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Estimating the Sequestration Potential of Organic Carbon in Forest Soils in the Central Middle Atlas: A Tool to Fight Climate Change

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Abstract

Soil organic carbon sequestration is an important matter in international negotiations to fight climate change through a reduction in greenhouse gas (GHG) emissions. This study was carried out in the forests of the Moroccan Central Middle Atlas, with the objective of determining the storage of carbon in the high organo-mineral layer of soils (<30 cm deep) and under different spontaneous forest species in this area. It shows that the soil organic carbon stock (SOCS) in these forest ecosystems is higher in green oak and deciduous zeen oak forest stands, recording 264.73 and 251.54 t/ha respectively on a basaltic substrate followed by cedar (resinous species) (178.07 t/ha). Mixed forest stands come at last with low SOCS (109.02 t/ha). This variation may be attributed to several factors, mainly the type of vegetation, the physical and chemical soil properties and soil type of the studied area.

Keywords: Sequestration, Central Middle Atlas, Organic carbon, Stock.

Introduction

The quantification of the organic carbon stock in forest ecosystems is to well understand the general carbon cycling in these ecosystems. Indeed, this quantity, in forest soil, is the result of the balance between the net primary production of vegetation and the decomposition of organic matter (Liski & Westman, 1997). These two processes depend on climatic conditions, mainly temperature and humidity. However, forest soils may be a significant source of CO_2 as a result of global warming, which lead to a mineralization of organic matter higher than the net primary production of vegetation (Liski, 1999, Bernoux et al., 2005). Every change in the organic carbon reservoir in the soil can significantly affect the concentration of CO_2 in the atmosphere, since the soil contains twice as much carbon as the atmosphere (Schlesinger 1977; Post et al., 1982; Watson et al., 1990).

In addition, each tree species has different functional characteristics that allow it to have a unique influence on its environment, including the soil on which it grows. For example, depending on differences in shade tolerance, foliage persistence (evergreen vs. deciduous leaves), evapotranspiration capacity, and composition of the herbaceous stratum, soil moisture and temperature conditions may vary depending on stand type (Lag-

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anière et al., 2011).

Apart from the influence that a single tree species can have on its environment, mixing two or more tree species in mixed stands could have an impact on carbon sequestration in soils. The present study aims to partially fill this knowledge gap, especially with regard to the quantification of carbon stock in forest soils as a result of the forest composition comprising four natural species, namely Cedar, Maritime Pine, Green Oak and Zeen Oak in three types of forest stands in the Moroccan Central Middle Atlas, namely the south of Jbel Aoua , Azrou and Jaaba forests.

Materials and Methods

Description of the Study Areas

This study was carried out in three natural forests of the Central Middle Atlas, namely the forests of south of Jbel Aoua, Azrou and Jaaba (Figure 1).

The South of Jbel Aoua Forest

The South of Jbel Aoua forest covers an area of 7865.42 ha. It is composed of a green oak coppice, a maritime pine grove and a cedar grove. The geological formations of the area are dominated by lower Jurassic (or lias) formations, which include sandy dolomites and dolomitic limestones. Two types of soils are described in the region. Soils developed on hard limestone namely fersialitic red soils and soils developed on sandy dolomite which are para rendzine that are relatively rare. The climate in the area is of a mediterranean type, the drought period is 5.5 months (mid-May - late October) and that the bioclimate is subhumid of cold variant (HCEFLCD, 2007).

Azrou Forest

Located on the northern edge of the Middle Atlas Plateau, the Azrou Forest covers an area of 17806.79 ha. This forest is characterized by a contrasted relief with very variable altitudes where one may observe the inversion of the altitudinal layers of vegetation (case of Michlifene and Jbel Habri) due to the oppositions of the slopes and the accumulation of cold air in the closed depressions. From a bioclimatic point of view, the Azrou forest is of the humid bioclimatic type with a cold variant or sub-humid type with a temperate variant. The climate is also characterized by major storms, making it more favourable for the establishment and development of the cedar grove. The composition of the plant formations of the Azrou forest includes pure cedar stands, mixed cedar, green oak stands, pure green oak stands and reforestation stands of cedar and cypresses (Laaribya, 2016).

