5. Soil carbon monitoring in the United Republic of Tanzania

SOIL ORGANIC CARBON STOCK INVENTORY IN THE UNITED REPUBLIC OF TANZANIA

Background and rationale

Among other non-industrialized (non-Annex I) countries of the UNFCCC, the United Republic of Tanzania had very limited and spatially unrepresentative information on soil carbon and former data did not enable estimation of the soil organic carbon stock on a country or regional scale. In this report, the United Republic of Tanzania represents a tropical non-Annex I country, where a nationwide soil survey needed to be designed in order to provide information necessary for national purposes, as well as for reporting under the UNFCCC.

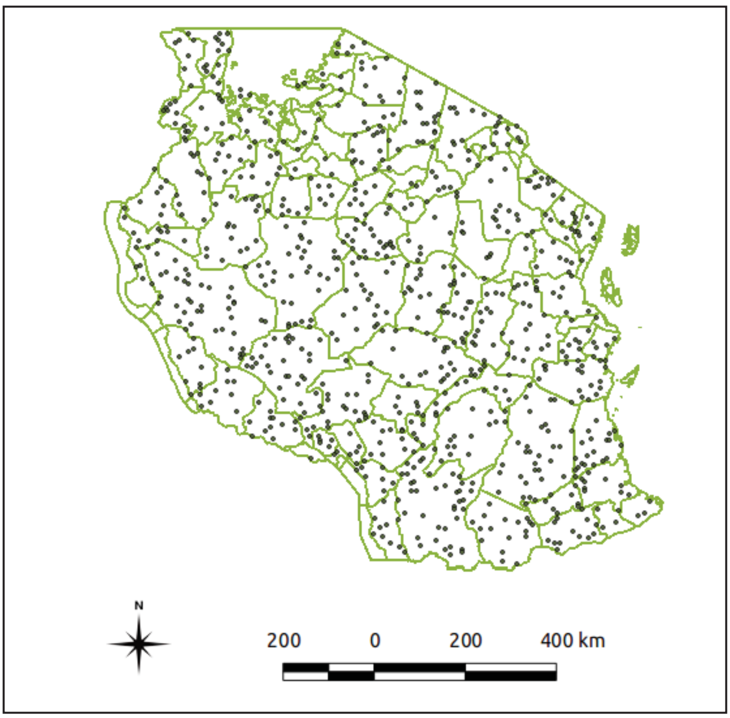
The objective of the first soil inventory is to obtain unbiased estimates for the mean and the between-site variation of the soil organic carbon stock in the United Republic of Tanzania. These estimates will be determined for three land-use categories: forest land (including natural and planted forests), cropland and grassland.

Soil organic matter is influenced by a number of factors, mainly climate (temperature and rainfall), vegetation types, soil types and human activities. The influence of climate and natural vegetation on the levels of soil organic matter is recognized over broad geographic areas. Generally, in similar moisture conditions and comparable soils and vegetation, the soil organic matter is higher in cooler climates than in warmer ones. Moreover, high rainfall promotes vegetation growth and hence production and accumulation of soil organic matter. Since plants (particularly natural vegetation) are the major source of soil organic matter, vegetation types and their density influence the soil organic carbon stock. Soil drainage and texture influence soil organic matter and hence soil organic carbon within local landscapes. Generally, fine-textured soils are known to have a higher soil organic matter content than sandy soils. This is mainly because the organic residues returned to fine-textured soils are generally higher than in coarse-textured soils as a result of their greater nutrient- and water-holding capacities, which promote greater plant production. In addition, the formation of clay-humus complexes in fine-textured soils minimizes soil organic matter degradation. Other factors that influence soil organic carbon content include human activities such as cropping and tillage systems and soil management practices. These factors should therefore be considered when planning a cost-effective long-term soil sampling scheme for a soil carbon monitoring system in the United Republic of Tanzania.

NAFORMA sampling design

In the United Republic of Tanzania, National Forestry Resources Monitoring and Assessment (NAFORMA) was designed in 2010, since the state and trends of forestry resources were largely unknown and available information was fragmented and outdated (Tomppo *et al.*, 2010; NAFORMA, 2010). NAFORMA utilizes stratified sampling design. In the first phase, a dense grid of clusters, at 5 x 5 km spacing, was made over the United Republic of Tanzania. From this grid the optimal sampling ratio (Phase II) was calculated for each stratum considering the following variables: wood volume estimates based on satellite images calibrated with field data from past inventories, measurement time and slope. In this stratification, information on soil properties (e.g. FAO World Reference Base for Soil Resources or the Harmonized World Soil Database [FAO and the International Institute for Applied Systems Analysis – IIASA]) was not used, since the major target was assessment of the growing stock. In addition, global soil databases focus more on morphological characteristics of the soil than on soil carbon quantity and dynamics. To come up with the final NAFORMA sampling design, the variations in number of plots, crew days and coefficients of variation of area and volume at different costs for the United Republic of Tanzania were tested. Eventually the model with 3 419 clusters and 32 551 plots to be measured in 6 259 days was adopted (estimated costs were USD2.5 million). The distribution of NAFORMA clusters countrywide is shown in Figure 6.

FIGURE 6
Location of the permanent sampling clusters of NAFORMA where soil samples are taken



The NAFORMA cluster is an inverted L-shaped arrangement of plots. The distance between clusters varies by stratum, from 10 to 45 km. A normal cluster in a flat terrain has ten plots, five on each leg. Clusters in difficult terrain in terms of accessibility and prohibitive slopes have six or eight plots. Forested areas have more clusters than non-forested areas. The original 5 x 5 km grid has therefore been thinned, based on the probability of favouring denser plots in areas with higher wood volume. The distance between plots in a cluster is 250 m. The actual total number of clusters equals 3 419, and the total number of plots equals 32 660. A quarter of the clusters (854) are permanent; the permanent clusters were also used in the soil survey.

