Baseline organic carbon stocks of Rwandan topsoils

Ann Verdoodt[A], Geert Baert[B] and Eric Van Ranst[A]

[A]Department of Geology and Soil Science, Ghent University, Gent, Belgium, Email ann.verdoodt@ugent.be, eric.vanranst@ugent.be
[B]Faculty of Faculty of Biosciences and Landscape Architecture, Hogeschool Gent, Gent, Belgium, Email geert.baert@hogent.be

Abstract
Rwandan soil resources are very diverse. Yet, socio-economic drivers foster inappropriate land management and threaten soil quality. This manuscript quantifies the baseline topsoil (0-30 cm) organic carbon stocks (C_{stock}) of the country using analytical data comprised in the Rwanda Soil Information System. Based on data of 121 soil profiles, having measured soil organic carbon, volume of coarse fragments and bulk density values for all horizons within the upper 30 cm of the soil surface, the average C_{stock} in this tropical highland country amounts to 86.1 ± 4.7 Mg C/ha. Large differences in C_{stock} were identified as a function of soil reference group and land use. Especially the forested highlands have large potentials for organic carbon sequestration, though deforestation in favour of cropping activities clearly leads to significant carbon losses.

Key Words
Organic carbon stocks, reference groups, land use, Rwanda, soil survey database, data mining

Introduction
Central African soil resources are characterised by a large variability, ranging from stony, shallow or sandy soils with poor life-sustaining capabilities to deeply weathered soils that recycle and support large amounts of biomass (Bationo *et al.,* 2006). Socio-economic drivers within this largely rural region foster inappropriate land management, threaten soil quality and finally culminate into a declining soil productivity and increasing food insecurity. For the development of sustainable land use strategies targeting development planning and natural hazard mitigation, the decision makers need good baseline soil information. Because of the lack of bulk density measurements in many soil survey databases, estimates of organic carbon stocks generally rely on the use of pedotransfer functions filling gaps in datasets, yet increasing the uncertainty of the output results. This manuscript evaluates the quality and representativity of the Rwandan soil profile database and illustrates its potential value for developing baseline data for soil organic carbon stocks based on measured data.

Materials and Methods
Rwanda Soil Information System
The Rwanda Soil Information System comprises a soil profile database containing records for 1833 georeferenced soil profiles. All information was gathered from 1981 to 1989 during the national soil survey, which was realised through cooperation between the Rwandan Ministry of Agriculture, Livestock and Forestry and the Belgian Government. Based on unique combinations of parent material, profile development, soil depth, drainage, texture and physico-chemical properties, 276 different soil series were identified to characterise the Rwandan soilscape on 43 soil map sheets at a scale of 1:50,000 covering the entire territory (Verdoodt & Van Ranst, 2006a; Verdoodt & Van Ranst, 2006b). The soil profiles were sampled for a routine physico-chemical characterization of their horizons, using standardised methods, in the project soil survey laboratory in Kigali (Rwanda), and the soil science laboratory of Ghent University and of the Catholic University of Louvain-La-Neuve (Belgium).

Data quality control and analysis of representativeness
To control the quality of the stored information, the soil profile database was subjected to auditing routines based on (1) a confrontation of the spatial distribution of those attributes for which independent thematic layers exist (e.g. administrative maps, digital terrain model), and (2) theoretical limits set to each soil property, using correlations with other soil attributes, enabling the elimination of values outside the expected range (e.g. pH, granulometry). The representativity of the soil profiles was assessed by comparing the distribution of the soil profile population with respect to soil and land use types with the aerial extent of the soil reference groups, as reflected on the soil map, and the land use types characterizing the countryside.

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Data handling and analysis
For all physico-chemical soil properties, weighted average parameter values characterising the mineral topsoil (0-30 cm) were calculated. Descriptive statistics were produced to illustrate range, mean and standard deviation of the measured parameters.
The C_{stock} (Mg/ha) within each horizon was calculated from the soil organic carbon content C_{conc} (g/kg), bulk density BD (g/cm³), coarse fragments CF (vol%) and thickness of the horizon d (cm) according to:

$$C_{stock} = C_{conc} \times BD \times (1-CF) \times d \times 0.1 \quad (1)$$

Measured C_{conc} (Walkley and Black), CF (sieving > 2 mm) and BD (volumetric ring method) data were taken from the soil analytical database. Topsoil carbon stocks per unit area were then calculated by summing the C_{stock} of all horizons within 30 cm depth. Land use data were taken from the soil profile description, and pivot tables were generated highlighting the influence of soil type and land use on soil organic carbon stocks.