Jaaba Forest

The Jaaba forest has a total area of 10449.16 ha. It receives an annual average rainfall varying between 810 and 976 mm over a 30-year climatic period with a bioclimatic type ranging from cool sub-humid to wet very cold. In this forest, forest stand typology is defined by the combined effects of the nature of the substrate and the topographic position. Indeed, Zeen oak stands develop on the basalt substrate and in depressions, while on carbonate rock (limestone and dolomite), the type of forest stand is based on green oak. The Jaaba forest includes three types of forest formations: Pure Green Oak, Pure Zeen Oak and a mixture of Green Oak - Zeen Oak (HCEFLCD, 2007).

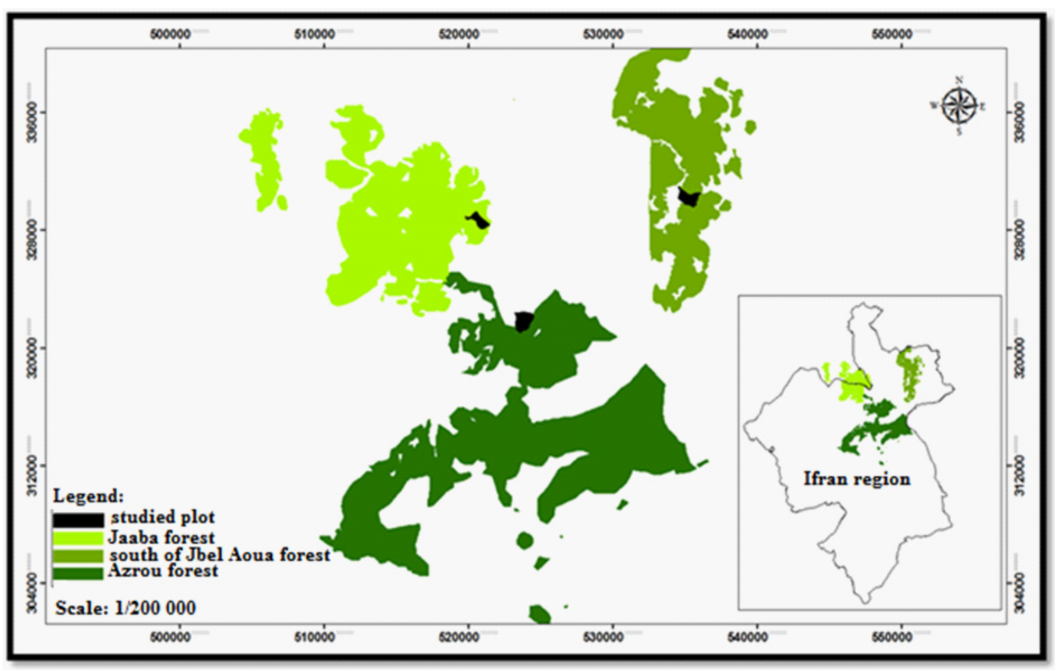

Figure 1. Map of the studied area.

Methodological Approach

At the level of each forest, a representative plot was chosen taking into account the topo-climatic position and the type of forest stand. Using a Geographic Information System (GIS) and field validation visits, nine (09) different forest stands were identified (Table 1). At the level of each stand, soil samples from the higher organo-mineral soil (<30 cm deep) were collected from six (06) soil site replicates. According to Benjelloun (1997), this layer is the one where root concentration is higher and exchanges between the soil and plant roots are important (Figure 2, 3 and 4).

After sieving the soil samples through 2 mm meshes, we carried out the following physical and chemical analyses: grain size, bulk density, organic matter, carbon, total nitrogen and acidity (pH (H_2O), pH (KCl)). These analyses were carried out in the soil and environmental microbiology laboratory of the Faculty of Science of Meknes.

Determination of Soil Carbon Stock

The percentage of carbon and the bulk density allow the determination of carbon stocks and organic matter per unit area using the following formula:

$$q(i) = 0.1 \times Ei \times da(i) \times Ci$$

Where:

- q (i): soil Corganic content (t/ha),
- Ei: depth (i) (cm),
- da(i): apparent density of the fine fraction (< 2 mm) in depth (i) ($g.cm^{-3}$),
- Ci: concentration of organic carbon in fine soil for depth (i) ($g.kg^{-1}$).

MO = C org x 1.724 (t/ha)

Statistical Data Analysis

This step of the work consists of analyzing the data obtained and processing them statistically. Indeed, an analysis of descriptive statistics, mainly means, standard deviations and coefficients of variation, was carried out to explain the variability of sites within the same forest formation (forest stand). Comparisons of formation means for the different studied variables were obtained through a single-criteria analysis of variance (ANOVA 1). The ANOVAs were conducted to verify whether the average carbon stocks of the different strata were significantly different from each other. The assumptions of this test, which are the normality of the distribution and the homogeneity of the variance, were verified beforehand.

