A Modelling Framework for Addressing the Synergies between Global Conventions through Land Use Changes:
Carbon Sequestration, Biodiversity Conservation, Prevention of Land Degradation and Food Security in Agricultural and Forested Lands in Developing Countries

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Summary

This paper proposed a methodological framework for the assessment of carbon stocks and the development and identification of land use, land use change and land management scenarios, whereby enhancing carbon sequestration synergistically increases biodiversity, the prevention of land degradation and food security through the increases in crop yields. The framework integrates satellite image interpretation, computer modelling tools (i.e. software customization of off-the-shelf soil organic matter turnover simulation models) and Geographical Information Systems (GIS). The framework addresses directly and indirectly the cross-cutting ecological concerns foci of major global conventions: climate change, biodiversity, the combat of desertification and food security. Their synergies are targeted by providing procedures for assessing and identifying simultaneously carbon sinks, potential increases in plant diversity, measures to prevent land degradation and enhancements in food security through crop yields, implicit in each land use change and land management scenario. The scenarios aim at providing "win-win" options to decision makers through the framework's decision support tools. Issues concerning complex model parameterization and spatial representation were tackled through tight coupling soil carbon models to GIS via software customization. Results of applying the framework in the field in two developing countries indicate that reasonably accurate estimates of carbon sequestration can be obtained through modeling; and that alternative best soil organic matter management practices that arrest shifting "slash-and-burn" cultivation and prevent burning and emissions, can be identified. Such options also result in increased crop yields and food security for an average family size in the area, while enhancing biodiversity and preventing land degradation. These options demonstrate that the judicious management of organic matter is central to greenhouse gas mitigation and the attainment of synergistic ecological benefits, which is the concern of global conventions. The framework is to be further developed through successive approximations and refinement in future, extending its applicability to other landscapes.

Keywords: Climate Change, Greenhouse Gas Mitigation, Carbon Sequestration, Soil Organic Matter, Modeling, Land-Use Change, Land Management, Ecological Synergies, Agriculture

JEL Classification: C15, C21, Q1, Q15, Q24

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Introduction

The validation of standard methodologies for carbon stock inventories that incorporate "sinks" projects must be solved satisfactorily, if practical implementations of the mechanisms of the Protocol are to be effective. In particular, the implementation of projects to promote carbon "sinks" in non-annex I countries, under the Clean Development Mechanism (CDM). Standard methods and procedures for the inventory and monitoring of carbon stocks and carbon sequestration in both, current and potential land use systems, for all situations of data and technical and ecological circumstances, must be validated and certified. Else, the variability of assessment methods and their uncertainties may hamper carbon transactions from field-implemented "sinks" projects. Deliberate land management actions that enhance the sequestration of CO_2 or reduce its emissions have the potential to remove a significant amount of CO_2 from the atmosphere over the short and medium term.

Equitable ways of accounting for carbon sinks and reward activities that increase the amount of carbon stored in terrestrial ecosystems require of standard procedures and methods. The challenge remains; a commonly agreed and scientifically sound, yet flexible methodological framework must be in place for assessment, monitoring and verification purposes, part of any carbon trading transactions involving afforestation and reforestation activities under the Clean Development Mechanism of the Kyoto Protocol.

Under "sinks" projects, on the one hand, land use changes pursuing the fast accrual of biomass and soil organic matter can have adverse impacts on biodiversity and may even accelerate land degradation; if for example the intent is to encourage only mono-cropping with one or a few carbon-sequestration efficient species. On the other hand, afforestation / reforestation, land use change and land management activities can also be designed so that they may be potential contributors to biodiversity conservation (Secretariat of the Convention on Biological Diversity, 2003). Therefore, such activities depending on their concrete design have the chance to simultaneously contribute to the Kyoto Protocol, to the Convention on Biological Diversity (CBD) and the Convention to Combat Desertification (CCD). To achieve these synergies, issues such as the integration of biodiversity considerations and land degradation in the implementation of the Kyoto Protocol through sinks projects must be fully achieved and documented.

Measures promoting carbon sequestration, biodiversity conservation and prevention of land degradation are expected to have other positive effects such as the increase in crop yields improving local food security, and help in alleviating rural poverty (FAO, 1999). In this paper the development and testing of a proposed framework of methods and procedures is described. The framework allows for measuring and inventorying carbon stocks in biomass and in soil, and for generating projections of carbon sequestration potential, resulting from land use changes and associated land management regimes, while considering their effects on biodiversity, land degradation and crop yields. Such kind of methodological framework has been the concern of agencies such as the FAO of the UN and others in the last few years (FAO, 1999).

The results of practical application of the framework in two contrasting pilot areas in Latin America (i.e. Mexico) are presented. It is also shown that the framework and tools proved quite useful in generating and identifying favorable scenarios of land use change and land management. In particular, it was demonstrated that soil organic matter plays a central role in arresting and stabilizing shifting "slash-and-burn" cultivation into permanent agriculture through sequestering carbon in soils over time, enhancing biodiversity, increasing crop yields and producing sufficient amounts of staple foods to meet the requirements of an average family size in the area studied.

The Methodological Framework

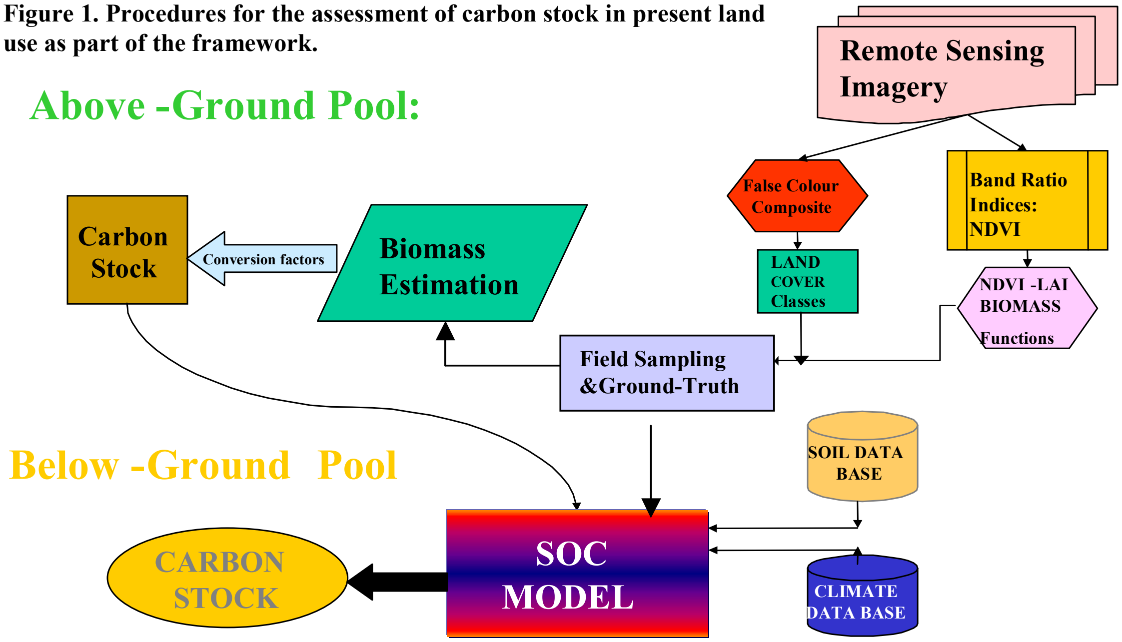
The framework consists of methods for assessing the present status of carbon stocks in current land use systems, and those of plant diversity and land degradation.

The estimation of carbon in all its forms (i.e. as above- and below-ground biomass and as soil organic matter) over pre-determined time periods is central to the framework. Projections of soil organic matter turnover into future scenarios of carbon stocks and possible sequestration in soils resulting from proposed land use changes and land management can be obtained within the framework. The framework is modular in structure. The main modular components are: (1) the estimation of biomass (above and belowground) and its conversion to carbon; (2) estimation of carbon stocks and sequestration potential in soils over time, through computer simulation modelling of soil organic matter turnover; (3) establishment of the status of plant diversity in present land use through standard indices calculated from field data; (4) the assessment of the status of the different forms of chemical, physical and biological land degradation, through a parametric semi-quantitative approach based on indicators; (5) the identification of land use and land management scenarios that represent a win-win situations in terms of carbon sequestration in parallel with enhanced soil fertility resulting in increased crop yields, enhanced biodiversity and prevention of land degradation.

Estimation of carbon stocks and carbon sequestration potential of present land use.

The procedures concerning the estimation of carbon stock, as part of the methodological framework consist of steps set around the estimation of the two main pools: above- and below-ground. The biomass estimation methods used for both pools are illustrated in figure 1.

Figure 1. Procedures for the assessment of carbon stock in present land use as part of the framework.



Carbon stock in above- and below-ground biomass

The methods for the assessment of biomass estimate the present biomass and carbon content of all components of the ecosystem regardless of cover type, but they are based on conventional forestry allometric and plant morphometric measurements. They are not restricted to forests since a given area of study may be a landscape consisting of a patchwork of woodlots, grasslands and croplands, with the latter dominating in predominantly agricultural areas. The live mass above and below ground of trees, shrubs, palms, saplings and debris, as well as the herbaceous layer on the floor and in the soil are considered. The greatest fraction of the total above-ground biomass is represented by these components and, generally speaking, their estimation doest not represent many logistic problems.(Brown, 1997). Remote sensing imagery have proven to be extremely useful in regional carbon stock inventories and estimation of carbon fluxes (Ahern et al, 1991; Running, et al, 1994; Foody et al, 1996; Fazakas et al, 1999; Houghton et al, 2001; Friedl, et al, 2002; Joint Research Centre, 2003), but their use is also of value in local inventories (Ponce-Hernandez, 1999; Nelson et al, 2000). In local assessments, remotes sensing has proven useful in several ways, including: (a) the estimation of above-ground biomass, indirectly, through quantitative relationships between band-ratio indices (e.g. NDVI, GVI, etc.) with measures of biomass or with parameters directly related to biomass (e.g. Leaf Area Index, LAI). (b) Classification of vegetation cover and generation of a vegetation types map. This partitions spatial variability of vegetation into relatively uniform classes, which can be used as sampling framework for the location of ground measurement sites and the identification of plant species. (c) As up-scaling mechanism using mapped vegetation classes with reasonable internal uniformity as interpolating means, or to facilitate the application of spatial interpolation procedures for variables such as estimates of biomass, biodiversity indices and land degradation indices. Figure 2 illustrates, as a flow chart, the procedures involved in above-ground biomass estimation through remote sensing imagery, backed up by field measurements, as part of the methodological framework proposed.