The results of the first inventory form the basis for estimating changes in the soil organic carbon stock over time. These results will be needed independently of the method to be used to estimate temporal soil carbon changes. If these changes are to be estimated using repeated measurements of the soils after some years, the results of the first inventory provide reference data for the initial organic carbon stock of the soils as well as information necessary to design an effective and adequate sampling for the second inventory. If the changes over time are estimated using a model-based approach, such as that based on the Yasso07 soil carbon model, the results of the first inventory can be used to test the validity of the model-based soil carbon stock estimates or calibrate the model-based method to reproduce the measured soil carbon stock values.

Sampling design in first soil survey

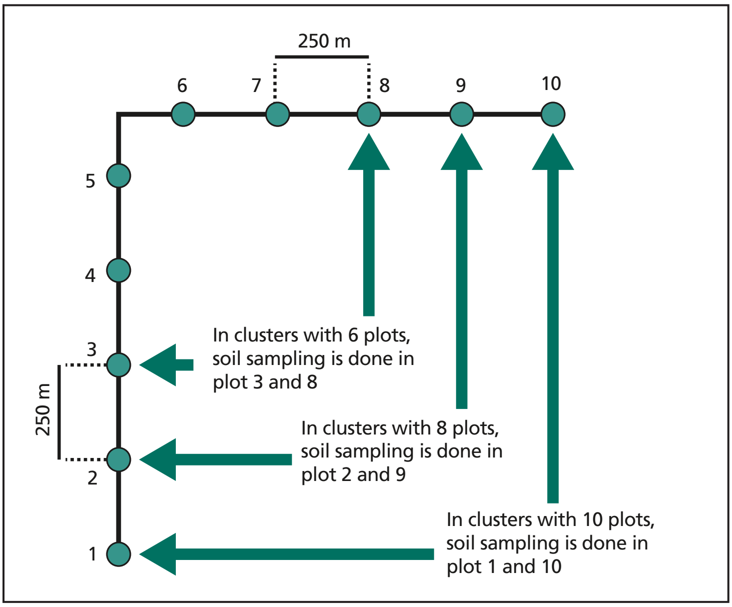
The soil sampling design consists of decisions at five hierarchic levels, namely:

- cluster selection for sampling
- sample plot selection within the clusters
- selection of sample point locations inside the sample plots
- selection of soil sample collection method and decision on sampling depth
- decisions on soil sample composition technique.

In the case of the Tanzanian soil survey, a grid of sampling clusters was designed as part of the planning process of the NAFORMA stratified sampling design (Tomppo *et al.*, 2010) and the soil survey used a subsample of the plots from permanent NAFORMA clusters (Figure 7). Soil samples were taken from each permanent cluster (n>800).

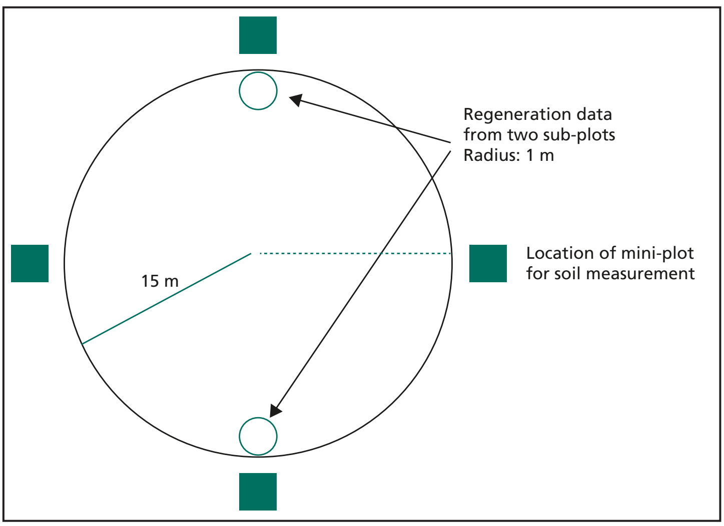
Systematic sampling of plots from each cluster is employed, since a priori information on the soil carbon changes in the sampled population is not available. The sampling gives the possibility of assessing the relationship between soil variables and stand variables as well as monitoring the effects of land-use changes on soil organic carbon by site. In practice, on each permanent cluster, two plots located at the extreme ends of the cluster were selected for soil sampling (Figure 7). Therefore, in a ten-plot cluster soil samples will be taken from plots one and ten, and in an eight-plot cluster they are taken from plots two and nine. In a six-plot cluster soil samples will be taken from plots three and eight.

FIGURE 7
Selection of plots for soil sampling from a permanent NAFORMA cluster



The NAFORMA plot consists of concentric circles of 1-, 5-, 10- and 15-m radii in which trees are measured depending upon their size. Soil samples are taken just outside the 15-m radius of the plots. At each soil sampling plot, four soil mini-pits are excavated and samples taken. The sampling points should be located at the main compass points east, south, west and north (Figure 8). In each pit, three samples are taken at soil depths of 1–10, 10–20 and 20–30 cm. Samples from the four pits are combined according to the three depth levels and put into one plastic bag to form a composite soil sample of the site.