Results

A. Physical Properties

The results of the physical properties are presented in Table 2.

Texture

Because texture, directly or indirectly, conditions other physical properties of the soil, it plays an important role in porosity, drainage and especially carbon stocks in the soil (Jessica, 2009). The textural classes of the studied soils are represented in the textural diagram (Figure 5). The most represented textures of these soils are fine silt (S1, S2, S8 and S9), clayey-sandy silt (S4 and S6) and clayey-sandy silt (S3, S5 and S7). Thus, most of the forest soils have a rather coarse texture linked to the lithological nature of the parent material. The results of the single-criterion ANOVA show that the proportion of clays is significantly different from one site to another (p=0.04) for a significance level of 5%.

Table 1. Description of the identified sites.

Site No.	Localisation	Coordinates	Exposition	Slope (%)	Altitude (m)	Parent Rock	Forest Vegetation
01	Jaaba forest	Long=-5°10’28’’ Lati=33°33’7’’	NW	14	1593	Basalt	Mixture of an adult forest of zeen oak and green oak
02	Jaaba forest	Long=-5°10'38’’ Lati=33°33’16’’	North	10	1562	Basalt	Mature zeen oak forest
03	South Jbel Aoua forest	Long=-5°01'33’’ Lati=33°34’26’’	NE	13	1745	Sandy dolomite	Mature green oak forest
04	South Jbel Aoua forest	Long=-5°01'26’’ Lati=33°34’21’’	NE	15	1750	Sandy dolomite	Young cedar forest
05	South Jbel Aoua forest	Long=-5°00'54’’ Lati=33°34’10’’	NE	18	1740	Sandy dolomite	Mature maritime pine forest
06	South Jbel Aoua forest	Long=-5°00'51’’ Lati=33°34’03’’	NE	20	1768	Sandy dolomite	mixture of a young green oak forest and a mature cedar forest
07	Azrou forest	Long=-5°08'31’’ Lati=33°29’57’’	NE	20	1690	Basalt	Pure cedar forest
08	Azrou forest	Long=-5°08'39’’ Lati=33°29’34’’	SW	10	1720	Basalt	Mature zeen oak forest
09	Azrou forest	Long=-5°08'43’’ Lati=33°29’30’’	SW	25	1710	Basalt	Mature green oak forest

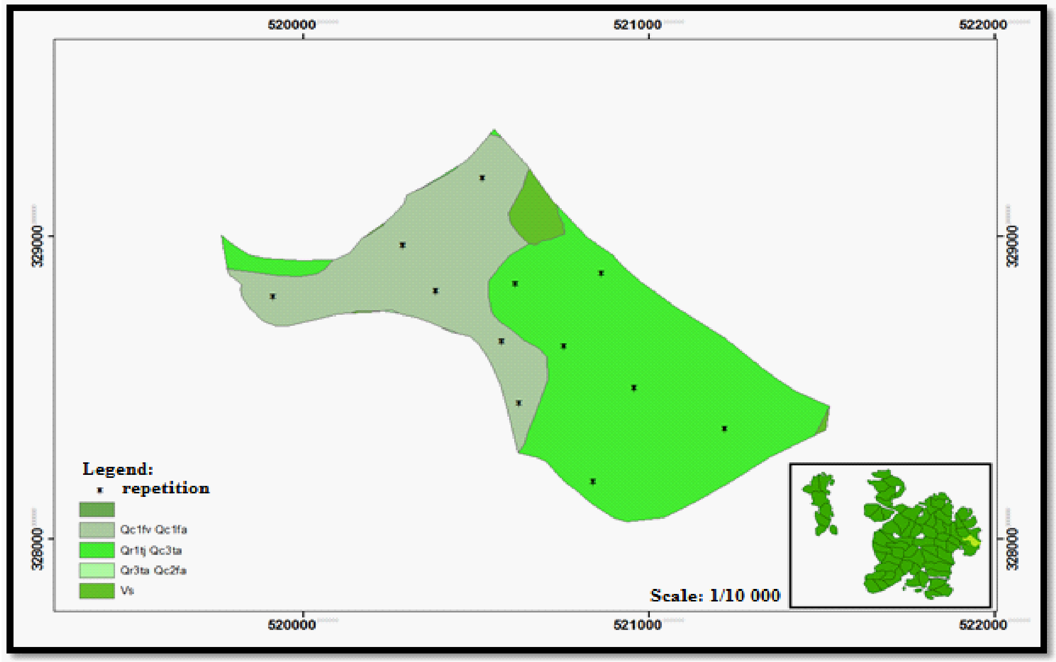

Figure 2. Distribution of soil sampling sites (replicates) in the forest stands of the Jaaba forest.