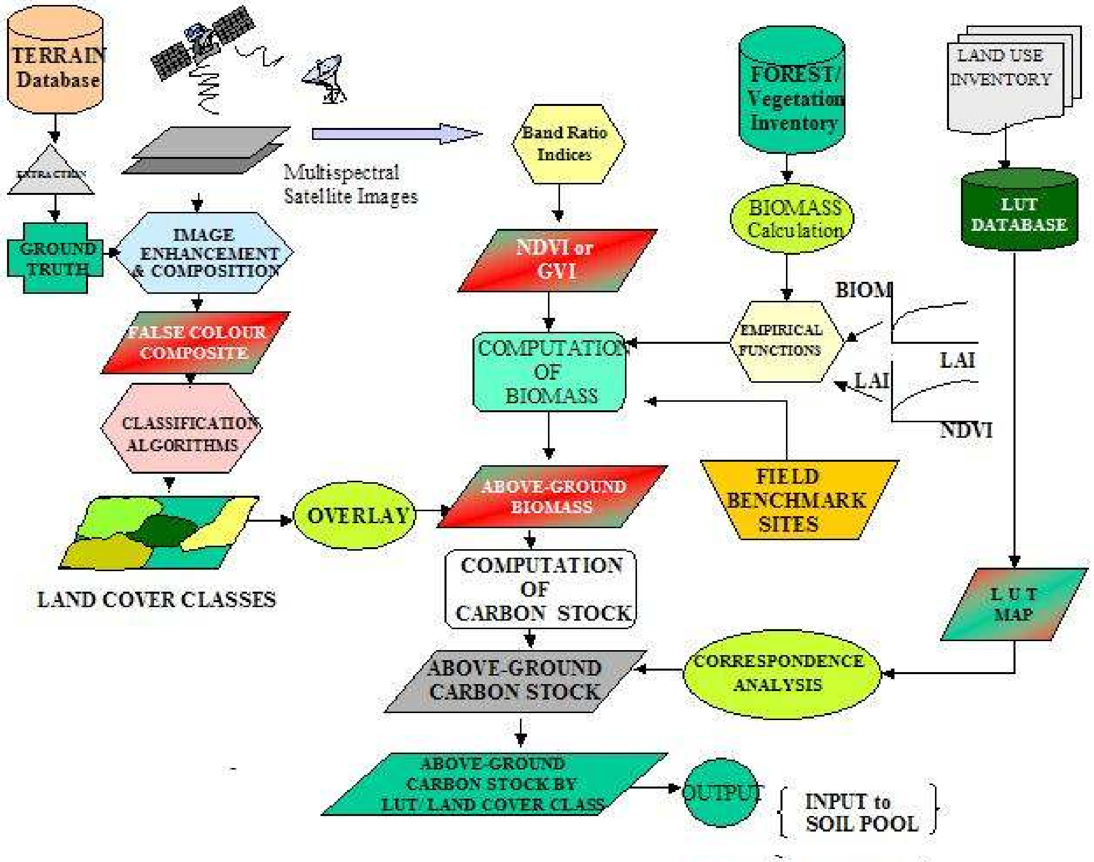


Fig. 2. Satellite image analysis for biomass and Carbon inventories at regional and local scales within the FAO methodological framework developed (Ponce-Hernandez et al, 2004).

Procedures for Field Sampling and Ground-truth: Multi-purpose field survey and sampling design

A multipurpose field sampling design is recommended in the framework to achieve efficiencies in data collection and minimize costs. The same sites are used for obtaining measurements of above-ground biomass, for estimation of biodiversity and for land degradation assessment via indicators. Sampling quadrats of regular shape of dimensions 10 x 10m, 5x 5m and 1 x 1m, nested within each other (figure 3) are used as the units for sampling the landscape in the field and for estimating biomass, biodiversity and land degradation. The dimensions of the quadrats represent a compromise between recommended practice, accuracy and practical considerations of time and effort.

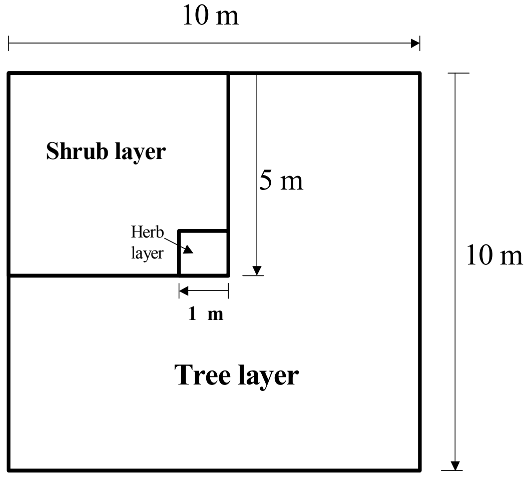


Fig 3. QUADRAT SAMPLING for biomass, biodiversity and land degradation assessments

The largest quadrats (10x10 m) were used for morphometric measurements of trees (tronk and canopy and large deadwood, identification of tree species and counts of individuals for biodiversity assessment; also for observation of land degradation field indicators. The medium quadrats (i.e. 5x5 m) were used for morphometric measurements in the shrub layer, small deadwood and identification and count of shrub species. The smallest quadrats (i.e. 1x1 m) were used for sampling biomass of herbaceous species and grasses and roots, litter fall and debris which were subsequently dried out and weighted to determine live and dead biomass

A stratified random sampling design with proportional probability allocation of sites to a land cover polygon, based on area size, is recommended for locating quadrat sampling sites in the field.

Estimation of above- and below-ground biomass

Above-ground biomass is estimated through standard forestry morphometric and allometric measurements of standing vegetation, canopy of various strata of trees and shrubs, as well as debris, deadwood, saplings, and samples of herbs and litter within the corresponding sampling quadrats. Above-ground biomass is estimated from quadrat measurements by volume, through allometric calculations involving standard forestry measurements and procedures (i.e. tree height, diameter at breast height, basal area, wood density and crown dimensions). Predictive allometric equations, based on least-squares regressions are used to estimate biomass. These models, (e.g. Brown et al, 1989) are standard practice due to their wide applicability (FAO, 1998). The complete list of selected allometric regression equations part of the framework and used in this study can be found in Ponce-Hernandez (2004). For brevity and focus they are not provided here.

Depending on the type of forest and the ecological condition in turn, above-ground biomass can be estimated by applying the corresponding allometric regression equation. Total biomass is calculated for each tree in the sample quadrat by the addition of the trunk and crown biomass estimates, then summing up the results for all trees in the sample quadrat (kg/100m^2) converted to tonnes per hectare. To the tree biomass estimate in the 10 x 10m quadrat, the estimates from shrubs, deadwood and debris measured in the nested 5 x 5m quadrat are added. The herbaceous layer, the litter and other organic debris collected in the field from the 1x1m quadrat are taken to the laboratory, dried out and weighted. The surface dry organic matter estimate per m^2 is added to the estimates of total above-ground biomass for each of the field sampling sites (10x10m quadrats). Below-ground biomass is estimated from root biomass as a function of above-ground biomass by non-destructive methods. These are based on calculations of below-ground biomass for similar types of vegetation and conversion coefficients (see Ponce-Hernandez, 2004 for details). For agro-ecosystems the estimation of biomass makes sense only as the fraction of crop residues added back to the soil and not removed, used as animal feed, or for any other non-destructive use, discounting the harvest fraction. Crop growth computer models (De Wit et al, 1978; Van Diepen et al, 1989; Jones et al, 1991) are used to project estimates of biomass into the future, when an estimate is required. Thus, average expected crop yields and crop residue production are used as indicators of biomass production in crops.

Estimation of the status of biodiversity.

Biodiversity is a complex multi-scale and inclusive concept. Operationally, the diversity of plant and animal species is to be considered from that at the genetic level to that of habitats and landscapes. This complexity and the ambulatory nature of animals makes it difficult to consider biodiversity in its broadest sense for rapid assessments on the ground, particularly when assessments of carbon sequestration may only be concerned with direct effects to plant diversity. It is for these reasons that relatively expedite assessments are required within the framework proposed, therefore, only plant diversity is considered. Thus, biodiversity in the context of the framework is limited, in the examples in this paper, as plant diversity. A number of quantitative indices have been designed to provide information on the various aspects of biodiversity in landscapes. The most common are listed in Magurran (1988). Of this set, only three were applied to the case studies, notably: the total number of species or species richness (S); Species abundance from the Simpson's diversity index; and species evenness from the Shannon information index. These indices can be computed readily from species counts in the sampling quadrats, and an automated template customized within a spreadsheet software, was designed and used in the filed for the case studies. These indices are standard in the landscape ecology literature (e.g. Magurran, 1988; Whittaker, 1972). Plant species are identified and counted for calculation of these biodiversity indices. Alfa and Beta plant diversity (Whittaker, 1972) are determined by calculating standard indices from field surveys and species counts (Hernandez-Stefanoni and Ponce-Hernandez, 2003). In some instances, due to practical constraints, it is not possible to collect, for the purpose of plant identification, plants with all the morphological components needed for identification in a herbarium. Therefore, the indigenous knowledge of local folk can be used to identify plant species using local names.

For the purposes of identifying the optimal sample size, an interactive approach is suggested. Pielou's pooled quadrat method (Magurran, 1988) is 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 incrementally and interactively calculating the diversity values (indices) in the quadrats entered, 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). In practice, since the sampling sites are multi-purpose 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.

The methodological framework includes links to GIS of the plant diversity indices calculated by each sampling quadrat from the customized template, to enable display of the spatial variability of these indices. This is achieved by either, spatial interpolation of point-estimates (where the quadrats represent points on the landscape), or by generalization of average values from quadrats to map units representing vegetation classes. This is a typical problem of up-scaling of estimates of environmental variables.

Land degradation assessment.

To perform the assessment of land degradation assessment within the framework, a parametric semi-quantitative approach is adopted using a set of indicator variables from those proposed in the FAO/UNEP methodology (FAO, 1978). The approach is based on the observation of parameters that are directly related to physical, chemical and biological processes of land degradation, through their most visible indicators, which are related to the same land degradation processes. The main aim of the assessment is to obtain a picture of the current status of degradation of the land in expedite, low-cost and useful manner with little demand for either, specific expertise in modelling or on data. The fundamental premise of the approach is that by observing diagnostic parameters or indicators of climate, soil, topography and human factors in any field situation, compound indices of physical, chemical and biological land degradation can be derived and mapped across the landscape. Table 1 shows a partial set of the indicators used in the framework for this type of assessment. These are the indicators of biological land degradation. For brevity and conciseness, other indicators for physical and chemical land degradation are not shown. The complete set of physical and chemical land degradation indicators used in the framework can be found in FAO, (1978); and with adaptations for the framework and for the case studies presented in this paper in Ponce-Hernandez, (2004).

Table 1. Indicators of biological land degradation centred on the decline of soil organic matter

Process	Factors			
	Climate	Soils	Topography	Human Factor
Decline in Soil Organic Matter	Humus Decay (%/yr) = HI / 10 $HI = e^{ct_1} + e^{ct_2} + 2e^{ct_3}$ t_1= temperature of warmest month (C°) t_2= temperature of coldest month t_3= mean annual temperature Coeff. of humus mineralization (K_2): $K_2 = 1/2e^{0.1065t}(P/PET)$ (for $P < PET$) for $P > PET$ then make $P/PET = 1$ for $t < 0$ then make $t = 0$. t= mean temperature of the period P= mean precipitation of the period PET= potential evapo-transpiration Humus content at equilibrium (B): $B = m(K_1 / K_2)$; K_1 is the coefficient of humification m= annual addition of organic matter (including crop residues and manures)	Texture: Sandy> Clay $K_2 = 1200/(A+200)(C+200)$ A= Clay (%) C = $CaCO_3$ (%) $5 < pH < 7.5$ little effect	N.A.	- Land Cover and shade (affects soil temperature) - C/N ratio of crops in the LUT - Additions of Organic Matter If OM decreases and SOM is mineralized slower than it is added as organic residues to the soil, then there is biological degradation

These indicators of biological land degradation are particularly relevant to the role that soil organic matter (SOM) plays in the ecosystem and in the carbon cycle. They provide an initial indication of the status and expected conditions of SOM in a field, as a function of climatic conditions and the annual additions of organic matter as crop residues and manures. Other indicators of physical degradation include soil erosion by water and wind and compaction and crusting; for chemical degradation: nutrient depletion, acidification, salinity and the presence of organic and organic toxic substances are included. As with indicators of land degradation, some of them are not directly observable in the field, or only partially, but most can either, be inferred through surrogate variables, or can be calculated from available data. In the framework here proposed, readily attainable meteorological and soil data are required for calculation of the indices.

