.354870775	1.190	18.280	35.000	65.000	INTENSE CRUSTING	
05 – 01	2159.528	36	3.354870775	1.190	18.280	35.000	65.000	INTENSE CRUSTING	
07 – 01	2180.962	36	3.354870775	1.190	18.280	35.000	65.000	INTENSE CRUSTING	
07 – 02	2125.7	36	2.978817299	1.045	23.540	35.000	65.000	INTENSE CRUSTING	
07 – 03	2136.104	36	3.354870775	1.190	18.280	35.000	65.000	INTENSE CRUSTING	
08 – 01	1745.541	36	2.308481532	1.221	31.650	35.000	65.000	INTENSE CRUSTING	
08 – 02	1751.186	36	2.308481532	1.221	31.650	35.000	65.000	INTENSE CRUSTING	
08 – 03	2189.053	36	3.354870775	1.190	18.280	35.000	65.000	INTENSE CRUSTING	
08 – 04 (a)	2144.704	36	3.354870775	1.190	18.280	35.000	65.000	INTENSE CRUSTING	
08 – 04 (b)	2173.057	36	2.978817299	1.045	23.540	35.000	65.000	INTENSE CRUSTING	

TABLE 22 – Data compiled for the assessment of salinization and sodication of soils

Strat/ plot_ID	CLIMATE	Evidence of salts on surface	Value Na	SOILS	TOPOGRAPHY	HUMAN FACTOR	Comments
01 – 01	0.476269421	1	488.625	0.724498614	susceptible to flooding	Excessive irrigation, deficient infiltration and water quality	temporal and irrigated
01 – 02	0.476269421	1	1265.231	0.724498614	flat		temporal and irrigated/drainage
01 – 03	0.476269421	1	1265.231	0.724498614	susceptible to flooding		temporal and irrigated
02 – 01	0.476269421	1	1265.231	0.724498614	abrupt hills	na	na
02 – 02	0.476269421	1	1265.231	0.724498614	open watershed	temporal/conventional usage	Conventional use
03 – 01	0.449495774		45.500	0.449495774	flat, depositional	temporal	Conventional use
04 – 01	0.487430529	0	82.000	0.487430529	open watershed, susceptible to flooding	temporal (natural)	
05 – 01	0.487430529	+	82.000	0.487430529	open watershed, susceptible to erosion	temporal (natural) - excessive erosion during rain events	
07 – 01	0.449495774	–	82.000	0.449495774			
07 – 02	0.487430529		45.500	0.487430529			
07 – 03	0.487430529	+	82.000	0.487430529	flat, open watershed	temporal/conventional usage	
08 – 01	0.487430529	+	65.000	0.487430529	mountainous / abruptly hilly	temporal	
08 – 02	0.487430529	+	65.000	0.487430529	no	no	
08 – 03	0.487430529	–	82.000	0.487430529	flooded hollow	no	

TABLE 23 – Data collected on soil toxicity

Strat/ plot_ID	CLIMATE		SOILS	TOPOGRAPHY	HUMAN FACTOR	Comments
	P/PET < 1	Dry climate				
01 – 01	0.476269421	yes	igneous rock, contamination heavy metals	flat	excessive pesticides, high salinity, sodicity fertilizers	high salinity, sodium, fertilizers
01 – 02	0.476269421	yes				
01 – 03	0.476269421	yes	igneous rock, sedimentary	flat	heavy metals	
02 – 01	0.476269421	yes	igneous rock, slightly saline,	flat	pesticides, fertilizers, moderate salinity, irrigated, dispersed waste,	
02 – 02	0.476269421	yes	igneous rock, sedimentary	flat	heavy metals/household and industrial chemicals	
05 – 01	0.487430529	yes	igneous	flat	fertilizers/pesticides/powerlines	powerlines/rainfed agri
07 – 03	0.487430529	yes	igneous	flat	fertilizers/pesticides	maiz bien desunolado(?)
08 – 01	0.487430529	yes	igneous	yes	surrounded by canal, trail	surrounded by canal, trail
08 – 02	0.487430529	yes	igneous, not toxic	gently rolling hills	truck, near a canal of "agua blanco"	
08 – 04 (a)	0.449495774	yes	igneous rock	flat	gravel pit, 500 m away, pesticides, fertilizers	
14 – 03	0.487430529	yes	derived from limestone		no	
14 – A – 01	0.487430529	yes	igneous rocks	no	fertilizers N	fertilized with N
14 – A – 02	0.487430529	yes	igneous rocks	no	fertilizers	fertilized/chemicals
14 – A – 03	0.487430529	yes	igneous rocks	no	fertilizers/leaching	washed ("lavado")
14 – B – 03	0.487430529	yes	igneous rocks	no	fertilizers/insecticides/leaching	washed
18 – 01	0.487430529	yes	presence of aluminium (Andosols) Fe Mn	no	no	

TABLE 24 – Data and information collected on the biological degradation of soils

Strat/ plot_ID	CLIMATE			SOILS			TOPOGRAPHY		HUMAN FACTOR			Comments		
	PP	PET		CaCO ₃	Clay	$K_2 = \frac{1}{2}\Sigma e^{0.1065t} (P/ETP)$	K1= Humidification Coefficient	$K_2 = \frac{1\ 200/(A + 200)}{(C + 200)}$	B= m(K ₁ /K ₂)	Not applicable	Cover and shade affect the soil temperature		Incorporation of organic matter	C/N relation of the LUT
01 – 02	643.7	1391.6		38.686	5.938	15.81940012	Very severe	43600	1035.358	42.111	*	100	residual of OM - pasture/sewage	
01 – 03	643.7	1391.6		38.686	5.938	15.81940012	Very severe	43600	1035.358	42.111		100	little OM	
02 – 01	572.328	1257		38.686	5.938	15.81940012	Very severe	43600	1035.358	42.111				wood extraction
02 – 02	572.328	1257		38.686	5.938	15.81940012	Very severe	43600	1035.358	42.111		40	residual of OM "deshierbes	
03 – 01	572.328	1257		23.540	0.930	14.18620651	Very severe	43600	1078.625749	40.421		95	residual of OM of desierbes, branches on tree	
04 – 01 x	597.042	1257		18.280	0.079	16.72634125	Very severe	43600	1099.939527	39.638				C>N
05 – 01	643.7	1391.6		18.280	0.079	16.72634125	Very severe	43600	1099.939527	39.638		small amount of cover	none/little incorp. of OM	>N for fertilization
07 – 01	571.538	1516		18.280	0.079	14.18620651	Very severe	43600	1099.939527	39.638		60	residual of OM of "deshierbe", few branches on trees	
07 – 02	571.538	1516		23.540	0.930	16.72634125	Very severe	43600	1078.625749	40.42180527		35	residual of OM of deshierbe	C/N relation small
07 – 03	571.538	1516		18.280	0.790	16.72634125	Very severe	43600	1103.848268	39.49818218				
08 – 01	597.042	1257		31.650	0.798	16.72634125	Very severe	43600	1040.179581	41.91583914				
08 – 02	597.042	1257		31.650	0.798	16.72634125	Very severe	43600	1040.179581	41.91583914		80	deshierbes residual, spread waste	

TABLE 25 – Data and information used in the assessment of land degradation per land cover class or LUT

Location	SOIL Dominant soil	C(2)	SALINE? Presence Sz	ADJACENT TO SALINE?			K ₂	Textural class	TOPOGRAPHY		HUMAN Land use	% cover	a Ca	b
				Adj Sz	Clay type	%CaCO ₃			Slope	Slope class				
01 – 01	Zg + VCn/2	1.93817	1	1	Kaolinite	0.937	15.8194	2	0	A	irrigated with sewage	100	92.7499	
01 – 02	Zg + VCn/2	1.769814	1	1	Kaolinite	5.938	15.8194	2	0	A	irrigated with sewage	88	92.7499	
01 – 03	Zg + VCn/2	1.769814	1	1	Kaolinite	5.938	15.8194	2	0	A	irrigated with sewage	100	92.7499	
02 – 01	?	1.769814	1	1	Kaolinite	5.938	15.8194	?	?	A	irrigated in saline soils	100	92.7499	
02 – 02	?	1.769814	1	1	Kaolinite	5.938	15.8194	?	?	A	irrigated in saline soils	95	92.7499	
03 – 01	Urban	2.978817	0	0	Kaolinite	0.93	14.18621	0	0	A	suburban expansion		87.29445	
04 – 01		3.354871	0	0	Kaolinite	0.079	16.72634					80	82.11394	
05 – 01	Hh/2	3.354871	0	0	Kaolinite	0.079	16.72634	2	3.16	A	rural suburbia	40	82.11394	
07 – 01	Hh/2	3.354871	0	0	Kaolinite	0.079	14.18621	2	3.61	A	irrigated agriculture	40	87.29445	
07 – 02	Zg + VCn/2	2.978817	0	1	Kaolinite	0.93	16.72634	2	0	A	irrigated agriculture		82.11394	
07 – 03	Urban	3.354871	0	0	Kaolinite	0.79	16.72634		0	A	irrigated agriculture	95	82.11394	
08 – 01	Bh/2	2.308482	0	0	Kaolinite	0.798	16.72634	2	9.06	ab	rainfed agriculture	70	82.1139	
08 – 02	Bh/2	2.308482	0	0	Kaolinite	0.798	16.72634	2	8.25	ab	rainfed agriculture	100	82.1139	
08 – 03	Hh/2	3.354871	0	0	Kaolinite	0.79	16.72634	2	5.83	a	rainfed agriculture	100	82.1139	
08 – 04 (a)	Hh/2	3.354871	0	0	Kaolinite	0.79	14.18621	2	2.83	a	rainfed agriculture	60	87.29445	
08 – 04 (b)	Hh/2	2.978817	0	0	Kaolinite	0.93	16.72634	2	5	a	rainfed agriculture	35	82.11394	
08 – 04 (c)		2.575943	0	0	Kaolinite	0.946	16.72634						82.11394	
08 – 05	Hh/2	2.978817	0	0	Kaolinite	0.93	15.8194	2	1.41	a	rainfed agriculture		92.7499	

TABLE 26 – Rating system for land degradation assessment (after FAO, 1979) – soil erosion by water

Indicator/measure		Limits			Notes				
Water		Definition	Values	Initial weighting					
Climate	R'	light moderate severe very severe	0–50 50–500 500–1000 > 1000		FAO (1979)				
Soils	K soil type	slight	I	0.5					
		medium	II	1.0					
		high	III	2.0					
	K soil texture	coarse	1	0.02					
		medium	2	0.3					
		fine	3	0.1					
stony		stony	0.5						
Topography	Slope	a	0–8	0.35					
		ab	0–20	2					
		b	8–30	3.5					
		bc	8–>30	8					
		c	>30	11					
Vegetation	C-factor	C-factor	% cover		by % cover and type of cover				
			pasture	0.1 1–2 20–40 40–50 60–80 80–100		0.45 0.3 0.2 0.12 0.7 0.02			
		forest with appreciable brush	0.1 1–2 20–40 40–50 60–80 80–100	0.45 0.32 0.18 0.16 0.01 0.006	by % cover and type of cover				
			forest without appreciable brush	0.1 1–2 20–40 40–50 60–80 80–100		0.45 0.32 0.2 0.1 0.06 0.01	by % cover and type of cover		
				USLE - A tonnes/ha/year		none to slight moderate high very high		0–20 20–50 50–200 > 200	FAO (1979)

TABLE 27 – Rating system for land degradation assessment (after FAO, 1979) – degradation by wind erosion

Indicator/measure		Limits			Notes	
Water		Definition	Values	Initial weighting		
Climate	C'	light moderate severe very severe	0–20 20–50 20–150 > 150		FAO (1979) Ortiz et al. (1994)	
Soils	soil texture/comp. non-calcerous	coarse	1	3.5		
		medium	2	1.25		
		fine	3	1.85		
	calcerous	coarse	1	3.5		
		medium	2	1.75		
		fine	3	1.85		
	soils with gravel	coarse	1	1.75		
		medium	2	0.62		
		fine	3	0.92		
				0.86		
Vegetation/ cover	vegetation type of cover	type of cover	% cover			
		annual crops	-	0.7		
		humid tropical crops	-	0.4		
		irrigated agriculture	-	0.2		
		plain/pasture	0–1	1		
			1–20	0.7		
			20–40	0.5		
			40–60	0.3		
			60–80	0.15		
			80–100	0.05		
			savannah with trees	0–1	1	
				1–20	0.7	
		20–40		0.4		
		40–60		0.25		
		60–80		0.1		
		80–100		0.03		
		savannah selvatica		0–1	1	
				1–20	0.6	
			20–40	0.3		
			40–60	0.2		
			60–80	0.1		
			80–100	0.01		
			high forest	0–1	0.9	
				1–20	0.5	
		20–40		0.3		
		40–60		0.15		
		60–80		0.5		
		80–100		0.001		
Soil erosion tonnes/ha/year	none to slight	0–20			FAO (1979)	
	moderate	20–50				
	high	50–200				
	very high	> 200				

TABLE 28 – Rating system for land degradation assessment (after FAO, 1979) – based on indicator variables of biological degradation

Indicator/measure		Limits			Notes
Biological degradation		Definition	Values	Initial weighting	
Climate	K2 rate of humus decay	none to slight	0–1		
		moderate	1–3		
		high	3–10		
		very high	> 10		
Soils	texture	1		1.5	
		2		1	
		3		0.5	
	% CaCO ₃	0	0	1	
		calcareous soil	5	0.8	
		calcic horizon	15	0.6	
		Rendzina	40	0.3	
	soil pH	< 5.0	lowers rate of decay		
		> 7.5	lowers rate of decay		
		5.0–7.5	no effect		
Human factor					
	management	C/N ratio			
		RothC/CENTURY results			
		decrease in soil C			
		increase in soil C			
Biological degradation	decrease in humus 0–30 cm layer		%/year		
		none to slight	< 1		
		moderate	1–2.5		
		high	2.5–5		
		very high	> 5		

TABLE 29 – Ratings for evaluating physical land degradation – based on values of indicator variables for compaction and crusting

Indicator/measure		Limits			Notes
Compaction and crusting		Definition	Values	Initial weighting	
Climate	R'	light	0–50	0–5	
		moderate	50–500	5–7.5	
		severe	500–1 000	7.5–10	
		very severe	> 1 000	10	
		irr/flooded soil		10	
Soils	CI (2)	slight	< 1.2	0.001	
		moderate	1.2–1.6	0.1	
		high	1.6–2.0	0.75	
		very severe	> 2.0	1	
Topography	Slope%	a	0–8	1	
		b	8–30	0.5	
		c	> 30	0.3	
Human factor	machinery/ land use	natural	none		
		trails/human	low		
		low-impact agri.	moderate		
		high-impact agri. forestry	high severe		
Increase in bulk density	initial level < 1.0 g/m ³	none to slight	< 5		
		moderate	5–10		
		high	10–15		
		very high	> 15		
	initial level 1–1.25 g/m ³	none to slight	< 2.5		
		moderate	2.5–5		
		high	5–7.5		
		very high	> 7.5		
	initial level 1.25–1.4 g/m ³	none to slight	< 1.5		
		moderate	1.5–2.5		
		high	2.5–5		
		very high	> 5		
	initial level 1.4–1.6 g/m ³	none to slight	< 1		
		moderate	1–2		
		high	2–3		
		very high	> 3		
Decrease in permeability	initial level rapid (20 cm/h)	% change/year			
		none to slight	<2.5		
		moderate	2.5–10		
		high	10–50		
		very high	>50		
	initial level moderate (5–10 cm/h)	none to slight	<1.25		
		moderate	1.25–5		
		high	5–20		
		very high	> 20		
	initial level slow (5 cm/h)	none to slight	< 1		
		moderate	1–2		
		high	2–10		
		very high	> 10		

TABLE 30 – Calculated current risk for each type of degradation

Location	Risk of water erosion Climate	Risk of acidification HeRisk	Risk of bio. deg. CcRisk	Risk of physical deg. (decr. in permeability) SzRisk	Risk of salinity SoRisk	Risk of sodication AzRisk	Risk of bio. deg. BdRisk
01 – 01	9.738739	12.5	3	0.724499	3	0	15.8194
01 – 02	9.738739	17.5	3	0.724499	3	0	12.65552
01 – 03	9.738739	17.5	3	0.724499	3	0	12.65552
05 – 01	4.310982	125	0.795	0.487431	0	0	16.72634
07 – 01	4.582959	125	1.5	0.449496	0	0	14.18621
07 – 02	8.621964	125	3	0.487431	0.487431	0	16.72634
08 – 01	24.63418	125	0.3975	0.048743	0	0	16.72634
08 – 02	24.63418	125	0.3975	0.048743	0	0	16.72634
08 – 03	4.310982	125	0.795	0.487431	0	0	16.72634
08 – 04 (a)	4.582959	125	0.81	0.449496	0	0	14.18621
08 – 04 (b)	4.310982	125	0.795	0.487431	0	0	16.72634
18 – 01	86.21964	12.5	0.795	0.048743	0	0	16.72634

TABLE 31 – Calculated state of present land degradation (e.g. Texcoco River Watershed, Mexico)

Location	Present water erosion HeState	Present wind erosion WieState	Present phys. deg. CcState	Present salinity SzState	Present sodicity SoState	Present leaching AzState
01 – 01	7.790992	2.5	3	0.524898	2.173496	
01 – 02	7.790992	3.5	4.5	0.524898	2.173496	
01 – 03	7.790992	3.5	3	0.524898	2.173496	
02 – 01	0	0	0	0.524898	2.173496	
02 – 02	0	0	0	0.524898	2.173496	
03 – 01	0	0	0	0	0	
05 – 01	0	0	1.59	0	0	
07 – 01	3.666367	25	2.25	0	0	
07 – 02	6.897571	25	3	0	0	
07 – 03	0	0	0	0	0	
08 – 01	19.70735	87.5	0.3975	0	0	
08 – 02	19.70735	87.5	0.3975	0	0	
08 – 03	3.448786	87.5	0.795	0	0	
08 – 04 (a)	3.666367	87.5	1.62	0	0	
08 – 04 (b)	3.448786	87.5	1.59	0	0	

TABLE 32 – Degradation classes for Texcoco watershed by sampling quadrats

Quadrat site	Erosion by water HeClass	Erosion by water USLE Class	Erosion by wind WieClass	Compaction & crusting CcClass	Acidification AzClass	Salinization SzClass	Sodicity SoClass	Biological degradation BdClass
01 – 01	1	1	1	2	1	2	3	4
02 – 01			1	1	1	2	3	4
03 – 01	1		1	1	1	1	1	1
05 – 01	1	1	1	1	1	1	1	4
07 – 01	1	1	2	1	1	1	1	4
08 – 01	2	2	3	1	1	1	1	4
12 – 07	1	2	1	1	1	1	1	4
14 – B – 01	1		1	1	1	1	1	1
18 – 01	1	2	1	1	1	1	1	4

Using the ratings provided by FAO (1979), it was possible to classify the values into classes that reflect the degree of affectation by a given factor causing degradation of the land. The classes were given categorical names for communication purposes. The classes and their meaning are:

- ▶ 1 = none to slight,
- ▶ 2 = moderate,
- ▶ 3 = high/severe,
- ▶ 4 = very high/severe.

As an example of such a classification, Table 32 shows degradation classes by land degradation type in one of the case study areas.

Mapping land degradation

Upscaling quadrat sampling assessments

Once the status of land degradation at each quadrat sampling site has been assessed and the classification for each quadrat completed upscaling the assessment in terms of degradation class, applicable to the entire land cover polygon, becomes a spatial interpolation/extrapolation exercise again. The starting point is point samples within a framework of polygons (vector format) or classes of pixels (raster format) mapping.

In addition to the problem of assigning to a polygon a single rating from a possible number of ratings from more than one site in the polygon, there is the problem of dealing with assessments for several individual indicators of processes and types of degradation at a given site. Therefore, the problem is a multivariate problem in the sense that it requires consideration of the multiple types of degradation indicators to be combined into one single rating. This rating should convey, in a synthesized fashion, the complete status of land degradation for a given location.

Wherever possible optimal spatial interpolation techniques (i.e. the various forms of kriging, splines, etc.) should be attempted. However, their major constraint is the large number of sampling sites (data points) required for reliable interpolation. A conservative approach can solve both the multivariate and the upscaling problems.

In order to combine the various degradation assessments for a given mapping unit (land cover classes or LUT) into one rating or symbol, it could be decided that, for land cover classes or LUTs polygons containing more than one sampling quadrat, the

rating of the quadrat site with the highest classification for each land degradation process be assigned. That is to say, it is preferable to portray in map form for a given polygon the class of the quadrat site with the highest degree of degradation and assign it to the entire polygon. This is also a form of spatial interpolation. The approach is precautionary and conservative in the sense of preferring to reflect the “worse case” scenario in terms of intensity and type of land degradation. By way of example, Table 33 shows the level of degradation affecting each land cover polygon modelled in the case study of the Texcoco watershed, Mexico.

A table of classes as shown in Table 33 can be useful for attributing the values of the class (i.e. degradation intensity) by type of degradation process (i.e. the columns in the Table 33, which are attributes of polygons in a map) to polygons in a map where the spatial representation of each type of land degradation can be made by means of the GIS. Figure 27 shows an example with the mapping of soil erosion by wind, as a process of physical degradation type.

Mapping land degradation by types of degradation

In order to obtain a map of land degradation by type, which integrates all ratings of degradation by indicators and processes within a given land degradation type into a single map, the “maximum limitation” method is adopted. This method consists of combining ratings of land degradation processes into a single rating by land degradation type, by selecting the rating that is the most severe among the degradation indicators and processes to achieve measures of total physical, chemical and biological degradation. To illustrate, Table 34 shows the results for total physical, chemical and biological degradation across the studied area (e.g. the Texcoco watershed). The spatial representation of such a table can be seen in terms of three land degradation maps (by type) and their corresponding compound symbology in Figure 28. Maps of this kind constitute one of the main outputs of the assessment.