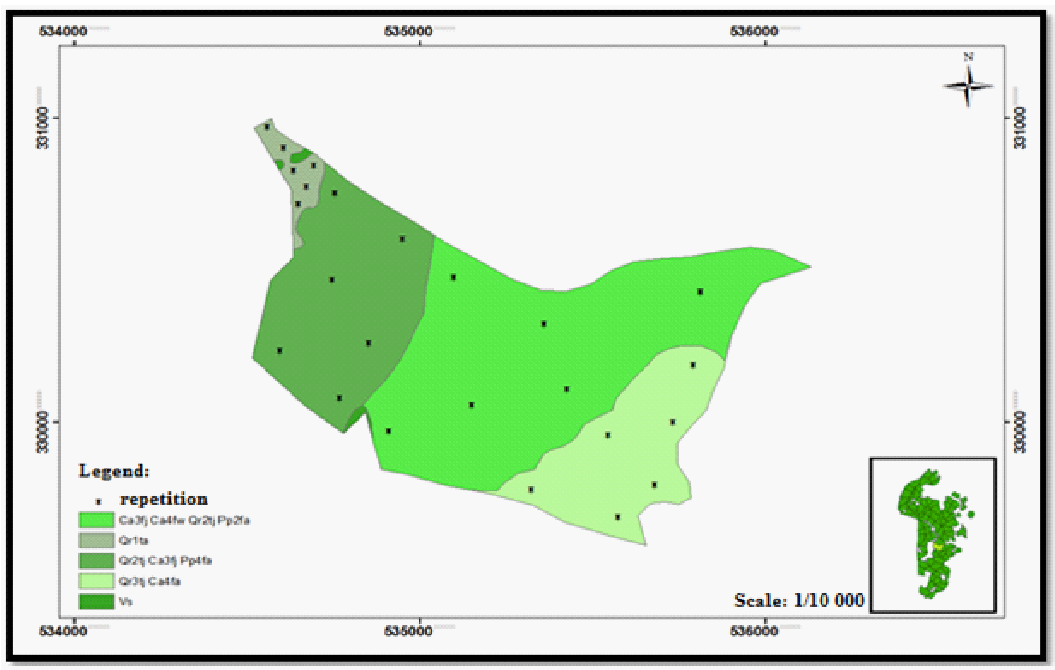

Figure 3. Distribution of soil sampling sites (replicates) in the forest stands of the South of Jbel Aoua forest.

Apparent Density (DA)

The apparent density of the soil is a necessary parameter for calculating carbon stocks. Values range from 0.74 to 0.85 g/cm^3. Thus, we should say that the studied soils have a good structure allowing them to have a good aeration. The results of the single-criterion ANOVA show that there is no significant difference in the average site density for a significance level of 5%. There is also a high degree of homogeneity within the sites between replicates, expressed by the values of the coefficients of variation, which vary from 3 to 19%.

B. Chemical Properties

The results of the chemical properties of the soils studied are presented in Table 3.

Carbon and Organic Matter (OM) Concentrations

The average organic carbon content varies from 4.69% (S6) to 11.10% (S9), and the distribution of organic carbon is relatively heterogeneous across all sites based on the values of the coefficient of variation ranging from 29 to 74%. According to

