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Estimation of Carbon Sequestration; Using Allometric Equations; in Azrou Cedar Forests (*Cedrus atlantica* Manetti) in the Central Middle Atlas of Morocco under Climate Change

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Abstract

The topic of carbon sequestration in forest ecosystems has recently taken a lot of attention due to concerns about global climate change. As a spontaneous species of the Central Middle Atlas, the Atlas Cedar was the subject of our study. Thus, a total of 30 sample trees were subjected to the weight measurements for the estimation of biomass and organic carbon stock in a logging lot in the Azrou forest. The amount of sequestered carbon was then extrapolated in all stand forests studied from the developed carbomass models. The results obtained show that the largest allocation of carbon stock (93%) is in the stem, followed by branches (5%) and foliage (2%). The average carbon storage in this cedar forest is 99.42 tC/ha (aboveground and belowground), or 364.58 t/ha of CO_2, a value significantly higher than that found in other Moroccan forest ecosystems.

Keywords

Atlas Cedar, Carbon, Climate Change, Sequestration, Stock

1. Introduction

The increase in greenhouse gas (GHG) concentrations in the atmosphere is currently recognized as the main cause of climate change, which, according to several studies, will result in an increase in global temperature and the frequency of extreme weather events, as well as a rise in sea level (Boer et al., 2000). This reality is generating growing interest in carbon sequestration projects, based on woody species that store a considerable amount of this element in their biomass through photosynthesis (Mcghee et al., 2016). The most significant increases in catchment occur when moving from a low biomass system (annual crops, grasslands, fallows) to a tree-based system (Palm et al., 2000). Indeed, the forest is the most important terrestrial carbon reservoir. It sequesters 9.2 gigatonnes of net CO_2 emissions per year, equivalent to 33% of global GHG emissions (IPCC, 2014).

The Atlas Cedar (*Cedrus atlantica* Manetti) is a species found in mountainous areas and grows between 1500 and 2500 m of altitude (Emberger, 1939; Pujos, 1964). It is a much more majestic and imposing looking tree than other species (Lepoutre & Pujos, 1964; M'hirit, 1994a; M'hirit, 1994b). It easily exceeds 40 m in height and 2 to 3 m in circumference. It covers more than 116,000 ha in the Middle and High Atlas and 15,000 ha in the Rif (IFN, 2003). Outside Morocco, its natural area occupies about 50,000 ha in the mountains of Algeria (Damnati et al., 2014). It covers a wide range of climates, from sub-humid, humid to the Mediterranean mountainous region. Its optimal bioclimatic environment, which is located at the Mediterranean mountain level between 1,600 m and 2,000 m, specifies the good forest stands, mainly in a humid bioclimatic environment with a cold to very cold variant (Achehboune, 2006).

The drought of recent years and especially a decrease in density, following the phenomenon of depressant and various cuts in these stand forests, have reduced its area of distribution (HCEFLCD, 2006). It is a traditional element of Moroccan culture and landscape; it is also an important economic resource for Morocco, accounting for 90% of the country's timber resources and providing about 90,000 m^3 of firewood each year (El Abid, 1993).

According to our investigations, no work has so far targeted carbon sequestration in Moroccan cedar ecosystems. The objective of this study is to evaluate the organic carbon stock sequestered in cedar stands in the Central Middle Atlas using new adjustment and modelling approaches and techniques. The developed carbomasses are necessary and essential tools for sustainable and rational management of the Atlas Cedar ecosystem.

2. Material and Methods

2.1. Presentation of the Studied Area

The study was carried out in the Azrou forest, located on the northern edge of the Middle Atlas Plateau during 2018 (**Figure 1**), characterized by contrasting relief with very variable elevations ranging from 1250 m to 2103 m. Rainfall is relatively high, averaging around 982 mm/year over a 30-year cycle and occurring as rain or snow. As for the thermal regime, January is the coldest month with a minimum monthly average value of −1.31˚C over a 30-year cycle followed by February and December. The highest maximum monthly average temperatures are observed in July (29.50˚C) and August (29.51˚C) (Achehboune, 2006;