TABLE 33 – Land degradation process classification by land cover polygon

Polygon ID	Water		Wind		Compaction & crusting	Acidification	Salinization	Sodicity	Biological degradation
	HeClass		WieClass		CcClass	AzClass	SzClass	SoClass	BdClass
1	1	1	1		2	3	1	2	4
2	1		1		2	3	1	1	4
5	1	1	1		1	1	1	1	4
7B	1	1	2		1	1	1	1	4
8B	2	2	3		1	1	1	1	4
12	1	2	1		1	1	1	1	4
14B	2	2	1		1	1	1	1	2
18	1	2	1		1	1	1	1	4

TABLE 34 – Results of applying the maximum limitation method on land degradation for the Texcoco watershed by land cover class polygon

LUid	PhysDeg	ChemDeg	BioDeg
1	2Cc	3So/2Sz	4Bd
2	none-slight	3So/2Sz	4Bd
5	none-slight	none-slight	4Bd
7B	2Wi	none-slight	4Bd
7C	2Wi,Cc	none-slight	4Bd
7D	none-slight	none-slight	none-slight
8B	3Wi/2U	none-slight	4Bd
8D	3Wi/2U	none-slight	4Bd
8A	3Wi/2U	none-slight	4Bd
12	2U	none-slight	4Bd
14C	2U	none-slight	4Bd
14	2U	none-slight	4Bd
14A	3U/2Wi	none-slight	4Bd
14B	2U	none-slight	4Bd
18	2U	none-slight	4Bd

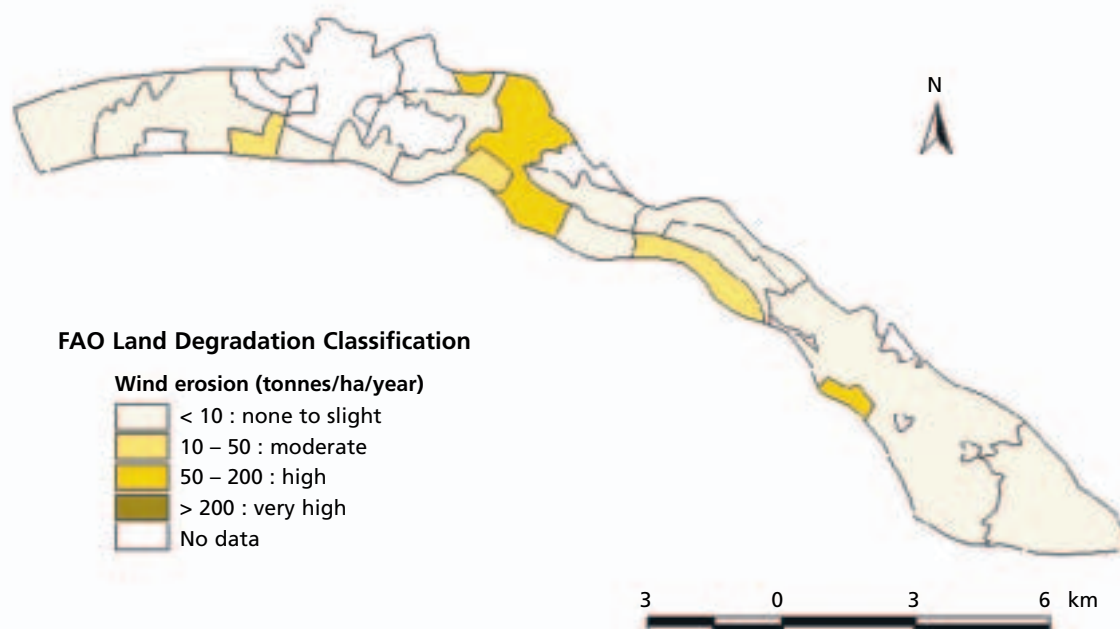
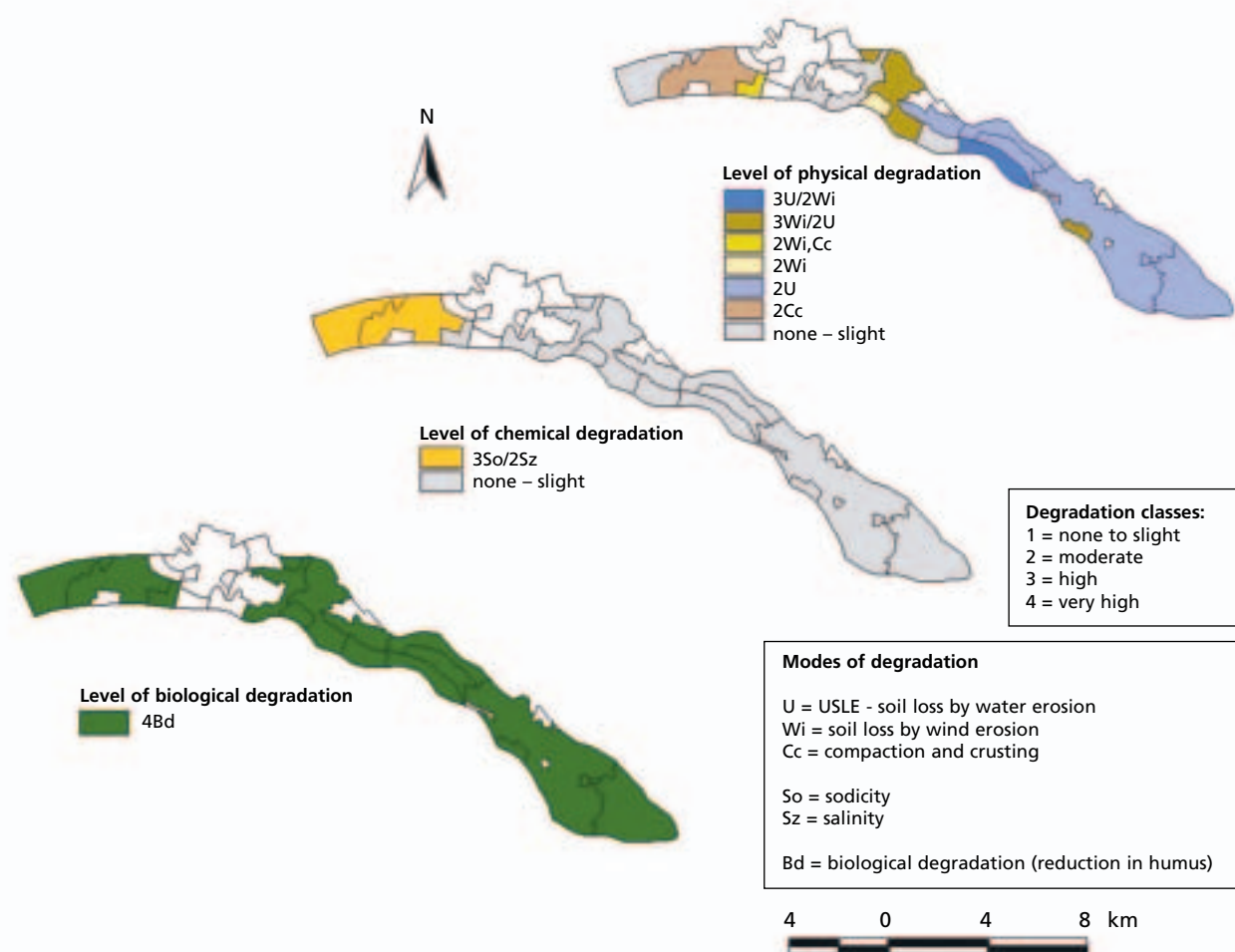
FIGURE 27 – Physical degradation – soil erosion by wind

FIGURE 28 – Maximum limitation classification of land degradation by land cover class for physical, chemical and biological degradation



CHAPTER 8

ANALYSIS OF LAND-USE CHANGE SCENARIOS FOR DECISION-MAKING

CHAPTER 8

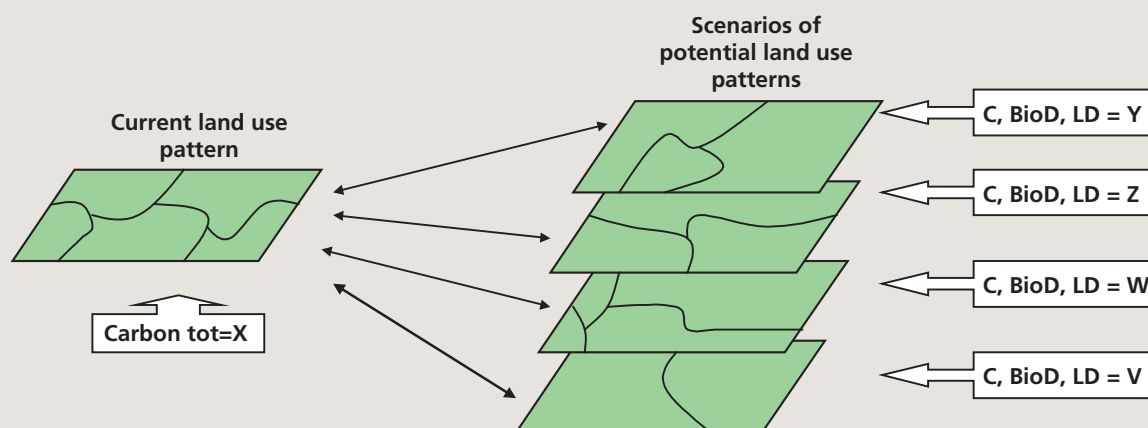
Analysis of LUC scenarios for decision-making

Having prepared the scenarios of the stock of C in biomass and in soil, the current status of species diversity, and the present status of land degradation, the process should move towards the integration of such scenarios and their comparison with scenarios of implementation of PLUT patterns in the area of concern. This should be done in order to determine the possible variations occurring from changes in land use in all the factors or criteria considered, namely: carbon stock and sequestration, biodiversity and land degradation. Ideally, after this exercise, the decision-makers, be they watershed planners, policy-makers in a designated government agency

or farmers, should have a collection of scenarios before them (Figure 29).

The selection of the more “advantageous” scenario amounts to an exercise in multicriteria decision-making (MCDM). For the purpose of this report, the main criteria identified are: the carbon stock and sequestration potential; the status of biodiversity (constraint to plant diversity as per this exercise); and the status of land degradation and land degradation risk that can be incurred into by the proposed LUC in each planning unit (i.e. AEZ, soil unit, agro-ecological cell). Aside from these criteria, the decision-maker will have

FIGURE 29 – Assessment of carbon sequestration potential, biodiversity and land degradation from LUC scenarios



Soil unit/cell	Recommended LUTs			
1	LUT ₃	LUT ₁	LUT ₁₅	LUT ₈
2	C, BioD, LD, USS	C, BioD, LD, USS	C, BioD, LD, USS	C, BioD, LD, USS
3				
n				

other important considerations in mind in deciding on LUCs. For example, the most obvious of these will be food security in subsistence farming. The decision-makers (in this case the farmers) would tend to minimize the risk to their families that an LUC may bring, without foregoing the perceived benefits (e.g. cash income incentives owing to accrual of carbon stocks, prevention of land degradation and its implicit yield losses due to depletion of soil fertility, etc.). Important considerations include:

- ▶ the selection of an LUC scenario requires MCDM exercise;
- ▶ the multiple criteria for selection should include improvements to the carbon stock and sequestration potential, biodiversity conservation and prevention of land degradation implicit in the LUC;
- ▶ an indirect measure of food security, through yield improvements or increased income;
- ▶ improvements to the decision variables should be extensive and long-term.

Multicriteria techniques for participatory decision-making

The variety of approaches and techniques in the field of operations research, management, mathematical programming and in the recently developing field of MCDM is substantial. It is not the purpose of this report to review these approaches in order to justify the choice of approach and technique incorporated as part of the methodology proposed here. Individuals and organizations have made important contributions to the application of MCDM techniques in the land-use planning context (e.g. Romero and Rehman, 1989; El-Swaify and Yakowitz, 1998).

The FAO approach to MCDM

The approach followed by FAO in AEZs and the development of AEZWIN (Antoine, Fischer and Makowski, 1997) has provided a range of useful decision-support tools for MCDM in land-use planning. AEZWIN aims to support interactive

analysis of agricultural land-use options. The AEZWIN tool is a powerful multicriteria decision-support module for optimization, based on the “aspiration–reservation” approach. AEZWIN can be used in the optimization of land-use scenarios involving interactive MCDM. However, it may be cumbersome for the casual or non-specialist user. FAO (1999) provides a detailed review of AEZWIN.

FAO has also applied other MCDM techniques in its field projects. In particular, an emerging paradigm consists of the use of goal programming to optimize, in priority sequence, individual objective functions in a set. This leads on to the application of a participatory stakeholder model, based on the analytical hierarchy process (AHP), which is used first to find out what the decision-maker’s priorities are. This approach was first used by Ponce-Hernandez (1999) in the ecological and economic zoning of an area in the Amazon basin for the Amazon Cooperation Treaty, and has been followed by the techniques applied in SIRTPLAN in Chile, Brazil and Argentina (SIRTPLAN, 2001).

In order to set up a problem for optimization and decide on which data processing tools to use, it is necessary to formulate the problem formally as an optimization problem.

Formulation of the optimization problem

The decision-making problem could be seen in terms of an optimization problem. The optimization is based on multiple criteria. The criteria are:

- ▶ enhancement of carbon stock and sequestration,
- ▶ conservation of biodiversity,
- ▶ prevention of land degradation,
- ▶ enhancement of food production (as a “proxy” for food security).

The formal declaration of the problem from the optimization standpoint leads to its mathematical formulation in terms of objectives that need to be achieved simultaneously. The multiple objectives are:

- ▶ maximize the enhancement of carbon stock and sequestration;
- ▶ maximize the conservation of biodiversity;
- ▶ minimize land degradation;
- ▶ maximize food production.

Each of these objectives can be formulated mathematically as an objective function. The problem then consists in identifying from among the LUC scenarios developed earlier (giving a finite geographical area, e.g. the watershed or farmland) the land-use pattern that achieves the multiple objectives simultaneously.

Achieving one of the objectives is a “technical” problem (i.e. demands the search for a solution among a set of feasible solutions). Attempting to achieve the multiple objectives simultaneously is an “economic” problem in that it requires the achievement of a “compromise” solution” in the “Pareto optimality” sense. This is because the objectives may contradict each other in some situations.

For each of the objectives, the optimization model can be constructed from:

- ▶ decision variables. Identifying the decision variables (i.e. the area size assigned to be planted with a given LUT).
- ▶ technical coefficients of each decision variable. Identifying and deriving the technical coefficients of each decision variable (by compiling pertinent socio-economic data on prices, costs, marginal productivities and marginal costs) involved in the implementation and in the derived benefits of a unit area of each LUT.
- ▶ sets of constraints. Identifying and formulating the sets of constraints imposed by the biophysical and socio-economic environments and by the scarce resources. These constraints can be constructed and inserted in the model at this stage.

Figure 30 illustrates the formulation of an optimization model for a single objective, in this case, maximizing net profit.

In Figure 30, Np stands for net profit, while X_{LUT} are the decision variables that represent the optimal area to be devoted to a given LUT so that the Np is

FIGURE 30 – Example of the optimization model for a single objective

Objective function:

Maximize $N_p = a_1 X_{LUT1} + a_2 X_{LUT2} + ... + a_n X_{LUTn}$

Subject to:

$$X_{LUT1} + X_{LUT2} + ... + X_{LUTn} \leq A_{total}$$

Food security constraint:

$$X_{LUT1} + X_{LUT6} \geq A_{fs}$$

maximized. The a_i are the technical coefficients that represent the marginal productivity of each LUT. The parameter A_{total} represents the total area involved in the planning exercise, and A_{fs} is the minimum area to be planted with staple crops to guarantee food security. The right-hand side inequalities (i.e. A_{total} and A_{fs}) are the size of the constraints imposed on the optimization process.

The essence of a Pareto optimal (PO) or “efficient” solution is that no other feasible solution can achieve the same or better performance for all criteria under consideration and strictly better for at least one criterion. Thus, a PO or efficient solution is a feasible solution for which an increase in a value of one criterion cannot be achieved without having a deleterious effect on other variables and on the solution itself. Hence, this type of solution is difficult to achieve without “trade-offs” among criteria. Such trade-offs can realistically be achieved by consultation with the stakeholders in some form of participatory process.

Establishing priorities through a participatory process - the AHP

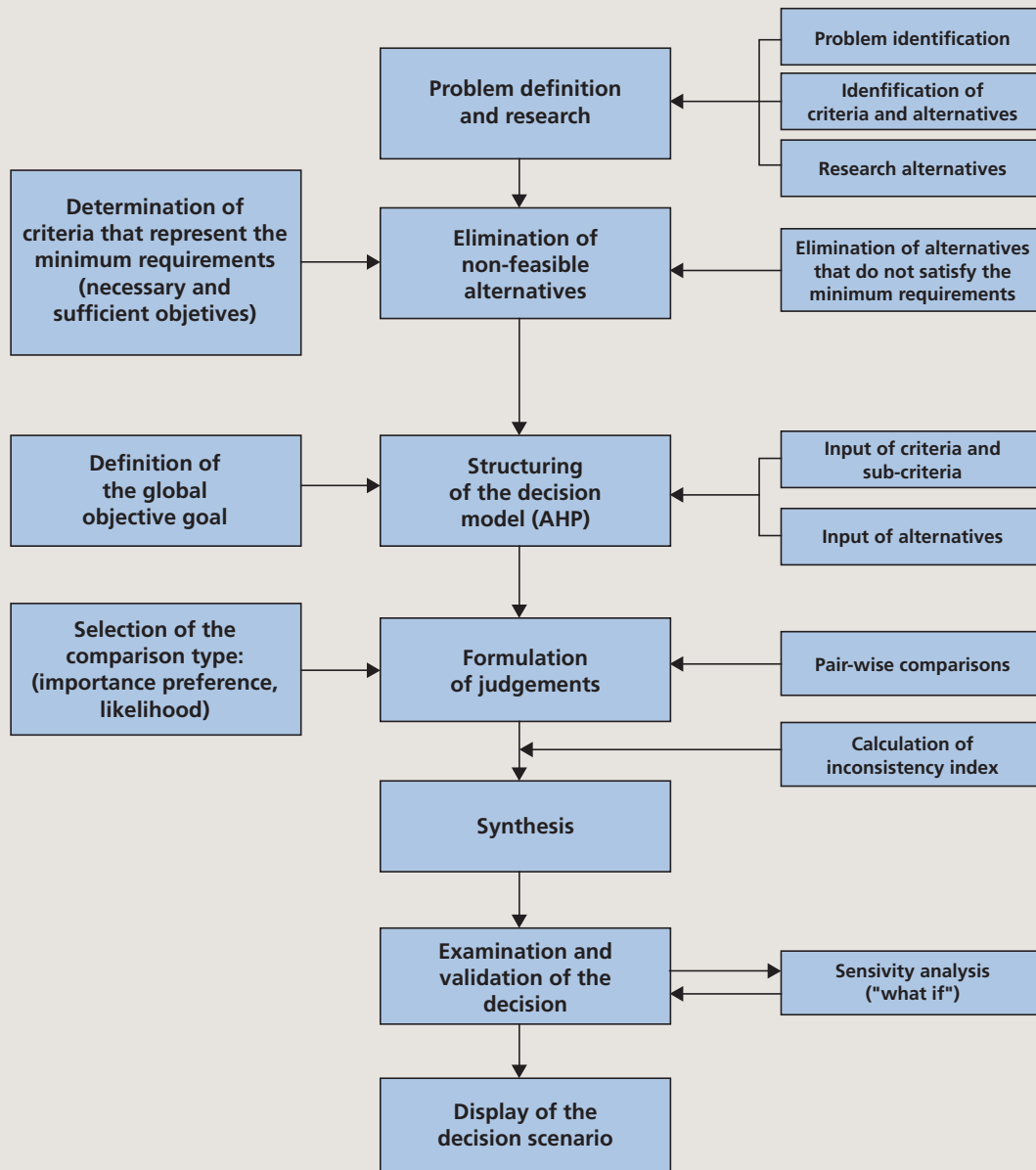
In this methodological framework, the apparent conflicts established by competing demands for land by different LUTs, from which the decision-maker selects on the bases of multiple criteria, can be seen as a process of conflict resolution. A technique that has proved quite successful in eliciting stakeholder preferences through multiple criteria choices is the AHP, proposed first by Saaty (1980). The AHP helps in participatory MCDM by providing a mechanism to structure the land-use conflict in a watershed or area of concern around a common global goal. It does this in order to allow stakeholders to articulate their preferences, values and aspirations related to potential land-use scenarios. This process can be achieved through some form of “electronic round table” (Ponce-Hernandez, 1999). This approach has been used in the zoning of a portion of the Amazon (Ponce-Hernandez, 1999) and in land-use planning in various countries in South America (SIRTPLAN, 2001).

The AHP consists essentially of a piecemeal decomposition of a problem, indicated by a global goal, into its most fundamental elements and parts, including factors, forces influencing the factors, criteria (as indicated above) and alternatives (as represented by the LUC scenarios). Then, after decomposition and the “structuring” of a problem hierarchically, all solutions of subproblems are brought together into a global solution consisting of a ranking of alternatives. Figure 31 illustrates the procedure for model development in the AHP. The sequence for “structuring” a problem into a hierarchy (i.e. model building) is:

- ▶ problem identification,
- ▶ definition of global objective,
- ▶ identification of criteria,
- ▶ identification of alternatives.