Mapping assessment and estimation results: up-scaling procedures for carbon stock estimates, biodiversity and land degradation indices in present land use.

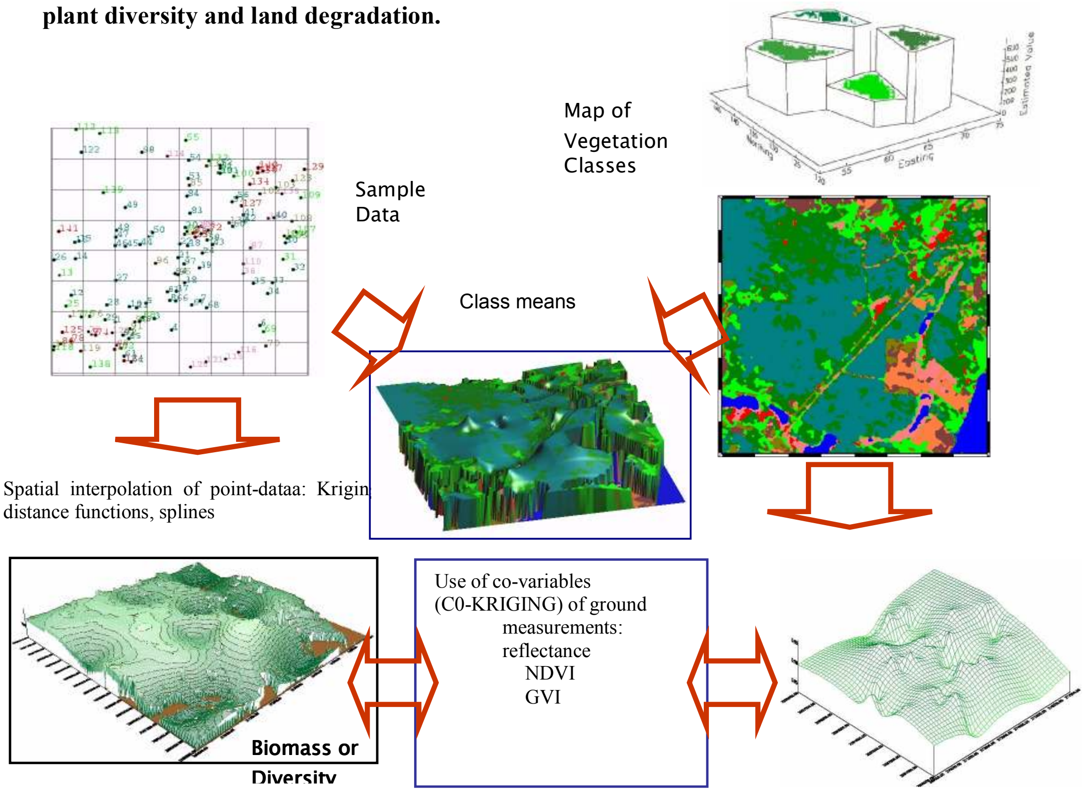
Carbon stock totals in present land use are derived from the addition of carbon in biomass to carbon in soils; i.e. Carbon stock $_{(total)}$ = C as biomass (above and below) + SOC. The conversion of biomass to carbon is achieved through standard species-dependent coefficients reported in published work (e.g. Mac Dicken, 1998). The soil organic carbon (SOC) is estimated from analytical data of samples taken at the quadrat sites, with support from reported soil survey data of the area of concern. Conversion of SOM to SOC, when values of SOC are not reported and laboratory analysis are not possible, can be made through standard conversion factors (e.g. SOC=0.57xSOM).

Mapping carbon stocks across the landscape is achieved in the proposed framework through: (a) up-scaling estimates of biomass or carbon from averages of quadrat sites within land cover polygons, (b) up-scaling carbon and biomass estimates by spatial interpolation, using Geostatistical techniques, notably, the various forms of Kriging; (c) Exploiting the presence of co-variables of biomass or carbon estimates (e.g. band-ratios of satellite images: NDVI or GVI) and then , either, apply co-kriging interpolation or a transfer function to convert the NDVI or GVI values into biomass or carbon estimates across the landscape. In summary, a reasonable course of action regarding up-scaling procedures of estimates, as suggested in the framework, would be: First, to decide on whether the quadrat sites are sufficient in number to compute reliable semi-variograms, and therefore interpolate optimally with Kriging. If there are insufficient sites (point-data) for Kriging, then class or within-polygon averages could be used. A band-ratio image (e.g. NDVI, GVI) can be converted into a map of biomass or total carbon, when such variables (e.g. NDVI and biomass) are strongly correlated or co-regionalized. This can be achieved by fitting a regression model and then use it to convert NDVI or GVI values in each pixel to biomass or directly to carbon. 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. The set of up-scaling procedures, part of the framework, is illustrated in figure 4.

Modelling Carbon dynamics in soils through SOM turnover simulation models.

Land management has significant effects on the inter- and intra-annual variations of SOM and on variability of stocks. The ability to predict the fate of amounts of litter, crop residues, manures, etc. added to the soil, is fundamental to carbon accounting in agro-ecosystems, and to the formulation of scenarios of land use and land use change that may increase carbon sequestration. Simulation models vary in their degree of complexity and other attributes relevant for model selection. The characteristics of such models vary in terms of their emphasis on some particular outputs, the conditions within which the model has performed best, aspects of the carbon cycle, their degree of compartmentalization, the underlying assumptions made by the developers of the model, model parameterization, their required inputs, nature of outputs, accessibility and ease of use. The European Soil Organic Matter Network, SOMNET (1999), published a systematic review of simulation models. It is beyond the scope of this paper to offer a summary of such listings. However, based on that and other key information, the models "CENTURY" and "RothC-26.3" were selected for simulating the dynamics of SOM turnover as part of the methodological framework.

Fig. 4. Up-scaling procedures of estimates of biomass, Carbon, plant diversity and land degradation.



These models represent extremes in a gradient of accessibility, ease of use and detail, CENTURY being the most detailed but structurally complex. Rothc-26.3 is a model that allows for the effects of soil type, temperature, moisture content and plant cover on the SOM turnover process. It uses a monthly time step to calculate total organic carbon (t ha $^{-1}$), microbial biomass carbon (t ha $^{-1}$) 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 *et al.* 1991; Jenkinson *et al.* 1992; Jenkinson and Coleman, 1994). RothC-26.3 needs few inputs and these are easily obtainable. The model computes the changes in organic carbon 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).

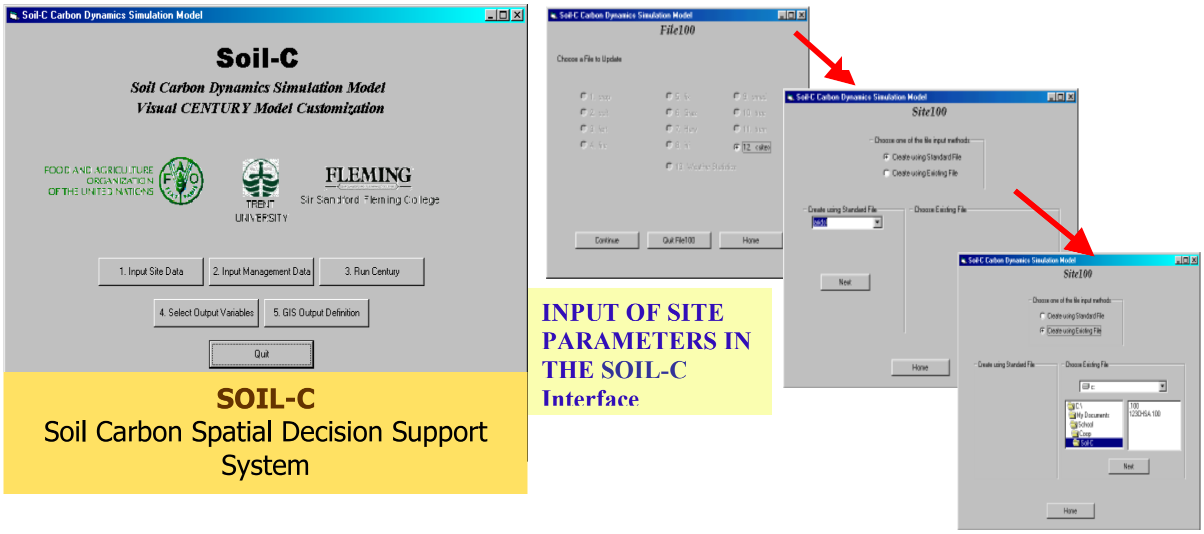
The CENTURY model, on the other hand, simulates the long-term dynamics of carbon (C), nitrogen (N), phosphorus (P), and sulphur (S) for different plant-soil systems. The model can simulate the dynamics of grassland systems, agricultural crop systems, forest systems, and savannah systems. The grassland/crop and forest systems have different plant production sub-models that are linked to a common soil organic matter sub-model. The soil organic matter sub-model 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 (Parton et al, 1992).

Model customization and SOM model-GIS integration

The full parameterization of CENTURY, v. 4.0, is a rather laborious process requiring many variables, some of them very specific or uncommon, on a cumbersome unfriendly MS-DOS interface in a PC computer. The difficulties in running and manipulating frequently the CENTURY model in routine assessments, in order to simulate the partition of SOM into its fractions over time for preparing different scenarios, brought about the need for developing enhanced input/output interfaces, particularly those related to model parameterization and to the model-GIS integration. After careful study of the model structure, software was developed in Visual Basic programming language to create a graphic user interface (GUI) to enable ease of input, model parameterization and GIS output. This resulted in a sort of spatial decision support system that was called "Soil-C" (fig 5). SOIL-C consists of a suite of programs, which interface with the input and output of the model CENTURY (v. 4.0). The options in the main screen of SOIL-C (figure 5) introduce the user to a hierarchy of menus for input of site data (equivalent to input data through a "FILE100" in CENTURY), 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 and the interface to run the model (fig 6).

The parameterization of the models is achieved through the computation of "pedo-climatic cells" (PCC), which are pixels indexed to attribute tables containing all soil and climate parameters necessary for running the simulation models. These PCC result from the spatial interpolation of point data from meteorological station values of the variables required by the model, and from soil profile analysis data. Then, these data layers were overlaid in the GIS to a common geo-referencing system.