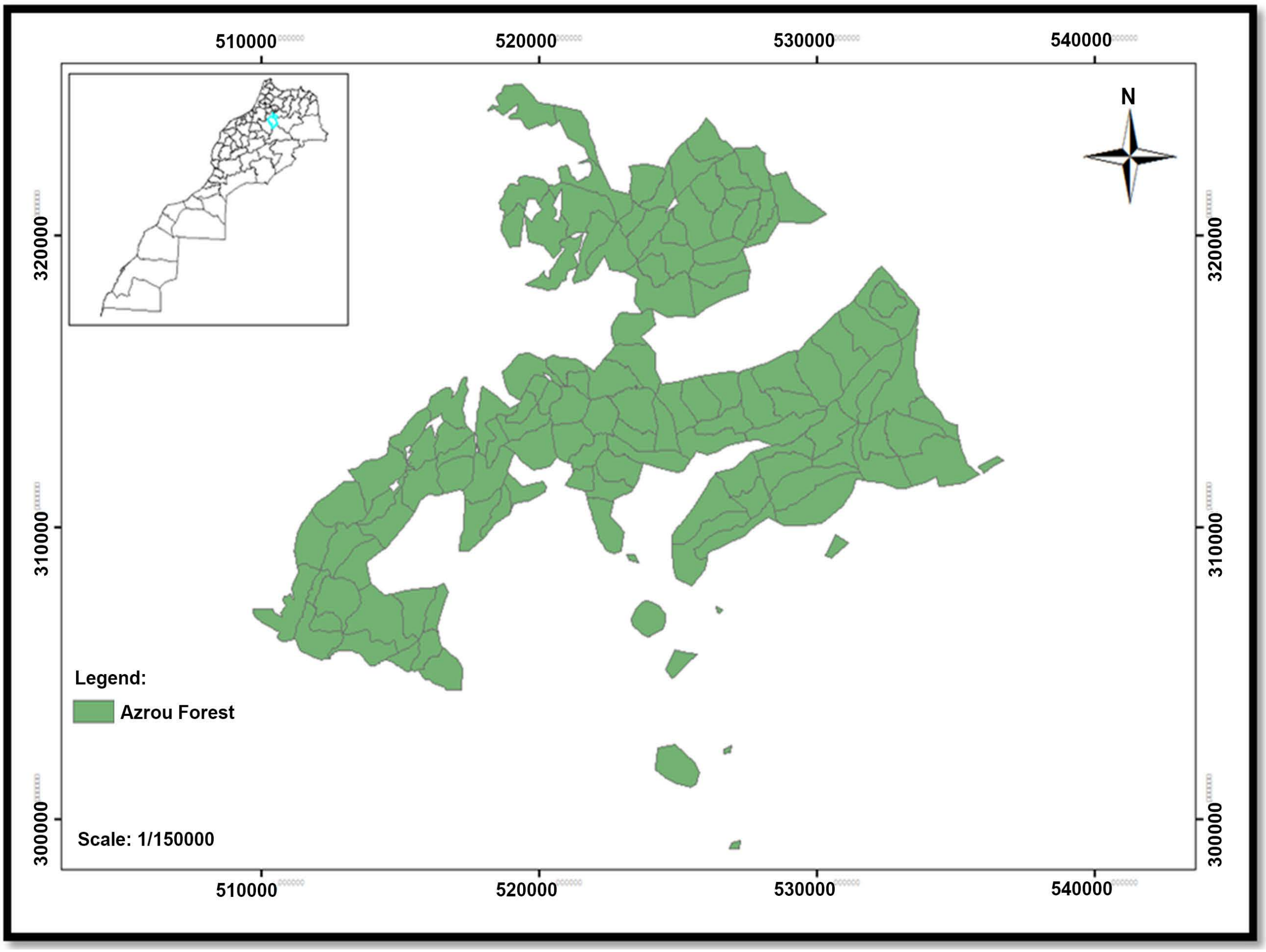

Figure 1. The map of studied area.

Laaribya, 2016). Emberger's rainfall coefficient at the level of this forest varies between 101 and 114, thus defining a humid Mediterranean bioclimate with a cold and sub-humid variant with a temperate variant. The climate is also characterized by severe storms, particularly in summer, making it more favorable to the establishment and development of the cedar forest.

The composition of forest formations in the Azrou Forest (Table 1) includes pure atlas cedar stands, cedar mixed mainly with green oak, pure green oak stands and reforestation with cedar, Arizona cypress and poplar (HCEFLCD, 2007).

