
A Simple Approach to Estimate Soil Organic Carbon and Soil CO₂ Emission

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RECEIVED ON 15.09.2010 ACCEPTED ON 03.01.2011

ABSTRACT

SOC (Soil Organic Carbon) and soil CO₂ (Carbon Dioxide) emission are among the indicator of carbon sequestration and hence global climate change. Researchers in developed countries benefit from advance technologies to estimate C (Carbon) sequestration. However, access to the latest technologies has always been challenging in developing countries to conduct such estimates. This paper presents a simple and comprehensive approach for estimating SOC and soil CO₂ emission from arable- and forest soils. The approach includes various protocols that can be followed in laboratories of the research organizations or academic institutions equipped with basic research instruments and technology. The protocols involve soil sampling, sample analysis for selected properties, and the use of a worldwide tested Rothamsted carbon turnover model. With this approach, it is possible to quantify SOC and soil CO₂ emission over short- and long-term basis for global climate change assessment studies.

Key Words: CO₂ Emission, Global Climate Change, Rothamsted Carbon Turnover Model, SOC.

1. INTRODUCTION

Scientists worldwide are agreeing on the reality of global climate change that results from human activities, i.e. industrial revolution, enhanced and frequent use of automobiles, and agricultural practices. The global climate change is becoming reality day by day since 1960 the 90% of the warmest years worldwide have occurred in the last two decades [1]. The year 1998, in the Northern Hemisphere, was the warmest among the last 1000 years [2], and the year 2001 was the second warmest on record [3]. Atmospheric greenhouse gases including CO₂ cause global warming effects. Twenty-Five percent of the total atmospheric CO₂ comes from agricultural activities [4]. Agricultural practices, at the same time, can enhance C sequestration

in soil [5] as with increased cropping intensity, more amount of crop residue and resultantly more C is sequestered in the soil than with a crop fallow system. Carbon dioxide is taken up by plants through photosynthesis and incorporated into soil through living plant matter as:



After plants die, the carbon-rich leaves plant matter decays in the soil and become SOM (Soil Organic Matter). Soil temperature as well as soil moisture increase the SOM decomposition rate that influences environmental processes at a global scale [6].

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In addition to photosynthesis and the decomposition of plant residues, the application of FYM (Farm Yard Manure) to the arable soils can increase C storage or sequestration [7]. A strongly stable form of SOM called humus is formed if SOM is left undisturbed in the soil. The SOM contains 58% of SOC. Benefit of increased SOC is not only in the form of improved soil structure and strong water-nutrient relationship, but also the soil ability sequester carbon and minimize soil emission of CO₂ [8].

Other than agricultural soils, forestlands affect global carbon cycle [9]. The forestlands sequester approximately 62-78% of global terrestrial C, seventy percent of which is sequestered in soil [10]. Because of slow turnover of C, the forestlands accumulate more C than the arable soils [11].

Global climate change, carbon sequestration, and environmental pollution are assessed with SOC and soil CO₂ emission. Modern technology and research tools are handy in developed countries but most of the times lack in developing countries. I have reviewed and present a simple but comprehensive approach for estimating C sequestration and CO₂ emission. It is believed that the set of protocols in this approach is suitable for conducting research in developing countries such as Pakistan. The steps involve soil sample collection, their analysis for selected basic properties, and the use of a worldwide tested free accessible Rothamsted carbon turnover model 26.3 [12] to be referred as RothC from here onward.

2. THE APPROACH

The contents reviewed and discussed in this section are required during estimation of SOC and soil CO₂ emission with RothC.

2.1 Soil Sampling

Three replicates of bulk and intact soil core samples can be taken from the study location at the depth to be considered for SOC estimation, i.e. to 10 or 20cm soil layer. The bulk soil samples should be thoroughly mixed to produce a representative sample. These samples must be air dried, sieved (<2mm), and sub-sampled for further use. The intact core samples do not need further processing as they are meant to be used for soil bulk density (ρ_b) determination.

