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Carbon and nutrients stocks in even-aged maritime pine stands from Portugal

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Abstract

To comply with the demands of the Kyoto Protocol, industrialized countries must reliably estimate the stored carbon (C) in different pools of forest ecosystems. The main objective of this study was to quantify the biomass, C and nutrients stocks in the forest floor, understory, downed dead wood (DDW) and mineral soil of even-aged maritime pine (*Pinus pinaster* Ait.) stands from three contrasting regions of Portugal. Assessing the specific contribution of DDW to the C and nutrients stocks and how C concentration in the plant material differs from 0.50, the reference value used in many practical applications, were also objectives of this research. Biomass content of forest floor was determined by a quadrat method. Sampling units of 1 m^2 were used for the understory. The line intersection method was adopted for sampling DDW and the mineral soil was sampled at three depths. Concentrations of C and nutrients were obtained by chemical analysis of samples from soil and milled plant material. Biomass and C in the trees were obtained using published equations. Total C stocks ranged between 100.6 Mg ha^{-1} and 308.6 Mg ha^{-1}. Mineral soil shared up to 70-74% of global stored C, being the main cause of the global C stock differences among regions. Phosphorous and potassium were at low to very low levels in the mineral soil and plant material. The contribution of DDW to the C and nutrients pools was negligible. The percentage of C in the plant material ranged between 52% and 54%.

Key words: carbon pools; stocks; biomass; nutrients; maritime pine.

Resumen

Contenido de carbono y nutrientes en masas regulares de pino marítimo en Portugal

Para cumplir con las exigencias del Protocolo de Kyoto, los países industrializados deben estimar con fiabilidad el carbono (C) almacenado en los diferentes compartimientos de los ecosistemas forestales. El objetivo principal de este estudio fue cuantificar la biomasa, C y contenido de nutrientes, en el suelo del bosque, sotobosque, madera muerta (DDW) y en el suelo mineral de masas regulares de pino marítimo (*Pinus pinaster* Ait.) en tres regiones contrastantes de Portugal. Otros objetivos fueron, la evaluación de la contribución específica de DDW para el contenido total de C y nutrientes así como averiguar de qué modo la concentración de C en el material vegetal se diferencia del valor 0,50, referencia en muchas aplicaciones prácticas. El contenido en biomasa del suelo forestal se determinó por un método de cuadrícula. Para el sotobosque se utilizaron unidades de muestreo de 1 m^2. El método de la línea de intersección se adoptó para el muestreo de DDW y se tomaron muestras a tres profundidades del suelo mineral. Las concentraciones de C y nutrientes se obtuvieron mediante el análisis químico de muestras de suelo y material vegetal molido. Para obtener la biomasa y C en los árboles fueron utilizadas ecuaciones publicadas. El total de las reservas de C oscilaron entre 100,6 Mg ha^{-1} y 308,6 Mg ha^{-1}. El suelo mineral compartió, hasta el 70-74% del C total almacenado, siendo la principal causa las diferencias significativas de C almacenado entre regiones. Fósforo y potasio se encuentran en reducidas concentraciones en el suelo y en la vegetación. La contribución del DDW para la reserva de C y nutrientes fue despreciable. El porcentaje de C en el material vegetal varió entre 52% y 54%.

Palabras clave: pool de carbono; stocks; biomasa; nutrientes; pino marítimo.

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Introduction

Maintaining and enhancing productivity of forests and their contribution to global carbon cycle is an important component of sustainable forest management. This is true not only for timber production but also for other wood and non-wood forest products and services as it is the case of carbon sequestration, one of the most important services that are expected from the forests nowadays. Carbon dioxide (CO_2) is the most relevant anthropogenic greenhouse gas (GHG). According to the 2007 report from the Intergovernmental Panel for Climatic Changes (IPCC, 2007), CO_2 annual emissions increased from 21 to 38×10^9 Mg (Gt) between 1970 and 2004. Moreover it is believed that CO_2 is highly responsible for the changes in the world climate that are being observed. Kyoto Protocol demands for transparent and verifiable methods to estimate the amount of carbon (C) stored in different pools of forest ecosystems of industrialised countries and its changes in time (articles 3.3 and 3.4) (*e.g.,* Bravo *et al.,* 2007; LeMay and Kurz, 2008). Reliable estimates of C sequestration at the regional and national levels can help Governments to evaluate their success at meeting international agreements on climate and pollution.

About 46% of the total C in terrestrial ecosystems is in forests (Fujimori, 2001). In comparison with other terrestrial biomes, forests have the greatest capacity for storing and cycling carbon (Barford and Wofsy, 2001). The main C pools in a forest ecosystem are the biomass of living trees, understory vegetation, dead wood, forest floor and mineral soil (Waldendorp *et al.,* 2002). It is important to quantify the C stock in each compartment, either by direct measurement or by estimation using models. The interest in the measurement and modelling of C storage in forests greatly increased in the last two decades.

In this study the C stocks in the trees, understory, forest floor, dead wood and mineral soil were quantified for even-aged stands of maritime pine (*Pinus pinaster* Ait.) in Portugal. Despite the main emphasis was on C stocks, nutrients stocks were also quantified, complementing and improving the information about the condition of these stands. The maritime pine is the most representative conifer species in Portugal, covering 926×10^3 ha (Tomé *et al.,* 2007) which is around 27% of the total forested area in the country. The species is distributed along the Atlantic coast from the basin of the Tagus River, near Lisbon, to the Portuguese border in the north, spreading to inland in the north and centre regions, ascending to altitudes of 700 to 900 m where the influence of the Atlantic Ocean prevails (Oliveira *et al.,* 2000). There are a few studies in Portugal that evaluate the biomass and C stocks in maritime pine stands. However, most of these works are mainly focused on one or few compartments (*e.g.,* Fernandes *et al.,* 2002; Lopes and Aranha, 2006; Martins *et al.,* 2007) and were often complementary to other research objectives. Comprehensive studies of C stocks, accomplishing all the main pools in forests, including downed woody debris and mineral soil are scarce in the maritime pine specific case. Even more scarce are studies assembling information about C and nutrients stocks.

This study had the following specific objectives: (i) to quantify and compare the biomass, the C and nutrients stock in the forest floor, understory, dead wood, and mineral soil of even-aged maritime pine stands from different regions of Portugal; (ii) to analyse the specific contribution of downed dead wood to C and nutrients stock in managed stands and determine the basic density of different decomposition classes, and (iii) to assess how carbon concentration in the plant material differ from the reference value, 0.50, used as a default value in so many practical applications.

Material and Methods

Study area

Three contrasting regions of maritime pine distribution area in Portugal were considered in this study (Minho, Tâmega and Sines). In each region, ten circular plots with an area of 500 m^2 were established in even-aged maritime pine stands (Fig. 1) from the end of July to the beginning of September, 2009. Therefore, a total of thirty stands were sampled for measuring C stocks in forest floor, understory vegetation, dead wood, live trees and mineral soil.