Results

Characterising the Rwandan soils
Rwanda, even though being a small (26,000 km²) landlocked country, hosts a great diversity in climatic, geologic, and geomorphic conditions. With its altitude ranging between 900 and 4500 m (Figure 1), it comprises both warm, semi-arid plains covered by savannah vegetation in the east to rainforest growing in the cool, humid (north) western highlands. Strongly weathered soils dominate the eastern and southern pediplains, whereas the soils in the valleys and highlands are subjected to regular rejuvenation through soil erosion and deposition of alluvium, colluvium, or even volcanic material. Besides nature conservation efforts within the 3 national parks, the land is generally used for agricultural production.

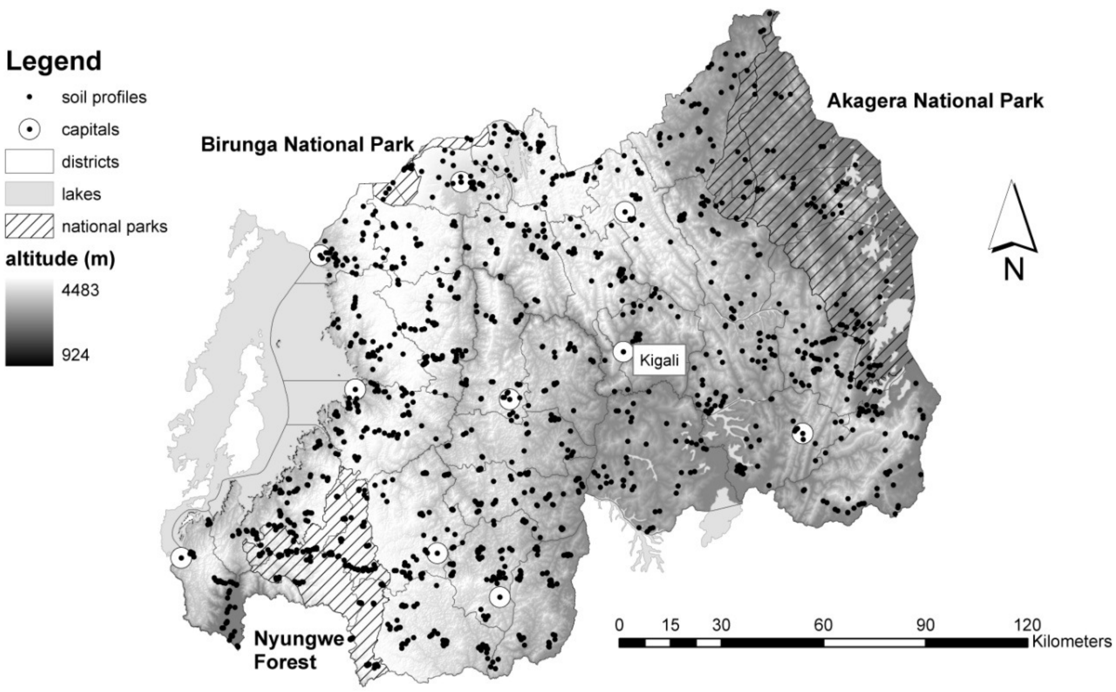

Figure 1. Distribution of the soil profiles.

Representativity of the Rwanda soil information system
Figure 1 shows the spatial distribution of the soil profile locations. The average sampling density was 1 profile for every 14 km², though large regional differences can be identified as the soil survey strategy focussed on pilot zones located within different geomorphologic environments. Cambisols (27%), Ferralsols (26%), Acrisols (14%) and Alisols (11%) dominate the profile database. The profile population furthermore comprises both cultivated and non-cultivated soils. Most soil profiles are under cropping (32%) or fallow (34%), followed by timber production (13%) and natural forests (13%). About 6% of the profiles was located within a natural reserve and 2% was exclusively used for pasture. This latter land use type seems to be underrepresented in the database, though in reality, many fallow lands are used for grazing as well.
After the initial quality control stage, 1518 soil profiles were retained for soil property modeling, albeit of varying completeness for individual properties. The diversity in soil formation factors is reflected in the large ranges of physical and chemical soil properties (Table 1).