2.2. Methodological Approach

Estimating the carbon stock of the trees as well as in their components (stem, branches and foliage) requires an assessment of their biomass. Indeed, the trees' wood contains a significant fraction of carbon contained in the biomass and considered as a carbon reservoir. Thus, knowing the relationship between biomass and tree carbon content in the studied area, it is relatively simple to estimate the amount of carbon sequestered by this forest. Estimating biomass is a

Table 1. The vegetal composition of the Azrou forest.

	Azrou forest	
Vegetation	**Area on ha**	**Percentage in the total forest (%)**
Pure Cedar	1˚497.41	8.41
Mixture of cedar and green oak forest	7˚182.03	40.33
Pure green oak	4419.77	24.82
Reforestation (Cedar + Cypress + Poplar)	315.12	1.78
Other (Asylvatic empties + secondary species)	4392.45	24.67

difficult operation and often faces two difficulties: one strictly material relating to the amount of work required to establish individual biomasses, the other concerns the extrapolation of individual results to the entire stand forest, which involves cutting down a significant number of trees (Belghazi & Ezzahiri, 2002).

In order to calculate the individual biomass, we took the opportunity of the current operations of the wood exploitation in a cedar stand forest plot. Thus, a sample of 30 trees based on circumference classes was selected to carry out the following measurements:

- Measurements of the circumferences at 1.30 m from the ground of standing trees using an electronic compass and the total lengths of these trees cut down using a tape measure;
- Separation of the different parts of each tree and weighing of the:
- The branches (in kg) using a Poket Balance with an accuracy of one kilogram;
- The foliage using an electronic scale with an accuracy of one gram;
- and calculating the weight of the stem by multiplying the volume by the density of the cedar wood.
- At the end of these weighings, we took a sample:
- On the stem, three 5 cm thick washers: one at the base, one at mid-length and one at the cut-out 5 cm in diameter;
- At the level of the average branch of each tree, a 3 cm thick washer at mid-length;
- On the foliage, a sample of about 100 grams of each tree.

The washers and foliage sample were placed in polyethylene pouches for oven drying for 24 hours at 105˚C for wood and 65˚C for foliage respectively to determine their dry weight (Riedacker, 1978 in Belghazi et al., 2001). In order to determine the organic carbon concentration in each component of the tree, wooden aliquots and foliage were collected from each tree sample. These aliquots were then placed in a muffle furnace for calcination at 600˚C for 24 hours.

In order to extrapolate the carbon stock estimate to all the studied stand forests, we carried out an exhaustive inventory of the circumferences at 1.30 m from the ground of all trees within plot 4, the subject of this study.

3. Allometric Models Used

The method commonly used for estimating the carbon stock in the epigeal part is based on allometric (carbomass models) equations that express the relationship between tree dimensions and the organic carbon stock. This method most often uses the circumference at 1.30 m from the ground and the total height as explicative variables. Thus, we estimated according to each compartment of the tree (Table 2), the general equations, widely used and mostly adopted in forest biomass studies (Boulmane, 2013; FAO, 2012; Mcghee et al., 2016; He et al., 2018). After their linearization, these equations were estimated by the linear regression method using the *R* program.

The choice of the best model was based on the analysis of a number of statistical parameters, namely:

- **The coefficient of determination (R^2)** which reflects the part of the variation explained by the model that must be high. This parameter is calculated as follows: $R^2 = 1 - SCR/SCT$.

With *SCR:* The total of the residue squares and *SCT* **=** The sum of the total squares.

- **Durbin-Watson statistics (*D*)** which reflect the independence of the residues;

According to the Durbin-Watson table, a value of less than 2 indicates the existence of a positive correlation between successive residues and a value of more than 2 corresponds to a negative correlation between these same hazards. On the other hand, a value close to 2 does not reject the hypothesis of the independence of the residues (Tranchefort, 1984). The calculation formula is as follows: $D = \frac{\sum_{i=2}^{n}\left(e_i - e_{i-1}\right)^2}{\sum_{i=1}^{n} e_i^2}$ with: *e* means residue.

- **Akaike Information Criterion (*AIC*)**, based on the principle of likelihood, it allows models to be penalized according to the number of parameters in order to satisfy the parsimony criterion. The model with the weakest Akaike information criterion is then chosen (Akaike, 1974). *AIC* is calculated as follows: $AIC = -2\ln l(\theta) + 2q$ with $l(\theta)$ is the vraisemblance of the model and q is the number of estimated free parameters.

Table 2. Models of equations adopted for estimating the carbon stock per tree compartment.