In the case of the MCDM problem, all the elements can be identified and the problem modelled. Once built, a model can serve as the basis for requesting stakeholder input about their preferences, values and aspirations, while the LUC scenarios are displayed before them. Thus, after structuring the problem, pair-wise comparisons are made among all the elements of the hierarchy. It is here where the stakeholders articulate preferences or choices. Then, the elements of the preference set are evaluated and synthesized, resulting in the ranking of alternatives. This is the final result of the process. Allowance is made for sensitivity analysis after the synthesis and assignment of rankings or weights to the different nodes of the hierarchy before each alternative scenario. The results from applying the AHP model are a set of coefficients or weights: λ that represents the priorities derived from stakeholder consensus as to preferences or priorities for the land-use scenarios. These weights are then used in the multiobjective optimization process to guide the priority sequence in which the objective functions should be optimized through goal programming. Figure 32 presents an example of a hierarchy with a global goal of “minimize environmental and economic conflict” for a region such as the Amazon basin.

FIGURE 31 – Procedure for model building and its application in participatory decision-making using the AHP



Multiobjective optimization

A goal programming function with multiple constraints is set up, drawing information from the economic parameters of decision variables. The goal programming model for the entire watershed or area studied meets the criteria represented by single-objective functions. These functions are built into the goal programming function by sequentially optimizing such single-objective functions in the

order of priority established by consensus from the participatory process implemented through the AHP.

The goal programming model is developed by setting up goals with corresponding levels of “overachievement” and “underachievement” over the initial objective functions. It is beyond the scope of this report to explore the theoretical and mathematical details of goal programming. Readers

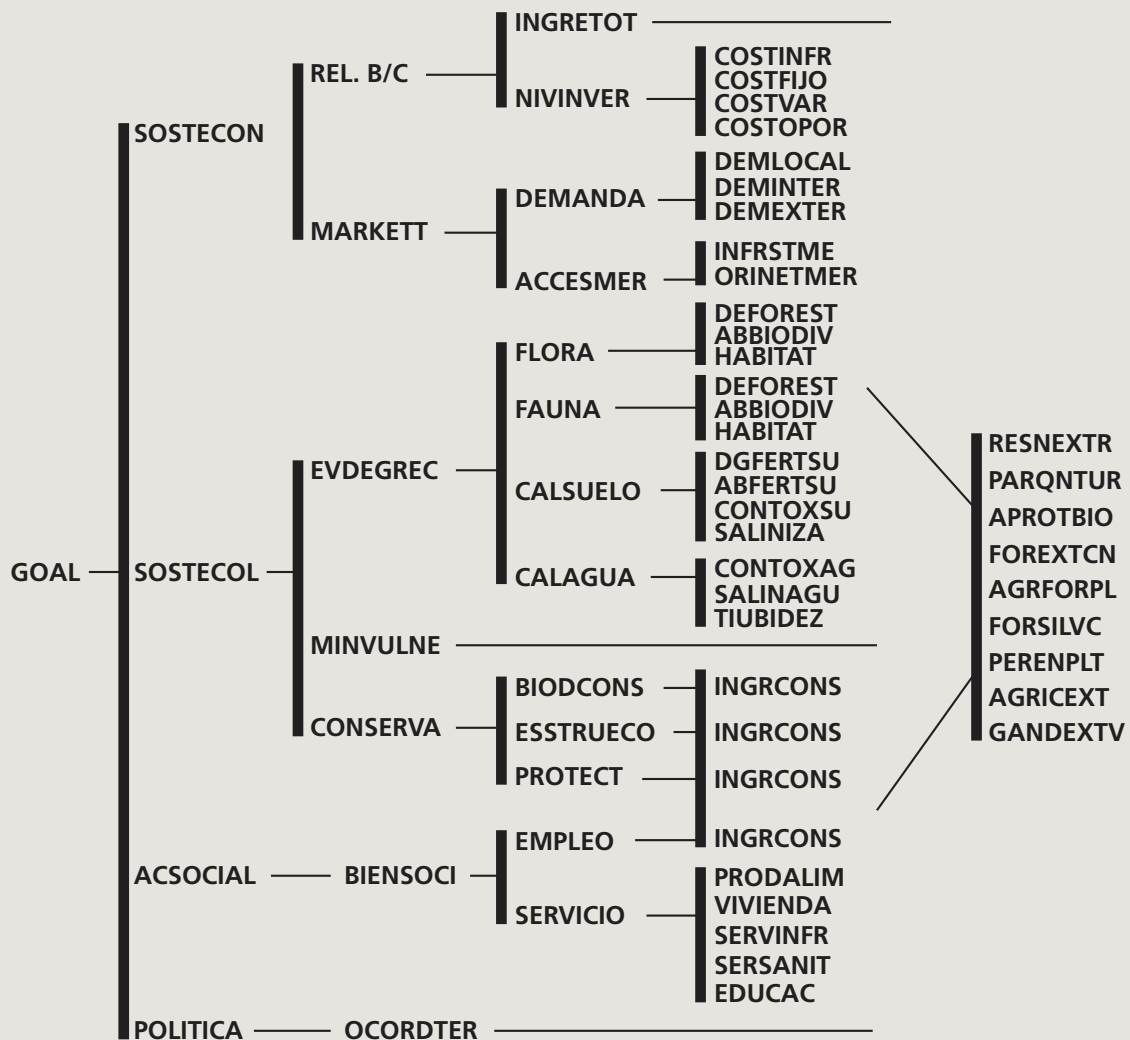
may refer to Romero and Rehman (1989) for an example of the use of goal programming.

Computer software programs for solving this type of problem (known as “solvers”) are standard. Models can be developed and processed interactively using, for example, the LINDO optimization software (Lindo Systems, 1995). Figure 33 illustrates the optimal land-use scenarios developed after linking the AHP and the results of the goal programming model to the GIS. Figure 34 shows an

example of the steps for processing a goal programming model with the LINDO software.

The procedures presented in the previous seven chapters describe a methodological framework that has been tested in three locations in Latin America and the Caribbean region. Results from the case studies illustrating the application of the methods described in these chapters are presented in the Appendix.

FIGURE 32 – Example of AHP model for gathering stakeholder preferences and participatory decision-making



Structure of the model built for the trial area in the Amazon. Example of structuring of a hierarchy.
Global goal: "minimize environmental and economic conflict".

FIGURE 33 – Optimal LUC scenarios developed by linking the AHP and the optimization (goal programming) process to the GIS

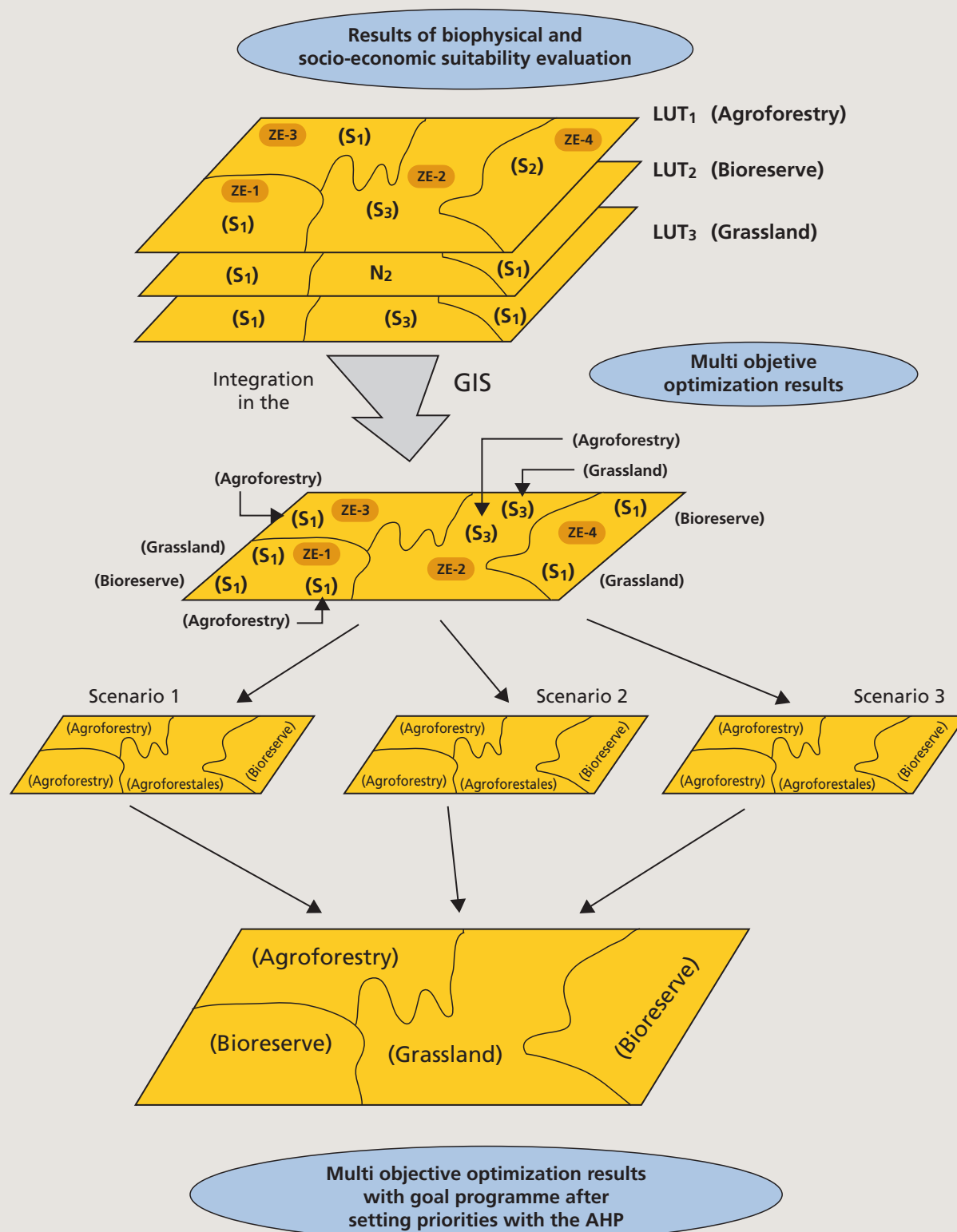
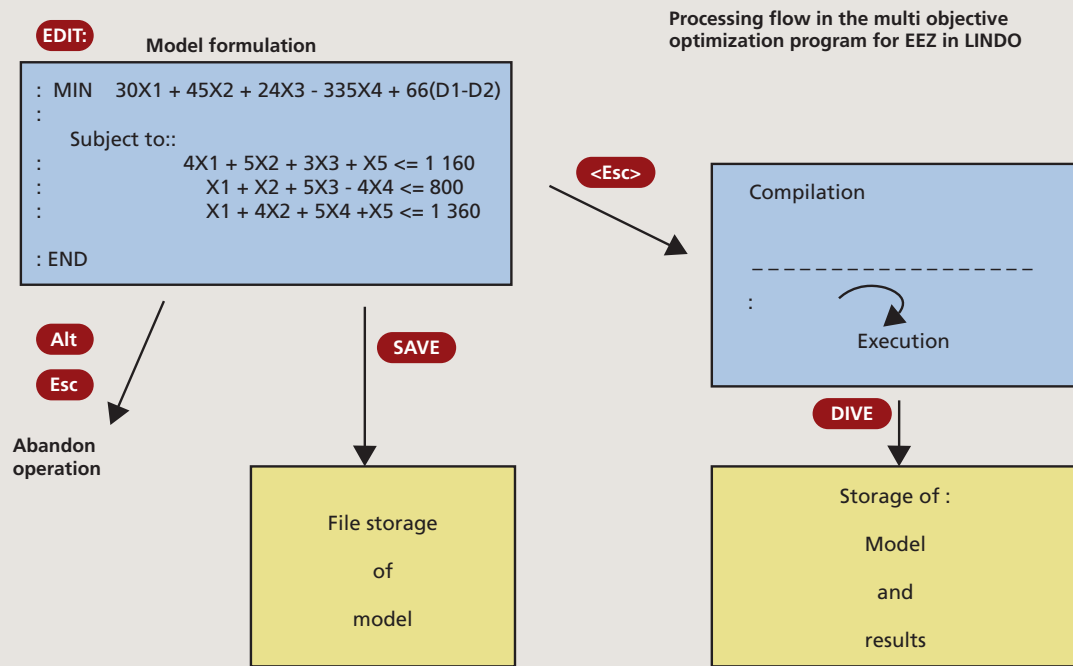


FIGURE 34 – Example of the implementation of a goal programming model with LINDO



CHAPTER 9

DISCUSSION

CHAPTER 9

Discussion

A discussion of the content of this report requires it to be divided into two component parts: (i) methodological issues; and (ii) the results of the application of the methodology to the case studies described in the Appendix.

Methodological issues

The design and formulation of the methodology to meet the project objectives and its application to real case studies on the ground brought a number of methodological issues to light.

First, the methodology is not intended to be ecosystem specific. It is not oriented specifically to the measurement of forests, grassland or cropland. Rather, it addresses the land use in a geographical area of interest regardless of the ecosystems that may be present.

In the methodology, LUC is considered the pivotal point for addressing synergistically the concerns of enhancing carbon sequestration, promoting biodiversity conservation and preventing land degradation, while deriving yields and produce to address food security and rural income. In this sense, “win-win” strategic LUC should emerge from the application of the proposed methods in terms of both the synergies expressed above and ecological benefits derived from such synergies.

The methods and procedures in this report aim to determine first the status of carbon stock, biodiversity and land degradation under current land use and management, and then to identify

promising land-use patterns. That is to say, it seeks to identify LUTs and the crops, trees and shrubs within them that are biophysically and socio-economically suitable for each zone or ecological condition in the area, and with enhanced CSP for generating potential scenarios of LUCs. Finally, it aims to optimize the multiple objectives of stakeholders in order to select the potential land-use pattern that optimizes such multiple objectives simultaneously. In the process, stakeholder participation is elicited through the articulation of preferences for scenarios, which become consensual priorities. These priorities guide the sequence in the optimization process.

Definition of study area

The watershed or subwatershed was found to be a convenient geographical framework, facilitating the identification and mapping of land cover classes, the identification and delineation of ecological units or ecozones, the design and deployment of a sampling scheme on the ground, and the compilation of data and information for data processing and analysis.

Methods used

The methods proposed here are a methodological framework. They allow for a certain degree of flexibility so they can be modified to suit the particular circumstances of implementation. They rely on accessible technologies and on the likely existence of databases, which should be available in many developing countries. Thus, it is assumed that the databases in the area of application hold necessary and sufficient attribute and spatial data, and that if some data need to be collected, this can

be done with ease and at low cost. This is a major obstacle to implementing modelling and data analysis techniques in some extreme conditions in the developing world. Hence, every attempt has been made to simplify the steps to achieve results in a typical environment in the developing world, e.g. Latin America and the Caribbean region. The ability to obtain results in remote areas of Mexico (the southern part of the Yucatan Peninsula) or the Rio Cauto watershed in the eastern part of Cuba, by working with existing data sets complemented with the field procedures described here, attests to the feasibility of the methods proposed.

From a methodological perspective, the main objective functions in the methodology, i.e. the maximizing of carbon sequestration, biodiversity conservation and minimizing of land degradation while maximizing production and income, should be seen as the main pillars of the methodology. The structure of the report follows these objectives.

Field sampling and upscaling

The issue of upscaling, i.e. spatial interpolation or “spatialization”, of site estimates of either biomass, carbon stock, biodiversity indices, land degradation indicators and any other variables measured or calculated at specific sites in the landscape, is a generic, important technical issue. It may mean significant differences in overall stock over an entire area. Therefore, it is a technical issue that practitioners may not want to underestimate and to which they may want to devote considerable attention and effort.

In situations such as the Bacalar case study, the band ratio image calculated is a useful mechanism for “spatialization” of estimates of aboveground biomass, rendering spatial interpolation unnecessary.

On the other hand, the case studies demonstrated that, in order to achieve efficiencies and economies of effort, time and cost, the field sampling procedures should be multipurpose in the sense of performing

simultaneous measurements for biomass, biodiversity and land degradation assessment. Such data sets should be collected in the field by a multidisciplinary team. Experience through the case studies has shown that a multidisciplinary team of 7–9 technicians can complete the ground measurement and data recording tasks efficiently. The sampling requires variable-size nested sampling units (i.e. quadrats). The number of sampling sites required to provide a statistically representative sample of conditions in the study area can be achieved through a multistage stratified random sampling. At each stage of sampling, the variability of key measured variables (biodiversity indices, biomass estimates, etc.) can be assessed iteratively (to judge whether or not further sampling is required) or through the estimation of the *a priori* variance of the variable of concern from pre-survey sampling. When further samples do not contribute significantly to the variance (e.g. asymptotic behaviour of diversity indices curves with respect to the axis depicting the number of samples), further sampling is redundant and wasteful in terms of cost and effort. The use of pre-designed field forms became quite useful in data recording and in achieving time and effort efficiencies. Such field forms can be modified to suit the local conditions of each area of study. Also of great importance is the geopositioning or accurate georeferencing of the sampling quadrat sites. GPS instruments with high accuracies are preferred in order to achieve less than 5-m accuracy in positioning.

Wherever possible, the judicious inclusion of forest inventory data may achieve considerable savings in field sampling efforts, while achieving a representative sample with fewer sampling sites. In order to minimize sampling effort, much existing data on local soil inventories, vegetation classes, land cover types, topography and characteristics of the cropping, pasture and agroforestry systems in the area of study can be organized and incorporated ahead of the field sampling campaign. In some instances, it became necessary to collect plant samples for botanical identification. The inclusion in the field

team of a botanist (equipped with a kit for collecting herbaria for later identification in the laboratory) may save considerable time and effort in the field.

Estimation of aboveground biomass

In terms of the estimation of aboveground biomass, all land cover types and ecosystems need to be assessed for accounting purposes. In this respect, the methods proposed make use of standard biomass inventory methods. Detailed estimates need to be produced for all land cover types including all levels of canopy, shrubs and herbaceous vegetation. The need to account for all strata is what makes the field surveys complex and somewhat labour intensive.

The methodological framework makes a commitment to direct carbon accounting instead of to sophisticated methods that are more technology-driven, such as monitoring C through CO₂ fluxes (e.g. eddy covariance methods). In this accounting approach, the partition into pools of aboveground and belowground biomass, whether live or dead, saplings, debris and litter, presented no real logistical or technical problems in any of the case studies. This was because the measurement and monitoring methods at the field plots were standard and well known.

On the other hand, the use of remote-sensing products and techniques (multispectral satellite images and air-photographs) proved to be very useful when backed up by quadrat sampling measurements on the ground. The land cover classes generated from a supervised classification, after correction and validation with the quadrat samples, were crucial in the case of densely vegetated areas, such as the tropical forests of Bacalar, in providing the spatial framework for the upscaling of aboveground estimates. The land cover classes also allowed exploration of empirical relationships between the various pixel reflectance values and their corresponding biomass estimates from sampling sites on the ground. In this sense, the satellite images lent themselves (as part of the interpolation and

upsampling mechanisms) as a good predictive regression equation of biomass as a function of the digital numbers of a band ratio index (GVI) was developed. As this relationship is site dependent, it was applicable only to the Bacalar study area. However, it indicates that the development of empirical regression equations to estimate biomass as a function of canopy reflectance, or the digital numbers of a band ratio index calculated from the original multispectral images (NDVI, GVI, etc.), may prove a profitable line of enquiry in other study areas where estimation may be required.

The use of standard regression equations of aboveground biomass as a function of measurements of trunk diameter, tree height, crown dimensions and other characteristics of the canopy proved quite advantageous in obtaining estimates, particularly as they incorporated other variables difficult to obtain from field measurements such as wood density. The key issue in the use of standard regression equations to estimate biomass is the careful selection of the equation that applies to the area of concern. This should be made according to the similarity in ecological conditions and forest type where the equation was developed. For routine monitoring programmes, calibration of such equations with locally measured data would be ideal.

An important issue in volumetric and biomass estimates in forested quadrats is the assessment of tree crown biomass. Estimation of canopy density and its contribution to tree biomass may be subjective and prone to contribute to the variance of estimates. The consistent use of specialized instruments to measure tree crown density and its contribution to tree biomass may help in alleviating this problem. A related issue is the estimation of litter and debris on the ground. The estimates of litter and debris biomass within the 1 x 1 m quadrat required extrapolation over the entire area of the 10 x 10 m quadrat (100 m²). This assumes that litter and debris ground cover is uniform and isotropic with the same thickness over the area of the larger

quadrat. This issue may only be relevant in relatively undisturbed forested areas where the contribution of litter and debris to biomass and C may be significant.

A conservative approach was adopted when estimating root biomass. This may result in underestimates of total live belowground biomass. However, the trade-off is preferable to performing destructive sampling, which is ecologically, economically and even logistically prohibitive. In estimating root biomass by an indirect method, e.g. by a standard regression equation, caution must be exercised in the selection of the equation and in its applicability. The Winrock method (MacDicken, 1997) and the equation by Santantonio, Hermann and Overton (1997) provided useful and satisfactory results. The coefficients used to derive estimates of belowground biomass as a function of aboveground biomass made sense when distinguishing between coniferous and broadleaf trees.

The mapping of biomass relied on the existence of maps and the presence of polygons representing vegetation classes or land cover classes. This could have also been achieved through the use of spatial interpolation techniques. In this sense, geostatistical theory and techniques have a major role to play in the upscaling of estimates to the entire area of study (i.e. the watershed) starting from the point data represented by the sampling quadrat sites. A major constraint on the use of geostatistical techniques and in particular of kriging is that their applicability depends strongly on the so-called “size of support” or number of point samples that support an interpolation. These techniques become reliable with an increasing number of samples.

Mapping the stock of carbon

Mapping the stock of C as biomass required a conversion factor only from biomass to C. This could be improved if tables containing the variations of carbon content in biomass by plant species were made available publicly. A similar issue is the

estimation of carbon content in SOM. For the purpose of the case studies, a standard and to some extent arbitrary coefficient was used (derived from literature) to estimate carbon content as a function of SOM. SOM values are readily available from soil survey reports, making it possible to estimate C in soil from SOM at sites where soil profile analysis were conducted during soil survey.