FIGURE 8
Four soil sampling mini-pits are located on the circle of the inventory plot at the main compass points (east, south, west and north)



Soil sampling

On mineral soils, soil sampling will cover the organic soil layer on top of the mineral soil, if an organic layer exists, plus the topmost 0–30 cm mineral soil layer at each sample point. On organic soils, similar sampling protocol according to the topmost 0–30 cm layers will be applied (definitions of organic and mineral soils are given in Annex 3A.5 in IPCC, 2006). A soil mini-pit will be dug at each sampling location to collect soil samples (see Figure 9). One wall of the pit will be prepared for soil sampling. A volumetric soil sample (e.g. 150 ml, a cylinder with a diameter of 6 cm and height of 5.3 cm) will be taken from the middle of each 10-cm deep mineral soil layer (0–10, 10–20 and 20–30 cm). Where the soil is too hard to dig a pit 30-cm deep, sampling will be limited to the upper 10 or 20 cm layers, and this will be noted in field forms.

In the field, the soil samples from each layer should be removed from the sampling cylinders (see Figure 9) and put into plastic bags with all necessary identification information (sampling time, person in charge, cluster, plot, soil layer) on the cover (and nothing else). Soil sampling and any deviations from the sampling design should be described on the field form. Soil samples should be air-dried as soon as feasible. Air-drying can be done in normal room temperatures or in the sun to prevent soil samples from harmful microbiological activity before proper drying in a constant temperature of 40° C (oven drying).

If an organic layer exists, a sample of this layer is taken next to the soil pit on its northern side. The sample should be taken as near to the pit as possible, but from locations that have not been disturbed when digging the soil pit. It is taken by cutting a 20 x 20 cm piece of the entire thickness of the organic layer. The sample should be cleaned carefully from the remains of mineral soil, because contamination of mineral soil will add measurement error to the carbon analyses that follow.

This volume-specific sampling method is preferred over sampling a slice of soil covering the entire 0–30 cm soil layer for two important reasons. First, it is not possible to determine the volume weight of soil based on the slice, and this information is needed to calculate the stock of soil organic carbon (kg C/ha and kg C/m^3). Second, sampling a slice of soil can easily result in a considerable measurement error because soil carbon content varies with depth and it will be difficult to obtain a slice where each soil layer is equally represented.

FIGURE 9A
The locations (in 0–10, 10–20 and 20–30 cm soil layers) of the volumetric samples are marked on the wall of the soil pit

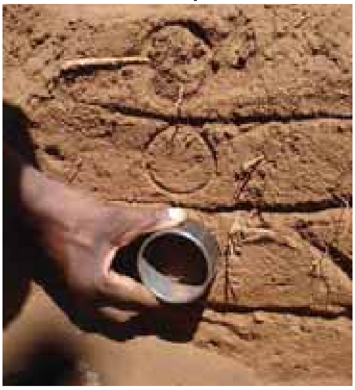


FIGURE 9C
The core with soil sample is extracted carefully from the wall of the pit, using a trowel or a knife if necessary

FIGURE 9D
Using a sharp field knife, any excess soil over the core should be removed to ensure a volumetric soil sample

FIGURE 9B
The sampling cylinder is pushed into the wall with a plastic hammer. When hammering, it helps to cover the cylinder with a wooden plank

FIGURE 9E
Where soil is dry and too loose *(top)* **to obtain a volumetric soil sample, it is more practical to take soil samples by pressing the cylinder in at the top** *(bottom)*

Photos by S. Dalsgaard

Observations at a sample point

The volume of stones is estimated visually from the wall of each soil pit by recording the coverage of stones in 10 percent classes (proportion of stones <10, 11–20, 21–30 percent …). The estimated stone volume is used in the calculations of the total carbon stock of the assessed soil layers (i.e. stone volume excluded, since there is no organic carbon in stones).

While in the field, the soil samples from the vertical side of the soil pits are also used to determine soil colour and estimate soil texture and structure. These properties are ascertained at the middle of 0–10, 10–20 and 20–30 cm depths. The protocol for estimation is included in the field manual (NAFORMA, 2010), Annex 3a, 3b and 3c. To save time in the field, soil colour and texture can be determined in the laboratory.

Compositing soil samples

All soil samples that represent the same soil layer are composited by a plot to reduce the costs of laboratory analyses. These composite samples should always comprise the same number of subsamples. Samples taken from different soil layers are kept separate as well as samples taken from different plots.

Plot-level samples are needed to be able to estimate variability between plots and to allow monitoring of soil carbon changes with a repeated inventory according to land-use category. Information on variability is necessary to calculate statistical confidence estimates for the soil organic carbon estimates obtained. Furthermore, these are used in the planning of an effective and adequate sampling for a repeated inventory in the future. Plot-level soil carbon estimates are also necessary in order to relate the results of soil carbon stocks and possible future soil carbon changes to the present and changed stand and tree characteristics. Sampling the same sites again as part of the possible repeated inventory is also cost efficient, because the resulting estimate of the change in soil carbon will be more reliable.