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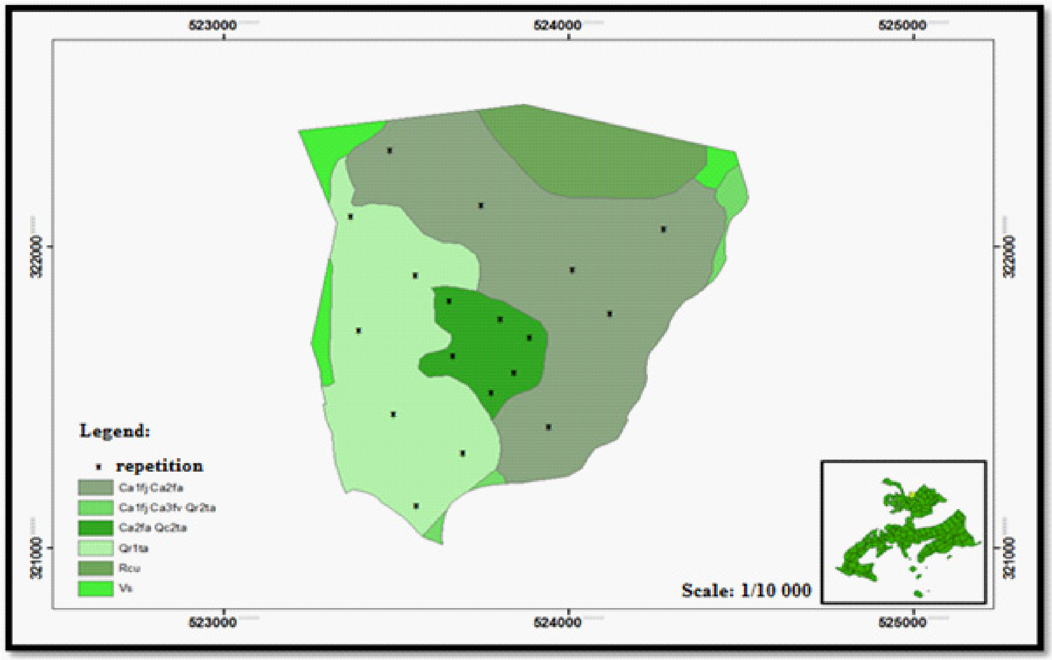

Figure 4. Distribution of soil sampling sites (replicates) in the forest stands of the Azrou forest.

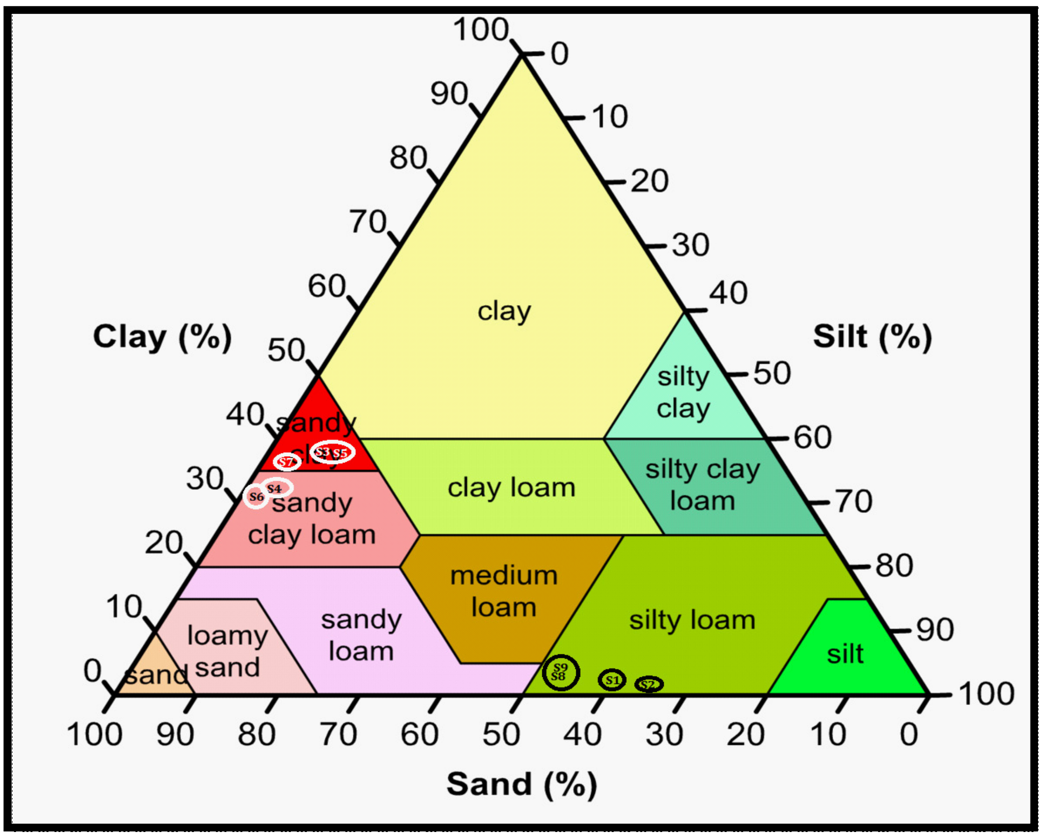

Figure 5. Textural diagram of the studied soils.

the ANOVA results, the averages are significantly different (p = 0.008), hence the influence of the site or forest stand on soil carbon sequestration and thus on soil organic matter reserve. The variation in the percentage of organic matter in the different sites follows the same trend as the carbon concentration since MO = C orgx 1.724 (Soltner, 1988).