Table 1. Ranges of a selected set of mineral topsoil (0-30 cm) physical and chemical soil properties comprised by the Rwandan soil profile database.

Description	Unit	N° of profiles	Average	Range
Physical soil fertility				
clay	%	1428	36 ± 15	2 – 85
silt	%	1428	21 ± 12	2 – 77
sand	%	1428	43 ± 17	0 – 90
bulk density	Mg m^{-3}	149	1.1 ± 7.4	0.5 – 1.7
moisture content at pF=2.5	%	208	30 ± 18	6 – 158
moisture content at pF=4.2	%	208	20 ± 13	3 – 122
Chemical soil fertility				
pH-H_2O	-	1448	5.1 ± 0.9	3.0 – 11.2
organic carbon	%	1450	2.92 ± 2.68	0.29 – 32.8
total nitrogen	%	1350	0.224 ± 0.392	0.028 – 12.850
available phosphorous	ppm	382	19.35 ± 44.39	0.00 – 372.00
exchangeable Ca^{2+}	cmol(+) kg^{-1} soil	1336	4.51 ± 6.79	0.00 – 92.80
exchangeable Mg^{2+}	cmol(+) kg^{-1} soil	1336	1.78 ± 2.98	0.00 – 51.07
exchangeable K^+	cmol(+) kg^{-1} soil	1336	0.42 ± 0.71	0.00 – 12.40
exchangeable Na^+	cmol(+) kg^{-1} soil	1336	0.22 ± 0.39	0.00 – 27.67
Soil mineralogy				
CEC-NH_4OAc	cmol(+) kg^{-1} soil	1343	17.90 ± 13.57	1.58 – 200.27
free Fe_2O_3	%	234	4.89 ± 3.71	0.00 – 28.31
amorphous Fe_2O_3	%	25	0.91 ± 0.76	0.13 – 2.73

Topsoil organic carbon stocks

Using the available data, the topsoil C_{stocks} have been calculated for 121 profiles, representing 99 soil series which spatially cover 47% of the Rwandan soilscape. On average, 86.1 ± 4.7 Mg C/ha has been stored in the Rwandan topsoils. Yet, differences are large with values ranging between 14.5 and 240.4 Mg C/ha, measured in a stony, organic matter depleted cropland topsoil in the province of Gitarama, and in a forest topsoil of the Birunga volcanic range, respectively. The distribution is furthermore skewed with only 10% of the profiles having SOC_{stocks} exceeding 150.0 Mg C/ha (Figure 2).

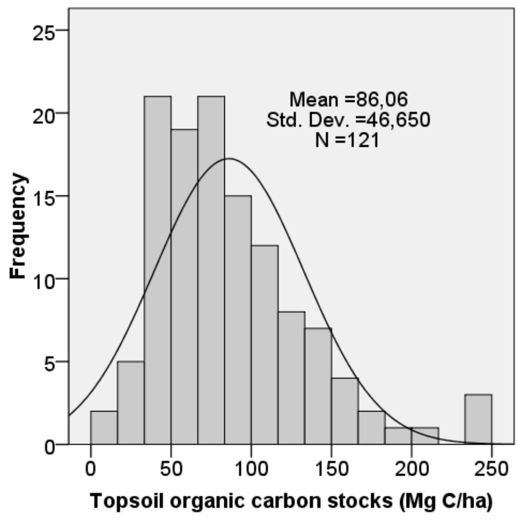

Figure 2. Histogram of the topsoil organic carbon stocks measured in 121 soil profiles of Rwanda

Analysis of the results as a function of soil type and land use illustrates that the Andosols are characterised by the highest C_{stock} of 149.4 ± 44.2 Mg C/ha as the humiferous topsoil organic matter is stabilised by the presence of Al-humus complexes. Cropping activities reduce the C stocks, through enhanced organic matter mineralisation and erosion losses, though the topsoil stocks recorded in the '80s were still considerable. The lowest C stocks, on the other hand, have been reported in the Luvisols and Ferralsols, characterised by average C_{stock} values of 55.5 and 59.4 Mg C/ha, respectively. Low topsoil stocks of the former reference group are clearly associated with agricultural land uses, whereas the Ferralsols are characterised by low stocks, regardless of the land use type.