The sampling in each region was made with the purpose of including a large range of ages and stand densities. Thus, different combinations of age, density and site index were considered when setting the plots in the field. An effort was made to select similar stand structures between regions, including the thinning regime, which is mainly from below, in order to make comparison more reliable. Stands with uncommon structure of thinning regimes were excluded.

Using available digital information from the Portuguese Environment Agency (APA, 2007), mean values

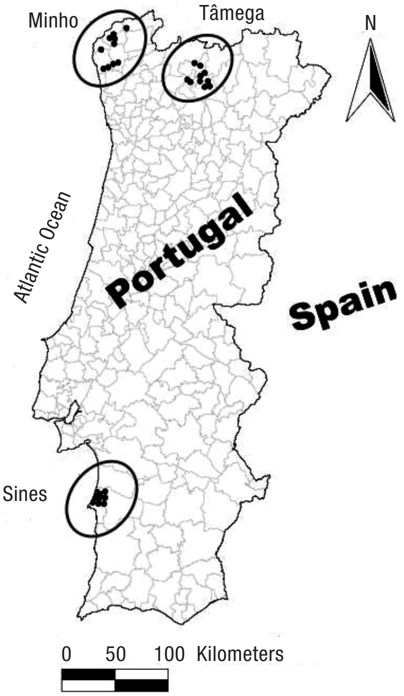

Figure 1. Location of sampled maritime pine stands.

of climate variables for the period (1960-1990) were obtained for the sampled plots using ArcGis software (Esri Inc, 2009) to spatially link climate information in a grid with a resolution of 2 × 2 km^2 with plot coordinates (see Table 1). Following the soil nomenclature of the IUSS WRB (2006) classification, haplic umbrisols prevail in Minho as well as in a broad range of areas in Tâmega. Leptic regosols are also present in this last region. Haplic podzols prevail in the Sines region.

The understory vegetation in Minho was dominated by *Pteridium aquilinum* in many sampled plots sometimes along with *Ulex sp*. *Ulex* was present with *Erica sp*., *Caluna vulgaris* and *Pterospartum tridentatum* in other plots. *Pterospartum tridentatum* was more abundant in Tâmega than in Minho, being present either alone or together with *Erica sp.*, *Caluna vulgaris* and *Ulex sp*. In Sines, the understory was dominated by *Ulex sp.* many times in consociation with *Stauracanthus spectabilis* (an endemism). Other observed species were *Helichrysum picardii, Lavandula pedunculata, Cynara cardunculus*, *Corema album*, *Juniperus turbinata*, *Daphne gnidium* and *Asparagus acutifolius*.

Measurements of trees inside the plots

In every plot, all the trees were measured for diameter at breast height (d), total height (h), crown width (cw), height to the base of live crown (hcb) and height to the level of the largest crown width (h_{lcw}). Azimuths and distances of each tree to the plot centre were taken,

Table 1. Summary statistics for climate variables of the studied regions

Statistics	dP	dF	RUN	P	RH	INS	ETP	RAD	T	ELEV
Minho										
mean	135	19	1,112	2,036	87	2,256	788	98	12.6	247
SE	8	9	173	232	7	135	49	0	1.2	106
minimum	118	8	700	1,673	78	2,021	750	98	11.3	65
maximum	144	35	1,200	2,301	93	2,450	850	98	13.8	360
Tâmega										
mean	114	81	552	1,247	80	2,530	630	143	12.6	714
SE	13	5	123	137	2	92	42	0	1.0	198
minimum	98	75	468	1,015	78	2,450	550	143	11.3	346
maximum	135	85	849	1,464	83	2,650	650	143	13.8	942
Sines										
mean	75	1	144	671	83	2,950	550	157	16.8	46
SE	0	0	31	53	0	0	0	2	0.0	14
minimum	75	1	125	605	83	2,950	550	153	16.8	30
maximum	75	1	216	750	83	2,950	550	158	16.8	80

dP: number of days with precipitation (days year^{-1}). dF: number of days with frost (days year^{-1}). RUN: runoff (mm year^{-1}). P: annual precipitation (mm). RH: relative humidity (%). INS: insolation (hours year^{-1}). ETP: evapotranspiration (mm year^{-1}). RAD: radiation (kcal cm^{-2}). T: temperature (°C). ELEV: elevation (m). SE: standard error.

Table 2. Summary statistics of the stand structure variables

Region	Statistics	G (m^2 ha^{-1})	dg (cm)	ddom (cm)	hdom (m)	$\bar{h}$ (m)	$\overline{cw}$ (m)	Nt	t (years)	SI
Minho	Maximum	47.5	38.3	44.5	26.1	25.1	6.0	1,840	53	26
	Minimum	11.9	16.7	22.4	14.5	13.4	2.5	200	23	18
	Mean	29.6	28.7	34.9	19.6	18.7	4.1	574	36	24
	SE	12.3	7.4	7.1	4.2	4.3	1.2	502	10	3
Tâmega	Maximum	40.1	39.9	46.5	22.6	22.2	5.8	1,000	52	23
	Minimum	12.4	15.0	18.8	9.0	7.9	2.4	240	20	13
	Mean	25.8	26.7	32.3	15.3	14.6	4.3	512	34	20
	SE	7.3	7.3	7.7	3.8	3.9	1.1	217	11	3
Sines	Maximum	37.6	39.8	43.8	22.6	22.1	7.7	1,580	49	23
	Minimum	10.3	13.6	20.4	11.9	10.2	2.0	160	19	17
	Mean	23.3	26.0	31.0	17.3	16.5	4.6	540	39	20
	SE	8.5	6.9	6.1	3.5	3.7	1.5	416	9	2

G: basal area. dg: quadratic mean diameter. ddom: dominant diameter. hdom: dominant height. $\bar{h}$: mean height. $\overline{cw}$: mean value of crown width. Nt: number of trees per hectare. t: age. SI: site index. SE: standard error.

beginning at the North direction and progressing clockwise. The plot centre coordinates were registered using a Trimble GeoXt GPS. The stand structural variables were computed based in the tree measurements (Table 2).

Measurements on the forest floor

The forest floor biomass was evaluated by a quadrat method, using metallic sampling units of 50 × 50 cm. Four samples were collected at a distance of 3 m from the plot centre in North, South, East and West directions. The forest floor thickness was measured in each sampling point. All the samples collected in a plot were placed inside identified plastic bags, one for the litter layer (L) and another for fermentative (F) and humus (H) horizons together (hereafter FH layer). The litter was further separated into leaves, twigs and cones. Total fresh weights of these components were registered and then sub-samples were oven-dried at 70°C until constant weight. The ratio of dry weight to fresh weight of sub-samples was used to calculate the oven-dried biomass of the global samples. Carbon and nutrients content in the several components of forest floor were obtained by chemical analysis of milled material (1 mm sieve).

Measurements of the understory vegetation

A sampling quadrat of 1 m^2 was set at a point with an understory cover representative of the understory conditions of the 500 m^2 plot, in terms of structure and composition. All the vegetation inside the 1 m^2 area was collected to a plastic bag and then separated by species and the respective fresh weight registered. Subsamples, for each species, were oven-dried at 70°C until constant weight. The material of these individual species was milled (1.5 mm sieve) for chemical analysis.