Total Nitrogen

The total soil nitrogen in the studied soils (higher soil layer) varies from 0.20% (S6) to 1.76% (S9). These values are recorded under mixed forest stands of cedar and green oak growing on a sandy dolomite substrate and under pure green oak stand

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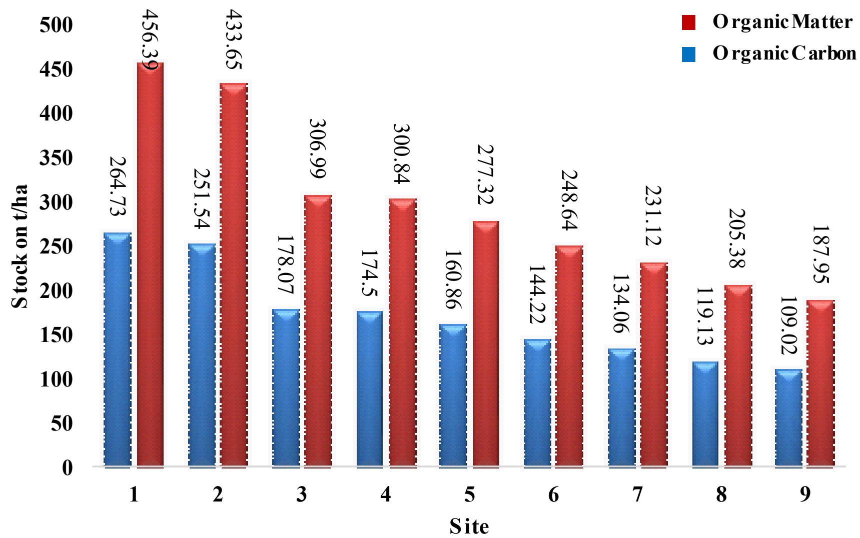

Figure 6. Carbon and organic matter stocks in the studied forest stands in decreasing order.

Table 2. Physical characteristics of the soils studied.

		S1	S2	S3	S4	S5	S6	S7	S8	S9
Particle size	**Clay (%)**	34,65 (32) a	36,12 (32) a	20,15 (53) b	29,17 (46) ab	22,28 (60) c	29,92 (46) ab	17,12 (17) d	26,72 (25) ab	27,45 (24) ab
	Thin silt (%)	14,28 (30)	13,30 (24)	9,02 (84)	11,27 (64)	9,05 (74)	12,05 (46)	13,18 (39)	13,83 (39)	12,62 (38)
	Coarse silt (%)	26,05 (12)	31,33 (21)	24,32 (60)	21,68 (54)	18,15 (76)	25,65 (38)	29,37 (40)	33,97 (20)	34,82 (38)
	Thin sand (%)	11,30 (44)	9,15 (26)	23,83 (53)	20,20 (79)	22,78 (59)	15,30 (73)	20,60 (44)	13,78 (37)	11,02 (41)
	Coarse sand (%)	12,72 (25)	10,10 (33)	22,68 (51)	17,68 (88)	27,75 (67)	17,03 (90)	19,77 (48)	11,72 (35)	14,10 (36)
	Texture	Silty thin	Silty thin	Sandy-clay	Sandy clay silt	Sandy-clay	Sandy clay silt	Sandy-clay	Silty thin	Silty thin
Apparent Density (g/cm^3)		0,74 (10)	0,83 (15)	0,80 (19)	0,85 (18)	0,87 (15)	0,85 (9)	0,83 (18)	0,78 (14)	0,79 (3)

S1: Green oak stand mixed with Zeen oak (Jaaba Forest), **S2**: Zeen oak stand (Jaaba Forest), **S3**: Green oak stand (Jbel Aoua Forest South), **S4** : cedar stand (South of Jbel Aoua Forest), **S5**: maritime pine stand (South of Jbel Aoua Forest), **S6**: cedar stand mixed with green oak, **S7** : cedar stand (Azou Forest), **S8** : Zeen oak stand (Azrou Forest), **S9** : green oak stand (Azrou Forest), Values in brackets indicate coefficients of variation in %, similar letters indicate that the values are not significantly different.

Table 3. Chemical properties of the soils studied.