2.2 Clay Contents of Soil

The representative sub-samples can be used for particle size analysis. Most of the research laboratories have facilities to conduct particle size analysis of a sample to determine its soil textural class (i.e. the portion of soil major particles, e.g. sand, silt, and clay). The particle size analysis uses hydrometer method [13], sieve analysis and/or pipet test, the major features of which are the destruction or dispersion of soil aggregates into discrete units by chemical, mechanical, or ultrasonic means. In absence of facilities to conduct standard particle size analysis, a comparatively low-tech alternative method can be used. This method estimates an approximate value of clay percent accurate enough to be used in RothC soil management file.

Pour a handful of the sub-sample sample in a glass jar half full of water. In order to disperse the soil particles, add a teaspoon of any kind of detergent powder. Fill up the jar with water, tighten the lid to make sure that the solution does not leak, and shake it well for over 5 minutes in order to mix the soap with water and soil. Let the soil particle settle for 24-48 hours. Sand, silt, and clay particles take 60-90 minutes, 1-2, and 24-48 hours, respectively, to settle. Sand being heavier settles in the bottom, silt follows it,

and clay being the lightest among the three settles as a top layer of the sediments. Measure the DT (Total Depth) of the settled sediments and consider it 100% settlement of the sediments. Then measure depths of sand (DSand), silt (DSilt), and clay (DClay) and convert these depths in ratios to determine %Sand=100x(DSand/DT), %Silt=100x(DSilt/DT), and %Clay=100x(DClay/DT), respectively.

2.3 Bulk Density of Soil

V (Volume) of the intact cores is calculated as $V=\pi r^2 \times h$, where $\pi=22/7$, r is radius and, h is the height of the core. Collect soil samples with a soil sampler. Carefully trim the soil samples, seal them with caps, place them in ziplock bags and take them to the laboratory for further steps. The cores are oven dried at 105°C for 24-48 hours. Determine the values ρ_b with standard procedures [14]:

$$\rho_b = \left(\frac{M_{105}}{V} \right) \quad (2)$$

where, M_{105} is the oven-dried sample weight.

2.4 Soil Organic Carbon

The bulk representative sub-samples can be further processed to determine LOI (Loss On Ignition). The LOI tests are carried out using a furnace or specifically muffle furnace that has capability to combust the samples at 550°C. The procedure described by Schulte and Hopkins [15] and adopted by Konen, et. al. [16] can be followed by putting 2-5 grams of <2mm oven dried (105°C; 24-48 hours) soil in ceramic containers that are carefully labeled for various treatments. Literature suggests varying ignition temperature and time range from 360°C for 2 hours [16] to

500-550°C for 2 hours or 550°C for 5 hours [17]. It is recommended to combust the samples at 550°C for 5 hours and then transfer them to an oven at 105°C for couple of hours. The combusted samples are weighed (M_{550}) after cooling in a desiccator. The purpose of cooling in desiccators is to bring the samples to a temperature easy to be handled without letting them to absorb atmospheric moisture contents. The reference loss on ignition is determined with the following relationship and can be taken as percent SOM [18]:

$$\text{LOI}(\%) = \text{SOM}(\%) = \left(\frac{M_{105} - M_{550}}{M_{105}} \right) \times 100 \quad (3)$$

Since the organic matter contains 58% of SOC, following relationship is used to estimate SOC(%) from SOM(%):

$$\text{SOC} = 0.58 \times \text{SOM} \quad (4)$$

To convert SOC (%), estimated from Equation (4), into tonnes of C ha⁻¹ in a soil layer of the depth, d (cm) and density, ρ_b (g cm⁻³), following relationship can be used [19].

$$\text{SOC} (\text{t C ha}^{-1}) = d \times \rho_b \times \text{SOC} (\%) \quad (5)$$

2.5 Inert Organic Matter

The value of IOM (Inert Organic Matter) can be calculated from the relationship given follows [20]:

$$\text{IOM} = 0.049 \times (\text{SOC})^{1.139} \quad (6)$$

2.6 Carbon Input from Farm Yard Manure

A sample from the FYM can be chemically analyzed for FYM C contents. If a particular batch of the commercially available FYM is used the information regarding FYM C

contents may come with the supply. The amount of C (usually given in % C on dry basis) can be converted into kg of C by multiplying it with the weight of FYM applied in the field and dividing it by 100 as:

$$C \text{ (kg)} = C \text{ (\%)} \times \text{FYM (kg)} / 100 \quad (7)$$

Convert C from Equation (7) into t C ha⁻¹ y⁻¹ which is equally distributed over a period of growing season in the land management input file of RothC as C input from FYM.