Measurements of dead wood

Logs (fallen trees, fallen branches, and pieces of stem or branches) were sampled inside the plot area using the line intersect method (Warren and Olsen, 1964; Van Wagner, 1968). Four 25 m length transects were used, going through the plot centre in North-South, East-West, Northeast-Southwest, Northwest-Southeast directions, were used. A length of 50 cm (*e.g.* Waldendorp *et al.,* 2004) and a diameter of 2.5 cm at both ends (*e.g.* McCarthy and Bailey, 1994; Ganjegunte *et al.,* 2004) were adopted as minimum dimension for logs. Diameters at the intersection points were measured at right angles with the logs longitudinal axis for volume calculation (m^3 ha^{-1}). Each tallied log was classified into one of three decay classes similarly to Davis *et al.* (2003), equivalent to the five classes classification frequently found in forestry literature related to coarse woody debris (CWD) (*e.g.* Sollins, 1982 or Siitonen *et al.,* 2000, and their adaptations) by coalition of classes II and III as well as IV and V. Samples for each decay class were extracted from three pieces of woody debris whenever present inside the plot area.

After volume determination by water displacement (m^3), the samples were oven-dried at 103 ± 2°C to obtain mean values of wood basic density in order to convert volume into biomass. Samples from each decay class were also collected inside the plot area and milled (1.5 mm sieve) for chemical analysis. Snags (dead trees over 1.3 m tall and standing at an angle superior to 45°), if present inside the plot area, were measured for *d* and *h* and classified into one of the three decay classes using the same procedure already referred for the logs.

Procedures in the mineral soil

In the four points where forest floor was collected inside each pot, soil samples were taken, using a corer, at the depths 0-10, 10-30, and 30-60 cm and placed in separate plastic containers. These sampling depth levels were considered in order to match the requirements of the Kyoto Protocol level and to complement the information from two other studies for future model development. The use of corers in forest soils is difficult; therefore it was necessary to dig holes in order to facilitate the corer use to collect samples at deeper levels. Composite samples of about 2 kg from each depth level were used for chemical analysis. A total of 88 samples (instead of 90) were analysed. In two plots it was not possible to collect suitable samples from the 30-60 cm depth because of the low thickness of the profile. Undisturbed soil samples were taken from the wall in the opened holes at the three depths using metallic cylinders with 196.35 cm^3. The bulk density ($g\ cm^{-3}$) was determined after oven-dry the samples at 105°C during 24 hours, sieve with a 2 mm mesh and adjusted for the mass and volume of rocks (> 2mm size). The amount of organic carbon (C_{org}) in a layer of mineral soil was obtained by multiplying the proportion of C in this layer to the oven-dried mass of the fine earth fraction.

Biomass and C stock in the live trees

Above ground biomass of the live trees was obtained by using the system of simultaneous equations from Faias (2009), which estimates biomass for stem wood (ww), stem bark (wb), branches (wbr) and leaves (wl). Stem biomass (ws) is the sum of ww and wb and total aboveground biomass (wa) is the sum of the biomass of all the four components. The roots biomass was estimated by employing Montero *et al.* (2005) equations. The values of C concentration for the different tree components presented in the study of Lopes and Aranha (2006) were adopted to obtain C stock in the trees.

Chemical analysis

In relation to the samples from plant material (forest floor, understory, and dead wood), phosphorous (P), potassium (K), calcium (Ca) and magnesium(Mg) were extracted by dry mineralization at 500 ± 20°C and the analytical determinations in the extract were undertaken by using optical emission spectrophotometry (ICP-OES). Carbon, nitrogen (N) and sulphur (S) were extracted by catalytic pyrolysis and contents were determined by using a LECO CNS elemental analyser.

The samples of mineral soil were first dried at 40°C and then sieved. Chemical analysis were performed on the fine earth fraction (< 2mm). Contents of C_{org} and total N were obtained by dry combustion using a LECO CNS analyser. Available K and P were obtained by ICP-OES after extraction with Égner-Rhiem method using a solution of ammonium lactate (0.1 N) and acetic acid (0.4 N) (Balbino, 1968). Available Mg was obtained by flame atomic absorption spectrophotometry (Flame-AAS) after using neutral 1N ammonium acetate (Warncke and Brown, 1998). Concerning exchangeable bases, available Ca and Mg were obtained by Flame-AAS and available K and Na by flame emission spectrophotometry (FES) after using neutral 1N ammonium acetate (modified from Chapman, 1965). Soil pH (H_2O) was obtained by potenciometric determination in a 1:2.5 soil-to-water (v/v) suspension.

Data analysis

Field data and data from the chemical analysis were processed in order to characterize the carbon and nutrients stocks in the three sites and study the differences between them. Carbon and nutrients stocks for each pool were computed using concentration values in dry biomass obtained from chemical analysis and were condensed in tabular form. One-way analysis of variance (ANOVA) of the carbon and nutrient amounts were performed using region as a three level factor. Analyses of covariance were discarded as the tried covariates (Nt, t and SI) were not significant. If the null hypotheses, no significant effect of the regions, were rejected least significant differences tests were used to compare mean carbon and nutrient stocks values between the regions. Kruskal-Wallis test and multiple comparisons of mean ranks were used when normality assumption was not verified. This analysis was complemented by several graphics, namely absolute and percent values of C stock in the different C pools, as well as radial diagrams for nutrients concentration. Radial diagrams are graphical representations that show the characteristic proportions of the main mineral nutrients in plants or plant components (Larcher, 2007).

Results

Carbon and nutrients stock in the forest floor

Carbon and nutrients stocks and concentrations in the forest floor are presented in Table 3. Total amount