	S1	S2	S3	S4	S5	S6	S7	S8	S9
Organic matter (%)	8,58 (38) ab	10,80 (74) ab	12,04 (39) ab	10,39 (44) ab	8,83 (64) ab	8,08 (57) a	12,87 (29) ab	18,89 (41) b	19,14 (31) b
Carbon (%)	4,98 (38) ab	6,27 (74) ab	6,99 (39) ab	6,03 (44) ab	5,12 (64) ab	4,69 (57) a	7,46 (29) ab	10,96 (41) b	11,10 (31) b
Total Nitrogen (%)	0,3 (25) a	0,60 (107) ab	0,70 (37) ab	0,63 (48) ab	0,52 (70) ab	0,20 (121) ab	0,89 (137) ab	0,28 (131) ab	1,76 (38) b
C/N	16,6 (43)	10,45 (121)	9,98 (89)	9,57 (81)	9,84 (175)	23,45 (101)	8,38 (103)	39,14 (120)	6,31 (97)
pH (H_2O)	6,52 (3)	6,46 (2)	7,23 (2)	7,21 (4)	7,37 (4)	7,09 (6)	6,51 (3)	6,10 (3)	6,33 (6)
pH (Kcl)	5,84 (2)	6,11 (8)	6,81 (3)	6,61 (4)	6,98 (3)	6,52 (5)	5,98 (1)	5,50 (5)	5,37 (3)

S1: Green oak stand mixed with Zeen oak (Jaaba Forest), **S2**: Zeen oak stand (Jaaba Forest), **S3**: Green oak stand (Jbel Aoua Forest South), **S4** : cedar stand (South of Jbel Aoua Forest), **S5**: maritime pine stand (South of Jbel Aoua Forest), **S6**: cedar stand mixed with green oak, **S7**: cedar stand (Azou Forest), **S8**: Zeen oak stand (Azrou Forest), **S9**: green oak stand (Azrou Forest), Values in brackets indicate coefficients of variation in %, similar letters indicate that the values are not significantly different.

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Table 4. Soil Organic Carbon Stock (SCOS) at the studied soils.

	S1	S2	S3	S4	S5	S6	S7	S8	S9
OCT Stock (t/ha)	109,02 ad	144,22 ad	174,50 abc	160,86 abc	134,06 abc	119,13 abc	178,07 abc	251,54 be	264,73 ce
Organic Matter Stock (t/ha)	187,95	248,64	300,84	277,32	231,12	205,38	306,99	433,65	456,39
CV (%)	(32)	(60)	(60)	(57)	(75)	(56)	(18)	(40)	(34)

S1: Green oak stand mixed with Zeen oak (Jaaba Forest), **S2**: Zeen oak stand (Jaaba Forest), **S3**: Green oak stand (Jbel Aoua Forest South), **S4**: cedar stand (South of Jbel Aoua Forest), **S5**: maritime pine stand (South of Jbel Aoua Forest), **S6**: cedar stand mixed with green oak, **S7**: cedar stand (Azou Forest), **S8**: Zeen oak stand (Azrou Forest), **S9**: green oak stand (Azrou Forest), Values in brackets indicate coefficients of variation in %, similar letters indicate that the values are not significantly different.

on basalt parent rock, respectively the results, obtained by the ANOVA using only one criterion, generate a statically significant difference between the different sites (p =0.04). In terms of fertility, the recorded values showed that all sites are considered to be very rich in total nitrogen according to the standard found by Dabin (1963) ranging from 0.15 to 0.25%.

C/N Ratio

The carbon-nitrogen ratio of a soil is determined as the weight ratio between the amount of organic carbon and nitrogen (Gobat et al. 2003). It allows the evaluation of the quality of organic matter as well as the estimation of the importance of humification and mineralization processes acting in soils (Jessica 2009). Lafond et al. (1992) and Akselsson et al. (2005) mentioned the C/N ratio as a good indicator for assessing carbon sequestration in soils. A high C/N ratio represents a low rate of carbon decomposition since decomposing organisms use nitrogen which quickly becomes limiting. A low C/N ratio indicates a high nitrogen concentration and a high degree of decomposition. The results obtained from the C/N ratio range from 6.31 (S9) to 39.14 (S8). Taking these values into account, the majority of which are less than 10, it can be said that the biological activity is good and that the nitrogen mineralization process outweighs the immobilization process by soil microorganisms.