Tree compartment	Adopted equations
Total tree and stem	$SCOT = a(C^2H)^b$
	$SCOT = aC^bH^d$
Branches	$SCOBr = a(C^2H)^b$
	$SCOBr = a + b(C^2H)$
Foliage	$SCOF = a + b(C^2H)$
	$SCOF = a + b(CH)$

C: tree circumference at 1.30 cm (m); ***H***: total tree height (m); ***a*, *b* and *d***: regression coefficients to be estimated; ***SCOT***: total organic carbon stock; ***SCOBr***: branch organic carbon stock; ***SCOF***: organic carbon stock of the foliage.

- **The Standard Mean Square Error (*RMSE*)** is the square root of the MSE (mean square error), it is the arithmetic mean of the squares of the differences between forecasts and observations, a value to be minimized in a simple or multiple regression. The method is based on the nullity of the average of the residues. The best model is the one with a lower *RMSE*. it is calculated as follows:

$RMSE = \sqrt{\sum_{n=1}^{n} \frac{\left(\ln Y_i - \ln \hat{Y}_i\right)^2}{n}}$ where Y_i and $\hat{Y}_i$ are observed and predicted values of the model, n is the number of sample tree.

- **Residue analysis** to verify the equality of variances, the normality of the residues and the absence of their self-correlation. As part of this study, we verified these assumptions using the graphical method.

4. Results

Dendrometric description of the forest stands studied:

The results of the inventory of the forest stands studied are summarized in Table 3. The average age of the stands in this forest was determined by counting the rings in the felling section.

Height-Circumference relationship:

Establishing the height-circumference relationship at 1.30 m allows the results of individual carbomass to be extrapolated to all stand forest. The relationship obtained is of a linear type that is better adapted to this type of observations, whose statistical characteristics and graphical residue analysis are presented in Table 4 and Figure 2.

This relationship makes it possible to estimate the total height of all trees in the stand, knowing their circumference at 1.30 m; this will then make it possible to estimate the carbomass per hectare which is correlated to both the circumference at 1.30 m and the total height of the tree.

Fitting of carbomass models:

The determination of the carbomass of the different compartments of the sample trees requires knowledge of their biomasses and carbon contents. The results of the average carbon concentration for each compartment calculated from the aliquots analyzed in the laboratory are presented in Table 5.

Table 5 shows that the average carbon concentration per tree remains slightly higher than those used by the IPCC (2007), which ranged from 0.47 to 0.55, that are often used as default C concentrations in forest biomass studies (Mcghee et al., 2016).

Table 3. Dendrometric characteristics of the Azrou forest.

Forest	Average age (years)	Area (ha)	Density (nb of tree/ha)	Basal area (m^2/ha)	Volume (m^3/ha)
Azrou	105	127.68	107	28.48	349.86

Table 4. Statistical characteristics of the height-circumference model.

Fitted model	R^2	*RMSE*	*D*	*AIC*
$H = -6.809 + 28.356C - 6.781C^2$	80.87	7.595	2.011	138.11

R^2: The Coefficient of Determination; *RMSE*: The Standard Mean Square Error; *D*: Durbin-Watson Statistics; *AIC*: Akaike Information Criterion; *C*: Tree Circumference at 1.30 cm (m); *H*: Total Height of the Tree (m).

Table 5. Carbon concentration in the tree component.

Compartment	Stem	Branches	Foliage	Average
% carbon	57.41	57.30	54.60	56.43

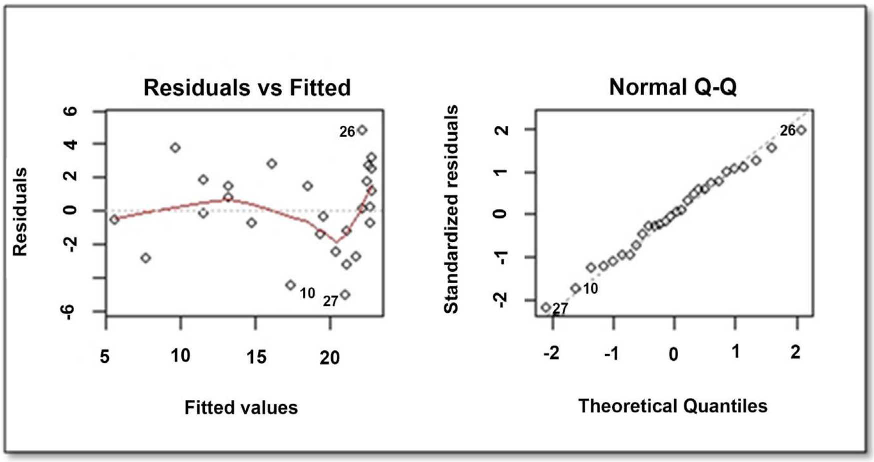

Figure 2. Graphical analysis of the residues of the height-circumference model.