Methods for estimating and measuring changes and fluxes of C in soil are direct and indirect. An indirect method for carbon estimation based on carbon accounting was preferred as direct methods are not feasible or affordable for routine assessment and monitoring programmes in the developing world.

The assessment of carbon stock and sequestration in the case studies of this report was carried out with data at each quadrat cell measured on the ground. Therefore, the upscaling of estimates is a crucial problem in determining the final accuracy of stocks for an area, watershed, district, state, etc. Central to this problem is the number of samples required in order to calculate a reliable semi-variogram or other form of auto-correlation function. Such a function could indicate the structure of spatial variability of the stocks in the area, and make it possible to use an optimal interpolator such as kriging with confidence. Considerations of cost, time and effort necessary for a relatively large number of samples to achieve a reliable semi-variogram and optimal interpolation must enter into a trade-off with considerations of accuracy of estimates, precision, ecosystem variability and area coverage (i.e. the size of the area that can be assessed and monitored). However, it is not possible to recommend a practical rule to achieve an optimal “compromise” solution to this problem.

Simulation models of soil organic matter turnover

Concerning the use of simulation models of SOM turnover, in order to determine the partitioning of added plant residues into the pools of SOM and contributions to them, a precondition is the presence

of minimum data sets in the databases of the study area. The parameterization of the models demands the availability of certain data from the databases. Depending on the model used, parameterization could be quite demanding and even challenging and time consuming. However, experience has shown that there is an apparent trade-off between the degree of sophistication (and therefore of expected accuracy of a given model) and the difficulty in its parameterization. No model is simple, their use as a powerful predictive tool requires a learning curve, training, economic resources and even experimental fieldwork for their calibration and validation.

The parameterization of models also requires the existence of data on the parameters for each one of the pixels or soil polygons present in the study area. In order to achieve such fairly large databases, it may be pertinent to undertake a comprehensive exercise in agro-ecological zoning in the area in order to generate the pixel-based databases (i.e. PCCs) on all the parameters demanded by the model. Geostatistical interpolation techniques have a very important role to play here in terms of enabling the creation of complete “coverages” or data layers of multiattribute data over the entire study area.

Experience from the case studies indicates that the selection of a carbon dynamics model is a trade-off between the model sophistication, the degree of “compartmentalization” of the recognizable carbon pools it simulates, the accuracy of simulated results and data requirements. All of these are set against intuitiveness, access and ease of manipulation of the model. It is difficult to derive a generic rule for model selection as many factors may intervene in the decision. Readers are advised to consult reliable “online” sources of model information, such as SOMNET, where all the characteristics of each model can be examined.

The models selected for the case studies (CENTURY and RothC-26.3) represent extremes in the spectrum of complexity, ease of access and

manipulation, parameterization and degree of compartmentalization. These, among other particular reasons, are why these models were selected. Moreover, both models had been adapted to simulate the turnover of SOM in tropical and subtropical conditions.

Model parameterization remains the major obstacle to the use of these types of models on a routine basis in assessment and monitoring programmes. The demands placed on databases by the parameterization of the models make it necessary to split spatial variability of soil and climate into relatively uniform ecological zones, each of which requires its independent set of model parameters. Spatial interpolation and GIS modelling techniques play an important role in the zoning process and the generation of PCCs as part of the biophysical characterization of the study area. This step in data preparation is as important as the parameterization and running of the model itself and its relevance in the methodology cannot be underestimated.

Another important step in data preparation for running model scenarios is a set of ad-hoc calculations necessary to estimate the monthly contributions of organic matter by the cropping/land use occurring in a particular location. This report offers a procedure for the rapid calculation of such contributions, beginning from crop yields and estimates of contributions from aboveground biomass.

In order to achieve realistic results through modelling, the calibration of simulation models is of extreme importance. Calibration should be performed using sites independent to those in the study, with reliable laboratory analyses of SOC, which in turn should be predicted with satisfactory accuracy by the model. Input interfaces could be a problem for non-specialist users of the simulation models. Both RothC-26.3 and CENTURY require interfaces. The current MS-DOS interface of CENTURY is particularly cumbersome and difficult. The model

itself, when used in all its parameters, may require almost 600 variables. As RothC-26.3 already had a primitive graphic user interface (GUI), no further development was needed on this model. On the other hand, a GUI was developed for CENTURY. This was achieved by customizing the input module of the model through developing software code through Visual Basic. Through the customization effort, it became possible to reduce the number of necessary input variables to a handful. Assumptions were made in order to achieve this. Such assumptions are not considered unreasonable as parameters suggested by the model developers were taken into consideration and then built into the customization. Therefore, the model customization is considered sufficiently robust.

Linking the SOM turnover output of simulation models to GIS was a rather laborious task in terms of the number of linking operations required to complete the transfer and formatting of files. From this perspective, customization of CENTURY represented a considerable advantage in simplifying such model–GIS linkage. Further customization work is still necessary to make the link seamless and transparent to the non-specialist user.

Suitability assessment of LUTs with potential for carbon sequestration

In determining the PLUTs to evaluate as candidates for an LUC in the study area, it is necessary to consider criteria such as the potential for: increasing carbon sequestration, increasing crop yields, enhancing biodiversity, and decreasing potential impacts on land degradation. These and a high physical and economic suitability to the ecological and economic conditions of the area must all be applied as rigorously as possible in the selection process. A full land suitability assessment, including the opinions of farmers and local experts in a participatory fashion, is fundamental to achieving realistic results. C₄ crops (photosynthetic pathway with assimilation rates of 70–100 mg CO₂/dm²/h; crop groups III and IV) and C₃ crops (photosynthetic pathway with assimilation rates of 40–50 mg CO₂/dm²/h; crop groups II and V)

are to be preferred in that order. Another key factor in determining carbon sequestration is the crop and land management activities that are part of the LUT selected. Land management practices are as important as, and could potentially offset the gains from, a careful selection of crop mixes in a new land-use plan. The mapping of suitability classes of PLUTs follows a standard procedure of allocation of attributes to land mapping units mapped as either classes of pixels or polygon class entities. These procedures are well known in GIS operations and should represent no technical problems for assessors implementing the methodology.

Regarding the PLUTs, where possible, the biomass of the cropping pattern should be predicted from well-calibrated crop growth models that estimate total biomass of crops and crop yields. The alternative to crop growth models is to estimate biomass and yield production from standard phenology-based equations. Such equations depend on crop species, simple climate variables and soil parameters. Estimates from the AEZ approach on expected constraint-free and constrained yields can be derived from suitability tables, where there are results from the application of an AEZ exercise in the area of concern (e.g. through the application of AEZWIN tools). Another option is to resort to records on average attainable yields in the area of study from experimental plots established in the area, where experimental information is available, or from official records or from farmers directly. From these data on biomass and yields, crop residue fractions, which are additions as inputs to local soils, should be estimated and verified against data from local farmer informants. The information about the contributions of organic matter from crops and vegetation to the soil is deemed crucial in the parameterization of the SOM turnover simulation models and the projected scenarios of SOC sequestration. Therefore, the estimation of crop residues and other organic inputs to soils should be verified carefully.

The scenarios of carbon stock and sequestration generated for the PLUTs required predictions of attainable biomass and yields and the predictions, through simulation, of the fate of organic C once in the soil. It is of considerable importance to verify such estimates in reality. This could be achieved by setting up validation sites in areas such as those of the case studies reported here, or in areas where the methodology had been applied. It is of extreme importance that follow up on the validation of the methods here proposed takes place in order to implement a set of test sites and studies, which could shed light on the accuracy of the methods proposed.

Estimation of biodiversity

Regarding biodiversity, it was found that concentrating on plant diversity was much more straightforward and brought faster assessment results than focusing on total biodiversity, including soil biodiversity with its micro and macro flora and fauna components. Therefore, plant diversity was considered a “proxy” for the other components of biodiversity. Later refinement of the methodology should examine the possibilities of including rapid assessments of other components of biodiversity, such as fauna and soil biodiversity, which is considered a key indicator and expected to be highly correlated to the accumulation of organic matter and C in the soil.

The variables used for assessing plant diversity were found appropriate to provide a picture of the status of plant diversity in the area. The indices used in the assessment (number of species, species richness, and species abundance) provided reasonably good information on the components of plant diversity. However, a fundamental problem was the *in-situ* identification of plant species. It is for this reason that a multidisciplinary team that includes a botanist is of key importance in the operational stages of the assessment. The use of local or indigenous knowledge concerning plant species and their distribution proved to be of key importance in this phase of the assessment. It is highly

recommended that these resources be tapped into while implementing the assessment in the field.

Sampling by stages proved to be a good strategy, when observing the behaviour of the diversity indices' curves as plotted against the number of samples (i.e. quadrat sites) already achieved. Increasing the number of samples on the ground until the curves became asymptotic to axis of the number of samples proved to be an efficient means of determining the optimal number of sampling sites on the ground. The customization of a database software program to allow for automatic entry of data and calculation of indices proved to be extremely effective in monitoring and achieving the optimal number of sampling sites.

Satellite image classification provided the appropriate geospatial framework (i.e. land cover classes) for interpolating and upscaling the calculated plant diversity indices at the quadrat sampling sites.

Follow-up work on this particular aspect of the methodology should incorporate rapid measurements or indicators of faunal diversity, and particularly of soil biodiversity, and their projected variations after LUCs.

Assessment of land degradation

The assessment of land degradation, carried out at the same quadrat site locations and during the field sampling and assessment of biomass and biodiversity, was based on a parametric semi-quantitative approach. This approach was found to be applicable and relatively straightforward as it uses data already recorded by inventory programmes of agencies in the developing world (e.g. climate and soil parameters). However, it was noted that, typically, there may be some data gaps that would require parameter estimation, particularly in the pre-field or initial stages. Nevertheless, these data gaps are relatively easy to fill as the variables used in the computation of the indices are commonly observed and recorded by national agencies in charge of natural resources.

The degradation assessment relied on four groups of individual indicators: soils, climate, topography and human activity. These were rated (weights) in their importance for determining land degradation and used to judge the status of each of physical, chemical and biological degradation of the land. This multivariate and multicriteria process was aided by the application of a synthesis process based on the “maximum limitation method”. This approach helped in calculating compound indices for each of the three types of degradation. In turn, these ratings were grouped into classes that reflected the degree of affectation of the land, and could be mapped as ratios attributed to land polygons in the legend of an overall land degradation map. Creating a map for each indicator, indicator group and type of degradation could be overwhelming and could create greater confusion as eventually a synthesis process is required to sum up the assessments of the different types. Thus, the derivation of ratios was found rather useful in the synthesis process. The diagnosis of the status of land degradation thus remained as quantitative as possible. The rating system provided by FAO (1978a) and the general framework of land degradation assessment proved extremely useful in the design of the approach and methods presented in this report.

The design and later use of pre-survey field forms facilitated considerably systematic assessments and data and observation gathering in the field. These forms also enabled more rapid data capture (digitally) and the computation of indices and indicators in the field and on the computer and with GIS.

The problem of upscaling or interpolating spatially these assessments made at the quadrat site locations is an important one. Techniques such as disjunctive kriging are worth exploring as they allow for the treatment of qualitative and semi-quantitative regionalized variables. This problem of “spatialization” of computations and estimates made at the site of the field quadrat was common to the three assessments made using this methodology. It

remains an important problem that warrants further investigation in follow-up activities to this project.

Multicriteria decision-making

In terms of decision-making regarding the scenarios for LUC, the application of multicriteria techniques, particularly the AHP, proved useful in helping structure the decision-maker’s problem and in providing a mechanism for establishing priorities for the optimization of land-use scenarios. The AHP sequence for establishing priorities about land-use scenarios, followed by optimization with goal programming, appears to provide the tools and sequence of operations necessary to optimize the scenarios for LUC. Concerning the optimization process, the FAO approach using tools, such as AEZWIN, may prove fruitful in situations where specialized personnel, familiar with such a powerful program, can manipulate the software and data with relative ease. However, its use in the optimization of scenarios was found cumbersome for the non-specialist user.

Case study results

In order to derive the full advantage possible from this discussion, the reader is advised to read the Appendix containing the case studies referred to in this section. They represent the practical experience of applying the suggested methods and procedures described in Chapters 2–8. This section concentrates on discussing the particular details of the suitability of the methods proposed to conditions of the sites studied separately.

The Texcoco River Watershed, Mexico

The Texcoco River Watershed is a narrow subwatershed, densely populated, with more than 120 000 habitants in an area of about 50 km² (a narrow strip of 2.5 km x 25 km). Hence, the watershed has endured major human impacts on its resources. It has been occupied by human groups for millennia. In pre-Hispanic times, indigenous groups (e.g. Coluhas, Chichimecs and Aztecs) grew crops,

harvested the forest and hunted on its lands. Thus, agriculture has been practised in some of these soils for millennia. The Spanish colonization saw a dramatic increase in resource exploitation: cattle ranching in the lowlands; crops on the lowlands and gentle slopes; and harvesting of the forests. The dramatic population increase in the last century has resulted in considerable degradation of resources, in particular: uncontrolled deforestation, soil erosion, and soil fertility depletion through intensive tillage, cultivation and mismanagement of soils. Urban encroachment on agricultural land and pastures and, in turn, of these on forest lands, has accelerated resource degradation. Related problems of water scarcity and pollution are also important in the watershed. Conversions of land to urban land use and rough terrain have further reduced the agricultural land to a narrow strip in the middle portion of the watershed and to the flat lowlands. A receding forest area is still of some importance at the higher elevations and steep slopes of the watershed in the sierra, towards headwaters. The issue of urban encroachment on agriculture and subsequently of this on forested land, and the impacts of human settlements on resources are perhaps the most crucial problems determining the fate of agricultural and forest land use in this watershed.

Maintaining soil fertility and SOM is a serious problem. Organic matter and plant nutrients in the soil are being “mined” out of the agro-ecosystems in the watershed. Crop residues are used as animal feed and not returned back to the soil. The shortage of pastures and fodder for animals is critical in the area. Thus, crop residues are much sought after and valued by farmers. This makes incorporation of crop residues into the soil an almost impossible practice as the market value of crop residues is relatively high.

The results obtained by running the SOM simulation models indicate that only when sufficient amounts of organic residues as inputs are present in the soil, together with sufficient moisture (most probably from irrigation or rainwater harvesting),

does carbon sequestration occur in this type of ecological and cultural condition. At present, no land and crop management practices conducive to the accrual of C in these soils are applied in the watershed. Consequently, the scenarios computed make assumptions of incorporation of organic residues to the soil. Overall, only in a few LUTs could simulated scenarios show that by 2012 there would be a demonstrated sink of C in the soil.

Biomass estimates

As far as C in biomass is concerned, forest biomass has been seriously depleted in the watershed since the later part of last century. Forests are communal lands in the watershed. Therefore, forest management is inadequate with loose regulatory and enforcement mechanisms. Extractions by local farmers for fuelwood, fencing and other domestic uses (so-called “leakages”) occur regularly and uncontrollably. The estimates of forest biomass indicate that the forest is sparse in some areas, with relatively low density of biomass as trees. Moreover, forest extraction rates, which the communities in the watershed give in concession to a private forest products company for a fee, tend to be such that current forest management practices are unsustainable. The incidence of other compounding factors and random disturbances, such as forest fires, exacerbate the problem of biomass depletion.

Litter and wood debris are a relatively large component of the carbon sinks in the forested lands of the watershed. The C in these materials could be lost from these ecosystems by erosion or by degradation of the organic matter on exposure to agriculture or other forms of intensive resource exploitation.

It was found that there were no standard procedures for special situations of biomass measurement such as the dimensioning of cacti plants, e.g. *Opuntia* spp., known locally as “nopal”. These are very abundant and used as plot barriers in the agricultural area of the middle zone of the

watershed. An *in-situ* procedure was developed to estimate the biomass of these plant species of rare intricate growth habit. This involved obtaining the average weight of morphological components of such species, and then counting the components present in each cactus plant to be measured.

The estimates of biomass in Texcoco indicate that the regression equation proposed by FAO (1999) was that best suited to the conditions of the watershed. Such an equation was found to be superior to the Winrock and Luckman equations in that it provided the closest estimates to those derived from morphometric measurements on the ground for the same sites. A formal error assessment, in the statistical sense, was not possible as no independent sites could be spared for use as “check sites”. For the analysis of the accuracy of estimates, only informal procedures based on rapid comparisons with ground morphometric measurements (based on volume measurements) were made. Therefore, this poses a fundamental question that needs to be tackled in the follow up on this project. A full study on error assessment of estimates for field validation and verification of carbon stock is the necessary and logical next step in refining the methodology proposed here. The conversion of biomass to carbon stock was automatic, by using a conversion coefficient. Another important observation concerning aboveground and belowground biomass estimation is that standing biomass estimates were only calculated for those mapping units with perennial vegetation, or with vegetation present at the time of measurement. This is reflected in the distribution of biomass in the maps produced as little or no biomass could be measured for most agricultural land owing to the fact that the fields were in fallow. Therefore, crop biomass was simulated for PLUT. Estimates of crop residues were used as inputs to models of SOM turnover.

Land suitability for PLUT for carbon sequestration

The land suitability assessment in Texcoco indicated that the staple crops, i.e. maize (cereal), beans and

squash, are only marginally suitable in most of the area of the watershed. This lends support to the evidence of only marginal yields being obtained in the area. However, in the flat lowlands of the watershed these crops have moderate suitability owing to the presence of deeper soils and of irrigation with groundwater. Other crops not currently grown in the watershed, such as sunflower, and a mix of horticultural crops (carrots, onion, lettuce, etc.) were found to be moderately suitable. A common limiting factor in the most suitable soils in the lowlands was the level of salinity and sodicity as the soils were closer to the dry lake bed. However, the most suitable crop pattern consisted of maize, barley, beans, onions and other horticultural crops. These were part of the scenarios of carbon sequestration developed through simulation.

SOM simulations with CENTURY

As far as the SOC pool is concerned, the scenarios of SOC dynamics, generated through simulation with the crops selected from suitability analysis with the CENTURY model, allowed for the elucidation of patterns of variation over space and time in the watershed under “business-as-usual” management. These scenarios show that there is a trend in terms of the spatial distribution of SOC dynamics in the watershed. Carbon losses to the atmosphere tend to increase with slope, altitude and terrain roughness, that is, with marginal conditions, in the agricultural portion of the watershed, and for the staple crops. The soils in the upper agricultural areas with moderate to strong slope, near the edge of the forested area, are experiencing the highest carbon losses (in a period of 12 years). These findings are somewhat intuitive as the SOM of formerly forested areas is degraded rapidly by the incorporation of relatively new agricultural areas to tillage. On average, these soils would lose up to 1 060 tonnes/ha of C over the 12-year period for maize, and 1 151 tonnes/ha for the same period for beans, assuming that the same crop and land management (“business as usual”) prevails in the same land in the 12-year period. This is so in spite of terracing and

other soil erosion control measures present in the same area of the watershed, and of chemical fertilizer applications. The soils are thin, already affected by erosion, and depleted of SOM by tillage, and above all, by the lack of applications of crop residues to the soil. The high radiation and dry conditions, and the export of organic matter from such ecosystems as crop residues for animal feed, create the conditions for important carbon losses both to the atmosphere and as carbon “mining”. According to the results of the modelling, the carbon losses in such agro-ecosystems occur mainly from the “slow” and “active” pools of SOM. The “passive” pool of SOM remains almost unaffected. Except for the redistribution of a small fraction of SOM among other pools, most carbon losses are to the atmosphere as CO₂.

In the middle portion of the watershed (rainfed agriculture on gentle slopes with ravines and hill slopes), similar carbon losses (averaging 1 160 and 1 163 tonnes/ha in a 12-year period for maize and beans, respectively) occur under “business-as-usual” management. The only exception to this trend for this part of the watershed is alfalfa cropping under limited irrigation. This scenario would require the application of limited amounts of irrigation and incorporation of realistic amounts of crop residues to this LUT. Carbon sequestration in soils of this middle part of the watershed under alfalfa cropping for the 12-year period occurs to a total amount of 3 381 tonnes/ha (scenario “Sn08Af”). A plausible explanation for these results lies in accounting for the C and N interactions, which the CENTURY model simulates well. The same also holds for the role of legume plants such as alfalfa in symbiotic Rhizobium fixation of atmospheric N, thus enhancing carbon sequestration. Hence, an increase in the area grown with alfalfa or similar legumes, whether in association or in rotation with cereals and fruit trees, would tend to enhance conditions for carbon sequestration in these soils of the watershed. There is also reason to believe that such carbon sequestration could be enhanced by conservation

agriculture strategies, such as no tillage, mulching with crop residues, legumes and green manures, and conservation of soil moisture.

In the flat lands at the lowest portion of the watershed, near the town of Texcoco and towards the edge of the agricultural area with the dry lake bed, the CENTURY-simulated scenarios showed a more positive trend towards carbon sequestration. These are deep, fertile alluvial and former lacustrine soils with moderate SOM content. The SOM is of pedogenetic origin (i.e. the lake bed) and also the result of contributions of nutrients from sewer, sludge and other residual waters from the upper portions of the watershed. These lands are irrigated by groundwater and by a mix of sewer and storm waters coming down from the communities at higher altitudes in the watershed.

The staple crops show only moderate to low carbon losses in the 12-year period under conventional management (averaging 191 and 1 021 tonnes/ha for maize and beans, respectively). In contrast, alfalfa (and possibly other legumes) together with vegetable crops, show a higher CSP. In the 12-year period, alfalfa in these flat lowlands could sequester an average of between 3 132 and 4 775 tonnes/ha with enhanced management (i.e. moderate irrigation, incorporation of crop residues and animal manures, and minimum tillage). The sequestration potential for horticultural cash crops, particularly legumes, in rotation or association with other crops could be as much as half the amount of carbon sequestration achieved with alfalfa under irrigation. The major increases occur in the “slow” (SOM2C) and “active” (SOM1C) pools of SOM, with moderate increases in the “passive” pool of SOM (SOM3C), to the rate of 40–70 tonnes/ha/year.