Feasibility of the soil sampling design and its practical implementation

The soil sampling design was planned for a soil survey and, as such, it is not neccessarily feasible for soil carbon monitoring purposes. Planning an appropriate soil sampling scheme for soil organic carbon monitoring is a big challenge. According to Rossi *et al.* (2009), measurements of soil organic carbon are normally restricted by the ability to produce rapid, cost-effective and precise sampling schemes. In order to design an effective sampling strategy (including stratification according to relevant variables that reflect rate of change) for soil carbon monitoring, additional data on spatial and temporal variation of the soil organic carbon are needed. In a study conducted in five common forest types in the southeastern United Republic of Tanzania, Rossi *et al.* (2009) concluded that the optimal sampling scheme varies greatly with vegetation type as a result of the different spatial behaviour of soil organic carbon in forests and depends on the required precision and research question. Hence, as discussed in Chapter 2, under Information needed to design a repeated soil carbon inventory., these factors should be taken into consideration when designing soil sampling strategies for monitoring soil organic carbon in tropical and subtropical regions, including the United Republic of Tanzania.

Continuous changes in land use and its effect on soil organic carbon is another challenge for soil carbon monitoring in the United Republic of Tanzania. For example, declines in soil organic matter as a result of converting forest land or natural vegetation to agricultural land have been reported in chromic luvisols in the semi-arid areas of the northern United Republic of Tanzania. These declines varied with initial vegetation type and were more rapid in coarse-textured rather than in fine-textured soils (Solomon, Lehmann and Zech, 2000). This implies that periodic measurements of soil organic carbon at the same location under the same land-use type for long periods will produce data that change consistently over time. Soil sampling in the NAFORMA permanent clusters (Figure 6) for soil organic carbon monitoring is currently the most practical and cost-effective strategy for the United Republic of Tanzania since these clusters cover the whole country and are also being sampled by NAFORMA for other related parameters that can explain soil organic carbon changes over time. The challenge here is that the sampling density in NAFORMA clusters is generally uniform throughout the country irrespective of vegetation or land-use type. It has been found by Rossi *et al.* (2009) that the optimal sampling distance for measuring mean soil organic carbon stocks varies with vegetation type and hence with land-use type. To be cost effective, sampling density should be lower in extensive areas with similar land cover or vegetation types than in areas with different vegetation types.

Because of practical limitations, only four subsamples per plot were collected from layers 0–10, 10–20 and 20–30 cm. However, effective soil monitoring, i.e. observing possible changes, may need ten to 30 subsamples per plot (from each soil layer) (e.g. Tamminen, 2003; Tamminen and Derome, 2005) and sampling for monitoring purposes will be more laborious. In the first soil survey conducted, soil samples were collected from the middle of layers 0–10, 10–20 and 20–30 cm, and the topmost 0–10 cm layer was not sampled totally. Since soil organic carbon content in the topmost 2 cm may be higher than in the 2–8 cm layer where the sample was taken, this sampling may slightly underestimate soil carbon stock, but it is less sensitive to between-team variation in the sampling technique (how carefully the litter layer is removed).

Soil sampling design, sampling practices in the field and efficacy of laboratory analyses were evaluated in March 2012; they appeared to have followed the instructions given and produced reliable soil survey data for the estimation of soil carbon stock in the United Republic of Tanzania.

MEASUREMENTS NEEDED FOR DESIGNING A REPEATED SOIL CARBON SURVEY IN THE UNITED REPUBLIC OF TANZANIA

Number of soil sampling plots to be measured

In the United Republic of Tanzania, the regionally representative mean soil carbon stock and its standard deviation are measured by NAFORMA and results will be available in the near future. This information, together with the estimate of soil carbon change, is used for the assessment of the number of sample plots needed for evaluation of changes with repeated measurements (see Chapter 2 for more details). A first estimate of the rate of soil carbon change according to land-use or vegetation cover classes can be derived with the help of soil modelling. The potential interval of soil carbon measurements may be a decade or a minimum of five years, but an appropriate interval can be determined when a priori information on between-site variation of soil carbon stock and an estimate of the rate of change are available (see Chapter 2).

Within-site variation and determination of number of subsamples per plot

Knowledge on within-site variation in the soil carbon stock is used to determine the number of subsamples per plot yielding estimates that are accurate and precise enough for monitoring purposes. In general, 20–30 subsamples per plot are considered to be an appropriate sample size (Tamminen, 2003; Tamminen and Derome, 2005; Rossi *et al.*, 2009; Muukkonen, Häkkinen and Mäkipää, 2009) but, in practice, a much smaller number of subsamples is currently used (e.g. Munishi and Shear, 2004). In the United Republic of Tanzania, a study on spatial within-site variation of soil carbon stock in different soil layers and in different soil types needs to be conducted before the second round of a soil inventory. Results obtained will improve the efficiency of consecutive inventories in the United Republic of Tanzania and in other countries with similar soil types and climatic conditions.

MODEL-BASED METHOD

Overview of the task

Practical application of a model-based soil carbon monitoring system in the United Republic of Tanzania is explained in this section, according to the steps described in Chapter 3, under Practical application of a model-based soil carbon monitoring system.

In the United Republic of Tanzania, the model-based soil carbon monitoring system needs to be employed, which relies on more limited input data than in countries having longer traditions of forest and soil inventories. In the United Republic of Tanzania, there is less input information available, the existing information may be less detailed or less reliable and information on the past is probably extremely limited. It is worth noting, however, that the availability of input information is currently improving greatly as a result of the first NAFORMA and soil carbon inventories conducted in the country.

The above evaluation of the situation follows from a NAFORMA description (mnrt.go.tz > Programmes and projects), which reads: "In Tanzania, the state and trends of forestry resources are largely unknown and the existing information is fragmented and outdated". "National Forestry Resources Monitoring and Assessment (NAFORMA) of Tanzania is a multistakeholder project aimed at capturing accurate and timely information regarding the state and extent of the forest and trees outside forest (TOF) resources of Tanzania. This is done through mapping the current and historical extent of the forest and TOF resources and by establishing a system of permanent sample sites throughout the country. Combined, these will allow for future monitoring of the development of the forest resources through continual re-measurements. NAFORMA was launched in May 2009."