The results of the estimation of the carbomass models by the linear regression technique with logarithmic transformation of the tree samples and their statistical analysis are reported in Table 6 and Figure 3. However, the logarithmic transformation introduced a systematic bias, which can generally be corrected with the correction factor (*CF*) calculated as follows:

$CF = \exp\left(SEE^2/2\right)$ (He et al., 2018)

With SEE is the standard error of the estimate.

By comparing the statistical criteria presented in the previous table and the graphical analysis of the residues of the fitted models (Figures 3-6), we have selected the following best performing models:

$-SCOT = 53.05C^{2.09897}H^{0.4063}$ for total tree, whose initial expression is:

$\ln(SCOT) = 1.378 + 2.09897\ln(C) + 0.40631\ln(H)$

- $SCOTr = 53.624C^{2.19062}H^{0.36418}$ for stem;
- $SCOBr = C^{1.03640}H^{0.8917}$ for the branches;
- $SCOF = 0.671045 + 0.024967(CH)$ for the foliage.

Organic carbon stock in the above-ground part:

The application of the carbomass tariffs used for each part of the tree and for the entire tree allowed us to estimate the organic carbon stock per hectare at the

Table 6. Statistical characteristics of the fitted models.

Components	Fitted models	R^2	*RMSE*	*D*	*AIC*	*CF*
Total tree	$\ln(SCOT) = 1.033 + 0.86057\ln(C^2H)$	98.51	1.57	1.46	−26.42	1.009
	$\ln(SCOT) = 1.378 + 2.09897\ln(C) + 0.40631\ln(H)$	99.42	1.57	2.45	−50.64	1.004
Stem	$\ln(SCOTr) = 0.970 + 0.88865\ln(C^2H)$	98.21	1.65	1.34	−19.09	1.013
	$\ln(SCOTr) = 1.380 + 2.19062\ln(C) + 0.36418\ln(H)$	99.33	1.65	2.38	−45.64	1.005
Branches	$\ln(SCOBr) = -0.476 + 0.6386\ln(C^2H)$	80.27	1.27	1.85	37.08	1.10
	$SCOBr = 11.82779 + 0.19125(C^2H)$	66.78	16.95	1.52	198.78	-
	$\ln(SCOBr) = 1.03640\ln(C) + 0.89171\ln(H)$	98.25	1.26	2.03	34.83	1.09
Foliage	$SCOF = 1.0523186 + 0.0062839(C^2H)$	63.65	0.89	1.26	36.01	-
	$SCOF = 0.671045 + 0.024967(CH)$	69.02	0.90	1.56	31.70	-

R^2: The Coefficient of Determination; ***RMSE***: The Standard Mean Square Error; ***D***: Durbin-Watson Statistics; ***AIC***: Akaike Information Criterion; ***CF***: Correction Factor; ***SCOT***: Total Organic Carbon Stock of the Tree (kg); ***SCOTr***: Total Organic Carbon Stock of the Stem (kg); ***SCOBr***: Total Organic Carbon Stock of the Branches (kg); ***SCOF***: Total Organic Carbon Stock of the Foliage (kg); ***C***: Tree Circumference at 1.30 cm (m); ***H***: Total Height of the Tree (m).