Fig.5. SOIL-C: Customization of the CENTURY model interfaces with Visual Basic programming language

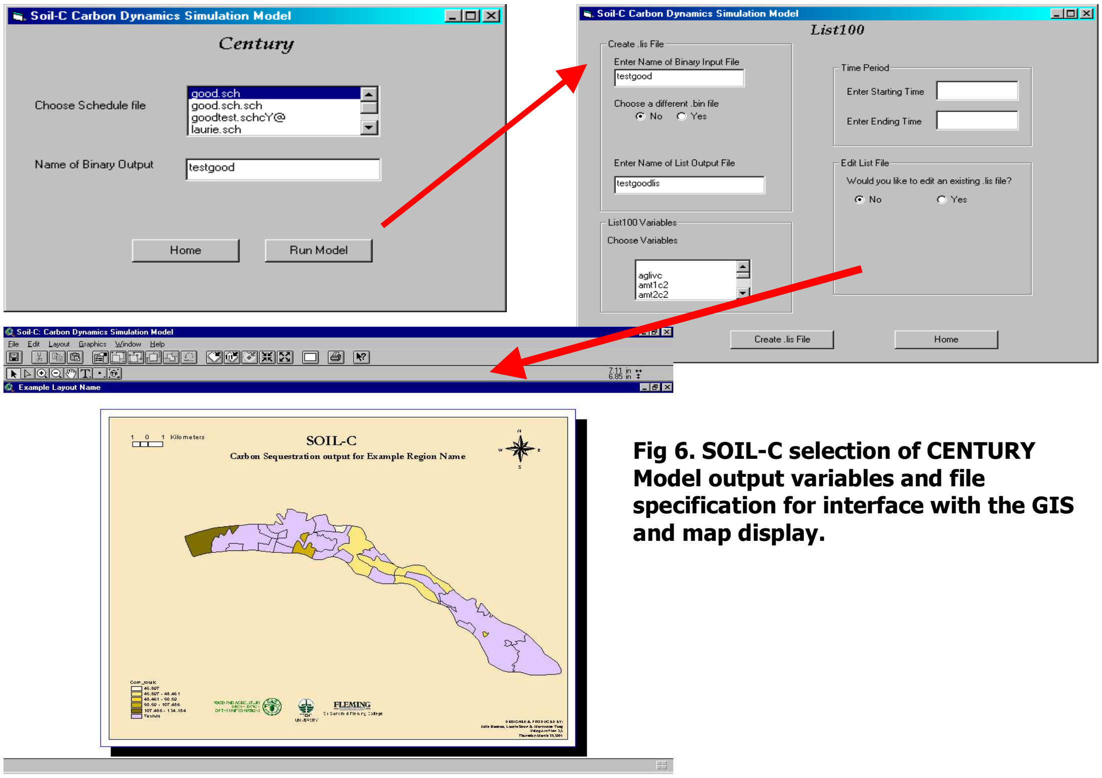


SOIL-C
Soil Carbon Spatial Decision Support System

INPUT OF SITE PARAMETERS IN THE SOIL-C Interface

Estimation of Carbon stock and sequestration in potential land utilization types (LUT)

In order to generate possible scenarios of land use change (LUC) within the framework, potential LUT are considered. First, a short list of candidate LUT is developed by including in the selection criteria, high efficiency for CO_2 photosynthetic absorption and conversion to biomass. Plants with photosynthetic pathways C3 and C4 are selected. Then their physical suitability for the ecological conditions of the land in the study area is evaluated through standard land suitability assessment procedures (FAO, 1984). Bio-physically suitable and photo-synthetically efficient crops are selected and crop patterns then formed. Crop growth models (Van Diepen et al, 1989; Jones et al, 1991) are used for predicting biomass and yields over time, under the climate and soil conditions predominant in the different PCC or land polygons of the area under study. The estimated inputs of organic matter in the form of litter, crop residues and manures from these LUT become then the starting point for modelling SOM turnover and for projecting such outcomes into future periods.



Choose Schedule file: good.sch, good.sch.sch, goodtest.schcY@, laurie.sch

Name of Binary Output: testgood

Enter Name of Binary Input File: testgood

Choose a different .bin file ● No ○ Yes

Enter Name of List Output File: testgoodlis

Enter Starting Time:

Enter Ending Time:

Would you like to edit an existing .lis file? ● No ○ Yes

Choose Variables: aglivc, amt1c2, amt2c2

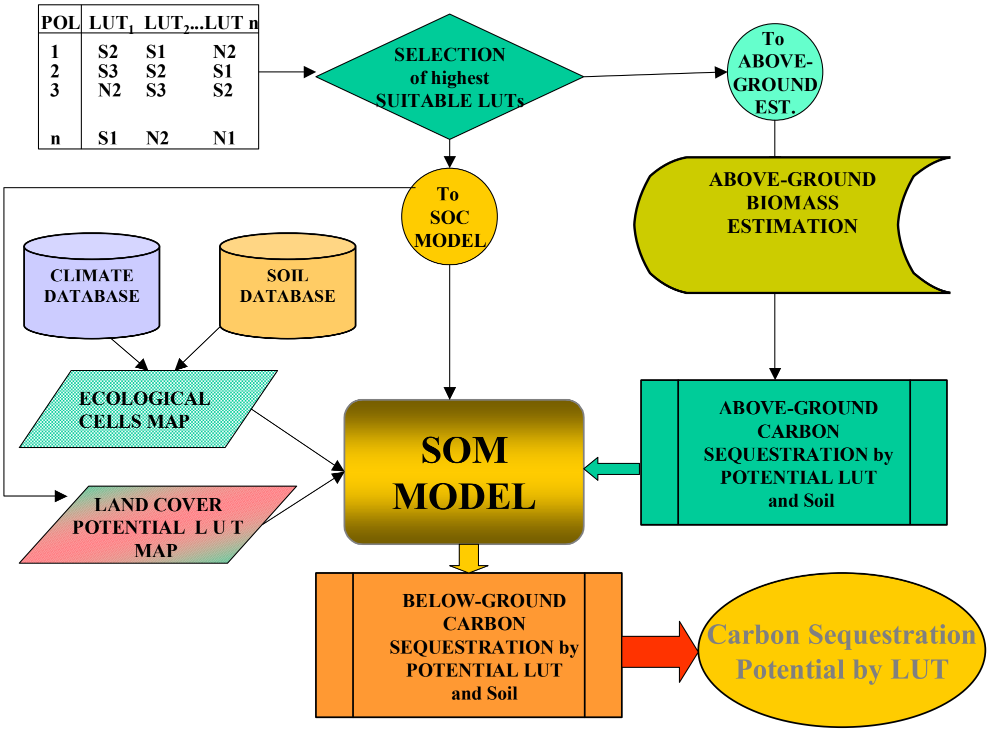
Fig 6. SOIL-C selection of CENTURY Model output variables and file specification for interface with the GIS and map display.

Full carbon accounting then takes place, and the difference between the actual carbon stock of present land use and that of any potential LUT can be accounted for as either, carbon sequestration or emission. Figure 7 illustrates with a flow chart such sequence of procedures for potential LUT, as part of the methodological framework. The land suitability assessment process could be a cumbersome one, depending on the land-use/crop requirements considered and the data on the land qualities and land characteristics available to match such requirements. FAO (1984) has published comprehensive literature and guidelines for land evaluation under many types of agriculture. The details of the suitability assessment process can be obtained directly from that source. What is new here is that the suitability assessment process includes now high efficiency for CO_2 photosynthetic absorption and conversion to biomass, i.e. high carbon sequestration efficiency, as a criterion for crop selection. It is worth mention too that the suitability assessment process is automated through the development of decision-trees using the Automated Land Evaluation System (ALES) (Rossiter, 1995).

Applying the methodological framework in the field through case studies

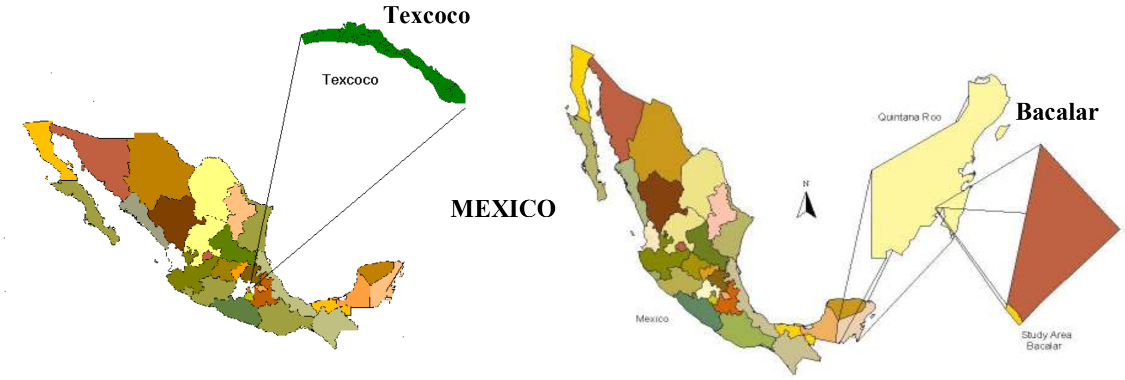
Results from applying the methodological framework to two contrasting areas in Mexico (figure 8), are presented in this paper. The areas selected are the Texcoco watershed (agriculturally-based, dry, highland sub-tropics) in a rural area near Mexico City (fig. 9) and an area of about 1000 ha near Bacalar, in the Yucatan Peninsula (tropical sub-deciduous forests subject to cycles of “slash-and-burn” shifting cultivation and fallow, with an ancient Mayan subsistence agricultural tradition). In both case study areas, land cover units were mapped through remote sensing procedures (figure 2), and quadrat sampling sites were located according to the sampling procedures outlined in the framework. Figure 9 illustrates the position of the quadrat sampling sites in the Texcoco watershed. Above- and below-ground biomass estimates were computed at quadrat sites and interpolated. Estimates of biomass and carbon content were derived for each land cover polygon throughout the watershed, thus providing estimates of the carbon stocks in present land use.

Fig. 7. Assessment of Carbon stock and sequestration for Potential Land Utilization Types



A land suitability assessment exercise, including carbon efficiency in the suitability criteria, yielded a list of potential LUT for the formulation of scenarios. SOM turnover was simulated with the SOIL-C interface to the CENTURY v 4.0 model and a parallel run with the RothC 26.3 model was also performed on the potential LUT selected from suitability analysis.

Fig 8. Case Studies: Texcoco (left) and Bacalar (right) in Mexico



Results from the Texcoco watershed case study

The models were run for a period of 12 years (2000-2012) for each of the LUT selected.The different fractions of SOM were requested as outputs, including total carbon and CO_2 losses to the atmosphere. Results were tabulated and the trends of the different SOM fractions over time were plotted.

