INTRODUCTION

In the current context of climate change, increasing concentrations of greenhouse gases in the atmosphere, particularly carbon dioxide (CO$_2$), are recognized as the main cause of global warming. As such, the quantification of soil organic carbon (SOC) stocks in forest ecosystems is vital, given that forest soils represent an important carbon reservoir (Vanguelova et al., 2013). They contribute to about 70% of the CO$_2$ exchange between the atmosphere and the terrestrial biosphere (Jandl et al., 2007). The evaluation of the SOC stocks is essential in the assessment of greenhouse gas emissions, established in accordance with the recommendations of the United Nations Framework Convention on Climate Change (UNFCCC, 1992) and the Kyoto Protocol (1997). SOC sequestration is the process by which carbon is fixed from the atmosphere via plants and stored in the soil (Lefèvre et al., 2017). The variation of SOC stocks depends on several parameters including climate, vegetation type, physico-chemical properties of soils (Conant et al., 2003) and the extent as well as frequency of natural disturbances and forestry interventions. It is therefore difficult to estimate SOC stocks accurately at the regional scale and to obtain good empirical data that represent this heterogeneity well.

Effect of plant Communities and Ecological Parameters on Soil Organic Carbon Stocks in the Mamora Forest, Morocco

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ABSTRACT

Several studies on the assessment of soil organic carbon (SOC) stocks have been carried out at the global level. However, reliable information on SOC stocks is not readily available at the regional level. In addition, very few studies have assessed the factors responsible for the variation of SOC stocks, in particular the effect of plant communities. For this purpose, the main objective was to analyze the effects of three plant communities and ecological parameters on the SOC stock in the Mamora forest. Specifically, the authors looked to examine the relationships between SOC stock and plant communities and to define the main parameters that directly influence SOC stock. Ten soil profiles with three replications were sampled at each plant community, from which SOC stock was determined. To assess the effect of plant communities on SOC stocks, phytosociological surveys were carried out according to the phytosociological stigma method developed by Braun-Blanquet. The results show that the SOC stocks in cork oak soils are characterized by high variability, with values ranging from 55 t·ha$^{-1}$ to 95 t·ha$^{-1}$. Indeed, the findings of this study showed that the SOC stocks fluctuated significantly with plant communities. In addition, SOC stocks were also affected by the interactions between plant communities, the amount of litter and the density of the cork oak stand. These outcomes of this study highlight the critical need to incorporate community-specific carbon values into future carbon sequestration modeling.

Keywords: SOC stocks, carbon sequestration, plant communities, ecological parameters, Mamora forest, Morocco.
Several studies have been carried out worldwide on the assessment of SOC stocks. However, in most regions and countries, reliable information on SOC stocks remains limited. Indeed, much of the knowledge is concentrated on the quantification in a few specific forest ecosystems. Similarly, very few studies have focused on assessing the factors responsible for variation in SOC stocks; in particular, the effect of plant communities, which are homogeneous units, characterized by the same ecological conditions, and are considered determinants of soil carbon cycling and storage (Fry et al., 2018). The relationship between plant communities and SOC stocks is very complex, as plant communities themselves assemble according to climate and soil type, and a myriad of other factors (Fry et al., 2018). Thus, there remain huge gaps in the distribution of SOC stocks within the same ecosystem, depending on plant communities.

To study this relationship between plant communities and SOC stocks, this study focused on the plant communities present in cork oak (Quercus suber L.) stands. Cork oak is an endemic species of the Mediterranean basin and covers nearly 377000 ha in Morocco (HCEFLCD, 2021). The Mamora forest is one of the largest cork oak forests in the world. Phytosociologically, this forest is characterized by the presence of a single climax association referred to as Telino linifoliae-Quercetum suberis (Benabid, 2000), which, under the factors of deforestation and forest degradation, has given way to degradation-based associations of Thymelaea lythroides and Chamaerops humilis (Aafi, 2007). The soils that underlie the cork oak ecosystem of the Mamora Forest are a considerable organic carbon sink, retaining approximately 51% of SOC stocks, with the top 30 cm of soil containing up to 80% of SOC (Oubrahim et al., 2016). In addition, the soils under cork oak have been reported to store more carbon than any other land use in Mamora Forest (Oubrahim et al., 2016).