The C_{stock} values calculated from the Rwandan soil profile database thus roughly correspond to the Central African estimates for Ferralsols (58 ± 47 Mg/ha), Acrisols (65 ± 48 Mg/ha), and Cambisols (81 ± 50 Mg/ha) reported by Batjes (2008). The higher stocks measured in the Rwandan Acrisols and Cambisols can be explained by the positive impact of the relatively cool climatic conditions of this high altitude country on soil organic carbon contents.

Variations in altitude, topographic position and soil texture furthermore explain the moderate variation recorded within each reference group – land use type class. In future, the baseline dataset could be considerably enlarged (C_{conc} and CF measured for about 1428 profiles) if the missing BD data are estimated using regionally validated PTFs. This would allow a more comprehensive analysis of the topsoil organic carbon stocks in Rwanda as a function of several soil forming factors and the development of an topsoil C_{stock} map.

Table 3. Topsoil (0-30 cm) organic carbon stocks (Mg/ha) of Rwanda stratified according to the major soil reference groups and land use types.

Soil reference group	Land use					
	Forest	Grassland	Timber	Cropland	Savannah	*Average*
Andosol	164.9 ± 2.5	158.1 ± 71.7	162.5	114.1 ± 3.8	-	*149.4 ± 44.2*
Cambisol	148.8 ± 63.8	95.8 ± 45.0	98.9 ± 39.2	80.6 ± 51.5	-	*100.8 ± 49.0*
Alisol	-	124.4 ± 60.8	93.3 ± 24.8	87.7 ± 41.6	-	*95.5 ± 41.8*
Acrisol	170.3 ± 99.2	73.6 ± 25.8	76.2 ± 10.1	85.3 ± 44.3	34.4	*86.2 ± 48.0*
Ferralsol	52.9 ± 9.1	66.9 ± 26.7	68.3 ± 70.5	60.7 ± 20.1	43.6 ± 14.7	*59.4 ± 25.0*
Luvisol	-	89.8 ± 34.1	52.0	35.6 ± 14.6	-	*55.5 ± 33.0*
Average	*129.5 ± 68.7*	*92.7 ± 46.6*	*89.6 ± 37.3*	*71.8 ± 37.8*	*42.0 ±13.6*	

Conclusion

The Rwanda Soil Information System is one of the most comprehensive soil resources databases of the African continent. It is a key instrument for the description of the physical environment that farmers face in the different agricultural regions of the country and for the development of baseline values for various soil properties. To that end, the dataset should be exploited to produce nationally and/or regionally consistent spatial estimates of key soil properties. With respect to topsoil organic carbon stocks, the database reveals a high potential for C sequestration, especially in the highlands. These soils, being prone to erosion, are subjected to significant C losses once deforested and cultivated. The value of the database also goes beyond national interest. In view of the large range of tropical environmental conditions covered by the dataset, the information can prove useful to the development of PTFs for physical and chemical soil properties, being of interest to the Central African highlands.

References

Bationo A, Hartemink A, Lungu O, Niami M, Okoth P, Smaling E, Thiombiano L (2006) African soils: their productivity and profitability of fertiliser use. Background paper prepared for the African Fertiliser Summit, June 9-13, 2006, Abuja, Nigeria.

Batjes NH (2008) Mapping soil carbon stocks of Central Africa using SOTER. *Geoderma* **146**, 58-65.

Verdoodt A, Van Ranst E (2006a) Environmental assessment tools for multi-scale natural resources information systems. A case study of Rwanda. *Agriculture, Ecosystems and Environment* **114**, 170-184.

Verdoodt A, Van Ranst E (2006b) The soil information system of Rwanda: A useful tool to identify guidelines towards sustainable land management. *Afrika Focus* **19(1-2)**, 69-92.