Cultivated grasslands, modelled by CENTURY on this portion of the watershed, could not yield comparable results to those positive carbon sequestration results obtained for alfalfa.

The soils in the primarily agricultural zone in the middle portion of the watershed are Phaeozems (Haplic) and Cambisols (Distric and Eutric) with significant inclusions of Lithosols and Regosols. These soils are thin, with the presence of a hardpan layer of 10–40 cm in depth (“tepetate”), and have low organic matter content. The intensive use to which they have been subjected has led to important erosive processes consisting mainly of water and wind erosion. Only the Mollic Andosols in the forested areas of the upper sierra zone of the watershed are of moderate to high fertility with sufficient SOM. Other soils of the flat lowlands, downstream near the dry lake, are affected by salinity and sodicity.

The climate in the watershed does not create favourable conditions for carbon sequestration in soils. The evapotranspirative demand exceeds precipitation for more than seven months of the year. The precipitation is not well distributed throughout the year. Therefore, soil moisture protection from radiation and the accumulation of SOM is not possible. Thus, management practices that aim to protect SOM (e.g. mulching and no tillage) are to be encouraged.

It was possible to generate a scenario of carbon sequestration under staple crops (maize and beans) and alfalfa (already cropped in the area) in the soils of the middle gentle slopes and lower plains of the watershed. In this scenario, maize achieves 40–50 tonnes/ha of C as SOM for 12 years for soils in the middle portion of the watershed under rainfed conditions, provided that 20–30 tonnes/ha of organic inputs (crop residues, manures, etc.) are applied yearly to these soils. For the Vertisols and alluvial soils in the lowland plains, 50–101 tonnes/ha of SOM can be sequestered with the same inputs of organic materials, but with the added organic inputs from residual (sewer and storm) waters as irrigation sources. In such a scenario, alfalfa accrues 47–80 tonnes/ha of C as SOM but with minimal amounts of organic inputs as crop residues and simply with the organic additions from sewer water irrigation.

According to the CENTURY simulations, these scenarios indicate that it is possible to achieve carbon sequestration in soils. However, considerable amounts of organic inputs (i.e. crop residues, manures or others) into the soil are necessary to achieve this. Such inputs are not currently applied to such soils as part of land management in that part of the watershed, and it is difficult to visualize farmers not deviating the crop residues from their fields in order to feed their livestock.

SOM simulations with RothC-26.3

The scenarios created from the simulations of SOM turnover by the RothC-26.3 model showed the existence of a spatial and temporal pattern of C in the soils of the watershed. Carbon sequestration occurred in the alluvial soils and Vertisols of the flat lowlands of the ex-lacustrine zone under irrigated horticultural crops, specifically onions. All fractions of SOM showed increased values after 12 years. The resistant fraction (RPM) accumulates 8 tonnes/ha whereas the humic fraction (HUM) accrues almost 6 tonnes/ha. There is an increase in BIO of 1.2 tonnes/ha whereas the active fraction remains almost unchanged, and about 55 tonnes of C as CO₂ are lost to the atmosphere in the 12-year period. The same LUT sequesters C in soils (Haplic Phaeozems, Eutric Cambisols and Regosols) of the middle portion of the watershed on gentle slopes of hillsides and ravines. The compartments of SOM that increased in the 12-year period are RPM with 8.02 tonnes/ha, HUM with 6.35 tonnes/ha, BIO with 1.165 tonnes/ha, producing 54 tonnes/ha of CO₂ for the 12-year period. Although they may seem small, these figures on carbon sequestration should be viewed against the background of dry climate, degraded soils and land and crop management strategies that are not conducive to carbon storage in soils. Moreover, they result from the application of assumed minimum management improvements, such as small additions of FYM. Another LUT in the middle zone of the watershed, irrigated beans, shows accumulation of C in SOM in the humic fraction (HUM = 12.22 tonnes/ha) in the 12-year period,

where slight improvements in crop and land management are assumed. However, the CO₂ losses amount to 105.5 tonnes/ha for the same period.

Even where staple crops such as maize, beans and squash are grown under rainfed conditions in the middle lands of the watershed, they show small accruals of certain fractions of SOM. For example, for squash, the accrual of BIO is 0.043 tonnes/ha, whereas that of RPM is 1.32 tonnes/ha. For rainfed beans, there are 1.06 tonnes/ha of the humus fraction accumulated in the period. These accumulations occur when improvements in management (amounting to small additions of crop residues) are assumed. In other instances, there is a redistribution of C within the different fractions of SOM. That is to say, losses in one SOM fraction end up as gains in another. For example, for irrigated beans in the middle zone, there is a slight humification (HUM) of BIO, or of BIO and RPM. However, for all other crops in the proposed LUT in the flat lowlands and the middle zone of the watershed, all initial contributions of crop residues end up as emissions to the atmosphere owing to land management.

In the upper watershed, consisting of degraded Eutric and Dystric Cambisols, Lithosols and Haplic Phaeozems on sloping lands of the transition between the middle and the sierra zone, a squash crop reports depletion of BIO, which increases CO₂ emissions. For all other crops in this agricultural fringe, there are only carbon losses to the atmosphere as CO₂. This can also be interpreted as part of the degradation of the initial organic matter in past forest soils open to cultivation for about half a century (first half of the twentieth century) in this watershed. The only LUT that shows evidence of carbon sequestration in this upper zone of the watershed is a forest balsam fir (*Abbies religiosa*). This area is an area of rich Humic Cambisols and Mollic Andosols with reasonable amounts of litter on the soil surface on steep slopes of the sierra zone. In these soils, RPM increases by 12.81 tonnes/ha and BIO by 0.06 tonnes/ha. However, the humic fraction decreases by 1.29 tonnes/ha in the 12-year period. This indicates that the humic fraction is being

attracted by the BIO, converting it to a resistant (sequestered) fraction. About 55 tonnes/ha are lost to the atmosphere in this process during that period.

Finally, as with CENTURY, it was possible to generate scenarios that sequester C in the watershed from RothC model simulations. On the gentle slopes of the middle of the watershed, the scenario shows that rainfed maize can achieve 48–56 tonnes/ha of C as SOM, but only if 20–30 tonnes/ha/year of organic inputs are applied. Rainfed beans achieve 15.3–20 tonnes/ha of C as SOM with similar organic inputs for the same soils. On the other hand, in the lower plains of the watershed, maize with irrigation from a mix of sewer and storm waters can achieve 130–153 tonnes/ha of C as SOM with the same crop residue inputs. For the same area and soils, alfalfa irrigated with sewer and storm waters achieves an accrual of 40–60 tonnes/ha of C as SOM.

Comparison of results from SOM simulations with CENTURY and RothC-26.3

Judging from the results of the Texcoco case study, it can be said that the similar or comparable trends in the spatial and temporal distribution of carbon dynamics in soils can be derived from the simulations by both models. CENTURY provides a greater number of compartments and recognizes a larger number of fractions and pools of SOM than does RothC-26.3. Therefore, it provides a more detailed breakdown of pools and of the soil processes involved in the fate of organic inputs into the soil. This far greater detail comes at a price. The number of input variables necessary to fully parameterize the model could potentially be in the hundreds (about 650 in total). The number of output variables is similarly large. A situation may arise where the model user does not request variables on output that would help to explain the partition of forms of SOM and to account for the fate of the total of organic inputs, as the number of possible output variables are so many. Another and perhaps more serious problem is that some of the input variables are not commonly recorded, measured or observed. For example, fractions of lignin in types of

tree foliage is a variable that ecologists with a definite research purpose may collect data on, but it cannot be expected in conventional studies of vegetation or soils conducted by agencies.

Concerning this problem, the customization of the CENTURY model undertaken through this project (“Soil-C”) could become a rather useful tool to guide non-specialist users to carry out simulations with the model, starting from relatively ordinary data sets for soil, climate and vegetation/crop management.

For answers to simple questions, such as how much CO₂ is lost to the atmosphere by a given LUT and land management practices after a finite period of time, or the amount of resistant organic matter left in the soil after the same period, it may be better to use the RothC-26.3 model. However, there are no known interfaces to link this model to standard GIS software in order to generate spatial scenarios. Moreover, the RothC model does not simulate the C–N interactions (which are so important in the attack of SOM by microbial activity and in its fate) as well as and in the detail achieved with CENTURY. Therefore, where accuracy of results and a greater level of detail in the fate of SOM are required, it may be better to use CENTURY or a similar model, with the added advantage of a computer interface that would facilitate its use.

An important consideration is that both models, and indeed any simulation model, should be well calibrated to the conditions in which they are applied, with experimental data from the area. This could only be done in this project in one case study (Bacalar, Mexico), for which there were data for calibration and validation of the model. Further studies ought to be conducted in the region (Latin America and the Caribbean). These should collect data from any long-term experiments in the area, and set up such experiments for a variety of ecological zones and conditions in order to determine the range of conditions for the applicability of such models in Latin America and the Caribbean.

Biodiversity assessment

Related to the spatial distribution of biodiversity (in this case plant diversity) in the Texcoco watershed, the indices calculated and mapped out showed that the middle portion of the watershed is characterized by the highest values of species richness and fewer “abundant” species and more “rare” species. This indicates that these classes are not dominated by a few species, which is confirmed by the high values of the Reciprocal Simpson Diversity Index and the Shannon Diversity Index in the area. This could be explained in terms of the introduction of horticultural species in backyard intensive plots and the greater richness of weed species. Hence, the lower the altitude of the rainfed agricultural plots in the watershed, the more diverse the plant population becomes, with the exception of the intensive mechanized monocropping of irrigated alfalfa and maize for forage, which tends to be grown on the lower and alluvial plains at the bottom of the watershed.

In summary, the results suggest the possible existence of a pattern in terms of the distribution of plant diversity and vegetation classes (landscape element types) throughout the watershed representing different ecological conditions and different stages of forest succession (in the upper part of the watershed). The older the stage of forest succession, the more species there are and the less is the dominance of any given species. Thus, losing these agro-ecosystems in the middle portion of the watershed (e.g. through urban encroachment) and those forests of the upper portion of the watershed (through agricultural encroachment causing deforestation) would be more costly in terms of plant biodiversity than anywhere else in the watershed.

Land degradation assessment

The three types of land degradation assessed in the study, chemical, physical and biological, also show a spatial pattern across the watershed. The lands most chemically degraded, owing essentially to salinity, alkalinity and possibly to the presence of heavy metals in excess (sewer water irrigation), are those

located at the bottom of the watershed, near the edge with the salted lake bed. Elsewhere, the lands of the watershed show only slight signs of chemical degradation at most. However, as no analytical work was part of the assessment, no conclusive evidence of other possible sources of chemical degradation could be detected (e.g. pesticide in soils). Thus, the lower the altitude the greater the chemical degradation in this watershed.

As far as physical land degradation is concerned, soil compaction was considered moderate to high in the low plains, owing to the intense use of farm machinery and tillage, whereas in the rest of the watershed it was found to be only slight. The middle and upper middle portions of the watershed, which are the areas of rainfed agriculture, are the areas more affected by both aeolic (10–50 tonnes/ha/year and even 50–200 tonnes/ha/year of soil losses in some areas) and water erosion (10–50 tonnes/ha/year in most of the middle part and all of the upper part of the watershed, except for a few areas in the middle part, which lose 50–200 tonnes/ha/year of soil), as estimated from both experimental runoff plot data and from applying the USLE. These patterns are realistic and coincide with the empirical field observations on the state of soil erosion, which persists at such rates in spite of terracing and other conservation measures.

Finally, with regard to biological land degradation, it became clear that, given the ongoing processes and the current land management practices, and except for one or two landscape units, the lands in the entire watershed are affected by high to very high biological degradation. This is mainly because of the gross decline in the levels of organic matter in the soil and the environmental, cultural and economic conditions in the watershed. These conditions will ensure the steady decline of SOM unless strong remedial actions (e.g. dramatic increase in crop residue inputs, mulching, no tillage, soil conservation and water harvesting) and different land management practices are adopted. The land-use

patterns and PLUTs suggested in the scenarios should involve the application of such improved land management practices.

The tropical forest lowlands of Bacalar, Quintana Roo, Mexico

This study area can be thought of as the antithesis of the study site at Texcoco in terms of vegetation type, vegetation density and agricultural activity. This study site also represents a very contrasting situation to Texcoco in terms of population density and, therefore, in terms of anthropic impacts on ecosystems. In Bacalar, there are no permanent residents in the study area, and the surrounding areas are sparsely populated. By contrast, Texcoco has a very high population density. The main socio-economic activity consists of subsistence farming and of forest- and agriculturally-based family production systems. The staple foods produced in these systems are a result of slash-and-burn agriculture (SABA) or shifting cultivation. This type of use of the forest introduces the most dominant dimension in the carbon dynamics in this part of the world: the management of forest biomass. The use of forest biomass, at different stages of succession, to boost soil fertility through the ashes of the burned forests has enabled crop growth and yields to sustain Mayan populations for millennia. However, much C has been lost to the atmosphere as CO₂ in the process.

The soils of the Yucatan Peninsula are naturally very shallow, and are formed by the *in-situ* weathering of the emerged thin layer of marine sediments on the limestone shield. In the lowlands and plains, the soils are Luvisols and Cambisols, and they can be described as relatively deep red soils. On the small hills and slopes of the undulated landscape, weathering of the shield and its residual materials has created Rendzinas and Lithosols, soils with fine textures and varying degrees of coarse fragments, stoniness and rock fragments. These soils can only sustain crop growth and crop yields through a rapid recycling of organic matter. The nutrients from the ashes of a 40–50-year-old forest incorporated into the soil can sustain crop

yields for three to five years. Then, as yields decline, the agricultural plot has to be abandoned and moved to a new patch of mature forest, which is cleared for growing staple crops (maize, beans and squashes).

There is a strong correlation between soil type and position on the landscape: Rendzina (called Bosh-lu'um in the Mayan soil classification) and Lithosols (Tzek'el) at the top of small hills; Regosols (Ho'l lu'um and Chich lu'um) on the slopes of undulations; and Luvisols (K'ankab) and Cambisols (Chack lu'um) on the small plains and flat areas of red and reddish-brown soils. Gleysols or Vertisols (Ak'alche) could replace the latter depending on the degree of hydromorphism of the soil in flat lands, savannahs and concavities, where periodic flooding may occur. The Maya soil classification, derived from millennia of experience and empirical knowledge, recognizes such soil-landscape associations. These associations are extremely important as they can determine vegetation succession and, therefore, the carbon stock as biomass in such forests. Hence, forest biomass and its carbon stocks are related closely to vegetation classes, as recognized by the indigenous knowledge: Monte Alto, Kelenche, Juche, Akalche, Sabanna and Canada.

Biomass estimates

The estimation of biomass was complicated by the sheer amount of biomass in terms of the very large number of trees to measure, the amount of biomass and the undergrowth, shrubs and saplings in a sometimes impenetrable tropical forest. Substantial aboveground carbon stocks in the biomass of tropical forests characterize the Bacalar case study area.

The measurements at the quadrat sites took several orders of magnitude in time more than the time taken to measure quadrats in a more open temperate forest, such as in Texcoco. This is a factor to consider in terms of its impact on time, effort and costs to obtain the ground measurements for the estimates of biomass.

The regression equation method, based on biomass as a function of measurements of volume, proved to be the most adequate method for estimating the biomass of the type of tropical forests in Bacalar in the Yucatan Peninsula. The Bacalar study area receives about 1 000 mm of precipitation per year and is characterized as a lowland area. Thus, the results using biomass regression equation FAO-1 for “dry” tropical areas receiving more than 900 mm of annual precipitation (FAO, 1997) were found to be the most suitable method for predicting biomass as a function of measurements of volume.

The vegetation types recognized by the Maya, and mapped out through the supervised classification of a Landsat TM multispectral image of the area, proved extremely useful as both a frame for sampling design and as a mechanism for upscaling estimates calculated at quadrat sites to the entire area. A close relationship between the radiance values of pixels in the multispectral image and the biomass estimates from quadrat sites on the ground was found and expressed in terms of a regression equation. This equation allowed for the conversion of the digital values of a satellite image into values of biomass at each of the pixels. Where based on a good regression model fit, this type of “biomass transfer function” can be extremely useful in generating estimates of carbon stocks in biomass of dense tropical forests such as those of the Yucatan Peninsula. However, it is doubtful that a similar approach would work as well in less densely forested areas. The map of forest biomass obtained through the satellite image shows a pattern of distribution of values of biomass, which followed closely the distribution of classes of vegetation as from the supervised classification of the image in terms of the Mayan classes.

However, the degree of accuracy of biomass and carbon stock estimates in the tropical forests of Bacalar is unknown. Their accuracy can only be determined through independent error assessment in a follow-up study to this project. Indirect indicators of the accuracy of estimates can be the value of the

coefficient of determination (R^2) and the standard error of the regression models used.

The biomass in forest litter and debris in Bacalar forests is considerable and contributed significantly to the inventory of carbon stock. Where the layer of litter is removed, as in deforestation for SABA, considerable losses in biomass occur through burning and through degradation of organic matter. Forest litter was found to play a crucial role in understanding the dynamics of SOM turnover in shifting cultivation.

Scenarios generated by SOM simulation models

In Bacalar, it became imperative to use a slightly different approach to carbon accounting in SOM from that used in the other two case studies. Instead of considering individual LUTs one at a time, and evaluating them in their potential for carbon sequestration, a “farming systems” approach was deemed appropriate to describe the flows of energy and materials involved in all productive activities in the family unit production system, as such flows are much more dynamic in this area. The approach would help in accounting for flows of organic materials and “leakages” to other subsystems (e.g. from forest to agriculture, and from this to backyard poultry and livestock, and back to the agricultural plot as FYM).

Another consideration concerned the unique characteristics of SABA. In Bacalar, the most effective measure to reduce CO₂ emissions from forest burns was to consider the stabilization of SABA from shifting cultivation to continuous cropping in the same land plot. This would prevent deforestation through forest slash and yearly burnings of numerous patches of forest. In the family unit farming system, the representative subsystems accounted for, through their contributions of organic inputs through modelling, were: the felled forest of the agricultural plot, crop residues from the previous cropping cycle, the family backyard orchard, and FYM from livestock (including backyard poultry).

With food security as an objective, the modelling scenarios aimed at determining the management of organic inputs to the land growing a mix of staple crops (maize, beans and squash) that would guarantee sustaining or increasing yields, while sequestering enough organic C in the soil, over time, so as to make the system sustainable.

After model parameterization, model calibration was achieved with the only five years of SOM measurement data available. For example, the fit of the RothC-26.3 model predictions of SOM to the actual SOM values measured is quite good, and lent confidence to the use of these models in spite of the limited number of data points for the calibrations.

The scenarios computed for staple crops in continuous cropping with a variety of organic matter inputs from different sources (i.e. subsystems of the family unit farming system) show that in all of the scenarios there are C losses and no carbon sequestration in the soil. The amount of C lost to the atmosphere is related to management. Carbon sequestration only begins to occur after continuous cropping of staple crops, when the amounts of organic matter as inputs to the soil are high enough to provide substrate to begin the further accumulation of SOC in its different compartments or pools. It was demonstrated that the management of organic residues is crucial as a carbon sequestration strategy. It was shown that carbon sequestration (as measured by total C in the soil) only occurs under careful land management. Thus, after investigating various organic matter inputs into the soil as recommended by various workers in the specialized literature (e.g. Lal *et al.*, 1998; Sanchez *et al.*, 1989; Szott, Fernandes and Sanchez, 1991), it was found that scenario SK15, which uses sources characteristic of the SABA occurring on the Yucatan Peninsula, was the best scenario in terms of carbon sequestration. The plots are left fallow for one year, a SABA event, followed by continuous cropping with annual FYM inputs. The total carbon inputs for this scenario are 3.3 tonnes/ha from the SABA event for

the first year only, followed by 5.39 tonnes/ha from the cropping residues, 20 tonnes/ha from orchard residues and 25.58 tonnes/ha in FYM annually.

The production of crop yields as a function of SOM developed by regression analysis in Bacalar allowed for the estimation of yields as a function of the SOM simulated by the models. These computations permitted the generation of predictions of crop yields values into the future scenarios of carbon sequestration, thus providing a measure of food security. It was found that with the SK15 scenario, the sequestration of C in SOM was such that it would allow for the production of enough maize grain to sustain a family of six individuals.

According to RothC-26.3 simulations, the C sequestered in the Chromic Luvisol soils (Kan'kab) under Juche vegetation and past cropped areas (“canyada”) changes from 730 to 740 tonnes/ha of C in SOM. This represents a gain of about 10 tonnes of C in SOM per hectare in a 12-year period under continuous cropping and assumed organic matter inputs as in the scenario SK15. It is not known what the practical requirements are in order to achieve the levels of organic inputs demanded by the SK15 scenario. Nor are the practical constraints imposed on farmers in the area known. However, it is clear that the carbon sequestered would lead to sustainability of crop yields and to food security for the family.

A comparable simulation of this scenario SK15 with the CENTURY model produced similar results. However, the values of C in SOM were more modest. The changes occur between 116.29 and 121.35 tonnes/ha of C in SOM; a gain (sequestration) of 5.06 tonnes/ha of C in SOM for the red Kan'kab soils.

The “business-as-usual” scenario for the 12-year period involved changes in total C in soils such that all systems, except for SK15, behaved as net emitters. For tall and old (30–50 years) forest (Monte Alto and Kelenche) on thin Lithosols and Regosols,

500–550 tonnes/ha of C were transformed to 350–400 tonnes/ha of C after SABA during the 12-year period. For a young successional forest (i.e. Juche), the values changed from 150–200 tonnes/ha of C to 50–100 tonnes/ha of C on the relatively deep Chromic Luvisols (Kan'kab). Where the same type of young successional vegetation (Juche) is found on thinner soils such as Regosols or Lithosols, then the losses are larger than even for the old forest: from 500–550 tonnes/ha of C, to 300–350 tonnes/ha of C in SOM.