Given the importance of forest plant communities in carbon sequestration, the objective of this research project was to assess the SOC stocks in the upper soil layers (top 30 cm) of the forest soils of the cork oak ecosystem of the Mamora forest. This study also aimed to find the relationships between SOC stocks and plant communities as well as to define the main parameters that have a direct influence on SOC stocks.

**MATERIAL AND METHODS**

**Study area**

The study was carried out in the Mamora forest, which extends over 130000 ha and is located...
between 34° and 34°20’ North and 6° and 6°45’ West in the cities of Kenitra, Khémisset and Salé in Morocco (Figure 1). The soils are mainly of sandy over clay type, with pH values ranging from 4.8 to 6. The thickness of the sand layer is heterogeneous and can reach several meters in some places (Aafi, 2007). The climate type of this forest ranges from sub-humid to semi-arid, with mean annual precipitation ranging from 350 to 650 mm. The mean monthly temperature ranges from 12°C in January to 25°C during the summer months of July and August (Aafi, 2007). The vegetation type is dominated by cork oak (*Quercus suber* L.) which covers about 65487 ha, representing 51% of the study area. The remaining area is made up of pine, eucalyptus and Australian acacia plantations (HCEFLCD, 2021).

**Sample collection**

The choice of stratified sampling provided a basis for assessing the impact of plant communities and ecological parameters on the soil organic carbon (SOC) stock. This is an efficient sampling method recommended by several authors, including Roleček et al. (2007). Accordingly, ten soil profiles with three laboratory replications were sampled at each plant community (10 soil profiles × 3 plant communities × 3 replications). Uniform soil depths were considered (D: 0-30 cm) for comparison between the studied soils.

**Sample preparation and analyses**

The soil samples were first air-dried and crushed to pass through a 2 mm sieve. For each sample, the following properties were measured:

- soil bulk density (ρb) using the core (3 cm diameter; 10 cm height) method (Blake & Hartge, 1986);
- the particle size distribution by the international pipette method (Piper, 1966);
- soil pH by the glass electrode pH meter (Jackson, 1973);
- soil organic carbon (SOC) content by the Walkley and Black method (Walkley & Black, 1934).

The SOC stocks were quantified by collecting soil from the upper 30 cm. In each 20 × 20 m plot, the SOC stock was calculated by multiplying the corresponding values of fine bulk density and SOC content. To assess the effect of plant communities on the SOC stocks, a floristic survey was carried out on each 20 × 20 m plot at the peak of the growing season. Subsequently, abundance/dominance indices were assigned to each plant species in accordance with the phytosociological stigmatization method developed by Braun-Blanquet (1932). This method is widely used in Morocco and helps to describe plant communities (Dallahi et al., 2016). Using this method, the following arboreal plant communities were identified:

- *Quercus suber-Teline linifolia* plant community (PC-Qs-Tel)
- *Quercus suber-Thymelaea lythroides* plant community (PC-Qs-Thl)
- *Quercus suber-Chamaerops humilis* plant community (PC-Qs-Ch)

**Overview of plant communities**

**Quercus suber-Teline linifolia (PC-Qs-Tel)**

This plant community develops in the most stable and least disturbed areas of the Mamora forest. It is characterized by the strong presence of cork oak and needle-leaved broom (*Teline linifolia*) species. The needle-leaved broom is a leguminous shrub known for its symbiotic nitrogen fixation estimated at 50% of the plant’s nitrogen content (Hracherras et al., 2013). The PC-Qs-Tel plant community is species-rich, with an estimated 158 plant species. The floristic composition indicates a thermophilic forest environment, developed in a sub-humid and semi-arid temperate to warm bioclimate, whereas these species reflect the cork oak climax forest. This plant community exists between 140 and 203 m above sea level on sandy soils where humus is absent or rare and evolved. The most dominant aspect types are northwest, north and northeast. The average ground cover of trees, shrubs and herbaceous species is 30%, 60% and 35% respectively, while the corresponding heights are 11 m, 70 cm and 20 cm, respectively.