Table 3. Carbon and nutrients: stock and concentration in the forest floor

				Stocks						Concentration						
Region	**Layer**	**Mass**	**C**	**N**	**P**	**K**	**Ca**	**Mg**	**S**	**N**	**P**	**K**	**Ca**	**Mg**	**S**	**C:N**
		(Mg ha^{-1})		**(kg ha^{-1})**						**(g kg^{-1})**						
Minho	Leaves n = 10	2.44^{a} (1.31)	1.34^{a} (0.72)	13.05^{b} (7.00)	0.60^{ab} (0.32)	1.79^{a} (0.96)	3.34^{a} (1.79)	2.73^{a} (1.47)	1.31^{a} (0.70)	5.34^{b} (0.47)	0.24^{a} (0.08)	0.73^{ab} (0.41)	1.37^{a} (0.49)	1.12^{a} (0.41)	0.53^{a} (0.03)	103 (8)
	Twigs n = 9	0.84^{a} (0.54)	0.45^{a} (0.29)	3.60^{a} (2.30)	0.17^{a} (0.11)	0.38^{b} (0.24)	1.44^{a} (0.92)	0.62^{a} (0.40)	0.37^{a} (0.24)	4.30^{a} (0.07)	0.20^{a} (0.05)	0.45^{a} (0.32)	1.72^{a} (0.55)	0.74^{a} (0.14)	0.45^{a} (0.06)	127 (19)
	Cones n = 7	1.31^{a} (0.89)	0.70^{a} (0.47)	4.29^{a} (2.89)	0.21^{a} (0.14)	0.20^{a} (0.13)	0.76^{a} (0.51)	0.46^{a} (0.31)	0.43^{a} (0.29)	3.27^{a} (2.00)	0.16^{a} (0.11)	0.15^{a} (0.09)	0.57^{a} (0.15)	0.35^{a} (0.20)	0.32^{a} (0.19)	259 (158)
	FH n = 10	21.15^{a} (10.90)	11.42^{a} (5.89)	239.4^{b} (123.38)	8.18^{b} (4.21)	9.08^{a} (4.68)	42.30^{a} (21.79)	23.12^{b} (11.91)	22.76^{b} (11.73)	11.32^{b} (1.63)	0.39^{a} (0.02)	0.43^{a} (0.22)	2.00^{a} (0.20)	1.09^{a} (0.18)	1.08^{a} (0.19)	48 (8)
	Total n = 10	25.74^{a} (12.01)	13.91^{a} (6.49)	260.36^{b} (127.87)	9.15^{b} (4.43)	11.45^{a} (5.25)	47.83^{a} (23.19)	26.94^{b} (12.77)	24.86^{b} (12.18)							
Tâmega	Leaves n = 10	3.09^{a} (1.10)	1.70^{a} (0.60)	14.27^{b} (5.07)	0.69^{b} (0.24)	1.51^{a} (0.53)	6.78^{b} (2.41)	3.67^{a} (1.30)	1.44^{a} (0.51)	4.63^{b} (0.54)	0.22^{a} (0.06)	0.49^{a} (0.03)	2.20^{b} (0.54)	1.19^{a} (0.50)	0.47^{a} (0.04)	119 (14)
	Twigs n = 9	1.05^{a} (0.62)	0.57^{a} (0.33)	3.86^{a} (2.27)	0.16^{a} (0.09)	0.30^{b} (0.18)	2.92^{a} (1.72)	0.73^{a} (0.43)	0.38^{a} (0.22)	3.68^{a} (0.09)	0.16^{a} (0.09)	0.29^{a} (0.05)	2.78^{a} (0.95)	0.70^{a} (0.21)	0.36^{a} (0.10)	153 (36)
	Cones n = 6	1.51^{a} (1.19)	0.80^{a} (0.63)	3.23^{a} (2.54)	0.14^{a} (0.11)	0.28^{a} (0.22)	0.59^{a} (0.46)	0.43^{a} (0.33)	0.39^{a} (0.31)	2.14^{a} (0.52)	0.10^{a} (0.05)	0.19^{a} (0.14)	0.39^{a} (0.22)	0.28^{a} (0.10)	0.26^{a} (0.08)	255 (53)
	FH n = 10	13.64^{a} (7.15)	7.23^{a} (3.79)	134.73^{a} (70.67)	6.12^{ab} (3.21)	6.79^{a} (3.56)	31.27^{a} (16.40)	11.89^{a} (6.23)	11.65^{a} (6.11)	9.88^{b} (1.28)	0.45^{a} (0.08)	0.50^{a} (0.09)	2.29^{a} (1.46)	0.87^{a} (0.42)	0.85^{a} (0.17)	53 (4)
	Total n = 10	19.29^{a} (8.45)	10.30^{a} (4.50)	156.09^{a} (75.01)	7.11^{ab} (3.41)	8.89^{a} (4.01)	41.56^{a} (18.62)	16.72^{a} (7.28)	13.86^{a} (6.57)							
Sines	Leaves n = 10	2.42^{a} (0.74)	1.31^{a} (0.40)	7.96^{a} (2.42)	0.41^{a} (0.12)	3.92^{b} (1.19)	16.95^{c} (5.15)	6.14^{b} (1.86)	2.23^{b} (0.68)	3.29^{a} (0.12)	0.17^{a} (0.05)	1.62^{b} (0.65)	7.00^{c} (0.96)	2.54^{b} (0.21)	0.92^{b} (0.20)	163 (7)
	Twigs n = 10	0.55^{a} (0.47)	0.29^{a} (0.25)	1.99^{a} (1.71)	0.08^{a} (0.07)	0.12^{a} (0.11)	5.47^{b} (4.70)	0.41^{a} (0.35)	0.29^{a} (0.25)	3.64^{a} (0.19)	0.15^{a} (0.02)	0.23^{a} (0.07)	10.04^{b} (3.73)	0.76^{a} (0.04)	0.54^{a} (0.01)	147 (6)
	Cones n = 3	0.44^{a} (0.11)	0.23^{a} (0.06)	1.31^{a} (0.32)	0.05^{a} (0.01)	0.08^{a} (0.02)	0.20^{a} (0.05)	0.14^{a} (0.03)	0.12^{a} (0.03)	2.97^{a} (1.10)	0.12^{a} (0.07)	0.17^{a} (0.13)	0.46^{a} (0.19)	0.32^{a} (0.07)	0.28^{a} (0.10)	197 (66)
	FH n = 10	15.62^{a} (6.11)	7.97^{a} (3.11)	110.31^{a} (43.11)	4.41^{a} (1.72)	6.82^{a} (2.67)	120.38^{b} (47.05)	26.03^{b} (10.17)	13.55^{a} (5.30)	7.06^{a} (1.11)	0.28^{a} (0.10)	0.44^{a} (0.07)	7.71^{b} (1.10)	1.67^{b} (0.40)	0.87^{a} (0.09)	72 (11)
	Total n = 10	19.03^{a} (6.64)	9.80^{a} (3.41)	121.56^{a} (44.78)	4.96^{a} (1.81)	10.94^{a} (3.44)	143.00^{b} (51.44)	32.73^{b} (11.31)	16.20^{a} (5.73)							

Between parentheses are standard errors. Different letters means significant differences ($P < 0.05$) between the same component by region, using ANOVA and least significant differences test or Kruskal-Wallis and multiple comparison of mean ranks for non normality situations.

of C was higher in Minho (13.91 Mg ha^{-1}) than in Tâmega (10.30 Mg ha^{-1}) and Sines (9.80 Mg ha^{-1}) but the differences were not statistically significant. In Minho and Tâmega forest floor contains 5% of total C stock. In Sines the forest floor reaches 10% of the total C stock.

The layer FH contains higher C and nutrients stock than the other elements of forest floor. Leaves were the most relevant element in the litter layer (L). Average concentration of C was 54% for leaves and twigs and 53% for cones. The general pattern of nutrients concentration in leaves followed the decreasing order, N > Ca > Mg > K > S > P. In twigs and cones the general order (most to less abundant) was N > Ca > Mg > S > K > P. However, in Sines, Ca was higher than N in leaves and twigs. Nitrogen concentration was higher in the layer FH which presents a lower C:N ratio than the other components of the forest floor (Table 3). Nevertheless, except for Ca and Mg, nutrients concentration in the forest floor dry mater was quite low especially for P and also K.