Acidity

The pH (H_2O) analysis results (Table 3) show that the studied soils have pH values ranging from 6.10 to 7.37 indicating a weakly acidic to neutral chemical environment. The pH (KCl) is, always lower than the pH (H_2O), and varies between 5.50 and 6.98. According to the single-criterion ANOVA, there is a very significant difference between the means (P= 0.000) showing the effect of forest composition on soil acidity, with a high homogeneity within sites between repetitions which values of coefficients of variation vary between 1 and 6%.

Soil Organic Carbon Stock (SOCS)

The ecological variables as well as the physical and chemical properties of the soil may influence the accumulation of organic carbon in the soil. The results of SOCS in the studied soils are presented in Table 4 and highlighted in Figure 6. The ANOVA results generate a significant difference between sites (p = 0.012) in SOCS, hence the effect of the site and the forest type on the variation in SOCS. The quantities of carbon sequestered in the studied soils ranged from 109.02 to 264.73 t/ha. The highest stock is found under green oak and zeen oak deciduous forest trees (S8 and S9) on a basaltic parent rock, followed by cedar resinous trees on a basaltic substrate (S7). This mixing of stands may have led to the variability in soil bed quality, rooting depth of tree species and soil chemistry, which may also influence carbon storage. A student T test comparing the means for independent samples was performed, showing a significant difference (p = 0.012) between the means of SOCS in a basaltic and sandy dolomite substrate, hence the effect of the nature of the lithological material on the variation in SOCS under the same forest species. This is the case for S3 (green oak on sandy dolomite with a SCOS=174.50 t/ha) and S9 (green oak on basalt with a SOCS=264.73 t/ha).

Discussion

The forest soils contribute to about 70% of the carbon dioxide exchanges between the biosphere and the atmosphere. These quantities are mainly produced by the decomposition of organic matter and root respiration (Jessica 2009). These processes vary according to several parameters including climate, vegetation type, soil physico-chemical characteristics (Conant and Paustian 2001), frequency of natural disturbances and development. It is therefore difficult to accurately estimate organic carbon stocks at the regional level and to obtain quality empirical data that accurately represent this heterogeneity (Kulmatiski et al. 2003 in Jessica 2009).

The obtained results show that the forest soils of the Central Middle Atlas have a high carbon sequestration capacity. Indeed, the average organic carbon stock at the level of the studied forests is about 231.45 t/ha in the Azrou forest, 147.14 t/ha in the South of Jbel Aoua forest and 126.62 t/ha in the Jaaba forest in the first thirty centimetres of soil. This variation depends on the nature of the soil in the study area. The carbon stocks found in this layer under the green oak stands are higher than those observed by Boulmane (2010), which are of the order of 63 t/ha and 47 t/ha respectively in the forests of Tafechna and Reggada considered relatively degraded. This SCOS value is still higher than that recorded under cork oak stands in the Maamora forest (78 t/ha) (Oubrahim 2015) and in the Moroccan Rif (100 t/ha) (Sabir et al., 2002). These strong potentialities of the studied forest soils in terms of carbon sequestration can be explained by the large quantities of litter returned to the ground by the existing forest formations in the studied sites, and by the presence of allophanes resulting from the alteration of basaltic rocks (Jaaba and Azrou sites) and calcium (Ca^{++}) resulting from the alteration of limestone and dolomite (Jbel Aoua site), which have the ability to fix and retain organic matter in a stable state in the soil (Benjelloun 2017).

A similar study by Eglin (2005) and Lecointe et al (2005) in British forests estimated an SOCS in the organic layer (depth< 30 cm) of 136 and 153 t/ha respectively is still below the SOCS found in the study area.

A SOCS was evaluated in a Canadian forest by Jessica (2009) below 5 types of plant formations with values ranging from 61 to 133 t/ha, the highest of which is still observed under hardwood in the first organic layer of the soil (<30cm), and highlighted the effect of plant material on soil organic carbon accumulation.

Conclusion

The purpose of this study was to determine carbon stocks under different forest formations in the Central Middle Atlas. With regard to the results obtained, it can be said that there is spatial variability in carbon stocks in the study area and that this may be explained by the different nature of the forest formations concerned. However, several factors contribute to the understanding of these stocks and it will be essential to consider them in subsequent analyses. Indeed, the best SOCS are observed below the hardwoods (Green oak and Zeen oak) followed by cedar-based softwoods on a basaltic substrate. Mixed strata showed low carbon accumulations. The presence of allophanes and exchange earth bases (Ca++ and Mg++) in the soil contributes to the fixation and maintenance of soil organic matter in a stable state.

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