**Quercus suber-Thymelaea lythroides (PC-Qs-Thl)**

The PC-Qs-Thl plant community represents a sparsely populated matorral of cork oak at an advanced stage of degradation. It results from the decline of the PC-Qs-Tel climax and develops under less favorable ecological conditions. It is characterized by low species richness where the sand is typically brown to reddish and shallow to deep. This plant community is characterized by bioindicator species, such as *Thymelea*
lythroides, Urginea maritima, Chamaerops humilis, Quercus suber, Pyrus communis ssp. mamorenensis and Teline linifolia. The corresponding tree layer provides a ground cover of about 40% and has an average height of about 12.5 m, while the shrub layer accounts for about 45% of the cover and has an average height of about 85 cm. The herbaceous layer accounts for 45% of the ground cover and has an average height of 20 cm.

**Quercus suber-Chamaerops humilis (PC-Qs-Ch)**

The PC-Qs-Ch plant community is dominated by cork oak and the Mediterranean dwarf palm (Chamaerops humilis). It is widespread on the sands where the clay layer is closely adjacent to the soil surface. This soil feature results in high hydromorphy, which adversely affects the growth of cork oak. The PC-Qs-Ch community is similar to PC-Qs-Thl with regard to the plant composition, with the corresponding bioindicator species dominated by Chamaerops humilis, Thymelea lythroides, Quercus suber, Pyrus communis ssp. mamorenensis and Teline linifolia. The tree stratum representing this plant community accounts for a ground cover of about 40%, with an average height of about 12 m, while the shrub stratum represents 45%, with an average height of about 70 cm. The herbaceous layer covers 45% and has an average height of 25 cm.

**Overview of ecological descriptors**

The ecological descriptors that could have an impact on the distribution of plant communities and SOC stocks were identified. These include altitude, distance to the sea, mean annual rainfall, stand density and litterfall (Table 1).

**Statistical analyses**

The data were presented as the mean value of the three replicate sites for each plant community. The means were compared using the ANOVA method and the Newman-Keuls test. Pearson’s correlation index was used to test the significance ($p < 0.05$) of the relationships between the SOC stocks and elevation, stand density, distance to the Atlantic Ocean and amount of litterfall. In addition, the description of the relationships between plant communities, SOC stocks and other ecological parameters was carried out using hierarchical cluster analysis (HCA). HCA is a multivariate statistical tool used to identify the groups of samples that behave similarly or have similar characteristics (Roessner et al., 2011). XLSTAT was used to carry out the analyses.

**RESULTS**

**SOC stocks at the Mamora forest**

The results of the SOC stock assessment are presented in Table 2. The highest average SOC stocks were observed under the PC-Qs-Tel plant community with 86.67 ± 11.47 t·ha$^{-1}$, while the lowest were observed under the PC-Qs-Ch community with 79.00 ± 10.37 t·ha$^{-1}$. Interestingly, the relatively high average value of SOC stocks across all plant community types, which was recorded at 81.7 t·ha$^{-1}$ (Figure 2), indicates a high carbon sequestration potential of Mamora forest soils. The area under cork oak in the Mamora forest is 65487 ha, making the contribution of carbon to the environment significant. Indeed, it has been estimated