Carbon and nutrients stock in the understory vegetation

Stocks and concentrations of C and nutrients in the understory vegetation are presented in Table 4. The average amount of C in the understory was 2.48 Mg ha^{-1} in Minho, 2.68 Mg ha^{-1} in Sines and 4.36 Mg ha^{-1} in Tâmega. These stocks are not statistically different.

Height of the understory vegetation in Minho ranged between 45 and 135 cm with a mean value of 70 cm. In Tâmega it ranged from 48 to 125 cm with a mean value of 74 cm. In Sines the height interval was 49 to 84 cm with a mean height of 64 cm. On average, a very regular pattern was observed for the nutrient concentration in all regions, decreasing in the order N > K > Ca > Mg > S > P (Table 4). Average percent of C was 52% for all the three regions; nevertheless different percent C values were observed along the different understory species. Phosphorous concentration in dry weight was at very low levels in all regions. Potassium and sulfur are also at low levels. Calcium and magnesium while not high, present acceptable concentration, especially in Sines.

Carbon and nutrients stock in the downed dead wood

Carbon and nutrient stocks in the downed dead wood (logs) are presented in Table 5. Observed average values of C stocks were 0.47 Mg ha^{-1} in Minho, 0.34 Mg ha^{-1} in Tâmega and 0.57 Mg ha^{-1} in Sines. These values were not statistically different. The dead wood is very poor in terms of nutrient concentrations.

Basic density decreased from 0.414 g cm^{-3} in decay class 1 to 0.321 g cm^{-3} in decay class 3 (Table 6). Carbon concentration in dead wood remains more or less constant throughout the decomposition process. The average dead wood C concentration was 52% for all decay classes. Nitrogen concentration increases with the decay level despite the losses in mass and thus, the C:N ratio decreases because variations in C are minimal. Patterns of Ca, Mg and K concentration are similar, declining with the level of decay. Phosphorous and sulphur show a different pattern, firstly increasing in early stages of decomposition and then declining.

Table 4. Carbon and nutrients: stock and concentration in the understory vegetation

Region	Mass	C	N	P	K	Ca	Mg	S	N	P	K	Ca	Mg	S	C:N
			Stocks						Concentration						
	(Mg ha^{-1})		(kg ha^{-1})						(g kg^{-1})						
Minho	4.74^{a}	2.48^{a}	41.01^{a}	1.80^{a}	16.70^{a}	10.44^{a}	6.38^{a}	5.02^{a}	8.34^{a}	0.35^{a}	2.74^{a}	1.35^{a}	1.02^{a}	0.99^{a}	66
n = 10	(3.07)	(1.66)	(21.50)	(0.97)	(10.25)	(5.83)	(3.79)	(2.92)	(4.13)	(0.13)	(1.31)	(0.62)	(0.53)	(0.49)	(26)
Tâmega	8.26^{a}	4.36^{a}	57.69^{a}	2.39^{a}	17.16^{a}	12.27^{a}	7.69^{a}	5.24^{a}	9.71^{a}	0.45^{a}	3.29^{ab}	2.64^{ab}	1.24^{a}	0.94^{a}	63
n = 10	(4.30)	(2.29)	(24.17)	(1.06)	(7.17)	(5.84)	(3.79)	(3.45)	(4.39)	(0.17)	(2.32)	(1.62)	(0.63)	(0.37)	(24)
Sines	5.11^{a}	2.68^{a}	49.50^{a}	1.54^{a}	16.66^{a}	11.83^{a}	4.62^{a}	4.41^{a}	7.55^{a}	0.32^{a}	5.31^{b}	4.25^{b}	1.08^{a}	1.07^{a}	72
n = 10	(2.68)	(1.61)	(30.91)	(0.97)	(9.15)	(6.53)	(2.57)	(2.76)	(1.99)	(0.12)	(4.52)	(2.93)	(0.55)	(0.59)	(20)

Between parentheses are standard errors. Different letters means significant differences ($P < 0.05$) between regions, using ANOVA and least significant differences test or Kruskal-Wallis and multiple comparison of mean ranks for non normality situations.

Table 5. Carbon and nutrients stock in the dead wood (logs)

Region	Mass	C	N	P	K	Ca	Mg	S
	(Mg ha^{-1})		(kg ha^{-1})					
Minho n = 10	0.90^{a} (0.50)	0.47^{a} (0.26)	1.17^{a} (0.64)	0.06^{a} (0.03)	0.14^{a} (0.08)	0.40^{a} (0.23)	0.36^{a} (0.21)	0.12^{a} (0.07)
Tâmega n = 10	0.65^{a} (0.72)	0.34^{a} (0.37)	0.77^{a} (0.71)	0.04^{a} (0.03)	0.07^{a} (0.08)	0.54^{a} (0.50)	0.24^{a} (0.22)	0.09^{a} (0.08)
Sines n = 10	1.10^{a} (0.63)	0.57^{a} (0.33)	1.24^{a} (0.78)	0.05^{a} (0.03)	0.09^{a} (0.05)	1.39^{b} (0.73)	0.40^{a} (0.22)	0.25^{b} (0.16)

Between parentheses are standard errors. Different letters means significant differences ($P < 0.05$) between regions, using ANOVA and least significant differences test.

Carbon and nutrients stock in the mineral soil

Carbon storage in the mineral soil was much higher than in the other studied pools. Table 7 shows that C concentration decreased with soil depth. On average, 229 Mg ha^{-1}, 144 Mg ha^{-1} and 40 Mg ha^{-1} of C were stored between 0 and 60 cm of depth of the mineral soil in Minho, Tâmega and Sines, respectively. These values are significantly different according to the statistical analysis and are equivalent to 70-74% of total C stock of the ecosystem in Minho and Tâmega and 40% of total C stock in Sines. The soils are acid to very acid in Tâmega and Minho and moderately acid in Sines. Phosphorous is at very low levels in all sampled layers. Potassium is at low to moderate levels in the 0-10 cm depth of mineral soil and at low to very low levels for deeper layers. Concentration of magnesium is low in the upper layer (0-10 cm) being very low in the other two layers. Soils in Minho are rich in N. Nitrogen is at moderate levels in Tâmega and at low levels in Sines. Concentrations of 8.7 ppm and 19 ppm where used to compute the amount of available P and K in Sines (kg ha^{-1}) respectively as exact values were not available (Table 7). Exchangeable bases were at very low levels in Minho and Tâmega, and at low levels in Sines. Only results for Ca^{2+} and Mg^{2+} are present in Table 7. Reported values of Na^{+} and K^{+} were always < 0.10 cmol(+) kg^{-1}.

Carbon stock in the trees

Aboveground and root biomass for live trees and corresponding C stocks are presented in Table 8.