2.7 The Carbon Components

The rest of C input parameters including C components; i.e. IOM; DPM (Decomposable Plant Material); RPM (Resistant Plant Material); BIO (Microbial Biomass); HUM (Humified Organic Matter) and those of radio age ¹⁴C are generated during calibration of RothC when the model is run at equilibrium (10,000 years).

The above information are needed to complete the land management file of RothC. The other set of input information include weather data.

2.8 Weather Data

The model requires mean monthly °C (Temperature), cumulative monthly rainfall (mm), and open pan evaporation (mm) for its weather input file. These data can be achieved from a weather station close the study site, or from the country's weather database or any online weather database; e.g. WorldClimate database available at <http://www.worldclimate.com>. In case the data of open pan evaporation are unavailable, the monthly data of potential ET (Evapotranspiration) accurately calculated from Müller's collection of the worldwide meteorological data.

2.9 Estimation of Soil CO₂ Emission with RothC

RothC 26.3, [12] deals with organic carbon turn-over in non-waterlogged and was initially developed for temperate European conditions. It considers that the plant matter undergoes decomposition after entering the soil environment. During this processes the microbial biomass of soil forms a numerous C pools with CO₂ emission under changing resistance to degradation [21]. The RothC model is a five-portion system with separate IOM, DPM, RPM, BIO, and HUM. Rate of carbon decomposition depends on the model enforcing (inputs). Resultantly, RothC determines C balance in soil. Plant residue inputs decided with different DPM/RPM ratios, i.e. for agricultural soils or for forestlands.

RothC performance was reported very good under various environmental and experimental conditions [22]. Among RothC, CENTURY, CANDY, DNDC, DAISY and NCSOIL, RothC is in the top position. Wu, et. al. [23] reported that RothC simulated the SOC dynamics with good accuracy for the Northeast Thailand upland soils. The model has successfully been used to estimate carbon pool and CO₂ emission in Australia [21]. Shirato and Taniyama [24] evaluated RothC for agricultural soils of Japan. Shirato, et. al. [25] tested RothC for 3 sites in the Thai upland soils and reported the model performance to be very good. Guo, et. al. [26] calibrated this model for the soils in northern China in order to get input parameters of the model for large-scale studies. Abbas, F., and Fares [22] measured SOC and simulated soil CO₂ emission from an organically amended Hawaiian tropical soil with RothC; they reported the model performed well ($r^2 > 0.94$) under tropical and edaphic conditions of Hawaii.

The RothC is available on public domain. For its use, the model requires selected soil properties including percentage of clay content in the soil, ρ_b , SOC, IOM plant C input, C input from FYM, weather data (i.e. mean monthly temperature, monthly cumulative rainfall and open pan evaporation) and the C components of 14C. The model needs calibration to generate input parameters essential to run model simulations.

Land and weather management files of RothC need preparation for model calibration. The model is designed to operate in forward and inverse modes. Running model in inverse mode means running RothC at equilibrium (10,000 years) by iteratively fitting C inputs by plants, in the land management file of the model. The values of DPM/RPM values of 1.44 and 0.69 are used for arable and forest woodlands, respectively, during equilibrium run [12]. The other parameter needed in land management file is IOM. Therefore, a fraction of IOM is calculated from Equation (6). Percent clay content and option to select fallow or cover are the last two parameters to select for equilibrium run. The model is run on iterations by changing plant input C value until a close match between the modeled and the observed SOC is achieved [26]. A continuous crop cover is assumed during the past years during calibration process.