Finally, a scenario which includes the addition of only 2 tonnes/ha of C as FYM to the soil under maize–beans and squash cropping and modelled by RothC-26.3 did not have any effect on enhancing carbon sequestration in Chromic Luvisols (Kan'kab). This is because it depleted C as SOM, which changed from 150–200 tonnes/ha of C to 100–150 tonnes/ha of C. This indicates that it is not worth adding organic materials to the soil unless the quantities are sufficient as to create a substrate of SOM to begin sequestration in soils, as in scenario SK15.

Biodiversity assessment

In order to discuss the results of evaluating biodiversity in Bacalar, it is worth reviewing the key concepts that have been applied in calculations of indices.

Intuitively, biodiversity, or species diversity, is understood as the number of species in a given area, habitat or community. However, the formal treatment of the concept and its measurement is complex.

A biodiversity index “seeks to characterize the diversity of a sample or community by a single number” (Magurran, 1988). The concept of “species diversity” involves two components: the number of species, or richness; and the distribution of individuals among species, or evenness. Most indices try to encompass both of these dimensions. Many of

the differences between indices lie in the relative weighting that they give to evenness and richness.

The simplest measurement of species diversity is a species count. Simple species counts remain the most popular approach for evaluating species diversity and comparing habitats and species assemblages. Species counts have proved to be a very useful index in areas that are not densely vegetated, such as in the Texcoco or Cuba case studies. However, in densely vegetated areas, such as in Bacalar, they are often considered an early step in many ecological and community studies. The number of species per se provides little insight into the underlying ecological mechanisms that define biodiversity, nor does it encompass evenness. Species counts are insensitive to the ecological placement of species, including rare species, that may be present in tropical forests. For example, species counts in a forest would equally consider species with totally different ecological roles, such as trees and herbs. Species richness provides an extremely useful measure of diversity when a complete catalogue of species in the community is obtained (Magurran, 1988), and this was not the case for Bacalar. Thus, computation of the other indices of biodiversity to complement species richness became an important step in the assessment in this case study.

Concerning the number of species, there are clear spatio-temporal trends in the Bacalar study area. A clear association exists between age of forest succession and species richness. Thus, a spatial pattern emerges with forest succession age. For example, the Monte Alto vegetation class, which corresponds to the oldest forest succession, holds the greatest species richness (more than 50 species), followed by Kelenche (30–50 species), the second oldest forest succession class, Juche (10–30 species), which is the third oldest vegetation succession, etc. The vegetation areas with the lowest species richness are areas with intermittent flooding, such as Akalche and Sabana, where species adaptation to this type of flooding stress has played a selective role.

To a certain extent, the spatial distribution of these vegetation classes represents the distribution of species richness in the area studied. Hence, affecting any of these classes by deforestation would bring implications of possible losses of such species richness on a given patch of land, and considerations about the understanding of the role of SABA on species succession and ultimately on species diversity.

The fact that there is a strong association between species richness and vegetation classes, and that such classes could be recognized and discriminated through multispectral satellite image analysis, made it possible to map species richness through a conventional supervised classification of an FCC of the satellite images.

Perhaps the most widely used index of species diversity is the Shannon Diversity Index. The Shannon Diversity Index is very similar to the Simpson Diversity Index except for the underlying distribution. The Simpson Diversity Index assumes that the probability of observing an individual is proportional to their frequency in the habitat, while the Shannon Diversity Index assumes that the habitat contains an infinite number of individuals. The equation for the Shannon Diversity Index is:

$$H = \sum (p_i - \ln(p_i))$$

where p_i is the proportion of individuals n_i of species i in the total sample N . That is, $p_i = n_i/N$. This index considers both the number of species and the distribution of individuals among species. For a given number of species s , the largest value of H results when every individual belongs to a different species, that is $p_i = 1/n$, which allows for a relative measure of diversity, “evenness”: $E = H/\ln(S)$. However, comparisons among communities or habitats based on E are possible only where the sample size is the same. The value E or “evenness” is a measure of how similar the abundances of different species are. Where there are similar proportions of all species, then evenness is one, but where the abundances are very dissimilar (some rare and some common species), then the value decreases. Evenness

(*E*) has a high value where there are equal numbers of individuals in each species.

In the Bacalar case study, the calculated “evenness” for each vegetation class mapped showed a split in terms of evenness values down half of the vegetation classes and vegetation succession. Values closest to one were observed for the oldest stages of succession, i.e. Monte Alto, Kelenche and Juche. These values of evenness for such classes are in descending order, but very close to one another. This would indicate that after a period of recovery from SABA, equivalent to the age of a Juche (10–20 years), most of the species that would establish themselves in succession have already established themselves in comparable numbers of individuals. Hence, the transition from Juche to Kelenche does not bring more “rare” or new species, nor does the transition between Kelenche and Monte Alto, thereby indicating that the vegetation reaches some degree of equilibrium.

In contrast, Saakab and Akalche classes showed the lowest evenness values, indicating that these classes not only have the lowest richness, but also the most “rare” species, typical of wetlands or lands experiencing intermittent flooding. In this respect, the Sabana class can be considered an “anomaly”, given the fact that it showed the second largest evenness values after Monte Alto.

The Simpson Diversity Index measures the sum of the probabilities that two randomly chosen individuals belong to the same species, summed over all species in the sample. The Simpson Diversity Index assumes that the proportion of individuals in an area adequately weights their importance to diversity. The equation for this index is:

$$D = 1/(\sum (pi^2))$$

where *D* is the diversity and *pi* is the proportion of the *i*-th species in the total sample. This can also be written as:

$$D = 1 - [\sum n_i (n_i - 1) / N(N - 1)]$$

where *ni* is the number of individuals of the *i*-th species, and *N* is the total number of individuals. The value of *D* varies widely as the total number of species increases, depending on the type of species–abundance relationship used to calculate the index. This index goes from zero to the total number of species. An index of one indicates total “dominance” of one species, that is to say, that all of the individuals in the area belong to a single species. Where *D* = *S*, then every individual belongs to a different species. The Simpson Diversity Index is a commonly used dominance measure because it is weighed towards the abundances of the most common species rather than providing a measure of species richness.

The values of the Simpson Diversity Index computed for Bacalar show that in the oldest successional stages of the tropical forest (i.e. Monte Alto, Kelenche and Juche vegetation classes) a few species tend to dominate, even though the number of individuals in each of such species is quite even. The values of “dominance” approach 0.90. In contrast, the index values for the vegetation classes affected by flooding remained with less dominance of the species found in such habitats.

Other indices to measure species diversity have been proposed, but they have received little attention or are mathematically related to the more popular indices (*H* and *D*). However, one common characteristic of biodiversity indices is their requirement for statistically sound sampling. Sampling for species richness requires appropriate area and seasonal coverage in order to ensure that the sample includes a significant subset of all species. Indices that include both species and individuals/species data for their calculation require more intensive sampling. In the light of these observations, the procedures advanced in this methodology provide a picture of the status of plant diversity in the area of concern. This may require further investigation in order to

understand the underlying ecological processes leading to the distribution of species in the area and the diversity they represent.

Sixty-seven quadrat sites were sampled in Bacalar for the purpose of estimating the biodiversity indices. This number was considered adequate for the purposes of providing an initial assessment of the status of biodiversity, in this case plant diversity. This was confirmed by the shape of the curves of each of the three biodiversity indices calculated, when plotted against the number of samples (i.e. quadrat sites). At about 65 samples, the curves of biodiversity indices became asymptotic to the horizontal axis of the number of samples, which was considered an adequate compromise between information and costs.

Land degradation assessment

Land degradation in the Bacalar case study was reduced to biological land degradation, as detected by early observations from field quadrats. The absence of anthropogenic impacts on these forests and lands, other than SABA, owing to the rather low population densities, makes the presence of chemical degradation almost undetectable. There are reported uses of herbicides and pesticides together with chemical fertilizers. However, there are no records on the application rates of such chemicals and on the effects they may have on the status of the land.

Physical land degradation, particularly soil erosion by water and wind and compaction due to machinery, was considered negligible on these lands. The high forest protective cover and the microtopography and shallowness of the soils limits the use of machinery for tillage to the point of having negligible effects on the land. Therefore, for the purposes of this case study, both chemical and physical land degradation were considered as being negligible. In contrast, organic matter plays a key role in determining the productivity of these lands, to the point of obscuring any other possible types of degradation. SOM and the rather tight cycling of nutrients from vegetation in these shallow and stony

soils play a key role in determining the primary productivity of these lands, the types of vegetation succession, and crop growth and yields. Thus, only biological degradation was considered significant and evaluated in this case study through the decline of SOM in the soils of the area studied.

As far as the decline in organic matter is concerned, the state of biological degradation was assessed through the scenarios of future SOM turnover. Through these, it became clear that careful selection of crop mixes and additions of organic matter from different subsystems would create the conditions for carbon sequestration and accumulation of organic matter over time.

The Rio Cauto Watershed, Cuba

The results obtained from the Rio Cauto Watershed in eastern Cuba confirmed some of the findings from the two Mexico case studies. However, some other results were unique to the Cuba case study. There are major differences in the decision-making processes concerning land use and LUCs in Cuba compared with the other two case studies. Central planning has produced a land-use pattern that is less complex and more straightforward than in the Texcoco case study. There is continuity and larger areas in the mapping units of the land cover map generated in the Rio Cauto Watershed owing to the allocation of land use to parcels of land according to central planning. The decision-making process, also in terms of land management, is determined centrally and, therefore, more uniform for relatively large areas. These factors play a role in simplifying the generation of scenarios for PLUTs and LUCs in the area studied.

Access to data and information was initially difficult. However, the process became highly participatory once the cooperation of the local and national agencies was obtained. Obstacles relating to logistics and scarce local resources also played a role in constraining the number of samples that could be obtained in the field. However, the field component of the project was considered a success in terms of the

amounts of data gathered in the field by a quickly assembled multidisciplinary team in a rather short time.

The multispectral satellite image obtained of the area had considerable cloud cover and it was not possible to obtain any other image at the time. This hindered the definition of land cover classes by introducing confusion in the separation of the classes in the feature space, while performing a supervised classification of the image. Moreover, a compounding factor was the use of a relatively simplistic algorithm for classification (i.e. “box” classification), which was the only one available in Cuba at the time. As a result of these compounding factors, the initial land cover map developed from the supervised classification had about three misclassifications out of 17 classes defined (e.g. what was defined as “water body” is essentially part of the cloud cover; the class “cloud” was misclassified as “quarry”; etc.). The classes as determined by satellite image interpretation required extra fieldwork in order to be completed satisfactorily. This type of circumstances can be typical of the working environment in developing countries. Hence, procedures for dealing with missing data or software should be part of the contingency plans of any assessment and monitoring team.

After field validation, it was possible to establish as land cover classes: sugar cane; two classes of pastures (short and tall grasses in seven different mapping units); forests (two kinds: on sloping lands and on the banks of the river, in six mapping units); orchards (family orchards and small plantations, in three different mapping units); crops (three mapping units); maize (two types); urban land use and roads. The units mapped out correspond to what could be considered LUTs, for their differences lay in the management and level of inputs or infrastructural support, given the same type of activity (i.e. forest, pasture, orchard or crop). The area covered with sugar cane came out as being considerably smaller than the actual area covered by sugar cane. Hence, this was one of the major adjustments to the map after validation.

Biomass estimation

Biomass was calculated across the study area using measurements taken in 10 m x 10 m study quadrats. Similar to the Texcoco study area, the biomass calculated per quadrat is taken to be representative of the LUT polygon that it occurs within, averaging results between quadrats when more than one occurs within each polygon. Several methods of biomass calculation were applied to these data. The aboveground biomass of forested areas in the Rio Cauto study area were estimated using regression equation FAO-1 for “dry” tropical areas receiving more than 900 mm of annual precipitation. This equation gave the “best” fit to data in the least-squares sense.

The results indicate that forests contributed the most to the stock of aboveground biomass. This is in spite of the fact that much of the study area is agricultural land and forested land are only remnants of old forests on slopes of hills and on the sloping banks of the Cauto River. The level of contribution to the stocks of biomass and C is proportional to the level of health and degradation of these forests, some of which are enduring great ecological and human stresses (e.g. drought and selective cutting). Relatively healthy forests contributed about fourfold the total biomass of crops for the entire area. Stressed forests contributed twofold the biomass of crops in the area. The forested area constitutes about 15 percent of the total area studied.

Sugar cane was shown to contribute substantially to the stock of aboveground biomass. The biomass estimates for crops, particularly those for sugar cane (which covers about 65–70 percent of the total area and about 90 percent of the area cropped), were obtained from records of the National Institute for Sugar Cane Research (INICA) and verified by the institute’s local experts. In this situation, these records are considered more accurate than any estimates obtained from crop growth modelling. Variations in sugar-cane biomass estimates by mapping units are due to the variety and age of the

semi-perennial crop. On the other hand, biomass in pastureland was estimated from the 1 x 1 m quadrats and then upscaled to a hectare.

The spatial distribution of total biomass (aboveground and belowground) estimates shows the remnant forests on the slopes of the riverbanks and on gentle slopes of hills, stocking 20–80 times more biomass (1 657 and 8 176 tonnes/ha respectively) than sugar cane and pasture (51.5 and 7.5 tonnes/ha respectively). The resulting carbon estimates in biomass are simply a proportion (about 0.55) of the biomass stock. This fact draws attention to the potential benefits that could accrue from implementing afforestation or reforestation in the area, or from implementing some form of agroforestry systems, which may include fruit trees and woody species of economic importance.

There were some mapping units in the land cover classification map for which no biomass estimates were possible owing to the lack of sampling quadrat sites. The quadrat sites that could be measured, within the constraints imposed by circumstances, were a sufficient but not very large number. Hence, for the purposes of this study, it was decided to leave such mapping units without estimates, rather than generate estimates from a relatively weak interpolating procedure.

Results of SOM modelling

The soil data from the soil mapping effort by the INICA in Cuba was useful for parameterizing both models of SOC dynamics: RothC-26.3 and CENTURY. However, the soil inventory is more than 30 years old. Therefore, some of the analytical data, particularly chemical soil properties, may not reflect present conditions. The soil parameters were taken from this database to parameterize the RothC and CENTURY models. Running the RothC model “backwards” to equilibrium, until the current level of organic C in the soil (as per analysis) was achieved, proved to be a fruitful strategy for finding out the partitions of SOM in its different forms or pools, which are part of the

current SOM levels in the Rio Cauto soils. These were taken as the starting point of the simulation “forward” into the future for both models, in lieu of the lack of detailed analytical data on the different fractions of SOM in the soils of the area.

This initial simulation showed that for 2000, the forest soils (for those soils for which there were data) had the highest levels of SOC (up to 112.6 tonnes/ha). However, the stock in these soils is not significantly larger than that of the soils under sugar cane (102.3–108.93 tonnes/ha). This indicates that soils under sugar-cane cultivation for a period of up to seven years may accumulate amounts of organic residues comparable with soils under forests.

Scenarios that included SOM turnover simulations for 12 years (to 2012), with a combination of sugar-cane varieties grown on different soils and with two levels of additions of organic residues (0 and 2 tonnes/ha), were calculated. Such scenarios were considered conservative as far as the additions of organic residues were concerned. The scenarios were based on crops already part of the present cropping pattern in the area. No new crops in PLUTs were considered in these scenarios, as the suitability of the land for potential crops was not evaluated in Cuba. This was a decision resulting from considerations about the low likelihood of implementing any LUCs that may clash with the centrally-designed land-use plan.

Results of modelling with RothC-26.3

The modelling scenarios with RothC-26.3 included combinations of sugar cane, pastures and forests on dark gley plastic soils and on light grey carbonated soils, both with and without additions of 2 tonnes of C per hectare.

Of all the scenarios simulated for the dark gley soils, which are used mainly for sugar cane, only grasses achieved sequestration of C in SOM, both with 2 tonnes of C per hectare of organic residues as FYM and without any additions at all. When no

FYM is added, grasses accrue 2.22 tonnes of C per hectare (from 55.8 to 58 tonnes of C per hectare in 2012) as SOM. When FYM is added, up to 9.75 tonnes of C per hectare as SOM are sequestered in the 12-year period (scenarios Nmp1 and Fyp1).

In contrast, for these same soils, sugar-cane loses total C from SOM to the atmosphere, without any additions of FYM, from -8.26 tonnes of C per hectare (a change from 75.7 to 68.1 tonnes of C per hectare; scenario Nmc1) to -13.43 tonnes of C per hectare (a change from 65.85 to 52.43 tonnes of C per hectare; scenario Nmc3). However, when 2 tonnes of residues (FYM) per hectare are added, the losses are reduced to only one-quarter or one-sixth of the losses without FYM: from -1.13 tonnes of C per hectare (a change from 64.5 to 63.45 tonnes of C per hectare; scenario Fyc2) to -2.89 tonnes of C per hectare (a change from 65.52 to 62.63 tonnes of C per hectare; scenario Fyc4). These figures indicate that the additions of organic residues (FYM) at the rate of 2 tonnes of C per hectare to sugar cane reduce the losses of C to the atmosphere substantially, and presumably they would sequester C if the additions of FYM were in a greater quantity. Thus, the additions of organic residues as FYM of 2 tonnes of C per hectare are too little to achieve carbon sequestration within the 12-year period. Greater amounts would enhance carbon sequestration and collateral ecological benefits, such as increasing soil biodiversity and preventing further land degradation. Therefore, the solution is based on the implementation of appropriate land management strategies based on SOM.

The simulations computed with this model demonstrate that for the entire landscape, sugar cane and, in some soils, grasses as LUTs, with no additions of organic inputs, are net emitters of C to the atmosphere. Conversely, a mix of sugar cane and grasses with organic inputs to the soil of more than 2 tonnes/ha/year for the 12-year period would sequester C in SOM.

Results of modelling with CENTURY

On the whole, the forested areas that are left intact accrue SOC. Regardless of the land use, additions of organic matter to the soil are crucial to SOC sequestration. A scenario of land-use conversion of sugar cane to pasture illustrates the same point. The resistant C in the “slow” pool or fraction is shown to be less affected by management of organic residues.

The scenarios developed through modelling with CENTURY explored the use of organic inputs and no inputs at all, and an LUC from present land use to grassland. Total SOC and the resistant or “slow” fraction of SOM (SOM3C) were modelled.

Total SOC is in moderate to high contents in grasslands (108–112 tonnes of C per hectare) and in not much smaller quantities in sugar cane soils (102–108 tonnes of C per hectare). In fact, these figures indicate that the total carbon contents of soils under both types of land use are comparable. Then, when 2 tonnes of C per hectare of organic inputs are added to the soil yearly, the soils under sugar cane (dark gleysols) can sequester up to 8–10 tonnes of C per hectare for the 12-year period (a change from 102–108 tonnes of C per hectare to 112.6–116 tonnes of C per hectare). This contrasts with the results modelled with RothC-26.3, where a negative change was observed with the same amounts of organic inputs and in the same soils. This may be because of the sensitivity of the CENTURY model and the result of accounting for the C and N interactions, which were not modelled with RothC-26.3. Grasses also sequester C (116–121 tonnes of C per hectare) from an initial range of 108–112 tonnes of C per hectare, representing an accrual of 8 tonnes of C per hectare on average, over a 12-year period, when 2 tonnes of C per hectare are added as inputs to the soil. Forests maintained 97.7–102.3 tonnes of C per hectare where left undisturbed.

The scenarios of LUC to grasslands (except forests) indicated that, without organic inputs to the

soil, areas under sugar cane would lose an average of 20 tonnes of C per hectare for the 12-year period, and areas with other crops would lose as much as 40 tonnes of C per hectare as SOM in the same period. By contrast, undisturbed forests would sequester an average of 20 tonnes of C per hectare for the 12-year period. These results indicate that it may not be advantageous to convert land under sugar cane and other crops to grasslands. Furthermore, even where organic inputs (2 tonnes of C per hectare) are added to the conversion, former sugar-cane lands lose about 10 tonnes of C per hectare, which is half of the losses without organic inputs. Thus, the organic inputs only ameliorate the losses of the LUC.

The resistant fraction of SOM (SOM3C) experiences increases (sequestration) after the LUC and 12 years. Without organic inputs, 1 tonne of C per hectare of SOM3C is sequestered. About 2 tonnes of C per hectare of SOM3C are sequestered when organic inputs (FYM) are added to the soil.

The figures indicate that there is no point changing land use from sugar cane and other crops to pastureland. It may be more worthwhile to increase substantially the level of organic inputs to the soils under sugar cane and pastures as they actually are, and to increase or at least maintain the status of forest litter and forest cover in the area studied.

On the whole, the results obtained with CENTURY are comparable with those obtained with RothC-26.3. However, the CENTURY simulations allow for greater detail in the partition of the SOM fractions and may be considered more accurate. These considerations need to be balanced against the trade-offs of easy access and processing of the models and their data requirements.

Biodiversity assessment

As mentioned above, species richness provides an extremely useful measure of diversity where

complemented by measures of evenness of abundance and dominance.

There are clear spatio-temporal trends in Rio Cauto. The greater number of species (S) can be found in the forests. Forests on hill-slopes hold between 13 and 34 species of plants, whereas forests on riverbanks hold an average of 12 plant species. Then, there is a hiatus in terms of plant diversity. Grasslands hold between 6 and 12 species and sugar-cane fields an average of 5 species. However, these apparently diverse forests are dominated by one or a few “rare” species, creating uneven plant populations. This can be appreciated through the values of the Shannon Diversity Index and the Simpson Diversity Index.