<table>
<thead>
<tr>
<th>Ecological descriptors</th>
<th>Classes</th>
<th>Modalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude (m)</td>
<td>Alt-1</td>
<td>Alt-1 ≤ 150</td>
</tr>
<tr>
<td></td>
<td>Alt-2</td>
<td>Alt-2 ≥ 150</td>
</tr>
<tr>
<td>Distance from the sea (km)</td>
<td>Dis-1</td>
<td>Dis-1 ≤ 15</td>
</tr>
<tr>
<td></td>
<td>Dis-2</td>
<td>Dis-2 &gt; 15</td>
</tr>
<tr>
<td>Stand density (trees/ha)</td>
<td>Den-1: low density</td>
<td>Den-1 &lt; 100</td>
</tr>
<tr>
<td></td>
<td>Den-2: moderate density</td>
<td>100 ≤ Den-2 &lt; 200</td>
</tr>
<tr>
<td></td>
<td>Den-3: high density</td>
<td>Den-3 ≥ 200</td>
</tr>
<tr>
<td>Litter quantity</td>
<td>Lit-1</td>
<td>Litter quantity is low</td>
</tr>
<tr>
<td></td>
<td>Lit-2</td>
<td>Litter is abundant</td>
</tr>
<tr>
<td>SOC stock</td>
<td>SOCs-1</td>
<td>SOC stock is low</td>
</tr>
<tr>
<td></td>
<td>SOCs-2</td>
<td>SOC stock is abundant</td>
</tr>
</tbody>
</table>
that this area accounts for 3595236.3 – 6234362.4 t·ha\(^{-1}\) of soil organic carbon at a depth of 30 cm.

**Influence of plant communities on SOC stocks**

The results of the one-way ANOVA are presented in Table 3 and reveal that plant community types have a highly significant effect on the SOC stocks (p < 0.005). The multiple comparisons of the means using the Newman-Keuls test reveal two homogeneous groups (Table 4). These results show that the first plant community is markedly different from the other plant communities. Indeed, the PC-Qs-Tel community presents the highest SOC stocks.

**Relationship between the SOC stocks and ecological parameters**

The Pearson correlation coefficient was used to reflect the degree of linear correlation between the SOC stocks and the selected ecological parameters (Table 5).

### Table 2. Descriptive statistics of the SOC stocks for the studied plant communities

<table>
<thead>
<tr>
<th>Plant community</th>
<th>Samples</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC-Qs-Tel</td>
<td>30</td>
<td>86.67</td>
<td>11.47</td>
</tr>
<tr>
<td>PC-Qs-Thl</td>
<td>30</td>
<td>79.33</td>
<td>7.28</td>
</tr>
<tr>
<td>PC-Qs-Ch</td>
<td>30</td>
<td>79.00</td>
<td>10.37</td>
</tr>
</tbody>
</table>

![Figure 2. The SOC stocks at the Mamora Forest](image)

### Table 3. Analysis of variance (ANOVA): Effect of plant communities on the SOC stocks

<table>
<thead>
<tr>
<th>Source</th>
<th>Degrees of freedom</th>
<th>Sum of square</th>
<th>Mean square</th>
<th>F</th>
<th>Prob &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>2</td>
<td>1126.67</td>
<td>563.33</td>
<td>5.78</td>
<td>0.004</td>
</tr>
<tr>
<td>Error</td>
<td>87</td>
<td>8473.33</td>
<td>97.40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>89</td>
<td>9600.00</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 4. The result of multiple comparisons of means using the Newman-Keuls test

<table>
<thead>
<tr>
<th>Plant community</th>
<th>Mean (t ha(^{-1}))</th>
<th>Groups</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC-Qs-Tel</td>
<td>86.67</td>
<td>A</td>
</tr>
<tr>
<td>PC-Qs-Thl</td>
<td>79.33</td>
<td>B</td>
</tr>
<tr>
<td>PC-Qs-Ch</td>
<td>79.00</td>
<td>B</td>
</tr>
</tbody>
</table>
The results of the Pearson correlation test assessing the relationship between the SOC stocks and the selected parameters are presented in Table 5. The correlation coefficient ranged from -0.11 to 0.72. There was a strong relationship between the SOC stocks and the amount of litter and stand density, with correlation coefficients of 0.55 and 1.72, respectively. On the other hand, elevation had almost no effect on the distribution of the SOC stocks, with a correlation coefficient of 0.09. This was expected given its relatively low variation in the Mamora forest. As for the stand age factor, it was negatively correlated with the SOC stocks at -0.11, highlighting a decline in the SOC stocks under degraded old cork oak stands in the respective plant communities.