A great variability was observed in aboveground C stocks which is inherent to the diversity of ages, productivity levels and densities in the studied stands. As mentioned before, similar stand structures were selected at sampling design, trying to minimize variability between regions. Live trees, on average, store 62.6 Mg ha^{-1} of C in Minho, 49.7 Mg ha^{-1} in Tâmega and 47.9 Mg ha^{-1} in Sines (aboveground + roots). C stock in Minho was higher than in the other two regions but the

Table 6. Average values for basic density, carbon and nutrients content of dead wood decay classes

Decay Class	Density* (g cm^{-3})	C (%)	N	P	K	Ca	Mg	S	C:N
			(g kg^{-1})						
1 (n = 8)	0.414 (0.039)	52.12^{a} (0.39)	1.18^{a} (0.24)	0.07^{b} (0.02)	0.18^{a} (0.06)	1.29^{a} (0.71)	0.52^{b} (0.09)	0.14^{a} (0.08)	459 (08)
2 (n = 9)	0.373 (0.044)	51.73^{a} (0.31)	1.14^{a} (0.39)	0.04^{a} (0.02)	0.11^{a} (0.08)	0.88^{a} (0.48)	0.38^{a} (0.15)	0.13^{a} (0.05)	458 (275)
3 (n = 8)	0.321 (0.054)	52.31^{a} (0.73)	1.51^{a} (0.52)	0.08^{b} (0.03)	0.11^{a} (0.04)	0.82^{a} (0.47)	0.31^{a} (0.09)	0.18^{a} (0.06)	378 (110)

* sample size for density determination (n1 = 20; n2 = 55; n3= 57). Different letters means significant differences ($P < 0.05$) between decay classes, usings ANOVA and least significant differences test.

Table 7. Carbon and nutrients: stock and concentration in the mineral soil by layers down to 60 cm depth

Region	Depth (cm)	pH (H_2O)	Stocks					Concentration							
			C_{org}*	N	P	K	Mg	C_{org}	N	P	K	Mg	Ca++	Mg++	SBT
			(Mg ha^{-1})		(kg ha^{-1})			(%)	(%)	(ppm)	(ppm)	(ppm)	[cmol(+) kg^{-1}]		
Minho	0-10 (n = 10)	4.6	50.86^{c} (8.56)	2.76^{c} (0.78)	9.26^{a} (2.58)	38.50^{a} (13.31)	28.90^{a} (11.07)	6.97^{c}	0.38^{c}	12.17^{b}	50.82^{b}	37.88^{a}	$<0.59^{\dagger a}$	0.20^{a}	0.55
	10-30 (n = 10)	4.7	123.86^{b} (30.61)	4.37^{c} (2.18)	18.49^{a} (6.90)	56.00^{a} (39.70)	38.26^{a} (8.82)	5.17^{c}	0.30^{c}	12.28^{b}	39.04^{b}	25.70^{a}	$<0.59^{\dagger a}$	0.15^{a}	0.52
	30-60 (n = 9)	4.8	228.86^{c} (70.24)	5.57^{c} (3.41)	34.56^{a} (15.18)	59.47 (20.32)	57.08^{a} (15.38)	4.12^{c}	0.25^{b}	14.69^{b}	24.30^{a}	23.12^{a}	$<0.59^{\dagger a}$	0.12^{a}	0.46
Tâmega	0-10 (n = 10)	4.9	34.85^{b} (18.61)	1.31^{b} (0.61)	8.09^{a} (1.80)	44.77^{a} (34.91)	38.18^{a} (34.92)	4.19^{b}	0.16^{b}	9.08^{a}	47.69^{b}	40.75^{a}	$<0.59^{\dagger a}$	0.26^{a}	0.72
	10-30 (n = 10)	5.0	90.15^{b} (46.06)	2.27^{b} (1.34)	16.70^{a} (4.59)	66.60^{a} (47.61)	55.69^{a} (27.86)	3.28^{b}	0.14^{b}	9.03^{a}	35.85^{b}	30.90^{a}	$<0.59^{\dagger a}$	0.17^{a}	0.46
	30-60 (n = 9)	5.1	143.95^{b} (66.89)	2.57^{b} (1.94)	28.23^{a} (5.51)	66.20 (13.22)	85.11^{a} (76.06)	1.90^{b}	0.09^{a}	9.00^{a}	20.86^{a}	25.20^{a}	$<0.59^{\dagger a}$	0.19^{a}	0.49
Sines	0-10 (n = 10)	5.3	14.78^{a} (7.55)	0.57^{a} (0.23)	12.90^{b} (1.07)	32.56^{a} (8.99)	83.25^{b} (31.82)	1.03^{a}	0.04^{a}	$<9.50^{\dagger a}$	22.56^{a}	57.66^{a}	1.05^{a}	0.38^{a}	1.48
	10-30 (n = 10)	5.4	27.53^{a} (13.08)	0.65^{a} (0.18)	28.32^{b} (1.15)	61.86^{a} (2.51)	108.14^{b} (27.99)	0.39^{a}	0.02^{a}	$<9.50^{\dagger a}$	$<20.00^{\dagger a}$	33.39^{a}	$<0.59^{\dagger a}$	0.19^{a}	0.68
	30-60 (n = 10)	5.6	39.51^{a} (15.36)	0.81^{a} (0.28)	42.59^{a} (2.94)	94.73 (6.84)	140.23^{b} (41.46)	0.25^{a}	0.02^{a}	$<9.50^{\dagger a}$	$<20.00^{\dagger a}$	29.05^{a}	$<0.59^{\dagger a}$	0.25^{a}	0.59

*: cumulative values for C stock. †: as reported in the results of chemical analysis. SBT is the sum of exchangeable bases. Between parentheses are standard errors. Different letters means significant differences ($P < 0.05$) between the same component by region, using ANOVA and least significant differences test or Kruskal-Wallis and multiple comparison of mean ranks for non normality situations.

differences were not significant according to the statistical analysis.

Snags were present in only five plots all over the three regions. Their contribution for C stock was only 0.79 ± 0.43 Mg ha^{-1} in aboveground and 0.19 ± 0.04 Mg ha^{-1} in roots.

Table 8. Biomass and C stock in the live trees

Region	Biomass (Mg ha^{-1})		C (Mg ha^{-1})	
	Wa	Wr	Aboveground	Roots
Minho	127.49^{a} (53.99)	9.47^{a} (4.95)	58.04^{a} (24.58)	4.56^{a} (2.38)
Tâmega	99.95^{a} (49.76)	8.46^{a} (1.54)	45.64^{a} (22.60)	4.07^{a} (0.74)
Sines	96.70^{a} (40.58)	8.09^{a} (3.48)	43.99^{a} (18.41)	3.89^{a} (1.67)

Wa: aboveground biomass. Wr: root biomass. Between parentheses are standard errors. Different letters means significant differences ($P < 0.05$) between regions, using ANOVA and least significant differences test.

Discussion

In this study, biomass, C and nutrients stocks in the main carbon pools of even-aged maritime pine stands in Portugal were quantified for three contrasting regions. The sampling in each region was made so that a large range of ages and stand densities could be selected inside each region trying to sample stands of similar size and structure in the three regions. The average values for C storage in Minho, Tâmega and Sines were 308.6 Mg ha^{-1}, 208.7 Mg ha^{-1} and 100.6 Mg ha^{-1}, respectively (Fig. 2).