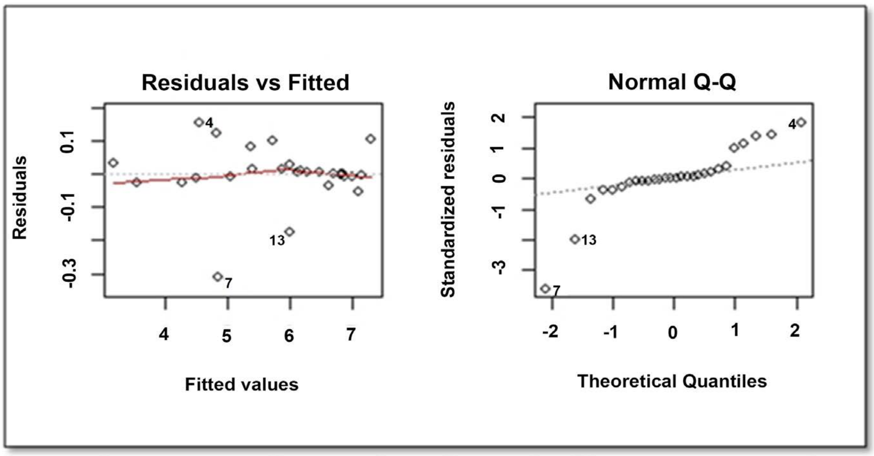

Figure 3. Graphical analysis of the residues of the model selected for the total tree.

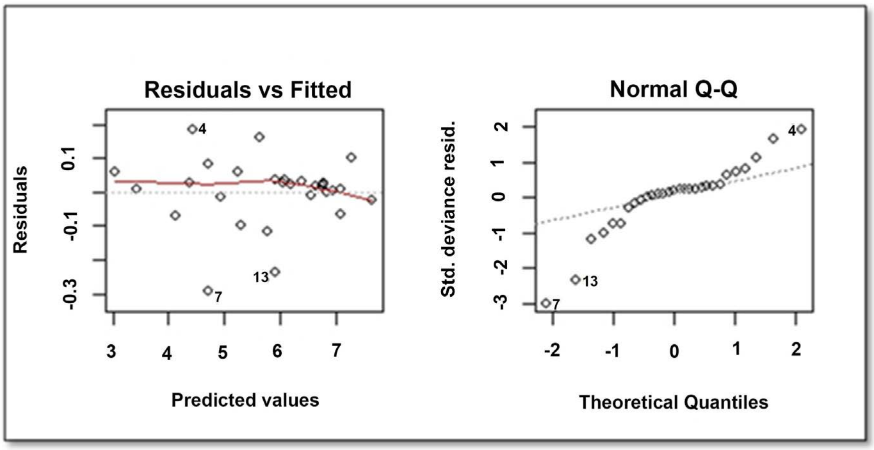

Figure 4. Graphical analysis of the residues of the model selected for stem.

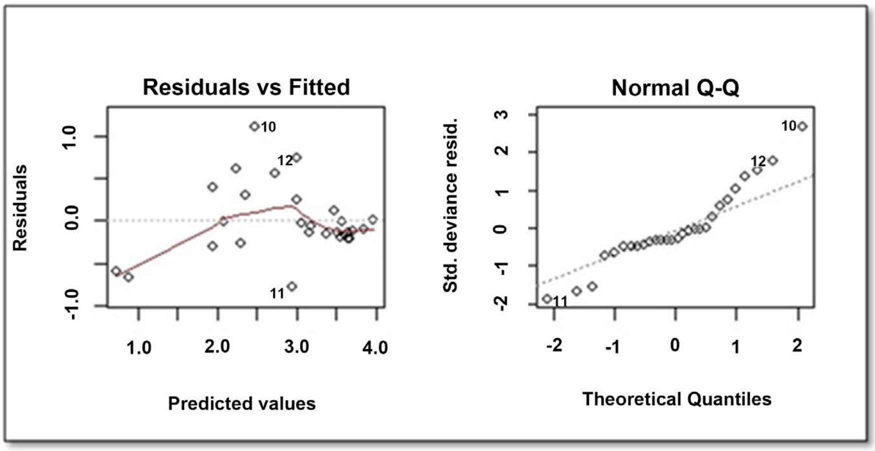

Figure 5. Graphical analysis of the residues of the model selected for the branches.