The Shannon Diversity Index (H) calculated for the recognized vegetation classes in Rio Cauto, Cuba, allowed for the calculation of a measure of the “evenness” ($E = H/\ln[S]$) of species distribution. The values of “evenness” calculated for all vegetation classes are generally low. Values of 0.32 for forests on hill-slopes, 0.26 for forests on riverbanks, 0.24 in sugar cane fields and 0.14 for grasslands indicate that there are disproportionate distributions of individuals to the species found. This means that while some species counted may have several individuals, there may be only one individual or at most a few individuals for other species. A value of $E = 1$ would indicate that there are similar proportions of individuals (abundances) in all species. In the case of Rio Cauto, the values are small, indicating uneven abundance or dominance of a few species. This is not counterintuitive when one considers sugar-cane fields, but it is when considering forests. Therefore, forests are not very diverse.

The Simpson Diversity Index measures the “dominance” of species over others. In the case of the Cauto Watershed, the forests on hill-slopes show values of 0.85–0.90, which means that there is great dominance of one or two tree species in the forest. In the forests on riverbanks, the values range between

0.31 and 0.85, which means that these populations are less dominated by one or two species and can therefore be considered more diverse. The grasslands are relatively diverse and non-dominated by one or two species, with D values of 0.19–0.31.

On the whole, it can be ascertained that the landscapes in Rio Cauto represent low diversity of species and great dominance of a few species in terms of number of individuals and their spatial coverage. It is reasonable to assume that the diversity of species would be increased if LUCs were introduced, particularly along the lines of agroforestry systems and appropriate management of the land and SOM.

Land degradation assessment

The lack of data to compile the indicators of land degradation for the Rio Cauto Watershed impeded the calculation of indices of chemical, physical and biological land degradation. However, informal observations reported through the field visits are summarized below.

In terms of physical land degradation, moderate to severe soil erosion by water and wind was observed. The presence of gullies and rills was quite evident, particularly in denuded soils with degraded grasses, and in the hill-slopes and, particularly on the banks of the Cauto River. Sheet erosion by water was also quite evident in areas not covered by sugar

cane. On the other hand, land compaction is expected and was also quite evident, particularly in sugar-cane fields in rotation, where the denuded soil could be observed. This is an expected phenomenon owing to the extreme reliance on heavy machinery and the size of the area under sugar-cane cropping.

In terms of chemical degradation, no evidence was observed of chemical contaminants in the area (e.g. pesticides and herbicides). However, it is expected that at least moderate levels of this type of contamination exist given the current paradigm of land and crop management. In contrast, salinity is a relatively important problem, particularly in areas planted with sugar cane and other areas near the banks of the Cauto River. Land reclamation efforts are being applied to the desalinization of some of these soils (dark plastic gleysols). Nevertheless, the salinity and sodication problems in specific low-lying areas range from severe to very severe. No spatial data could be obtained to determine the spatial extent of the problem.

In terms of biological degradation, the SOM imbalance throughout the entire watershed is clear. It is to be expected given the evapotranspiration deficits and the conditions for easy attack and oxidation of the organic matter with consequent losses to the atmosphere. As has been demonstrated through modelling, organic matter is key to managing these soils.

CHAPTER

10

CONCLUSIONS AND RECOMMENDATIONS

CHAPTER 10

Conclusions and recommendations

Conclusions

A great amount of methodological knowledge and case study information was gained from the multiple activities reported in this volume. In particular, this knowledge and information concerned the following:

- ▶ researching the theoretical underpinnings of all methods and techniques to be used in the methodological framework proposed;
- ▶ gathering and collating expert knowledge and information from expert consultations and meetings;
- ▶ deciding on the appropriateness of field, analytical and modelling methods and procedures used, which were to become part of the methodology;
- ▶ investigating the relatively large list of emerging technical issues that required detailed attention in order to design the diverse methodological components;
- ▶ designing the methodology and procedures of the proposal;
- ▶ applying such methods and procedures to the study areas in Texcoco and Bacalar in Mexico, and the Rio Cauto Watershed in Cuba;
- ▶ collecting, organizing and digitizing a large amount of multithematic and multivariate data from multiple sources and developing the spatial and attribute databases;
- ▶ processing the data and analysing the results;
- ▶ developing models and software as required.

The methods and procedures developed represent the results of intensive research,

refinement, development and testing in three case studies in Latin America and the Caribbean region.

The case studies represent the range of conditions in terms of ecological variability, in terms of the impact of human activities, and in terms of the decision-making structure related to LUCs.

The methodology makes use of a range of knowledge and tools. This makes it imperative that a multidisciplinary team undertake its application in assessment, inventory and monitoring exercises in the field. At least one member of the team should be a botanist. Ideally, the team would comprise soil scientists, ecologists, botanists, foresters and experts in land evaluation or resource planning, modelling and GIS/remote sensing. The level of expertise of such a team may range from a competent technician with sufficient experience in the area of study to graduate or postgraduate professionals.

As discussed in the body of this report, there are several complex technical issues that require further analysis, refinement and testing in order to become part of a robust methodology for the assessment, inventory and monitoring of carbon stocks and sequestration. Most of the technical issues relevant to the objectives of this project concern the accuracy of estimates of carbon content in the carbon pools in aboveground and belowground biomass and in SOM.

Remote-sensing techniques and products proved useful for providing a landscape to the study, for estimation of biomass, and for assessment of biodiversity and land degradation.

These tools also provided a geographical framework for partitioning the spatial variability of ecological parameters relevant in estimating the different pools of C in biomass and in the soil.

The use of nested sampling quadrats and of a supervised classification of a satellite image for stratification was found adequate for estimating biomass.

Nested quadrat dimensions provided a good compromise between accuracy of estimates derived from measurements and the amount of work required for field measurements of volume, species counting and degradation assessment.

The regression equation method for estimating aboveground biomass proved to be better than the use of volume measurements at quadrats and their spatial interpolation. The latter would have required a full geostatistical study in order to generate reliable estimates over an entire area, whereas the regression equation method simplifies computations.

The use of multispectral satellite images and band ratio indices related to biomass estimates from quadrats on the ground proved very promising for the upscaling of biomass estimates where forests are the dominant land cover types.

There are no universal regression equations to use for biomass estimation from specific site measurements of volume in all ecological conditions. In each area, these equations will have to be developed afresh or adapted to the conditions in which they will be used with prior rigorous calibration.

It proved impractical to obtain reliable tree crown measurements in areas with dense tropical forest cover, such as in Bacalar, because the density of crown cover obscured the limits of tree crowns. In these circumstances, it was found more useful to measure the volume of tree trunks and crowns for a subset of sampling quadrats, and relate them to band

ratio indices of reflectance in a satellite image through a regression equation. The image was then used for the upscaling of ground estimates.

The methodology does not account for the so-called leakages of biomass resulting from the multipurpose use of the forest by subsistence farmers, which is common in developing countries.

Biomass estimates for crops can be obtained reliably from crop growth models, the AEZ methodology or from the local records of experimental stations. Crop yield estimates can also be derived from these sources.

The search for promising LUTs with potential for carbon sequestration required a full land suitability assessment exercise, for which the FAO framework for land evaluation proved to be most useful. Criteria concerning the efficiency of CO₂ assimilation or other forms of biomass accumulation should be part of the suitability assessment procedure.

The models for suitability assessment based on decision trees and including criteria for carbon sequestration proved to be very effective in the selection of PLUTs. However, they may not necessarily be practically feasible as their development requires time, information on land qualities and the availability of decision-tree software.

Soils represent a larger pool of terrestrial C than biomass. Therefore, carbon sequestration in soils is of great importance in mitigating greenhouse gas concentrations. Land management practices have the strongest effect on the fate of SOM and on carbon sequestration, or on its release to the atmosphere as CO₂. This was demonstrated by the results obtained through SOM turnover modelling in all three case studies.

The turnover of SOM must be modelled over a definite period of time in order to determine whether

carbon sequestration is possible for soils under a given LUT.

Model parameterization is fundamental to accurate and reliable projections of quantities of SOM over a period of time. Data requirements for parameterization and the degree of complexity of the parameterization process vary with the complexity of the model and the detail and specificity of model outputs.

In using any organic matter turnover simulation model, model calibration is a necessary step in order to determine model behaviour and the bounds of accuracy of model predictions in the area of concern.

It proved fairly straightforward to parameterize and run simulations with the RothC-26.3 model. However, this model does not include all the possible partitions of SOM; nor does it consider the numerous interactions of C with other elements, particularly N and S.

The CENTURY model is powerful and very complete. It simulates to a high level of detail the environmental compartments and SOM fractions in which the organic matter is decomposed and degraded, accounting for the interactions with other elements and compounds in the soil, such as N and S. However, this model proved too large and complex for the ordinary professional and mid-level technician. Its parameterization was very laborious and difficult, particularly in terms of data requirements and the specification of input and output variables. As a trade-off, the model offers a wide range of output variables to examine, in detail, carbon fractions and their interactions with other nutrients.

The development of software for a GUI for the CENTURY model (named Soil-C) represents an important improvement. This interface software makes transparent to the user the intricacies of the CENTURY model parameterization, specification of

the management events, and all the circumstances of the scenario being modelled. Input and output is made much simpler, making the model more accessible.

The link between the Soil-C interface and a GIS still requires further software development and testing in order to include interfaces to commonly-used GIS software.

The RothC-26.3 model should be used where only limited detail is required about the fractions and pools of SOM, or where few data are available for model parameterization.

The CENTURY model with the Soil-C interface can be used: (i) where greater accuracy is required or greater detail in terms of the number of partitions or pools of SOM, or in explaining the fate of additions of organic materials under detailed management of SOM; (ii) where land and crop management are compounded by various factors that need to be included in the model, such as interactions of C in organic matter with other important elements and compounds; and (iii) where greater accuracy of estimates is required.

The results obtained from all three case studies showed that land management is crucial in determining carbon sequestration in soil, particularly in agricultural land. Land management turned out to have even more weight in enhancing carbon sequestration than the selection of carbon-efficient crops through land evaluation, although the latter is also an important factor.

Staple crops in associations or in rotations, particularly with N-fixing legumes (e.g. alfalfa and beans) appear to hold the greatest promise for carbon sequestration in soils. This can be further enhanced by including fruit trees in the association.

Irrigation, or moisture availability in the soil, and the addition of sufficient organic inputs from crop

residues or other sources, such as FYM, trigger the process of SOM accrual in the soil, particularly of the resistant fraction of SOM. The threshold value of organic inputs to the soil to enable carbon sequestration varies with soil type, climate conditions and prior land management history, particularly the management of organic matter.

It was demonstrated that SABA can be converted into stable, continuous cropping on the same field where sufficient amounts of organic inputs are brought into the field from a variety of sources in the family unit production system.

The modelling results showed that grasslands were not as efficient as expected in carbon sequestration in the soil, except for some instances in the dry tropics of Cuba.

The parametric semi-quantitative approach used for rapid assessment of land degradation based on indicators observed in the field and standard climate data sets yielded satisfactory results. Thus, it was possible to determine the causative factors and intensity of a given type of land degradation and its relative importance with respect to other types of degradation.

In Texcoco, physical, biological and chemical land degradation are acute. In particular, physical degradation caused by soil erosion and compaction is readily evident. Biological degradation, consisting of SOM depletion, appears to be the main determining factor, inhibiting carbon sequestration. Chemical degradation is quite evident in the lower part of the watershed.

The assessment of biodiversity using the indices selected in the methodology provided an initial picture of the state of plant diversity in the area. These biodiversity indices need to be combined with rapid assessments of soil biodiversity and faunal assessments, in order to provide a more complete picture of biodiversity. However, the measurement or

counts of faunal species (both macro and micro) on the ground and in the soil need to be balanced against the time and effort required. It is clear that the methodology will need to incorporate standard techniques for rapid assessment of fauna and soil biodiversity.

Species identification and cataloguing proved to be the bottleneck in the field procedures for biodiversity assessment in the case studies. A botanist and a zoologist are essential members of a field assessment team. Indigenous knowledge of plant species should also be used for plant identification.

The problem of upscaling and “spatialization” of point estimates is a generic and important one. The accuracy of estimates (biomass, SOM, indicators of degradation, biodiversity indices, etc.) will depend on the accuracy of the spatial interpolation techniques used for estimation at sites not measured or observed.

The experiences with the application of the methods and procedures developed in the case studies indicate that the methodology can be applied to routine assessments of carbon stock and sequestration potential elsewhere in the Latin American and Caribbean region with a well-organized, multidisciplinary team of middle-level professionals, with relatively little training.

The time taken to carry out all the phases of this study, from research on methods to data processing and reporting, including the three case studies, was about two years. However, once the methodology is in place and the tools have been learned and customized, the time involved in an assessment and generation of scenarios is estimated at about four months for each case study, for areas comparable in size and provided that all the elements necessary for field and laboratory work are present.

Recommendations

The experiences generated in this project provided answers to many technical and practical questions. However, they also left some partially answered. While the methods appear to be complete in some aspects, in others there are obvious improvements to be made. There are seven specific recommendations for follow up:

- ▶ the methodology needs to be tested rigorously and calibrated with data from validation experiments in representative areas of the region. Of particular concern is the accuracy of estimates of carbon stock in aboveground and belowground biomass, and in SOM.
- ▶ it is of paramount importance to determine the confidence intervals or expected standard error of the estimates of carbon stock in the different compartments under different ecological conditions and availability of data. These confidence intervals may well represent significant variations in financial incentives in cases where carbon credits would be contracted. A listing of the performance of tools and methods (e.g. in terms of standard error of estimates or other measures of accuracy) in a range of ecological conditions would be of great help to decision-makers.
- ▶ the methodology currently consists of an assemblage of databases, data processing algorithms, remote sensing, GIS and modelling tools. It is not yet transferable as an entity to any requesting party wishing to conduct assessments or inventory and monitoring work in the region. Therefore, efforts should be made to develop a carbon decision-support system (CDSS) for carbon inventory and monitoring programs, starting from the methods and tools developed in this project (e.g. Soil-C). This CDSS could be developed so as to be initially applicable to the Latin America and Caribbean region, but with the possibility of making it generically applicable to other regions. The development of the CDSS will require a serious commitment in terms of software engineering and testing in order to make it as user friendly as possible.
- ▶ further work is required in order to assemble a set of interpolation techniques and algorithms, and a knowledge base to guide their use, which can be useful in a variety of situations of abundance or scarcity of point data and of the regional distribution of the variable in question. This type of work is fundamental, and the resulting techniques and knowledge base should be incorporated into the methodology and tools, and eventually into the CDSS.
- ▶ concerning the multiobjective optimization of LUC scenarios with carbon sequestration as a leading criterion, further work is required to make this a truly user-friendly operational module. Current tools, such as AEZWIN and LINDO, are either proprietary or too cumbersome for the average user.
- ▶ many technical issues will require investigation in the development of tools to aid carbon inventory and monitoring programs through the CDSS. In particular, issues concerning interoperability of algorithms, databases and distributed systems (e.g. Internet) will have to be researched thoroughly and incorporated into the architecture of the system.
- ▶ the methodology should be further tested in many other areas within the Latin America and Caribbean region and other regions. Methods should be refined, and new methods and techniques incorporated as required. The present methodology should be seen as a work in progress.



BIBLIOGRAPHY

- Antoine, J., Fischer, G. & Makowski, M. 1997. Multiple criteria land-use analysis. *App. Math. Comp.*, 83(2-3): 195-215.
- Baret, F., Guyot, G. & Major, D.J. 1989. Crop biomass evaluation using radiometric measurements. *Photogrammetria*, 43: 241-256.
- Bohm, W. 1979. *Methods of studying roots systems*. Ecological Studies No. 33. Berlin, Germany, and New York, USA, Springer-Verlag.
- Brown, S.A.J., Gillespie, J.R. & Lugo, A.E. 1989. Biomass estimation methods for tropical forests with application to forest inventory data. *For. Sci.*, 35(4): 881-902.
- Bunce, R.G.H. 1968. Biomass and production of trees in a mixed deciduous woodland: girth and height as parameters for the estimation of tree height. *J. Ecol.*, 56: 759-75.
- Burrough, P.A. & McDonnell, R.A. 1998. *Principles of geographical information systems*. New York, USA, Oxford University Press.
- Cabrera, C.E., Souza, S.M. & Tellez, V.O. 1982. *Imagenes de la flora Quintanaroense*. Mexico, Centro de Investigaciones de Quintana Roo.
- Campbell, J.B. 1987. *Introduction to remote sensing*. New York, USA, The Guilford Press.
- Carter, M.R., Parton, W.J., Rowland, I.C., Schultz, J.E. & Steed, G.R. 1993. Simulation of soil organic carbon and nitrogen changes in cereal and pasture systems of Southern Australia. *Aus. J. Soil Res.*, 31: 481-491.
- CENTURY. 1992. *Soil organic matter model environment, technical documentation, agroecosystem version 4.0*. Fort Collins, USA, Colorado State University.
- Coleman, K. & Jenkinson, D.S. 1995a. RothC-26 3. A model for the turnover of carbon in soil: model description and users guide. ISBN 0951 4456 69.
- Coleman, K. & Jenkinson, D.S. 1995b. RothC-26 3. A model for the turnover of carbon in soil. In D.S. Powlson, P. Smith & J.U. Smith, eds. *Evaluation of soil organic matter models using existing long-term datasets*, pp. 237-246. NATO ASI Series I, Vol. 38. Heidelberg, Germany, Springer-Verlag.
- Crow, T.R. 1997. Common regressions to estimate tree biomass in tropical stands. *For. Sci.*, 24: 110-114.
- Daughtry, C.S.T., Gallo, K.P., Goward, S.N., Price, S.D. & Kustas, W.P. 1992. Spectral estimates of absorbed radiation and phytomass production in corn and soybean canopies. *Rem. Sen. Env.*, 39: 141-152.
- De Wit, C.T., Goudriaan J., van Laar H.H., Penning de Vries, F.W.T., Rabbinge, R., van Keulen, H., Louwerse, W., Sibma, L. & De Jonge, C. 1978. *Simulation of assimilation, respiration and transpiration of crops*. Wageningen, The Netherlands, Centre for Agricultural Publishing and Documentation.
- Duch, J.G. 1995. Los suelos, la agricultura y vegetation en Yucatan. In E. Hernandez-Xolocotzi, E. Bello & S. Levy, eds. *La milpa en Yucatan*, pp. 97-108. Montecillo, Mexico, Colegio de Postgraduados.
- Earth Resource Mapping Ltd. 1998. *ER mapper 6.1. User guide*. San Diego, USA.
- El-Swaify, S.A. & Yakowitz, D.S., eds. 1998. *Multiple objective decision making for land, water and environmental management*. Proceedings of the First International Conference in Multi-Objective Decision Support Systems for Land, Water and Environmental Management: concepts approaches and applications. Boca Raton, USA, Lewis Publishers.
- FAO. 1978a. *Methodology for assessing soil degradation*. Report on the FAO/UNEP expert consultation. Rome, 25-27 January 1978. Rome.
- FAO. 1978b. *Report on the Agro-Ecological Zones Project. Vol. 1. Methodology and results for Africa*. World Soil Resources Report No. 48. Rome.
- FAO. 1979. *Report of the second meeting of the Working Group on soil degradation assessment methodology*. Rome.
- FAO. 1980. *Metodologia provisional para la evaluación de la degradación de los suelos*. Rome, FAO/UNEP/UNESCO.
- FAO. 1981. *Report on the Agro-Ecological Zones Project. Vol. 3. Methodology and results for South and Central America*. World Soil Resources Reports No. 48. Rome.

- FAO. 1986. *Guidelines: land evaluation for rainfed agriculture*. FAO Soils Bulletin No. 52. Rome.
- FAO. 1993a. *Agro-ecological land resources assessment for agricultural development planning. A case study of Kenya. Resources data base and land productivity*. Main report. World Soil Resources Reports No. 71. Rome.
- FAO. 1993b. *Computerized systems of land resources appraisal for agricultural development*. World Soil Resources Reports No. 72. Rome.
- FAO. 1997. *Estimating biomass and biomass change of tropical forests: a primer*, by S. Brown. FAO Forestry Paper No. 134. Rome.
- FAO. 1999. *AEZWIN: an interactive multiple-criteria analysis tool for land resources appraisal*. World Soil Resources Reports No. 87. Rome.
- FAO. 2000. *Manual on integrated soil management and conservation practices*. Land and Water Bulletin No. 8. Rome. 204 pp.
- Fazakas, Z., Nilsson, M. & Olsson, H. 1999. Regional forest biomass and wood volume estimation using satellite data and ancillary data. *Ag. For. Met.*, 98–99: 417–425.
- Fearmside, P.M. 1997. Wood density for estimating forest biomass in Brazilian Amazonia. *For. Ecol. Man.*, 90: 59–87.
- Figuerroa-Cano, M. 2000. *Assessment of the sustainability of land-use systems for natural resources management*. Watershed Ecosystems Graduate Program. Trent University, Peterborough, Canada. (MSc thesis)
- Footy, M., Palubinskas, G., Lucas, M., Curran, P. & Honzak, M. 1996. Identifying terrestrial carbon sinks: classification of successional stages in regenerating tropical forests from Landsat TM data. *Rem. Sen. Env.*, 55: 205–216.
- Fuller, R.M., Groom, G.B. & Jones, A.R. 1994. Land cover map of Great Britain: an automated classification of Landsat Thematic Mapper data. *Photo. Eng. Rem. Sen.*, 60: 553–562.
- Fuller, R.M., Parsell, R.J., Oliver, M. & Wyatt, G. 1989. Visual and computer classifications of remotely-sensed images. A case study of grasslands in Cambridgeshire. *Int. J. Rem. Sen.*, 10: 193–210.
- Fuller, R.M., Groom, G.B., Mugisha, S., Ipule, P., Pomeroy, D., Katende, A., Bailey, R. & Ogutu-Ohwayo, R. 1997. The integration of field survey and remote sensing for biodiversity assessment: a case study in the tropical forest and wetlands of Sango Bay, Uganda. *Biol. Con.*, 86: 379–391.
- Galarza-Macías, J. 2000. *Estimation of tropical forest above-ground biomass by remote sensing*. Trent University, Canada. (MSc work in progress – unpublished data)
- Gilabert, M., Gandia, S. & Melia, J. 1996. Analysis of spectral biophysical relationships for a corn canopy. *Rem. Sen. Env.*, 63: 140–154.
- Goodchild, M.F. & Kemp, K.K. 1992. *Technical issues in GIS: core curriculum*. University of California, USA, NCGIA.
- Grupo de Sistemas de Información Geográfica (INICA). 2000. *Land-use mapping by FCC (ilwis) and LUT guidelines*. Cuba.
- Gupta, K., Prasa, T. & Vijayan, D. 2000. Relationships between LAI and NDVI for IRS LISS and Landsat TM bands. *Adv. Space Res.*, 26(7): 1047–1050.
- Hall, D.O. & Rao, K.K. 1999. *Photosynthesis*. Sixth edition. London, Edward Arnold.
- Hart, P.B.S. 1984. *Effects of soil type and past cropping on the nitrogen supplying ability of arable soils*. University of Reading, UK. (PhD thesis)
- Hernandez-Stefanoni, J. 2000. *A framework for evaluating biodiversity status of tropical forest based on landscape fragmentation metrics and spatial modelling in GIS*. Trent University, Canada. (PhD work in progress – unpublished data)
- Hernandez-Stefanoni, J.L. & Ponce-Hernandez, R. 2003. Mapping the spatial distribution of biodiversity indices of tropical forests using multi-spectral satellite image classification and field measurements. *Biodiv. Cons.* (in press).
- Hernandez-Xolocotzi, E., Bello, E. & Levy, S. 1995. *La milpa en Yucatan I*. Montecillo, Mexico, Colegio de postgraduados.
- Hoekman, D.H. & Quinones, M. 2000. Land cover type and biomass classification using AirSAR data for evaluation of monitoring scenarios in the

Colombian Amazon. *IEEE Trans. Geosci. Rem. Sen.*, 38: 2.