Fig 9. Quadrat sampling site locations in land cover map units of the Texcoco watershed

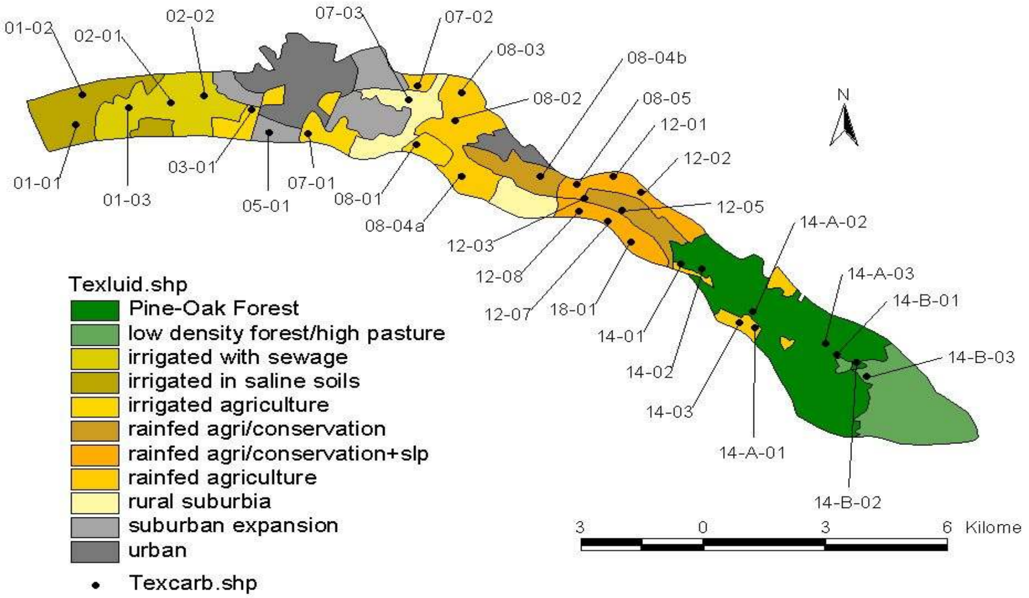


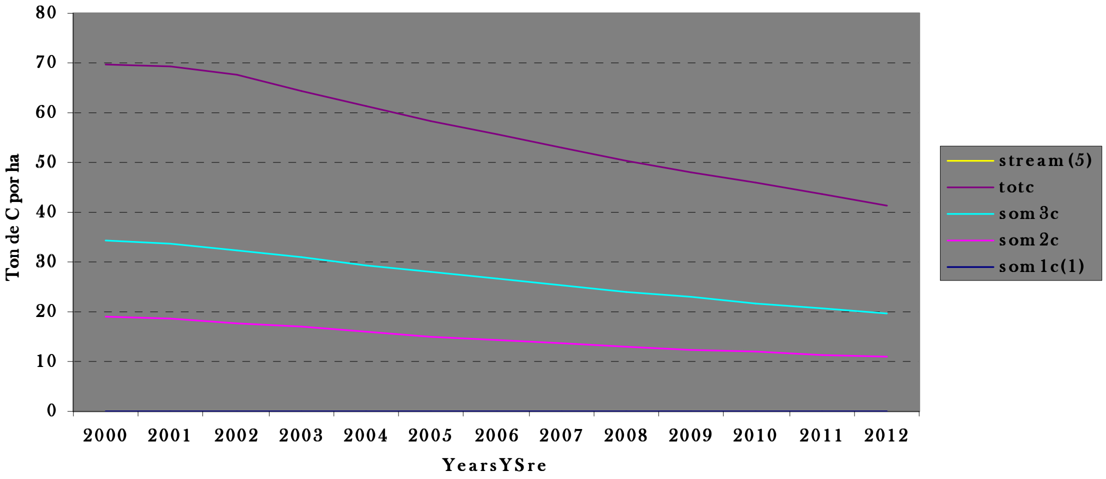
Table 2 shows results of the SOM turnover simulation for three LUT among those selected (alfalfa, oats and barley, in that order), at different land unit polygons. In table 2 these combinations of land unit-LUT are termed as "scenarios". It is clear from table 2, that cereals are outperformed by legumes (i.e. alfalfa), in terms of carbon sequestration. This is not surprising considering the dynamics of carbon and nitrogen interactions in legumes. After an initial increase, soil carbon under barley declines, after the second or third year, more rapidly than oats, which maintained an increase in "totC" a bit longer, declining at a later period. These scenarios were run without any additions of organic residues or manures. A similar pattern is observed for corn (*Zea maiz*) under rainfed agriculture and no inputs (figure 10), where the decline in SOM occurs at the end of the second year and in some of the SOM fractions even in the first year. Corn is the staple crop in that watershed and indeed in Mexico, and the management system is similar to that simulated.

Table 2. SOM turnover simulation with the CENTURY model from the SOIL-C interface for the period (2000-2012) for a variety of LUT. Crops modelled here are alfalfa, oats, and barley in descending order.

Scenario	Partition	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
ch7daf	Totc	2685.979	2700.74	3920.538	4407.509	4897.365	5264.552	5534.828	5873.99	6203.337	6461.257	6595.729	6808.396	6919.856
	som3c	1168.631	1169.243	1169.396	1170.098	1171.264	1172.755	1174.54	1176.746	1182.783	1186.764	1189.857	1192.874	1195.901
	som2c	1434.229	1597.743	1695.268	1902.605	2162.378	2437.844	2717.639	3010.295	3380.79	3660.845	3881.716	4090.009	4269.301
	som1c(1)	10	6.0396	63.1074	109.1415	123.1609	119.5783	119.7778	129.1633	5.3678	43.482	115.2146	114.122	116.6872
	Stream(5)	0	0	0	0	0	0	0	0	0	0	0	0	0
ch7dav	Totc	2685.979	2646.58	3070.958	2912.343	2846.493	2833.844	2749.197	2729.255	2683.265	2663.961	2688.066	2645.013	2643.657
	som3c	1168.631	1157.614	1146.244	1133.536	1119.699	1104.84	1088.961	1072.472	1055.365	1037.937	1020.13	1001.966	983.5297
	som2c	1434.229	1431.115	1495.411	1514.798	1515.627	1503.786	1476.849	1457.892	1440.207	1439.88	1442.573	1445.059	1447.831
	som1c(1)	10	4.7317	1.4674	1.8106	2.0459	1.3743	1.9103	1.5708	1.7624	2.2928	1.8313	2.23	1.9272
	Stream(5)	0	0.0195	0	0	0.014	0	0	0.0026	0	0.0029	0	0.0188	0.0129
ch7dbb	Totc	2685.979	2621.987	2386.884	2189.609	2012.72	1866.563	1732.153	1611.068	1499.92	1400.972	1309.896	1224.963	1146.552
	som3c	1168.631	1149.086	1125.648	1099.042	1069.994	1039.458	1007.524	974.6458	941.0803	907.2474	873.2645	839.2896	805.5464
	som2c	1434.229	1344.431	1208.178	1058.734	917.8648	805.6611	705.8766	619.9214	544.3121	480.8545	425.2172	375.5559	332.0298
	som1c(1)	10	4.2076	0.2572	0.0153	0.0009	0.0001	0	0	0	0	0	0	0
	Stream(5)	0	0.0066	0	0	0.0006	0	0	0.0003	0	0.0002	0	0.001	0.0006

Fig 10. Carbon dynamics in soil under Corn (maize), rainfed cultivation and none or minimal organic inputs

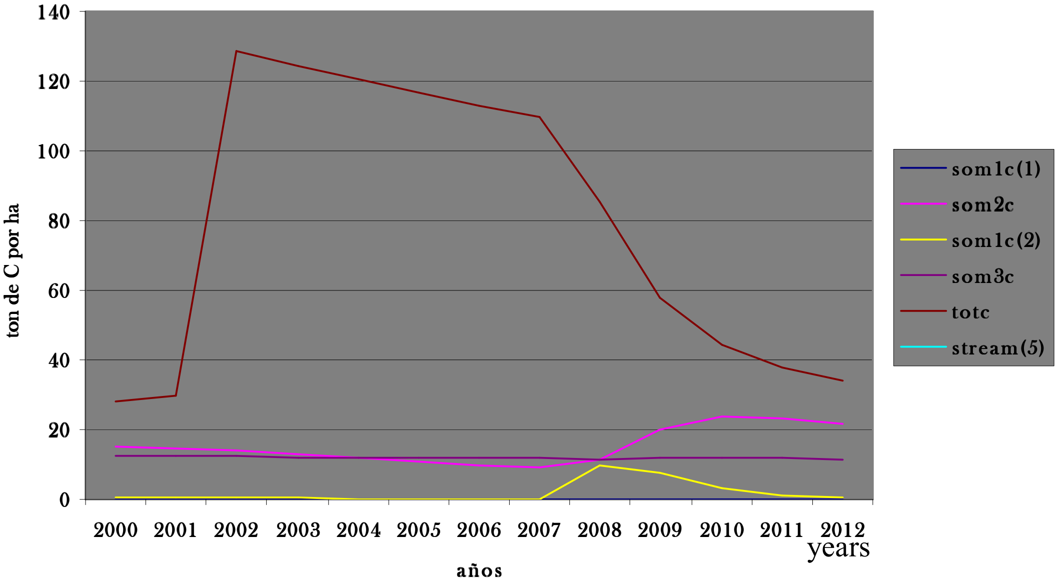
Land Unit 8a



These LUT are typically net emitters since no significant losses due to leaching are detected from model outputs. In contrast, when a minimal of organic matter inputs and moisture are added to a corn crop under irrigation (fig. 11), although on a different land unit, there is a sharp increase in total Carbon in the first three years, followed by a gradual decline in the following four years and then a more sharp decline then after.

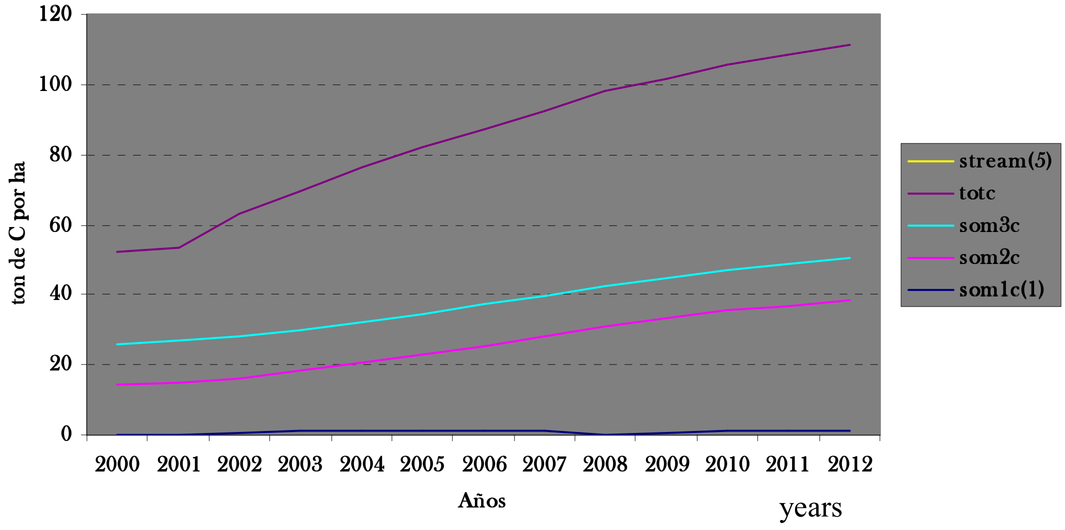
Fig. 11.

Soil Carbon dynamics under an Irrigated Corn (Maize) crop and minimum organic residue inputs in the Texcoco watershed Land Unit 2



This shows the impact of adding organic inputs and moisture to the soil, in terms of the variability of SOM over time, and the importance of SOM management. The decline must be attributed to the lack of further microbial substrate for biochemical activity, and the accrual of stable and resistant forms of SOM. The best scenario, in terms of efficiency of carbon sequestration, was obtained with irrigated alfalfa (fig 12). Modelling results here show that at there is a very gradual increase of carbon at the start of he period. Initially slow but with steeper increases after the third year. This shows the effect of both, the interactions Carbon/Nitrogen, typical of leguminous plants and the importance of the presence of Nitrogen and soil moisture in microbial activity for SOM turnover. The spatial distribution of this LUT is mapped out in the scenario shown in figure 13 in the map of the watershed, as an illustration of the SOIL-C GIS output.