While statistical analysis did not found significant differences among regions for the C stocks in forest floor, understory, downed dead wood and live trees, these differences were detected for the mineral soil till 60 cm of depth (Table 7). Therefore mineral soil is the main cause of differences among regions concerning total stored C. The amount of C in soil in terrestrial ecosystems, including forests, is far larger than that in biomass (Ravindranath and Ostwald, 2008). According to these authors, the ratio of C in soil and living biomass

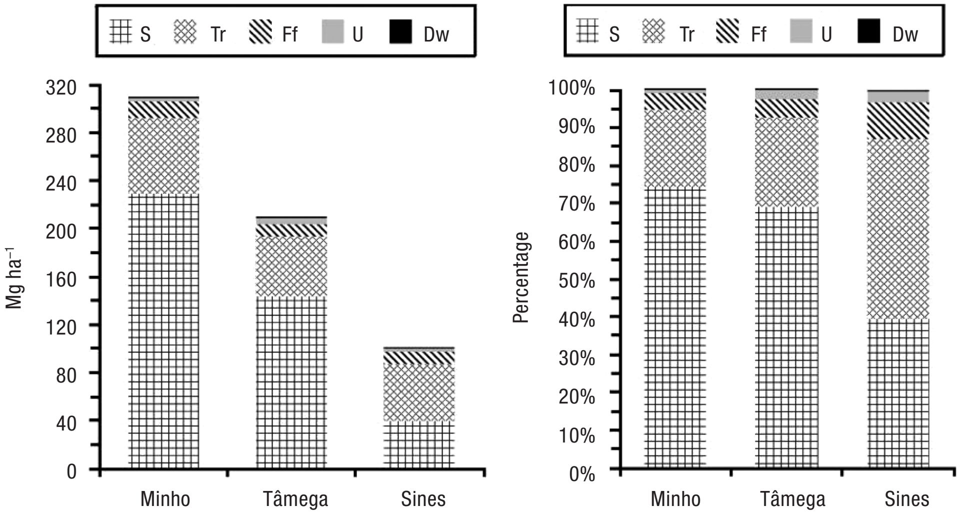

Figure 2. Carbon stocks in the main forest pools for the three studied regions. Tr: trees. Ff: forest floor. U: understory. Dw: dead wood. S: mineral soil.

in Europe is, on average, 64:25%. In this study, mineral soil till 60 cm of depth stored 70-74% of the total C stock in Minho and Tâmega, decreasing to 40% in Sines. Organic carbon stocks in the mineral soil presented in Table 7 are in agreement with results of Correia's (2004) work and are also inside the ranges reported for the Portuguese forest soils by Martins *et al.* (2009) which rely on a large sampling effort all over the country. These authors point out that there is a strong linear relationship between mean annual precipitation in Portugal and the C stock in mineral soil (0-100 cm), with higher stocks in soils from north-western Portugal (Minho region), decreasing to the South and to the inland regions as the climate becomes more arid. In Minho, the precipitation (P) surplus over evapotranspiration (ETP) is high (Table 1) with a climate Csb (dry summer cool) according to the Koppen classification. Haplic umbrisols are the prevailing soil type, with high levels of organic matter. In Tâmega, the surplus of P over ETP is also high but annual precipitation values are lower than in Minho. In this inland region, Koppen Csb and Csa (dry summer warm) types are present but maritime pine is mainly present where the Atlantic Ocean influence prevails. Despite the fact that high values of organic matter were observed in the Tâmega soils, on average, soil profiles are less developed than in Minho and C stocks decreased fast with depth (Table 7). From the three studied regions, the lowest C stock in the mineral soil till 60 cm of depth was observed in Sines. Haplic podzols are the main soil type in Sines. Cardoso (1965) states that in Portugal about 600 mm of precipitation are required to podzolization to occur, which is the case in Sines (Table 1). Dune sands from Sines are particularly prone to leaching because of their high permeability and low water storage capacity. Sevink (1991) states that pedological processes as the rates of decalcification, acidification and podzolization are strongly dependent on precipitation surplus over evapotranspiration and on the soil temperature regime. High precipitation surplus and cold temperatures (as in boreal zones) are very favourable for the podzolization process. However this is not the case in the Sines region where the low surplus of precipitation and a long dry summer (Csa) may require a very long period of time for podzolization to occur (Sevink, 1991). On average, soils in Sines are only moderately acid which is not common on «climatic» podzols. The spodic horizon appearing at most at 200 cm from the mineral soil surface according to the WRB classification was not observed. However, in this study, soil was only sampled to a depth of 60 cm because the objective was to complement available data on C stocks for the depths 0-30 and 30-60 cm from studies in two other regions. The whole data set will be used for modelling purposes of the C stock at the default level of Kyoto Protocol for reporting changes of C stock in mineral soil which is 0-30 cm. Moreover, it is important to notice that maritime pine stands in Portuguese coastal areas were mainly planted during the first half of the 20th century (1930's and 1950's) for dune fixation. These anthropic disturbances have certainly affected the initial condition of stored C and most of these soils are many times referred as «podzolized sands» or «podzolized soils» having low content of organic matter.

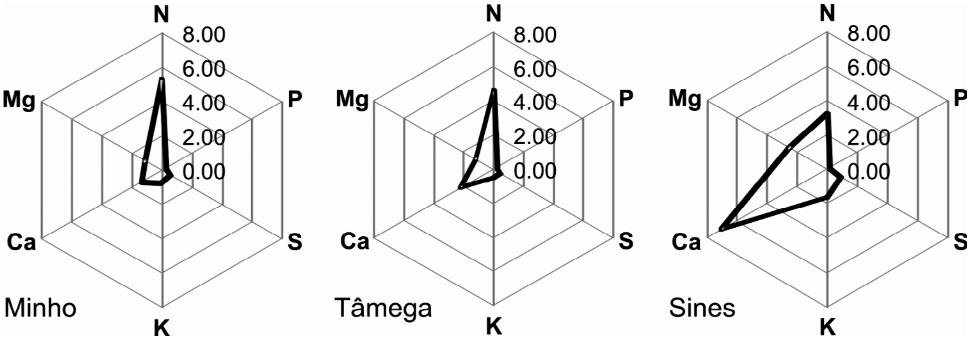

Figure 3. Radial diagrams with nutrients concentration (g kg^{-1}) in leaves (adapted from Larcher, 2007).

Comparing the nutrient content of the mineral soil, with the standards for Portugal reported by Santos (1996) and LQARS (2000), N, significantly different among regions, was at the highest levels in Minho and lowest levels in Sines. Deficiency of phosphorous was observed in all the soils, more pronounced in Tâmega and Sines. Only one plot in Minho showed a reasonable concentration of this nutrient. At the plot level, in Minho and Tâmega K was, on average, present in moderate concentrations in the 0-10 cm layer with one plot in Tâmega presenting a high concentration. These concentrations decreased to low levels in the 10-30 cm layer and to very low levels in the layer 30-60 cm in most of the plots from both regions. In Sines, K levels were low in the superficial layer and very low in the other sampled layers. For the Mg, moderate values of concentration were observed in some plots of the Sines region, decreasing to low and very low levels in the 10-30, and 30-60 cm layers, respectively. In Minho and Tâmega, concentrations on Mg were low at the 0-10 cm layer, decreasing to very low from then to deeper levels in all plots.