The ongoing inventories of forest resources and soil carbon will provide valuable information to establish and apply a model-based soil carbon monitoring system in the United Republic of Tanzania. It will then be possible to estimate current pools of soil carbon and thus start evaluating the reliability of the model-based soil carbon monitoring system in the country. As soon as the forest inventory is repeated in the future, the model-based soil carbon monitoring system can be used to estimate changes in the soil carbon pools compared with the present situation.

The model-based soil carbon monitoring system could also be used for scenarios of soil carbon development based on those of forest resource development if such forest scenarios were available. These scenarios could be used to study the effects of alternative trends in forest resources on soil carbon pools and to support the design of possible future soil carbon inventories using similar methods to those applied in northern forests (Peltoniemi *et al.*, 2007).

The basic source of biomass and litter production information for the model-based soil carbon monitoring system is NAFORMA forest inventory data. Thus, the model-based soil carbon monitoring system is elementally linked to the NAFORMA forest inventory. However, before being used in soil carbon modelling, the NAFORMA data must be complemented by information on biomass conversion and biomass turnover to estimate litter production. Some local information may be available on these complementing factors but it may also be necessary to use data from other countries and international literature.

Climate data needed for model-based soil carbon monitoring may be obtained from local sources or global databases, such as the IPCC Data Distribution Centre.

Soil carbon model choice

After forming an overall picture of the task (see previous section), the next step in applying a model-based soil carbon monitoring system in the United Republic of Tanzania is the selection of the soil carbon model to be used. There are certain requirements for the soil carbon model that may be used as selection criteria.

These requirements and the selection criteria can be grouped into four categories.

1. Relevancy. The soil carbon model needs to account for the most important factors affecting soil carbon pools and changes in soil carbon pools in the United Republic of Tanzania when it is used as a component of the model-based soil carbon monitoring system. These factors are basically i) climate; ii) litter input quantity and quality; iii) natural disturbances; iv) ecosystem management; and v) land-use change.
2. Practicability. It must be feasible to apply the soil carbon model in practice. This means that i) input information to the model is available; ii) it is possible to link the model calculations to NAFORMA information; and iii) the soil carbon model is suitable for establishing a practicable model-based soil carbon monitoring system.
3. Reliability. The soil carbon model needs to give reliable results in the soil carbon pool, change in the soil carbon pool, decomposition rate of litter and soil organic carbon, and heterotrophic soil respiration.
4. REDD+-readiness. The soil carbon model and the results produced need to meet the criteria set for carbon accounting systems under the REDD+ mechanism.

It is probably most practicable to select the soil carbon model to be used from the existing established soil carbon models such as CENTURY (Parton *et al.*, 1987); RothC (Coleman and Jenkinson, 1996); ROMUL (Chertov *et al.*, 2001); SCUAF (Young *et al.*, 1998) and Yasso07 (Tuomi *et al.*, 2009; 2011). Many current soil carbon models meet the selection criteria and could thus be used. However, if a complicated model with a lot of input data requirements is selected, all these data may not be available across the United Republic of Tanzania and it may be necessary to run the model using some default values. Some models may also be more suitable for a statistically sound uncertainty analysis of the results.

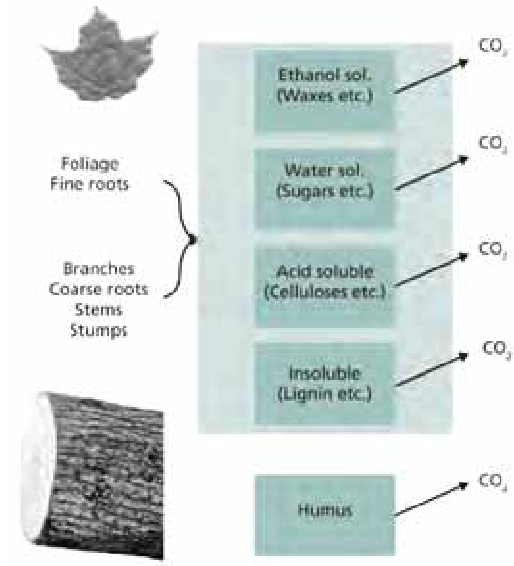
Yasso07 is one of the soil carbon models meeting the selection criteria (Figures 10, 11). The advantages of this model are i) that it requires limited and generally available input data; ii) the results of the model are accompanied by statistically meaningful uncertainty estimates; iii) it has been developed using large worldwide data sets also including measurements in the tropics; and iv) it has already been used for UNFCCC reporting in industrialized countries.

Information on uncertainty will improve the completeness of soil carbon estimates in line with UNFCCC decision 17/CP.8 stating that "non-Annex I Parties to the UNFCCC are encouraged to provide information on uncertainty associated with GHG inventory data, and to describe the methodologies used, if any, for estimating these uncertainties".

Whatever soil carbon model is selected it must give reliable results on soil carbon stocks, changes in soil carbon stocks and soil carbon dioxide emissions as well as the effects of the factors affecting these features.