Fig. 12. Soil Carbon dynamics under irrigated Alfalfa crop
and Carbon Sequestration in the Texcoco watershed
Land Unit 7b



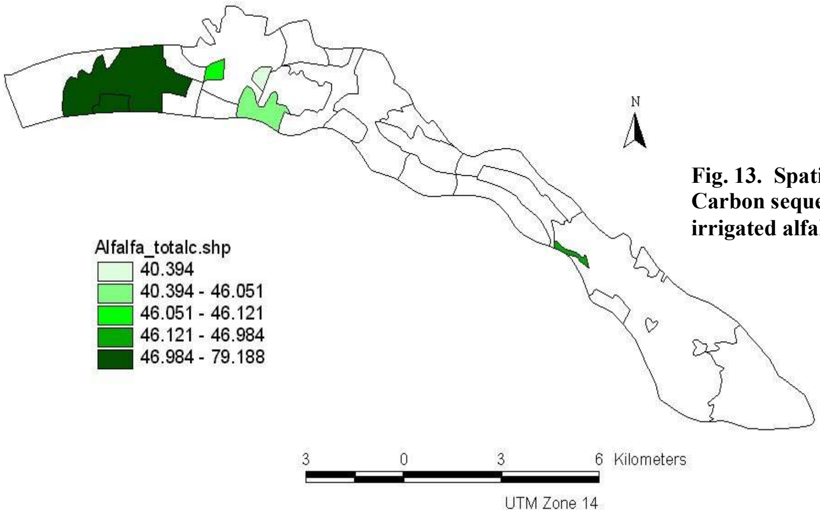
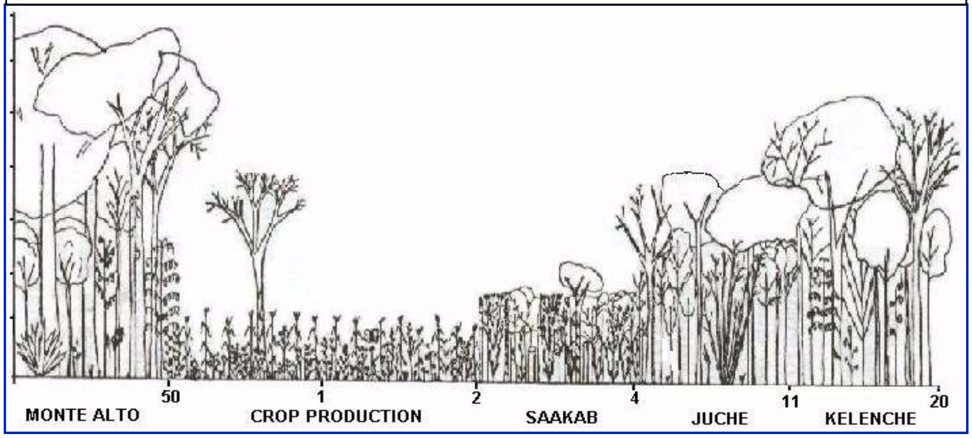


Fig. 13. Spatial distribution of Carbon sequestration with an irrigated alfalfa crop

The Bacalar case study

The tropical sub-deciduous forests around the Bacalar lagoon, in the Yucatan Peninsula, are succession forests (figure 14), subject, over centuries, to “slash-and-burn” agriculture (SABA) through shifting cultivation for the subsistence of the Maya civilization. Above- and below-ground biomass and carbon are very abundant in these forested ecosystems as standing vegetation, debris and litter. Tropical forests of 50 years and older can be found as large patches within a mosaic of other forests at different stages of succession. The Maya have characterized these stages with local terms (fig 14) beginning with the youngest re-growth after cultivation and fallow or “saakab”, and continuing with “juche”, “kelenche” and “Ka’na-Kaax” or “Monte Alto”, the latter being a climax forest of 50 years or older.

Fig 14. Stages of succession of tropical forests in Bacalar, Mex



Biomass and its carbon stock were estimated across the landscape through exploiting a strong relationship found between the digital numbers (DN) of pixel values of a Green Vegetation Index (GVI) derived from Landsat TM images band ratios (Nageswara and Mohankumar, 1994). derived from Landsat TM satellite imagery and the estimates of biomass from field measurements at the sampling quadrat sites (fig 16). A linearized exponential model fitted well the data,biomass was predicted at every pixel, and converted to carbon content, resulting in a map of carbon stock in biomass for the entire landscape (fig 17).

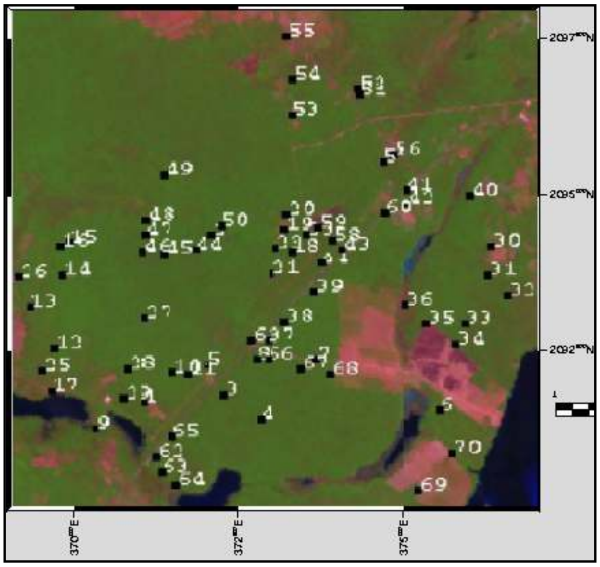
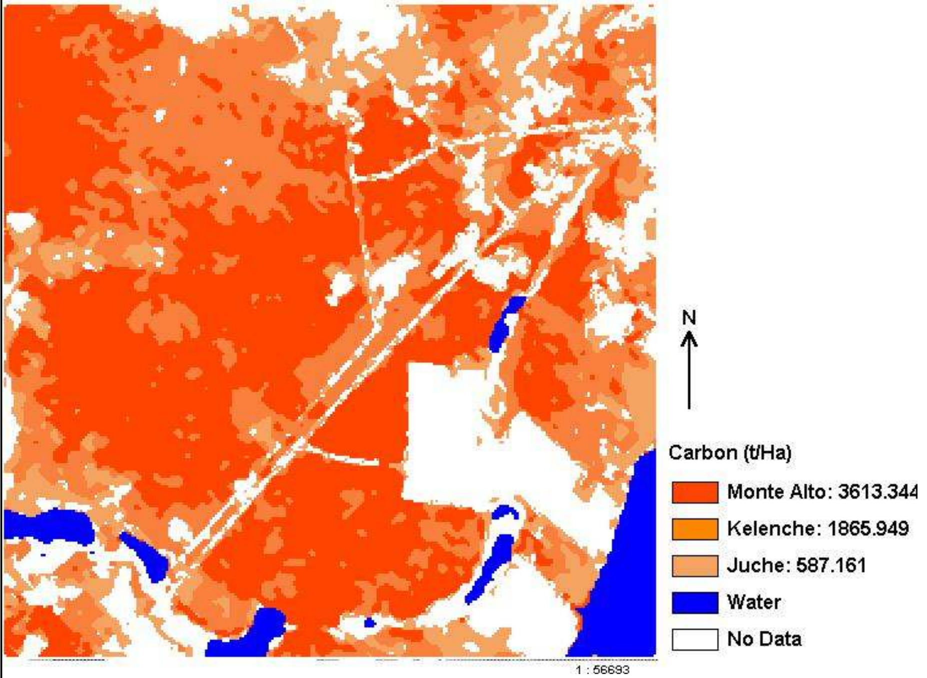


Figure 16. Clour composite image and the distribution of sampling quadrat sites in the Bacalar area.

Figure 17: Total live Carbon stock (above- and below-ground biomass) averaged by vegetation class in Bacalar, Quintana Roo, Mexico.



Modelling carbon sequestration in soils to identify win-win scenarios of synergies.

In the shifting cultivation systems of the Bacalar area SOM plays a crucial role in maintaining soil fertility after slash-and-burn, due to the incorporation of nutrients from ashes. SOM data from earlier surveys, allowed for parameterizing and calibrating the CENTURY and the RothC-26.3 models, against ground SOM data (fig. 18) in order to run the models. Since shifting cultivation emits CO_2 through SABA, scenarios aiming at finding the necessary contributions of organic inputs that need to be made from the various component sub-systems (i.e. backyard orchard, farm yard manure, backyard livestock, open forest, etc.) of the typical Mayan farming system (i.e. family unit production system) to the agricultural plot, needed to be identified. Such organic inputs involved in the “win-win” scenario, would increase the nutrient pool to the extent of not making it necessary to burn biomass, thus stabilizing shifting cultivation and SABA into continuous cropping in the same fields. A significant increase in crop yields and staple food production should persuade farmers not to shift agricultural plot and implement SABA, thus avoiding CO_2 emissions and possibly sequestering carbon in the soil.

The calibration of the models to SOM field data, once parameterized, was found to be reasonably good, as shown in figure 18 for the RothC-26.3 model. Then, the model was used to generate scenarios in search for sub-systems of the farming system and their potential contribution of organic inputs to the cropland. Production functions based on regression equations of crop yield (corn) as a function of soil organic matter (SOM) were fitted to data by least-squares for the two dominant soils, namely: Chromic Luvisols (K’ankab in Maya language) and Rendzinas or Regosols (Ho'l lu'um). The models are shown in table 2.

Since yields decline after the second year of cropping in the same plot under SABA, to a level between 0-25% of the second year, farmers are forced to shift cropping to a new plot by slashing and burning the vegetation before cropping. Considerable amounts of organic mater need to be managed judiciously to avoid crop yield decline and yet to achieve the accrual or sequestration of carbon in the soil. The scenarios combining SOM management with land use type, developed for the soils in Bacalar, were based on recommended practices by published work. In total, 56 scenarios were developed. A sample of the most contrasting scenarios for the soils in Bacalar is shown in table 3.