Once the initial values of plant C input are achieved, the modeled plant C input and other parameters including DPM, RPM, HUM, BIO and 14C parameters are used in direct or forward runs or simulation. The values of DPM, RPM, HUM, BIO and 14C parameters are used as they come from calibration run; whereas, the plant C input is distributed over the month for which the plant cover is available. Literature shows that Shirato, et. al. [24] and distributed plant C input evenly over the 12 months in his study [25] reported that the

method of distribution of C does not affect significantly. The next step is to calculate the C input from the application of FYM. This can be accomplished by conducting chemical analysis of FYM for C contents. The FYM C input should be distributed evenly over the period for which FYM is applied on the fields for specific experimental simulation. RothC requires the C inputs from plants and from FYM in t C ha⁻¹. For SOC and CO₂ emission from forest lands, no FYM C input is required if the nursery or fruit orchards are not being studied and/or fertilized. Weather file for simulation is prepared in similar fashion as for calibration. It should be preferred to use the current weather information of the period for which the simulation is being conducted. In the cases of unavailability of current weather information and simulation for future years, the long term weather information can be used.

RothC is used to simulate CO₂ emission (t ha⁻¹ y⁻¹) as it does for SOC. The model provides option to simulate CO₂ emission for a specific growing season or for the year when the soil CO₂ was measured on monthly or yearly basis. The model can also simulate for the past decades or for the long term estimation for future. The calibration and validation of RothC will remain same as in case of SOC.

2.10 Evaluating Model Performance via Statistical Analyses

Performance of RothC can be evaluated from statistical indices such as RMSE (Root Mean Square Error); D (Difference) - an indicator of model bias (negative values show under-prediction and vice versa); P (Probability) value at 90% confidence interval, where P>0.10 means no significant difference between observed and the modeled values; and r (the correlation coefficient). The RMSE is calculated as:

$$RMSE = \frac{100}{O} \sqrt{\frac{\sum_{i=1}^n (P_i - O_i)^2}{n}} \quad (8)$$

where O_i is observed, represents mean of observed data, P_i is predicted and n represents total number of samples.

Statistical analyses can be conducted using the available software to construct general ANOVA (Analysis of Variance) for observed SOC as affected by different experimental treatments. Tukey's or Duncan's mean separation (LSD) tests are used to separate the effect of any treatment when statistically significant effects are found. The Pearson correlation test can be used to cross correlate the observed and modeled SOC and CO₂; P- and r-values are used as statistical indices.

2.11 Possible Simulation Errors

Simulation models including RothC could over- or underestimate SOC and CO₂ emission. Different studies have reported simulation errors of the carbon turnover models; e.g. [26] and the references therein. Woomer [27] reported an under-estimation of SOC by CENTURY model compared with field observations. Wu, et. al. [23] evaluated RothC to under-estimate SOC especially under dry conditions. Abbas, F., and Fares [22] reported an under-estimation of SOC by RothC as compared with observed values. The possible reasons for under-estimation of SOC content include increased microbial activities than the rates considered by the model. Since RothC does not take the observed microbial activities into account, the increased observed SOC due to fauna and termites could result into under-estimation of SOC and CO₂ emission by RothC.