**Characterization of the study plots**

Hierarchical cluster analysis (HCA) was used to classify the study plots into clusters. The results are illustrated by the dendrogram in Figure 3. The first graphic revelation is that the sites can be divided into two distinct groups which differ in SOC stocks, plant community types, stand density and amount of litter. The first group is characterized by the SOC stocks above 80 t·ha⁻¹ and develops in the PC-Qs-Tel plant community. This group is marked by high densities (Den-1) of cork oak stands and an abundance of litter (Lit-2). Conversely, the second group features the SOC stocks under 80 t·ha⁻¹. It overlaps with the PC-Qs-Thl and PC-Qs-Ch plant communities. These communities are mainly composed of degraded cork oak stands and, consequently, are typically distinguished by low densities (Den-3) of cork oak stands and a low quantity of litter (Lit-1).

**DISCUSSION**

Forest soils are responsible for about 70% of carbon exchange between the atmosphere and the terrestrial biosphere. The main source of carbon exchange is the decomposition of organic matter and the root respiration of three plant species (Jandl et al., 2007). This process varies depending on several parameters, including vegetation type, amount of litter, stand density and soil physico-chemical properties (Conant et al., 2003).

This study shows that the soils of the Mamora forest have considerable potential for carbon sequestration. Indeed, the average SOC stocks ranged from 54.9 t·ha⁻¹ to 95.2 t·ha⁻¹, with an average value of about 81.7 t·ha⁻¹. This is consistent with the value (78 t·ha⁻¹) reported by Oubrahim

### Table 5. The Person correlation between the SOC stocks and ecological parameters

<table>
<thead>
<tr>
<th></th>
<th>SOC</th>
<th>Den</th>
<th>Lit</th>
<th>Alt</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOC</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Den</td>
<td>0.55**</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lit</td>
<td>0.72**</td>
<td>0.40</td>
<td>1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alt</td>
<td>0.09</td>
<td>0.07</td>
<td>0.33</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>Age</td>
<td>-0.11</td>
<td>-0.12</td>
<td>0.18</td>
<td>0.09</td>
<td>1.00</td>
</tr>
</tbody>
</table>

**Figure 3. Dendrogram with groups identified in the cluster analysis**
et al. (2016) in the same cork oak ecosystem in the Mamora forest. Nevertheless, it is much lower than the SOC stocks obtained in the Azrou forest (El Mderssa et al., 2018), composed mainly of Cedrus atlantica, Quercus rotundifolia and Quercus canariensis, under a basaltic substrate (231.45 t ha$^{-1}$). This superiority to the estimated stocks in the considered study area could be explained by the high stand densities, substrate type and the significant quantity of litter associated with those ecosystems.

The analysis of the relationship between the SOC stocks and plant communities also showed that there is a highly significant effect of plant communities on the SOC stocks. Multiple comparisons of means using the Newman-Keuls test showed the superiority of the Qs-Tel plant community. Indeed, this climax community presents the most favorable ecological conditions for the growth of cork oak (Aafi, 2007). Moreover, this association is marked by the strong presence of Teline linifolia, which is a leguminous shrub known for its symbiotic nitrogen fixation estimated at 50% of the plant’s nitrogen content (Hracherrass et al., 2013). The PC-Qs-Tel plant community is also associated with a high species richness, which is estimated at 158 plant species (Aafi, 2007). By contrast, the lowest SOC stocks are observed in the PC-Qs-Ch and PC-Qs-Thl plant communities. These formations are the result of the degradation of the PC-Qs-Tel climax association, and develop in less favorable conditions and marked by low species richness (Aafi, 2007).