Figure 18. Model calibration to existent SOM data in Bacalar, Mexico (RothC-26.3 model)

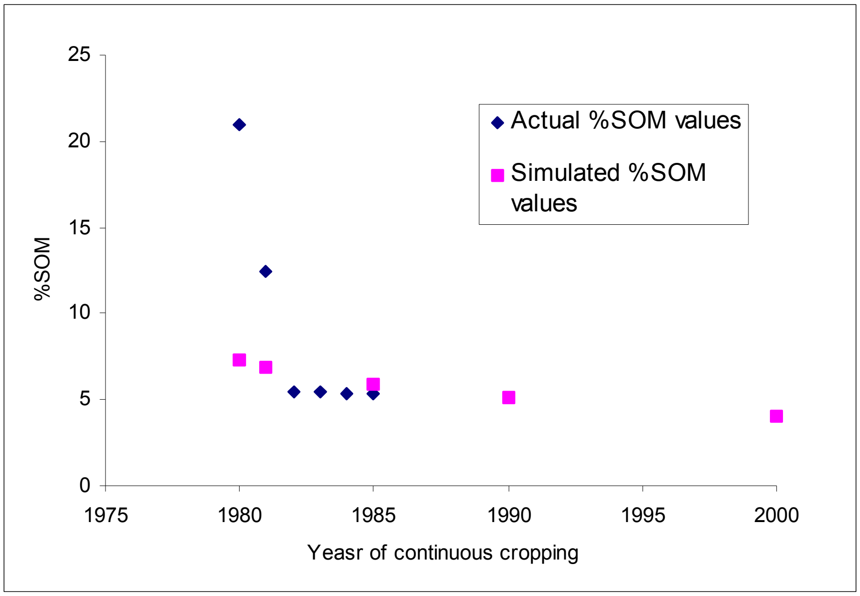


Table 2: Production functions of corn yield (Y) on soil organic matter (OM) for two different soil types in Bacalar (Quintana Roo), Mexico, showing the coefficient of determination R^2 and the significance level (PROB > F)

SOIL TYPE	MODEL	R^2	PROB > F
Bacalar - K'ankab (Chromic Luvisols)	$Y= 315.46 + 41.93OM + 0.475*OM^2$	0.88	0.01
Bacalar - Ho'l lu'um (Rendzinas and Regosols)	$Y= -178.53 + 6.96.27OM - 220.52*OM^2$	0.70	0.55

Out of the 56 scenarios tried, the most relevant scenarios in K’ankab (Chromic Luvisol) and Ho’l lu’m (Rendzina and Regosols) soils for Bacalar are shown in table 3. The scenarios were coded to reflect their SOM management, land cover type and soil type. Table 3 also provides the final results of the modelling for the most promising scenarios, and the predicted outcomes of total soil carbon for the 12 year simulated period.

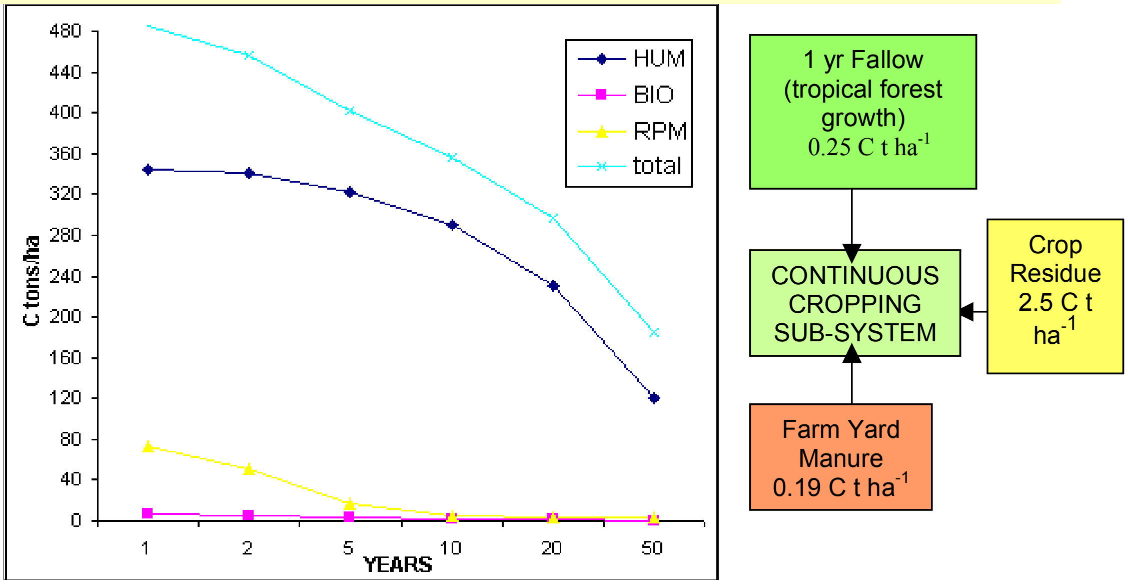
Table 3: Results of modelling scenarios of SOM (carbon) projected to 2012 by the model in Bacalar, Quintana Roo, Mexico.

Scenario code	**Soil type**	**LUT/Land cover and Organic Matter management**	**Current Soil Carbon (t/Ha)**	**Projected Soil Carbon, 2012 (t/Ha)**
Lima	Ho’l lu’m – Lithosol	Monte Alto	527.04	358.65
Rkel	Ho’l lu’m – Regosol	Kelenche	527.04	335.18
Kjkl	K’ankab – Chromic Luvisol	Kelenche/Juche	116.29	73.48
Kmzz	K’ankab – Chromic Luvisol	Corn (milpa), continuous cropping	116.29	66.33
Kmsb	K’ankab – Chromic Luvisol	Corn-Squash-Beans, continuous cropping	116.29	81.26
Kfsb	K’ankab – Chromic Luvisol	Corn-Squash-Beans, continuous cropping + 2 t C /Ha FYM*	116.29	86.05
SK15	K’ankab – Chromic Luvisol	Corn-Squash-Beans-Orchard + 0.19 t C /Ha FYM*	116.29	121.35

The results obtained from modelling, as shown in table 3, indicate that forested soils in fallow (scenarios “Lima”, “Rkel”, “Kjkl”) tend to be net emitters of carbon, when first brought into cropping. This is without the inclusion of losses by the burning of above-ground biomass. They experience soil carbon losses of up to 40% of the initial carbon content after the burn, over the 12-year period. The rest of the scenarios shown in table 3 involve experiments with simulating continuous cropping after initial slash-and-burn. They track changes after SABA following different lengths of fallow and forest succession. Scenario “Kmzz” represents the “business-as-usual” scenario except for the fact that continuous cropping is assumed. That is to say, growing corn (maize) with no additions of organic inputs (as usual), but staying in the same plot for 12 years instead of shifting land to another plot. This scenario is a net emitter of carbon, which is associated with the sharp decline in crop yields and explains why farmers currently shift to other plots in forest succession, after the second and, exceptionally, the third year of continuous cropping. Scenario “Kmsb” shows the results of simulating SOM dynamics with the most common crop association (i.e. corn, beans and squash) but in continuous cropping on Chromic Luvisols. The scenario also represents the “business as usual” situation and indicates carbon losses after the 12-year period of up to 30% of the initial stock in the soil after the burn, with no addition of organic inputs. However, when 2 tonnes per hectare of carbon as farm-yard manure (FYM) are added to the same management scenario and for the same soil (i.e. scenario “Kfsb”), the carbon losses are reduced over the 12-year period from 30% to 26% of the initial soil stock. This shows the important role of organic inputs in the agricultural plots in this study area.

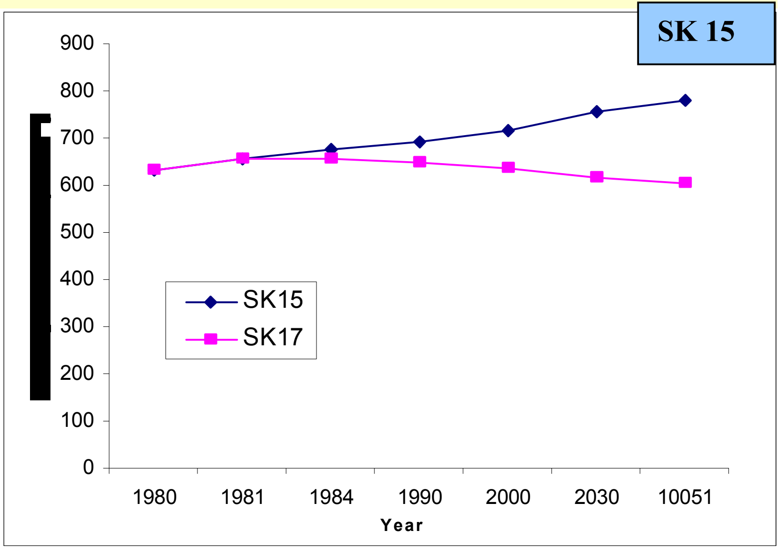
The changes of SOM fractions over time in a typical farming system in Bacalar, even with the addition of some organic inputs are shown in figure 19. All organic fractions decline in concentration in the soil over time. This indicates that the natural tendency in this soils when submitted to a cropping regime is to loose organic matter, mainly as CO_2. In contrast, the results presented by table 3 show that carbon sequestration (as measured by total carbon in the soil) only occurs under careful land and organic matter management (scenario SK15). Scenario “SK15” is the only scenario that achieves carbon sequestration over the 12 year period, changing from 116.29 to 121.35 tonnes /ha of soil carbon. This scenario represents the results of searching for a SOM management system, which would stabilize shifting cultivation and SABA, while producing enough staple food supplies for the family unit (average size 6 in this area) to be sustainable over the year. The win-win scenario (SK15) however, requires of four sub-systems (orchard, farm yard manure, crop residues and forest biomass), all of which should contribute different amounts of organic inputs to the agricultural plot (see figure 20). In the farming system in scenario SK15 the plots are prepared by SABA after 10 year fallow, followed by continuous cropping with annual farmyard manure inputs. The total carbon inputs for this scenario are 3.3 t C/ha from the SABA event (ashes), followed by 5.39 t C/ha from the cropping residues, 2 t C/ha from orchard residues and 0.19 t C/ha in FYM annually, or 25.58 t C/ha/ over the 12 year period. On the other hand, a production system with four sub-systems but with lesser amounts of organic inputs (scenario SK17), particularly those resulting from the initial burn and form manures, eventually looses carbon and therefore crop productivity, as can be seen graphically in figure 20. Both systems SK15 and SK17 are graphically illustrated in figure 20. Again, if scenario SK15 is achievable, it means that shifting cultivation and SABA could be stabilized while producing enough staple food supplies for the average family in Bacalar. This has great potential consequences for the ecology of the region. Not only land fertility and productivity would be enhanced, but emissions of CO_2 after burning of biomass can be avoided and, even further, carbon sequestration in soils could be achieved. Moreover, since the biodiversity of these forests increases strongly with their age and maturity (see table 7), burning older forests depletes their biodiversity sharply. Thus, arresting SABA achieves the desired synergies.

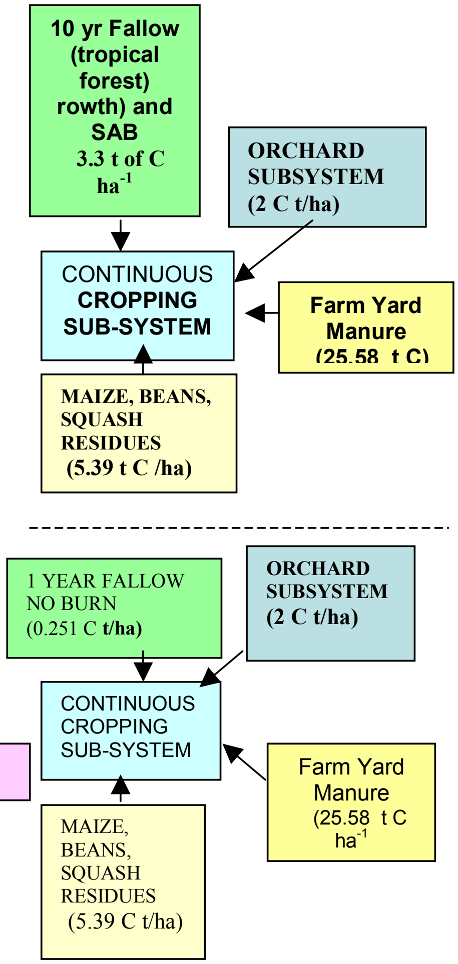
Figure 19 : Soil Organic Matter (SOM) fractions over time in a continuous cropping system of corn, beans and squash in association, with minimum organic inputs from three sub-systems of the farming system in Bacalar, Quintana Roo, Mexico.