2.12 Measurement of Soil CO₂ Emission with Soil Closed Chambers

Literature [28-29] describes method to determine soil CO₂ emission using closed chambers. The method was termed as SL (Soda Lime) technique as it involves the use of SL tins. The SL technique follows placing plastic rings over the soil, 1 day prior to measurements, from where the soil CO₂ emission is being determined. The diameter of the rings should resemble that of the measurement chamber. Prior to placing the ring, the surface litter should be removed and the rings should be inserted approximately 1cm into the soil. Other than removing the soil litter, the soil surface should not be disturbed. The SL tins utilized by Cropper, et. al. [29] and Raich, et. al. [30] were 5.2cm tall, 8.1cm diameter and 5.1cm tall, 7.8cm diameter, respectively. It is suggested to use the tins within the range of above dimensions so that they could carry 60g of 6-12 mesh (1.68-3.36mm) SL. The tins should be oven dried at 100-105°C for 24 hours, weighed precisely (W_1), and covered tightly prior to use. At the time of measuring soil CO₂ emission in the field, the plastic rings that were placed 24 hours prior to the measurements are removed from the soil, SL tins are uncovered, and placed exactly and firmly over the ring's evacuated place under certain weight on the top. The SL tins are removed after 24 hours and oven dried at 100-105°C for 24 hours, and reweighed again (W_2). At least three tins per site should be collected immediately and resealed to serve as blanks. The amount of CO₂ absorbed by the SL in the tins can be determined as the difference between W_1 and W_2 , and subtracting the average weight of blanks from this (W_1/W_2) difference. Edwards [28] suggested a correction factor of 1.41 that should be multiplied with the weight gains to correct the weight loss due to release of chemical water (H₂O₂) during chemical bonding of CO₂ to SL. The amount of CO₂ may be converted to g of CO₂ m⁻²d⁻¹; annual values to be computed by averaging all sampling days.

The dynamic techniques to measure CO₂ emission from soil are not mentioned here as such techniques involve onsite establishment of expensive experimental setup that may not be feasible and affordable for researchers working with limited resources. The techniques include those reported in literature [31-32].

2.13 Estimating SOC and Soil CO₂ Emission from Soil Properties

Xinglong and Boyd [33] measured soil CO₂ emission from empty ponds used to raise fish for 60 years following the method adopted by Boyd and Pipoppinyo [34] and Sonnenholzner and Boyd [35]. The ponds were receiving monthly applications of fertilizers and fish food during previous years. Plotting soil CO₂ emission (mg CO₂ per g of soil) versus SOC (%), they derived the following relationship (coefficient of determination; r²=0.923):

$$\text{Soil CO}_2 \text{ Emission} = -1.331 + 4.458 (\text{SOC}) \quad (9)$$

Abbas, F., and Fares [22] reported a highly significant linear relationship between modeled CO₂ emission (t ha⁻¹) and observed and modeled SOC (tha⁻¹) values (r²=0.88 and 0.99, respectively) for their experimental conditions under tropical soils of Hawaii.

$$\text{Soil CO}_2 \text{ Emission} = -39.1 + 1.32 (\text{SOC}) \quad (10)$$

Cropper [29] determined CO₂ concentrations at various depths ranging from 15-50cm in six karst soils in Malay and reported a logarithmic relationship between CO₂ and ρ_b. Abbas, F., and Fares [22] also developed a logarithmic relationship (r²=0.50) between CO₂ and ρ_b as:

$$\text{CO}_2 = \exp\left(\frac{1.42 - \rho_b}{0.12}\right) \quad (11)$$

Above relationship may be used to roughly estimate CO₂ emission from arable soils resembling to that used in Abbas, F., and Fares [22].

2.14 Cumulative Emission of Soil CO₂ Emission

Cumulative emission of CO₂ is calculated as:

$$\text{Cumulative CO}_2 \text{ (Mg ha}^{-1}\text{)} = \sum_{i=\text{first}}^{l=\text{last}} X_i + (X_{i+1}) \times N + (X_{i+2}) \times N + \dots + (X_{i+l} - B_i) \times N \quad (12)$$

where i is first day of the measurement of CO₂ rate, l is the last day of the measurement of CO₂ rate, X is CO₂ rate (Mg ha⁻¹d⁻¹), and N is number of days between the two consecutive CO₂ measurements.

3. CONCLUSIONS

The approach presented in this paper is suitable for studying a regional carbon budget that could help in quantifying the contribution of arable and forest lands to the global climate change and environmental pollution. This approach is suitable for research organization or academic institutions in the developing countries as it suggests the use of basic instruments and technology usually accessible in most of the laboratories with essential facilities. The methodology presented here is also useful for researchers and scientists working with limited resources in the developed countries.

ACKNOWLEDGEMENT

I am thankful to the Department of Natural Resources and Environmental Management, University of Hawaii, USA, for conducting of this research work.

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