Ibaugh, J.M. & Betters, D.R. 1995. Quantitative biodiversity measures applied to forest management. *Env. Rev.*, 3: 277–285.

IBSNAT. 1989. *Decision support systems for agrotechnology transfer (DSSAT) v2.10*. Honolulu, USA, Department of Agronomy and Soil Science, University of Hawaii.

IFAD/FAO. 1999. *Prevention of land degradation, enhancement of carbon sequestration and conservation of biodiversity through land-use change and sustainable land management with a focus on Latin America and the Caribbean*. Proceedings of an Expert Consultation. Rome, IFAD.

Imhoff, M., Carson, S. & Johnson, P. 1998. A low frequency radar experiment for measuring biomass. *IEEE Trans. Geosci. Rem. Sen.*, 36: 6.

INEGI. 1998. *Atlas Ejidal del Estado de México, Encuesta Nacional Agropecuaria*. Mexico.

INEGI. 1999. *Estadísticas Agropecuarias del Censo*. Mexico.

Innes, J.L. & Koch, B. 1998. Forest biodiversity and its assessment by remote sensing. *Glob. Ecol. Biogeog. Lett.*, 7(6): 397–419.

Izurralde, R.C., McGill, W.B., Jans-Hammermeister, D.C., Haugen-Kozyra, K.L., Grant, R.F. & Hiley, J.C. 1996. *Development of a technique to calculate carbon fluxes in agricultural soils at the ecodistrict level using simulation models and various aggregation techniques*. Final report. Agriculture and Agri-Food Canada Greenhouse Gas Initiative. Edmonton, Canada, University of Alberta. 67 pp.

Jackson, R.B., Canadell, J., Ehleringer, J.R., Mooney, H.A., Sala, O.E. & Schutze, E.D. 1996. A global analysis of root distributions for terrestrial biomes. *Oecologia*, 108: 389–411.

Jenkinson, D.S. 1990. The turnover of organic carbon and nitrogen in soil. *Phil. Trans. R. Soc.*, B. 329: 361–368.

Jenkinson, D.S. & Coleman, K. 1994. Calculating the annual input of organic matter to soil from measurements of total organic carbon and radiocarbon. *Eur. J. Soil Sci.*, 45: 167–174.

Jenkinson, D.S. & Rayner, J.H. 1977. The turnover of soil organic matter in some of the Rothamsted classical experiments. *Soil Sci.*, 123: 298–305.

Jenkinson, D.S., Adams, D.E. & Wild, A. 1991. Model estimates of CO₂ emissions from soil in response to global warming. *Nature*, 351(6322): 304–306.

Jenkinson, D.S., Hart, P.B.S., Rayner, J.H. & Parry, L.C. 1987. Modelling the turnover of organic matter in long-term experiments at Rothamsted. *INTECOL Bull.*, 15: 1–8.

Jenkinson, D.S., Harkness, D.D., Vance, E.D., Adams, D.E. & Harrison, A.F. 1992. Calculating net primary production and annual input of organic matter to soil from the amount and radiocarbon content of soil organic matter. *Soil Biol. Biochem.*, 24(4): 295–308.

Jensen, J.R. & Hodgson, M.E. 1985. Remote sensing of forest biomass: an evaluation using high resolution remote sensor data and Loblolly pine plots. *Prof. Geog.*, 37: 46–56.

Jones, C.A. & Kiniry, J.R., eds. 1986. *CERES-Maize*. College Station, USA, Texas A&M Univ. Press.

Jones, J.W., Boote, K.J., Jagtap, S.S., Hoogenboom, G. & Wilkerson, G.G. 1989. *SOYGRO V5.42 soybean crop growth simulation model: users guide*. Florida Agricultural Experiment Station Journal No. 8304. Gainesville, USA, Agricultural Engineering Department and Agronomy Department University of Florida.

Jones, C.A., Dyke, P.T., Williams, J.R., Kiniry, J.R., Benson, V.W. & Griggs, R.H. 1991. EPIC: an operational model for evaluation of agricultural sustainability. *Agric. Sys.*, 35: 341–350.

Kimes, D.S., Nelson, R.F., Skole, D.L. & Salas, W.A. 1998. Accuracies in mapping secondary tropical forest age from sequential satellite imagery. *Rem. Sen. Env.*, 65: 112–120.

Kittredge, J. 1944. Estimation of the amount of foliage of trees and stands. *J. For.*, 42: 905–912.

Korth, H.F. & Silberschatz, A. 1994. *Database systems concepts*. Second Edition. New York, USA, McGraw-Hill.

- Lal, R. 2000. *Soil quality and soil erosion*. CRC press. 352 pp.
- Lal, R., Kimble, J.M., Follet, R.F. & Stewart, B.A., eds. 1998. *Management of carbon sequestration in soil*. Boca Raton and New York, USA, CRC Press.
- Li, C., Frolking, S., Crocker, G.J., Grace, P.R., Klír, J., Körschens, M. & Poulton, P.R. 1997. Simulating trends in soil organic carbon in long-term experiments using the CNDP model. In P. Smith, D.S. Powlson, J.U. Smith & E.T. Elliot, eds. Evaluation and comparison of soil organic matter models. Special issue of *Geoderma*, Vol. 81, No. 1–2.
- Lindo Systems. 1995. *Solver suite*. Chicago, USA.
- Luckman, A., Baker, J., Mora, T., Corina da Costa, F. & Frery, C.A. 1997. A study of the relationship between radar backscatter and regeneration tropical forest biomass for spaceborne SAR instruments. *Rem. Sen. Env.*, 60: 1–13.
- MacDicken, K.G. 1997. *A guide to monitoring carbon storage in forestry and agroforestry projects*. USA, Winrock International Institute for Agricultural Development.
- Magurran, A.E. 1988. *Ecological diversity and its measurement*. Princeton, USA, Princeton University Press.
- Martinez, M. 1987. *Catalogo de nombres vulgares y científicos de plantas Mexicanas*. Mexico, Fondo de Cultura Economica.
- McGarigal, K. & Marks, B.J. 1994. *Fragstats: spatial pattern analysis program for quantifying landscape structure*. Corvallis, USA, Oregon State University.
- McGill, W.B. & Cole, C.V. 1981. Comparative aspects of cycling of organic C, N, S and P through soil organic matter. *Geoderma*, 28: 267–286.
- Myers, N. 1995. Environmental services of biodiversity. *Proc. Nat. Acad. Sci. U.S.A.*, 3: 2764–2763.
- Myers, N., Mittermeier, R.A., Mittermeier, C.G., da Fonseca, G.A.B. & Kent, J. 2000. Biodiversity hotspots for conservation priorities. *Nature*, 43(24): 853–858.
- Nagendra, H. & Gadgil, M. 1999a. Biodiversity assessment at multiple scales: Linking remotely sensed data with field information. *Proc. Nat. Acad. Sci. U.S.A.*, (96)16: 9154–9158.
- Nagendra, H. & Gadgil, M. 1999b. Satellite imagery as a tool for monitoring species diversity: an assessment. *J. Appl. Ecol.*, 36: 388–397.
- Nageswara, P.P. & Mohankumar, A. 1994. Cropland inventory in the command area of Krishnarajasagar project using satellite data. *Int. J. Rem. Sen.*, 15(6): 1295–1305.
- Nomoto, N. 1964. Primary productivity of beech forests in Japan. *Jap. J. Bot.*, 8: 385–421.
- Noss, R.F. 1990. Indicators for monitoring biodiversity: a hierarchical approach. *Cons. Biol.*, 4(4): 355–364.
- Noss, R.F. 1999. Assessing and monitoring forest biodiversity: a suggested framework and indicators. *For. Ecol. Man.*, 115: 135–146.
- Ogawa, H., Yoda, K., Ogino, K. & Kira, T. 1965. Comparative ecological studies on three main types of forest vegetation in Thailand. 11: Plant biomass. *Nat. Life in S.E. Asia*, 4: 49–80.
- Ogino K., Sabhasri S. & Shidei, T. 1964. The estimation of the standing crop of the forest in Northern Thailand. *South-east Asian Stud.*, 4: 89–97.
- Ojima, D.S., Parton, W.J., Schimel, D.S., Scurlock, J.M.O. & Kittel, T.G.F. 1993. Modelling the effects of climatic and CO₂ changes on grassland storage of soil C. *Wat., Air Soil Poll.*, 70: 643–657.
- Ortiz Solorio María de Luz Marcela. 1986. *Evaluación de la Velocidad de la Desertificación en la Cuenca del Río Téxcoco*. Mexico, C.P. Chapingo.
- Ovington, J.D. & Madgwick, H.A.I. 1959. The growth and composition of natural stands of birch. 1. Dry-matter production. *Pl. Soil*, 10: 271–88.
- Parton, W.J. & Rasmussen, P.E. 1994. Long-term effects of crop management in wheat/fallow system: II. Modelling change with the Century model. *Soil Sci. Soc. Am. J.*, 58: 530–536.
- Parton, W.J., Stewart, J.W.B. & Cole, C.V. 1988. Dynamics of C, N, P, and S in grassland soils: a model. *Biogeochemistry*, 5: 109–131.
- Parton, W.J., Wooster, P.L. & Martin, A. 1994. Modelling soil organic matter dynamics and plant

productivity in tropical ecosystems. In P. Wooster & M. Swift, eds. *The biological management of tropical soil fertility*, pp. 171–188. TSBF/John Wiley & Sons.

Parton, W.J., McKeown, R., Kirchner, V. & Ojima, D. 1992. *CENTURY users manual*. Ft. Collins, USA, Colorado State University, Natural Resource Ecology Laboratory.

Parton, W.J., Schimel, D.S., Cole, C.V. & Ojima, D.S. 1987. Analysis of factors controlling soil organic levels of grasslands in the Great Plains. *Soil Sci. Soc. Am. J.*, 51: 1173–1179.

Parton, W.J., Schimel, D.S., Ojima, D.S. & Cole, C.V. 1994. A general model for soil organic matter dynamics: sensitivity to litter chemistry, texture and management. In R.B. Bryant & R.W. Arnold, eds. *Quantitative modelling of soil forming processes*, pp. 137–167. SSSA Spec. Publ. 39. Madison, USA, ASA, CSSA and SSA.

Parton, W.J., Scurlock, J.M.O., Ojima, D.S., Gilmanov, T.G., Scholes, R.J., Schimel, D.S., Kirchner, T., Menaut, H.-C., Seastedt, T., Garcia Moya, E., Kamnalrut, A. & Kinyamario, J.L. 1993. Observations and modelling of biomass and soil organic matter dynamics for the grassland biome worldwide. *Glob. Biogeochem. Cyc.* 7(4): 785–809.

Paustian, K., Parton, W.J. & Persson, J. 1992. Influence of organic amendments and N fertilization on soil organic matter in long-term plots: model analyses. *Soil Sci.*, 56: 476–488.

Pierce, E., Bergen, K., Dobson, C. & Ulaby, T. 1998. Multitemporal land-cover classification using SIR-C/X-SAR imagery. *Rem. Sens. Env.*, 62: 20–33.

Ponce-Hernandez, R. 1998. *Zonificación Ecología Económica: una propuesta metodológica para Amazonia*. Tratado de Cooperación Amazónica, Publicación 65. Caracas.

Ponce-Hernandez, R. 1999. Assessing the carbon stock and carbon sequestration potential of current and potential land-use systems and the economic rationality of land-use conversions. In: *World Soil Resources Report No. 86*, pp 77–92. Rome, FAO.

Ponce-Hernandez, R. & Beernaert, F. 1991. *Manual for land evaluation*. Report for Project (MOZ/86/010). Maputo, Land and Water Department, I.N.I.A.

Ponce-Hernandez, R., Hannan, J., Snow, L. & Tong, M.A. 2001. *Soil-C: a customized graphic user interface to the Century model*. Version 1.0. User manual. Peterborough, Canada, Trent University.

Powlson, D.S., Smith, P. & Smith, J.U., eds. 1996. *Evaluation of soil organic matter models using existing, long-term datasets*. NATO ASI Series I Vol. 38. Berlin, Springer-Verlag. 429 pp.

Price, J.C. 1992. Estimating vegetation amount from visible and near infrared reflectances. *Rem. Sen. Env.*, 41: 29–34.

Primeau, R. 2000. *Alternatives to shifting agriculture: the role of soil organic matter in sustaining the agroecosystems of the Yucatan Peninsula*. Trent University, Canada. (BSc thesis)

Ranson, J. & Sun, G. 1997. Forest biomass from combined ecosystem and radar backscatter modelling. *Rem. Sen. Env.*, 59: 118–133.

Richter, D.D., Markenwitz, D., Trembore, S.E. & Wells, C.G. 1999. Rapid accumulation and turnover of soil carbon in aggrading forests. *Nature*, 400: 56–58.

Romero, C. & Rehman, T. 1989. *Multiple criteria analysis for agricultural decisions*. Amsterdam, The Netherlands, Elsevier.

Rossiter, D.G. 1995. *ALES: Automated Land Evaluation System*. User's manual. New York, USA, Cornell University.

Roy, P.S. & Tomar, S. 2000. Biodiversity characterization at landscape level using geospatial modelling technique. *Biol. Con.*, 95: 95–109.

Saaty, T.L. 1980. *The analytical hierarchy process. Planning, priority setting, resource allocation*. New York, USA, McGraw-Hill.

Salazar-Lazcano, I. 2000. *Estudio de Comunidad de Buena Vista, Quintana Roo*. Buena Vista, Mexico, Centro de Salud de Buena Vista.

Sanchez, P.A., Palm, C.A., Szott, L.T., Cuevas, E. & Lal, R. 1989. Organic input management in tropical ecosystems. In D.C. Coleman, J.M. Oades & G. Uehara, eds. *Dynamics of soil organic matter in tropical ecosystems*, pp. 125–152. Hawaii, USA, Nifital Project.

Sanford Jr., R.W., Parton, W.J., Ojima, D.S. & Lodge, D.J. 1991. Hurricane effect on soil organic matter dynamics and forest production in the

Luquillo Experimental Forest, Puerto Rico: results of simulation modelling. *Biotropica*, 23: 364–372.

Santantonio, D., Hermann, R.K. & Overton, W.S. 1977. Root biomass studies in forest ecosystems. *Pedobiologia*, 17: 1–31.

Satoo T. 1955. Materials for the study of growth in stands. *Tok. Univ. For. Bull.*, 48: 69–123. (in Japanese, English summary)

Schimel, D.S., Kittel, T.G.F. & Parton, W.J. 1991. Terrestrial biogeochemistry cycles: global interactions with the atmosphere and hydrology. *Tellus*, 43AB: 188–203.

Schimel, D.S., Parton, W.J., Kittel, T.G.F., Ojima, D.S. & Cole, C.V. 1990. Grassland biogeochemistry: links to atmospheric processes. *Clim. Change*, 17: 13–25.

Schimel, D.S., Braswell Jr., B.H., Holland, E.A., McKeown, R., Ojima, D.S., Painter, T.H., Parton, W.J. & Townsend, A.R. 1994. Climatic, edaphic and biotic controls over storage and turnover of carbon in soils. *Glob. Biogeochem. Cyc.*, 8(3): 279–293.

Sharpley, A.N. & Williams, J.R., eds. 1990. *EPIC: erosion/productivity impact calculator: 1. Model documentation*. U.S. Dept. Agric. Tech. Bull. No. 1768.

SIRTPLAN. 2001. *Sistema de informacion de recursos de tierras para la planificacion*. Proyecto FAO “Informacion sobre tierras y aguas para un desarrollo agricola sostenible”: GCP/RLA/126/JPN. Santiago.

Smith, P., Powlson, D.S., Smith, J.U. & Falloon, P. 1997a. SOMNET. A global network and database of soil organic matter models and long-term experimental datasets. *The Globe*, 38: 4–5.

Smith, P., Smith, J.U., Powlson, D.S., McGill, W.B., Arah, J.R.M., Chertov O.G., Coleman, K., Franko, U., Froking, S., Jenkinson, D.S., Jensen, L.S., Kelly, R.H., Klein-Gunnewiek, H., Komarov, A., Li, C., Molina, J.A.E., Mueller, T., Parton, W.J., Thornley, J.H.M. & Whitmore, A.P. 1997b. A comparison of the performance of nine soil organic matter models using seven long-term experimental datasets. In P. Smith, D.S. Powlson, J.U. Smith & E.T. Elliott, eds. *Evaluation and comparison of soil*

organic matter models using datasets from seven long-term experiments. *Geoderma*, 81: 153–225.

Snell, K. & Brown, K. 1978. Comparison of tree biomass estimators – DBH and sapwood area. *For. Sci.*, 24(4): 455–457.

Sommers, L.E., Gilmour, C.M., Wilding, R.E. & Beck, S.M. 1981. Effect of water potential and decomposition process in soils. *Water potential relations in soil microbiology*, pp. 97–117. Special Publication No. 9. Madison, USA, Soil Science Society of America.

Sosa, V., Flores, J.S., Rico-Gray, V., Lira, R. & Ortiz, J.J. 1985. *Etnoflora Yucatese. Lista floristica y sinonimia Maya*. Veracruz, Mexico, Instituto Nacional de Investigaciones sobre Recursos Bioticos.

Sparling, G.S., Cheshire, M.V. & Mundie, C.M. 1982. Effect of barley plants in the decomposition of ¹⁴C-labelled soil organic matter. *J. Soil Sci.*, 33: 89–100.

Sys, C. 1985. *Land evaluation. Parts I, II and III*. International training centre for post-graduate soil scientists. Belgium, State University of Ghent.

Szott, L.T., Fernandes, E.C.M. & Sanchez, P.A. 1991. Soil-plant interactions in agroforestry systems. *For. Ecol. Man.*, 45: 127–152.

Tabachnick, B.G. & Fidell, L.S. 1996. *Using multivariate statistics*. Third edition. New York, USA, Harper Collins.

Van Diepen, C.A., Wolf, J., van Keulen, H. & Rapoldt, C. 1989. WOFOST: a simulation model of crop production. *Soil Use Man.*, 5(1): 16–24.

van Veen, J.A. & Paul, E.A. 1981. Organic carbon dynamics in grassland soils. 1. Background information and computer simulation. *Can. J. Soil Sci.*, 61: 185–201.

Wenge, K. F. 1984. *Forestry handbook*. New York, USA, Wiley-Interscience.

Whittaker, R.A. 1972. Evolution and measures of species diversity. *Taxon*, 21: 213–251

Wiegand, C.L., Richardson, A.J., Escobar, D.E. & Gerbermann, A.H. 1991. Vegetation indices in crop assessment. *Rem. Sen. Env.*, 35: 105–119.

Wilcox, B.A. 1995. Tropical forest resources and biodiversity the risk of forest loss and degradation. *Unasylva* FAO, 46(181).

Winrock International Institute for Agricultural Development. 1997. *A guide to monitoring carbon storage in forestry and agroforestry projects.*

Winrock, USA, Forest Carbon Monitoring and Verification Services.

Wischmeier, W.H. & Smith, D.D. 1965.

Predicting rainfall erosion losses from cropland east of the Rocky Mountains. Handbook No. 282.

Washington, DC, USDA.

Wischmeier, W.H. & Smith, D.D. 1978.

Predicting rainfall erosion losses. A guide to conservation planning. Agric. Handbook No. 537.

Washington, DC, USDA.

Assessing carbon stocks and modelling win-win scenarios of carbon sequestration through land-use changes

This publication presents a methodology and software tools for assessing carbon stocks and modelling scenarios of carbon sequestration that were developed and tested in pilot field studies in Mexico and Cuba. The models and tools enable the analysis of land use change scenarios in order to identify in a given area (watershed or district) land use alternatives and land management practices that simultaneously maximize food production, maximize soil carbon sequestration, maximize biodiversity conservation and minimize land degradation. The objective is to develop and implement “win-win” options that satisfy the multiple goals of farmers, land users and other stakeholders in relation to food security, carbon sequestration, biodiversity and land conservation.



ISBN 92-5-105158-5



9 7 8 9 2 5 1 0 5 1 5 8 0

TC/M/Y5490E/1/07.04/1000