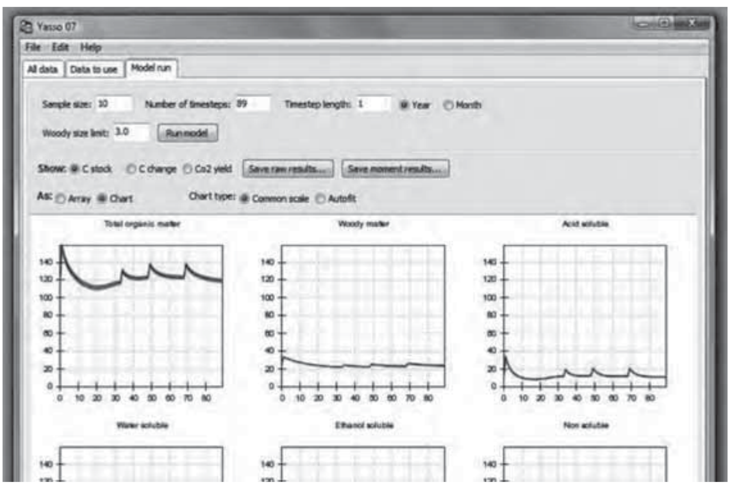
The remaining sections describing the application of a model-based soil carbon monitoring system in the United Republic of Tanzania are based on Yasso07, since this was selected as the soil carbon model to be used. Nevertheless, most of the information also applies to the use of any other soil carbon model.

FIGURE 10
Flow chart of the Yasso07 litter and soil carbon model



Source: Tuomi *et al.*, 2008; 2009; 2011; Thum *et al.*, 2011
Note: The boxes represent fractions of soil organic carbon, the arrows carbon fluxes. For input information, the Yasso07 model uses data on the quantity and quality of carbon input to soil and basic climate data. Output of the model consists of estimates for the stock of soil organic carbon, changes in the soil carbon stock and soil carbon dioxide emissions resulting from heterotrophic respiration.

FIGURE 11
The Yasso07 litter and soil carbon model can be run on a user interface



*Source:*Tuomi *et al.*, 2011
Note: This is available for Windows, Macintosh and Linux computer environments. It is useful both for learning the model and for limited studies. The computer code of the model is also available, which is more useful for extensive studies. The user interface, code and information are available at www.environment.fi/syke/yasso/

Reliability of model-calculated soil carbon estimates

The suitability of different soil carbon models for the model-based soil carbon monitoring system in the United Republic of Tanzania was discussed in the previous section. An essential prerequisite for the actual usefulness of any soil carbon model in this context is the reliability of the results of the model when linked to the entire monitoring system.

The reliability of the soil carbon results can be tested by comparing model-calculated estimates with measurements taken in the United Republic of Tanzania or under comparable conditions elsewhere. Relevant variables to compare are the soil carbon pool, soil carbon changes and decomposition rate of litter and soil organic matter.

Comparisons with data on the soil carbon pool can be carried out at site or regional scale. The soil carbon inventory carried out as part of NAFORMA will produce regional estimates of the soil carbon pool, which can be compared with similar estimates calculated using the model-based soil carbon monitoring system. These kinds of comparisons can also be conducted at a site scale if such data on the soil carbon pool are available. Similar comparisons can be carried out in terms of soil carbon pool changes if data are available.

Comparisons with data on litter decomposition can be conducted using measurements already taken elsewhere under similar climate conditions or in experiments established specifically for this purpose in the United Republic of Tanzania. For example, Yasso07 databases already contain litter decomposition measurements from the tropics in Central America (Tuomi *et al.*, 2009) and recent studies have been carried out in Benin in Africa (Guendehou *et al.*, submitted manuscript). Other soil carbon models have also been used in investigations in the tropics. Measurements on litter decomposition in the major land cover types in the United Republic of Tanzania would be highly useful.

If these comparisons reveal that the model-calculated estimates deviate significantly from the measurements in any way, then the model-based calculation system needs to be improved. It may be possible to recalibrate the soil carbon model using the new measurements. If this recalibration does not correct the error, it will be necessary to find a reason for the deviation in the structure of the model and modify it in order to solve the problem. This kind of continuous evaluation and improvement has already been a fundamental part of the development of the Yasso07 soil carbon model and similar studies are currently under way.

Reliability control of the soil carbon model is an important step in applying the model-based soil carbon monitoring system in the United Republic of Tanzania. It will be necessary to test the model adequately against measured data to evaluate the reliability and dependability of model-calculated results correctly.

Spatial calculation units

There are a few issues to be accounted for when deciding upon the geographic calculation units to be applied in model-based soil carbon monitoring in the United Republic of Tanzania, namely i) the availability of input data for these units; ii) homogeneity of conditions inside the units with respect to the soil carbon cycle; and iii) practical issues, such as the technical feasibility of the calculations and the spatial detail needed in the use of results. It is worth noting that the spatial calculation units may be non-uniform regions or uniform pixels.

Of the types of input information, climate data are probably the most flexible regarding the calculation units. Climate data can be obtained on a grid and it is possible to interpolate this information for more detailed resolutions or summarize it for coarser resolutions. It may also be possible to derive information on litter input information separately for each NAFORMA forest inventory site. However, it is still not certain whether it is feasible to carry out calculations at this level of detail by inventory site because it may not be possible to calculate estimates for the initial soil carbon pool separately for each inventory site (see section on Initial soil carbon stock). The method of accounting for land-use change may set its own restrictions on the choice of spatial resolution of soil carbon calculations.

Climate conditions need to be adequately homogenous inside the spatial calculation units, because climate is an essential factor affecting the soil carbon cycle. This is especially relevant if relatively large regions are chosen for the calculation units. The calculations of litter input may be at a more detailed spatial resolution, since it is possible to pool the litter input values over a larger region and use these pooled values in actual soil carbon calculations.