The spatial distribution of the modelled scenarios listed in table 3 corresponds to maps of the area displaying the variations over the 12-year period, mainly in the K'ankab soils (Chromic Luvisols). The common feature of such maps is that all but one (scenario SK15 in figure 21), represent carbon losses in both the Rendzina (H'ol L'um) soils and the Chromic Luvisols (K'ankab) soils.

Fig 20. Modelled scenarios of soil organic matter management and C accumulation in soils from farming systems and land management practices to stabilize slash-and-burn agriculture and provide food security in Bacalar, Yucatan Peninsula, Mexico.





Family Production System of 4 sub-systems with a Land management scenario SK15, produces sufficient Food requirements for a family of size 6 to be sustainable, and to stabilize shifting cultivation.

Scenario SK15 is mapped out through GIS output, as part of the procedures in the methodological framework here described in figure 21. This map shows soil carbon losses in the Rendzina soils, which correspond to a forest succession cover. In contrast, the cultivated soils (K'ankab or Chromic Luvisols) thanks to careful management of SOM and organic inputs achieve carbon sequestration, enhance biodiversity and therefore, prevent land degradation.

Carbon sequestration and Biodiversity

Biodiversity, in the context of the studied area, was constrained to measurable plant diversity and excluded fauna. From this perspective, plant diversity was assessed using the three commonly used indices: number of species, Simpson's Diversity Index (SDI) (abundance) and the Shannon Information Index (SII) (dominance) per study quadrat. The results were calculated by sampling quadrat and then averaged by all the quadrats within each vegetation class. As such, they are summarized in table 4. It can be seen from table 4 that the oldest and more mature forest succession classes (i.e. "Monte Alto" and "Kelenche") correspond to the highest species richness and abundance, and with variable dominance. This means, not surprisingly, that the highest diversity is in the oldest and mature forests. Therefore, arresting SABA and shifting cultivation not only sequesters carbon increasing fertility, but prevents CO_2 emissions, enhances the conservation of biodiversity and therefore prevents land degradation, thus achieving the synergies of conservation. The spatial distribution plant diversity (as represented by the species richness index in this case) across the study area is then displayed in figure 22a. Figures 22b and 22c show the spatial variability of Simpson's and Shannon's Indices respectively.

Figure 21. Scenario "SK15" of Carbon sequestration and stabilization (cropping on the same plot) of SABA shifting cultivation in K'ankab (Chromic Luvisols) soils under continuous annual cropping of corn-beans-squash, over the 12-year period, in Bacalar, Mexico.

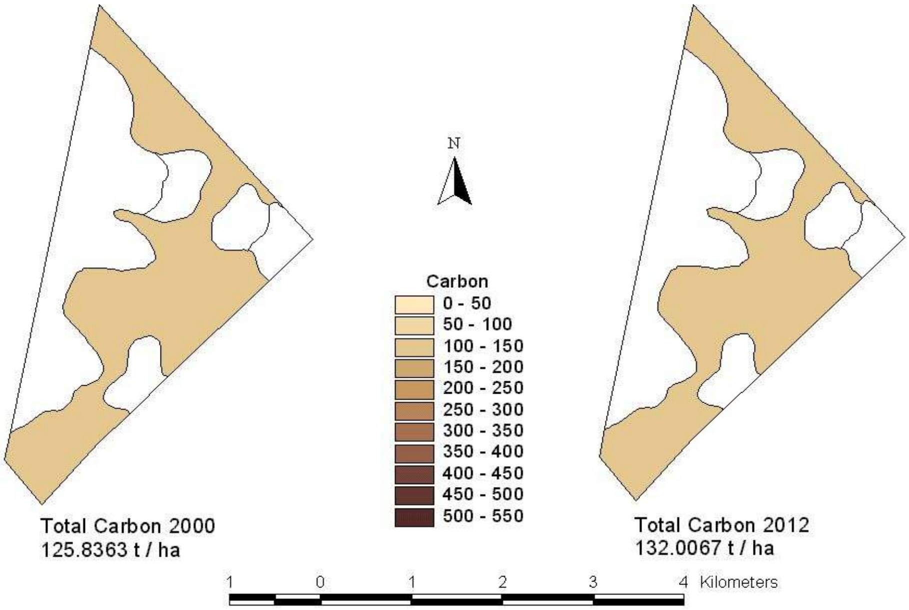


Table 4: Biodiversity indices by vegetation type, Bacalar, QR, Mexico.

VEGETATION TYPES	NUMBER OF SPECIES		SHANNON INDEX		SIMPSON INDEX	
	MEAN	STD. DEV.	MEAN	STD. DEV.	MEAN	STD. DEV.
Monte alto	34.82	5.61	3.05	0.28	0.92	0.03
Kelenche	32.10	5.33	2.89	0.20	0.91	0.02
Juche	28.17	6.10	2.69	0.28	0.89	0.03
Saakab	14.67	4.14	1.19	1.21	0.42	0.11
Akalche	3.67	2.80	0.45	0.40	0.21	0.12
Savanna	2.50	0.71	0.77	0.24	0.49	0.11

Conclusions

The methodological framework here proposed, with its tools and procedures was found very useful for conducting assessments of soil carbon stock and sequestration potentials and identifying synergistic win-win scenarios of land use, land use change and land management in different ago-ecological zones (e.g. the two case studies). The set of customized modelling tools, electronic field forms for data collection and databases available (e.g. "Soil-C" interface) to support the framework, were found particularly useful in exploring alternative scenarios of land use and management. Both, modelling tools and the framework are predicated on the key role of SOM in the ecosystem, enabling the convergence of multiple ecological benefits, which can be transformed into win-win situations for the farmer. The framework and tools enable such exploration by placing soil organic matter at the core of the methodology. The accrual of SOM is deemed crucial in any ecosystem, not only for its role in soil fertility and crop production (hence, food

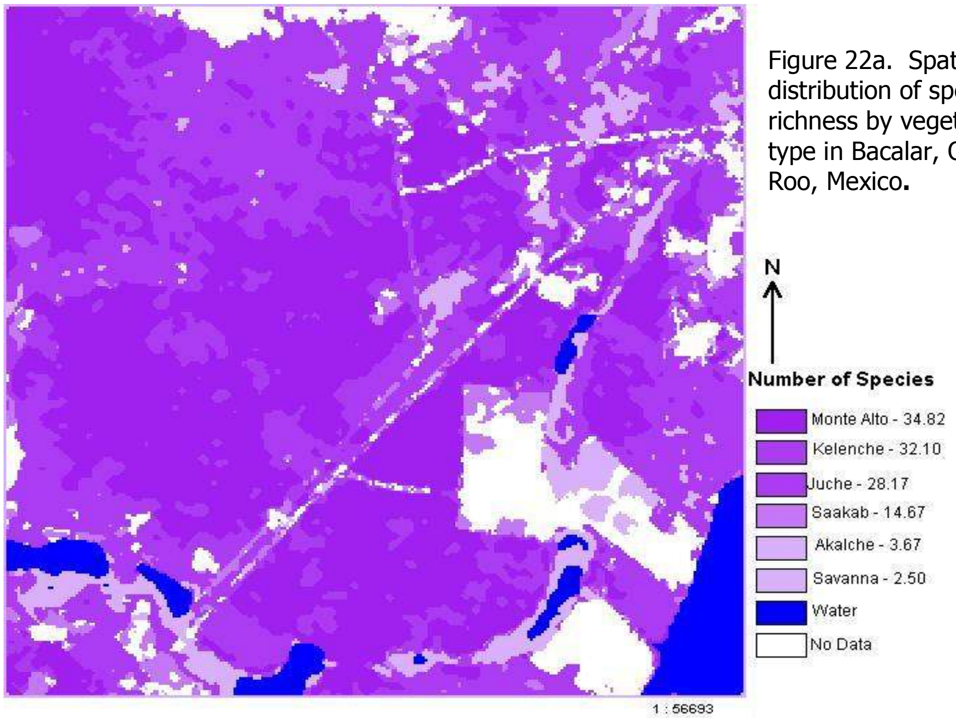


Figure 22a. Spatial distribution of species richness by vegetation type in Bacalar, Quintana Roo, Mexico**.**

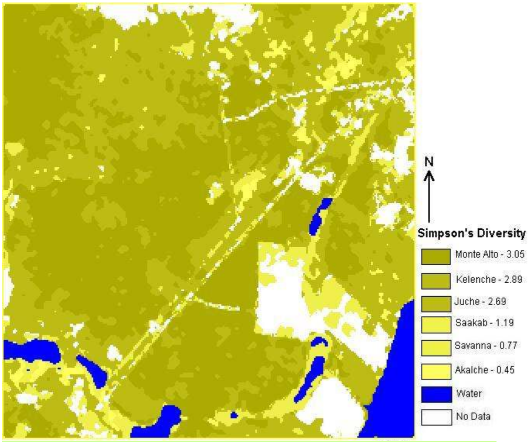


Figure 22b. Simpson's Index map

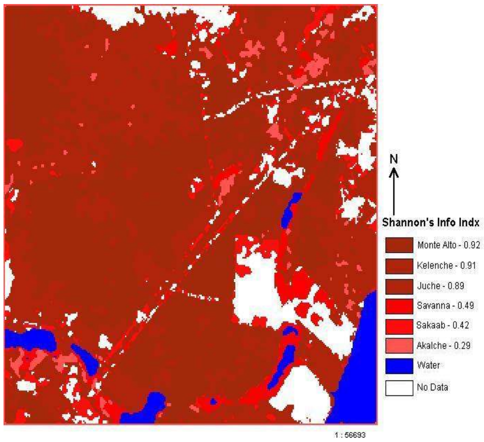


Fig 22c. Shannon's Index map

security) but also for the other ecosystem services that it brings, such as the conservation and the enhancement of biodiversity and the prevention of land degradation. This was demonstrated in the case studies, particularly in the Bacalar case study. The methods for the estimation of above-ground biomass have reached a level of reasonable accuracy. However there are still some sources of variation in the estimates and variability in the methods and circumstances that require further research in order to make biomass and carbon estimation methods, both standard and reliable. The up-scaling of biomass and carbon across relatively large areas can be achieved by exploiting existing useful relationships between band-ratio indices of satellite imagery and estimates of biomass on the ground, to enable the transformation of a band-ratio satellite into a map of carbon stock in biomass.

The integration of a suite of models of all kinds into a customized spatial decision-support system for assessments of carbon sequestration and synergistic ecological co-benefits, and for monitoring purposes, is highly desirable for it would bring methodological consistency, even in the face of the uncertainties of current day estimation methods. As starting point in determining the potential of lands for carbon sequestration and sinks projects, the status of indicators of soil biological degradation, through parametric semi-quantitative methods, such those in the framework proposed here, can be a very useful entry point in the identification and design of a sinks projects. The set of useful indicators to the current status of SOM can be used for indicating the health of soils, and the potential for GHG mitigation efforts. The procedures proposed here as part of the framework and their models and tools can fully exploit the virtues of Optimization Models as offered by the field of operations research in order to derive optimal scenarios of land use change and land management that also include economic and social decision variables to support decision making concerning carbon sinks and GHG mitigation measures. Further work to these tools should include the ability to include optimization criteria and multi-objective decision-making models. The present framework and its tools are targeted for application in field projects in support of initiatives in GHG mitigation and ecological co-benefits around the planet.

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