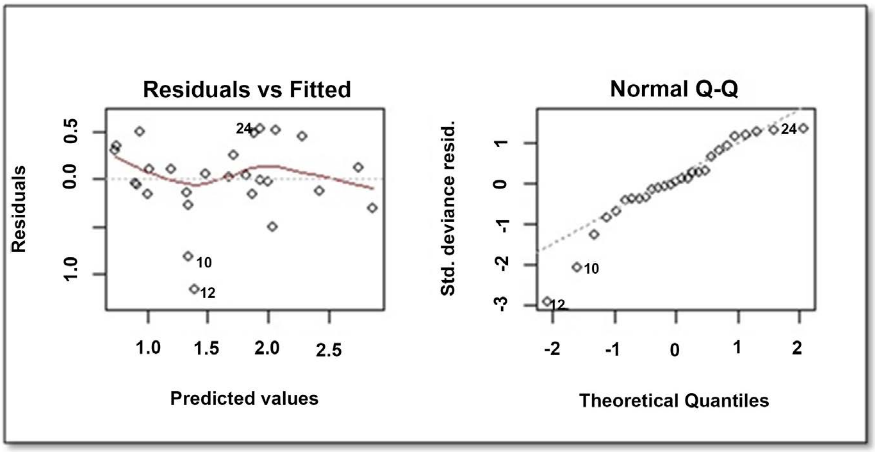

Figure 6. Graphical analysis of the residues of the model selected for the foliage.

level of the studied forest stands. The average storage rate is 77.07 tC/ha. The contributions of stem, branches and foliage in this storage are 93%, 5% and 2% respectively.

Organic carbon stock in the below-ground part:

If the below-ground biomass is considered a carbon reservoir, it can be calculated using the roots shoot ratio, which is the ratio of below-ground biomass to above-ground biomass. The below-ground biomass had been estimated by Mcghee et al. (2016) to be 25% of above-ground biomass. However, the same ratio is estimated at 0.29 of the above-ground biomass for conifers by IPCC (2006).

The stand forests understudied sequestered a significant amount of carbon in the below-ground portion estimated at 22.35 tC/ha in this forest.

Conversion of carbon to carbon dioxide:

To date, the carbon stock has been described in terms of biomass and carbon. Climate change refers to emissions from changes in land use patterns in terms of carbon dioxide (CO_2). To convert the amount of carbon to carbon dioxide, the amount of carbon must be multiplied by 3.667 (derived from the ratio of molecular weights of CO_2/C. i.e. 44/12 or 3.67) (IPCC, 2006; Mcghee et al., 2016). Using this coefficient, the quantity of CO_2 sequestered in the Azrou forest amounts to 364.58 t/ha.

5. Discussion

Mitigating the effects of climate change is now one of the strategies being considered to address global warming. This strategy aims to mitigate greenhouse gas (GHG) emissions by reducing their sources and consolidating their sinks (Nadhem, 2011). In view of the global GHG emissions balance on a global scale, the "plant matter compartment" plays an important regulatory role through organic carbon sequestration. Indeed, the studied forest contributes positively to this mechanism through the sequestration of a considerable amount of organic carbon. This stock records the value of 99.42 tC/ha in the Azrou forest. This important storage in the Azrou cedar forest can be explained by the dendrometric characteristics of these stands (density: 107 tree/ha; basal area: 28.48 m^2/ha). This finding is consistent with that of Le Clec'h et al. (2013), who concluded that the highest carbon stocks are found in the most forested areas (dense forests). To our knowledge, this work is the first of its kind in the Mediterranean region to estimate carbon stocks in cedar forests in the Atlas Mountains. The values found in this forest are still higher than those found in other forest ecosystems in Morocco. The study carried out by Oubrahim et al. (2015) estimated the carbon stock in Maâmora cork oak stands in Morocco at 40.84 and 77.70 tC/ha depending on afforestation density. Carbon sequestration in the green oak forests of the Middle Atlas was estimated by Boulmane et al. (2010) at 58 tC/ha in the Reggada forest and 64 tC/ha in the Tafchna forest. The superiority of the proportion of carbon sequestered by cedar can be explained by the fact that the volume increase of the species is 5 to 6 times higher than that of the green oak mentioned above.

6. Conclusion

Understanding the carbon balance and dynamics in plant matter for sustainable management of forest ecosystem resources and functions requires the quantification of biomass and tree carbon stock. It is with this in mind that our study aimed at estimating carbon sequestration in the Azrou cedar forest through the development of carbomass models, using regression techniques is part of this approach. This work shows that multiple linear regression models by logarithmic transformation are most efficient for the whole tree, trunk and branches. The simple linear regression model without logarithmic transformation is best suited for adjusting the carbon stock in needles. The largest allocation of this stock is included in stem (93%), followed by branches (5%) and foliage (2%). By extrapolating the carbon stock in all stands of the studied forest, which covers a total area of 17,806 ha, the quantity sequestered in this cedar forest is 99.42 tC/ha (overhead and underground), or 364.58 t/ha of CO_2 value significantly higher than that found in other Moroccan forest ecosystems.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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