Litter input and litter quality estimates

NAFORMA forest inventory data are the primary source of information to estimate litter input to soil in each spatial calculation unit. The use of these data forms a major link between the model-based soil carbon monitoring system and the NAFORMA forest inventory. In some areas in the United Republic of Tanzania, vegetation other than trees contributes significantly to litter production. In these areas, it is also important to account for this vegetation in order to estimate the total litter production correctly.

Among other things, the NAFORMA forest inventory produces estimates of forest resources in terms of timber volume, as forest inventories usually do. To derive estimates of litter production from these estimates of timber volume, the latter are usually converted to biomass estimates by tree biomass component (foliage, branches, stem, coarse roots and fine roots) using biomass expansion factors. Litter production estimates are then calculated from the biomass estimates by multiplying them by biomass-component-specific biomass turnover rates.

Timber volume -> (biomass expansion factors) -> biomass by biomass component (foliage, branches, stem, coarse roots and fine roots) -> (biomass turnover rates) -> litter input to soil from each biomass component.

The estimates of litter production are needed separately for each biomass component because litter of these components decomposes at different rates in soil.

Information needed for this derivation of litter production estimates from timber volume estimates may probably be obtained to some extent from specific ecosystem studies in the United Republic of Tanzania. Additional biomass and litter studies are suggested as one type of local measurement that would support the application of the model-based soil carbon monitoring system. Nevertheless, it seems necessary to complement the Tanzanian biomass and litter production information with similar information available elsewhere under comparable conditions.

Carbon is also brought to soil in the form of residues of ecosystem management operations (e.g. forest harvesting) and as a result of natural disturbances. These components of the soil carbon input must be estimated and included in the model-based soil carbon monitoring system. It is also important to estimate any existing litter production of vegetation other than trees.

In addition to the quantity of litter input to the soil, soil carbon models require information on the quality of the litter. This may be obtained from local sources to some extent but it may be necessary to complement the information using databases related to the soil carbon model to be used.

Climate data

Climate data requirements vary from one soil carbon model to another. However, each model uses information on temperature and precipitation in some form, because temperature and moisture are the main climate variables affecting carbon cycling in soil. It appears that the climate data needed for each model is available for the United Republic of Tanzania, either from local sources or from global databases, such as those available at the IPCC Data Distribution Centre.

As discussed above (section on Spatial calculation units), it may be necessary to fit the spatial resolution of the climate data to that of the spatial calculation units. This is quite a straightforward operation if the primary climate data are at quite a dense resolution. A change in the resolution by interpolating does not thus cause any significant error.

Land-use change estimates

The method of taking into account the effects of land-use change in soil carbon calculations depends on the spatial resolution of the land-use information and the spatial calculation units used. If the calculations are carried out separately for different land-use classes, land-use change means transfer of soil carbon from one land-use category to another. If the calculations are carried out for entire regions and the results summed over various land-use categories, land-use change is accounted for by changing the quantity and quality of carbon input to soil (as a result of changes in vegetation, ecosystem management and natural disturbances).

Initial soil carbon stock

Simulations of soil carbon using a dynamic model are usually started from steady-state conditions. This means that it is assumed that the input of carbon to soil equals the output of carbon from soil and, consequently, the carbon pool of soil does not change over time. The steady-state assumption is commonly used because it is the only practical way to start calculations and come up with a division of the total soil organic carbon between the pools of a soil carbon model. The suitability of this approach and assumption needs to be considered carefully in the United Republic of Tanzania and possible consequences carefully evaluated. Uncertainty about the initial soil carbon pool can be accounted for in the overall uncertainty analysis of the model-based soil carbon monitoring system.

The initial steady-state soil carbon pool needs to be calculated separately for each spatial calculation unit. There are two alternative methods of calculating these initial pools: i) by assuming steady state with litter input at the beginning of the calculation; or ii) making the model-calculated soil carbon pools similar to those measured in the soil carbon inventory by adjusting litter input to soil as needed.

Estimating these initial steady-state pools and comparing them with measured soil carbon pool values provide information on the consistency of the model-based soil carbon monitoring method compared with measurements. If the first method above is used and the calculated pools deviate significantly from the measured pools, this indicates that either i) litter input and soil carbon cycle are calculated correctly but the soil carbon pool is not in a steady state; ii) litter input or soil carbon cycle or both are calculated incorrectly but soil is still in a steady state; or iii) same as ii) but soil is not in a steady state. A possible issue related to the second method above is that if it is necessary to change the litter input values to come up with the inventoried soil carbon pool values it would be difficult to know which litter input values to use in the actual soil carbon simulations. It would be inconsistent to use the adjusted values to calculate the steady state and continue using non-adjusted values for the rest of the calculation period.

Simulation of soil carbon changes

The final step in applying the model-based soil carbon monitoring system is the actual simulation of the cycling of soil carbon. In this simulation, the initial soil carbon pools determined for each spatial calculation unit are used as starting-points. Time series of the driving variables (litter input, climate, land-use change, natural disturbances and ecosystem management) are used as input to the soil carbon model, and the model calculates the development of the soil carbon pool.

LOCAL MEASUREMENTS TO SUPPORT THE MODEL APPLICATION

Purpose of local measurements

Local measurements, in addition to NAFORMA forest inventory data, can support the application of the model-based soil carbon monitoring system in the United Republic of Tanzania in various ways. These measurements can be used i) as input data to the calculations; ii) for testing the validity of the system, i.e. the reliability of the results obtained; and iii) for improving the soil carbon model by recalibrating or restructuring it where necessary.