This study provides confirmation of the important relationship between biodiversity and soil carbon stock. Indeed, floristic biodiversity contributes to the formation of organic matter from organic litter, and thus to the improvement of the SOC stocks (Canedoli et al., 2020; Lefèvre et al., 2017; Thiele-Bruhn et al., 2012). These results also support the positive relationships between vegetation type and carbon stock and affirm the results obtained by Wang et al. (2020) who highlighted the negative impacts of plant diversity loss on carbon sequestration exacerbated over time in grasslands.

The results of this study indicate that the SOC stocks in the cork oak ecosystem increases in tandem with stand density. Indeed, the best SOC stocks were obtained at densities above 200 trees ha$^{-1}$. Similarly, Boulmane et al (2010) observed this effect under holm oak (Quercus rotundifolia) stands in the Middle Atlas region of Morocco in the Reggada (1584 trees/ha) and Tafchna (5192 trees/ha) forests where the SOC stocks were found to be 56 t ha$^{-1}$ and 80 t ha$^{-1}$, respectively. Dense forests often favor soil-forming processes and, therefore, are often characterized by deep and fertile soil, as well as high soil water content, which was shown by Zribi et al. (2016) to enhance the soil carbon sequestration potential under cork oak forests in Tunisia. Another important factor is the high carbon input from litter and plant roots incorporated in the soil. This corresponds to what was observed in the field, where the litter layer is considerably thick, which improves humification conditions and the formation of the very stable clay-humus complex in the soil (Duchaufour, 1970; Ono et al., 2011; Wei et al., 2018; Wei et al., 2020). As such, afforestation is still proposed as one of the most important climate change mitigation approaches, owing to its role in promoting the accumulation and concentration of SOC stocks, as well as being one of the most technically accessible and cost-effective climate engineering methods (Smith et al., 2016). Correspondingly, it is essential to ensure that the afforested areas are well managed, as their carbon sequestration potential has been shown to increase with age. Indeed, Varnagirytė-Kabašinskienė et al. (2021) found that the SOC concentrations in older afforestation sites were higher than in younger sites, particularly in the top 30 cm layer.

The important role of high density in humification and stability of soil organic matter, and subsequently in carbon stock accumulation was underlined in this study. Consistent with the findings, previous studies have indicated that SOC stocks increase with stand density (Wang et al., 2020; Chen et al., 2016) and higher stand densities can enhance soil carbon storage (Na et al., 2021). In addition, the role of litter as an important component of terrestrial ecosystems is highlighted in this study, as its production and accumulation contribute to carbon sequestration and soil fertility (Lee et al., 2020).

On the basis of the results of this study, stand age does not seem to have a direct influence on SOC stocks. Indeed, the correlation coefficient observed between the two variables was low, not exceeding 11%. The SOC stocks were found to not increase with age for the stands studied. However, some high carbon values are associated with older stands. The same results were reported by Peltoniemi et al. (2004) showed that soil carbon stock fluctuates significantly with stand age. This
is in contrast to other authors, such as Cao et al. (2019), who showed that stand age has a significant influence on soil carbon storage in dragon spruce (Picea asperata Mast). The other parameters, including altitude and mean annual precipitation, showed little variation in the study area and therefore their effects were not significant on the SOC stocks.

**CONCLUSIONS**

The purpose of this study was to evaluate the effect of plant communities and ecological parameters on the soil organic stock in Mamora forest. The results obtained confirm the relationship between plant communities and SOC stocks. The more the plant community is at its climax and stable, the higher the SOC stocks. The PC-Qs-Tel plant community yielded the highest SOC stocks. Conversely, the PC-Qs-Ch plant community had the lowest SOC stocks. Additionally, the main ecological parameters that strongly influence the soil carbon stock and that vary between plant communities are stand density and amount of litter. These results demonstrate the critical importance of incorporating separate carbon values for each community in future carbon sequestration models.

**REFERENCES**