Particularly useful local measurements include data on the soil carbon pool, decomposition rate and chemical quality of litter and litter production.

Soil carbon pool

The size of the soil carbon pool is a principal variable of the model-based soil carbon monitoring system. Many changes in the pool are calculated in proportion to its size. It is thus essential that the model-calculated estimates for the size of the soil carbon pool are reliable.

The soil carbon inventory conducted as part of NAFORMA data collection produces valuable information on the carbon pool of soil in the United Republic of Tanzania. These data can be used to test the validity of the model-based soil carbon monitoring system, improve it if needed and determine the initial soil carbon pools to be used as starting values of model-based soil carbon calculations.

Other local soil carbon measurements are also useful, where available. However, these may be taken for different purposes, particularly for soil fertility studies. The main difference that may make data from these measurements not comparable is that the sampling protocol employed may not be as representative across the entire country as the one used for the soil carbon inventory conducted by NAFORMA.

Litter decomposition and litter chemistry

Litter decomposition is an important process affecting changes in the soil carbon pool and heterotrophic soil respiration, especially at relatively short time scales of months or years. For this reason, in order to obtain correct estimates of soil carbon changes at these time scales, litter decomposition estimates must be reliable.

Litter chemical quality is used as an input variable of the Yasso07 model, and it is taken into account by dividing the litter into four chemical fractions.

Local measurements of litter decomposition and litter chemical quality thus provide valuable information supporting the model-based soil carbon monitoring system in the United Republic of Tanzania. An efficient way to collect this information is to conduct harmonized litter decomposition experiments. These experiments should aim at covering the range of variability in the decomposition rate and the chemical composition of common tree species across the United Republic of Tanzania.

A practical way of measuring the litter decomposition rate is to use the litter bag method (e.g. andrewsforest.oregonstate.edu/research/intersite/lidet.htm/). In this method, litter is left to decompose in mesh bags in the field for varying periods (months to a year in the tropics) and mass loss and chemical quality of the litter are followed by sampling the litter bags at certain intervals.

In practice, it would be useful to select litter of some of the most common tree species for a litter decomposition experiment. The sites of the experiments should, if possible, cover the main ranges across the United Republic of Tanzania of variability in temperature and precipitation, which are the main climate factors affecting litter decomposition. Such an experiment would provide valuable and useful information for testing the validity of litter decomposition estimates calculated using the Yasso07 soil carbon model. The data obtained could also be used to recalibrate the model for use in the country if necessary.

This kind of an experiment has already been conducted in Benin to support a national Yasso07 application. The experiment there resulted in valuable experience on conducting litter bag experiments and using the data to improve the Yasso07 model.

Litter production

Estimates of litter production provide essential input information for the model-based soil carbon monitoring system in the United Republic of Tanzania. These estimates are as crucial to soil carbon estimates as the soil carbon modelling itself, because model-calculated soil carbon estimates are affected directly by litter production estimates. For this reason, local measurements of litter production would provide crucial support.

RECOMMENDATIONS FOR SOIL CARBON MONITORING IN THE UNITED REPUBLIC OF TANZANIA

There are various aspects to consider when planning future actions of soil carbon monitoring in the United Republic of Tanzania. Relevant aspects include at least: i) acknowledgement of the growing need for soil carbon monitoring information; ii) ongoing and planned work and processes; iii) estimated cost efficiency; and iv) no-regret principle. With regard to these factors, the following are rational steps to be taken.

1. *Conduct the first soil carbon survey using resources available and the guidelines given in this report.* This survey will result in estimates for the carbon stock of soil and geographic distribution of the stock across the United Republic of Tanzania, based on actual samples from all permanent sampling clusters. These estimates are important as reference for any future soil carbon monitoring activities. Based on the variability observed during the first soil carbon survey, a cost-efficient soil sampling scheme will be proposed for a long-term soil carbon monitoring system. The soil samples obtained during the first survey include soil organic carbon, soil pH, bulk density, soil texture and soil colour. In forthcoming inventories, soil properties that do not normally change within a short period, such as soil texture, need not be determined, hence reducing the costs of analyses.
2. *Link a soil carbon simulation model to the NAFORMA forest inventory system and use this system to simulate scenarios of soil carbon development.* This can be done at relatively low cost and the system will support any method used to monitor soil carbon. If the survey-based method is applied, estimates of soil carbon changes can be used to design an effective sampling scheme for the second (repeated) soil carbon survey. If the model-based method is applied, this step actually means establishment of the method. In other words, since the United Republic of Tanzania is aiming at soil carbon monitoring, this would be a useful step in any case. The model needs to be tested and verified, and applicability in the NAFORMA context confirmed (see above section on Reliability of model-calculated soil carbon estimates)

before application in reporting soil organic carbon stock and carbon stock change estimates under UNFCCC is possible.

3. *Take actions to improve the reliability of the model-based system, if this system is to play a role in soil carbon monitoring.* The following steps support the development of the model-based method in particular. They can also been seen to support the survey-based method if the simulation of soil carbon changes is considered practicable to improve the efficiency of the second soil carbon survey. Experiments on litter decomposition rate should be carried out. This is important in order to relate the decomposition rate of different litter types to the rate at which organic matter is returned the soils. The validity of soil carbon modelling should be tested by comparing results with the first soil carbon survey and local measurements of litter decomposition rate. If necessary, the model should be improved according to the validity tests.

These steps will enable progress in soil carbon monitoring to be made, using either the repeated soil carbon survey or the model-based approach.