Forest floor represented 5-10% of total stored C and about 20% of total aboveground C stock. The values reported here (Table 3) are similar to the mean value (10 Mg ha^{-1}) indicated by Martins *et al.* (2009) for the organic horizons of forest soils in Portugal. Canopy litterfall represents the major above-ground pathway by which carbon and nutrients are returned to the forest floor, being an important path to the biogeochemistry cycles of the forest ecosystems (Saarsalmi *et al.,* 2007). The mineral composition of plants ash reflects the chemical nature of the soil on which they grow (Larcher, 2007). Comparative evaluation of the concentration of the nutrients in the plant material was based on reference percent values in dry matter presented by Prével *et al.* (1984), Bowen and Nambiar (1984) and Marschener (1986). Leaves are the main component of the L layer being rich in N > Ca > Mg > K > S > P by this decreasing order. Similar patterns for nutrients concentration in the leaves were observed by Martins *et al.* (2007) for 52 years old even-aged maritime pine stands in the Tâmega region with 988 trees per hectare and dominant height of 16.2 m as well as by Kavvadias *et al.* (2001) for old growth maritime pine forests in Greece. The P concentration in the leaves and in all the other studied components of the forest floor was at lower levels than that reported in the above referred studies on maritime pine. There is a deficiency of P in the soils of all the regions and this is reflected in the P concentration in the plant material, both in the forest floor (mainly in the leaves) (Table 3) and in the understory vegetation (Table 4). Potassium concentration in leaves was significantly higher in Sines than in the other regions (Table 3 and Fig. 3). The same trend is observed for the understory (Table 4 and Fig. 4). However the K levels in the forest floor for all regions are quite low which was expected from the soil results. Calcium concentration in leaves and understory was significantly higher in Sines than in Tâmega and Minho. This was also the pattern for Mg in leaves but no significant differences were detected for the understory (Tables 3 and 4) (Figs. 3 and 4). The moderate levels of Ca and Mg in the plant material in Sines reflect the concentration of these nutrients in the soil. In fact soils in Sines are only moderately acid in comparison to the other regions. Twigs had the higher concentration of Ca in the forest floor.

The ratio C:N is an indicator of available N to the plants. Recent litter usually presents C:N values greater than 100 but in the lowest layers of forest floor (humus), the C:N ratio can decrease beneath 10 (Oliver and Larson, 1990). The FH layer presented a C:N ratio around 50 in Minho and Tâmega and 72 in Sines (Table 3).

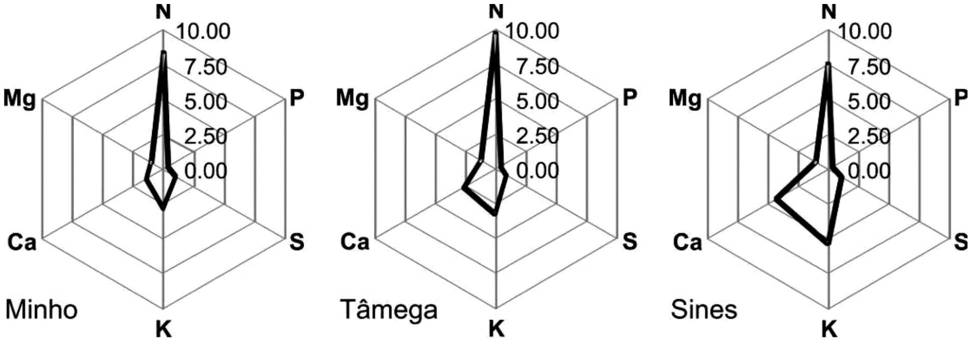

Figure 4. Radial diagrams with nutrients concentration (g kg^{-1}) in understory (adapted from Larcher, 2007).

Table 3 shows that N concentration in leaves is significantly higher in Minho and Tâmega than in Sines, following the same sequential decreasing order (Minho > Tâmega > Sines) as was observed for the mineral soil (Table 7). Nitrogen concentration in the understory did not significantly differ between regions (Table 4 and Fig. 4).

Porté *et al.* (2009) found an average value of 3.5 Mg ha^{-1} for the biomass stock in the understory of French maritime pine forests. In this study, biomass stocks in the understory were above the mean value reported by these authors (Table 4). Carbon stock in the understory ranged between 2.5 Mg ha^{-1} in Minho to 4.4 Mg ha^{-1} in Tâmega. On average, this carbon pool represented 2% of total C in the studied maritime pine stands and about 5% of total aboveground C stock.

Concerning dead wood, large woody debris can represent substantial amounts of biomass in old-growth natural forests (Carmona *et al.,* 2002). However, in managed forests large pieces of dead wood are scarce (Fridman and Walheim, 2000); thus the nutrient content of dead wood in such managed ecosystems (as it is the case of the sampled stands) is of little evidence (Laiho and Prescott, 2004). This was confirmed in this study where N, P, K, Ca, Mg, and S stored in the logs represented less than 1% of the forest floor, understory and dead wood nutrient stocks altogether. The values of C stock in woody debris (logs) roughly corresponded to 0.3% of the total stored C in the studied stands, including mineral soil, and to 0.8% of the total aboveground biomass (Table 5).

Wood density decreased with decay classes (Table 6), as observed in many studies (*e.g.* Harmon *et al.,* 1987; Yatskov *et al.,* 2003). Birdsey (1992) indicated average conversion factors of 0.521 and 0.491 for softwoods and hardwoods, respectively, to estimate carbon from wood biomass values. In this study, an average conversion factor of 0.520 was estimated. Carbon concentration remained practically constant along the decay classes. Nitrogen concentration increased throughout the decomposition process despite losses in mass, leading to a decrease of the C:N ratio. Thus, an immobilization process seems to occur. Phosphorous and S showed a similar increasing pattern along the decomposition classes. Quite opposite, K, Ca and Mg declined with the level of decomposition. Similar patterns were reported by other authors (*e.g.,* Idol *et al.,* 2001; Wilcke *et al.,* 2005).

Finally, C stock in the live trees (including roots) was higher in Minho than in the other regions. However these differences were not statistically significant (Table 8). Despite the rusticity of maritime pine with respect to the soil and climate conditions, in Minho there are more favourable conditions for tree growth. These climate and soil conditions may probably explain the slightly higher tree biomass in the Minho region. However it is important to note that although the sample selection tried to minimize differences between regions, trees in Minho presented slightly higher dominant height (Table 2).

Conclusions

Global C stocks of 308.6 Mg ha^{-1}, 208.7 Mg ha^{-1} and 100.6 Mg ha^{-1} were obtained in even-aged maritime pine stands of Minho, Tâmega and Sines regions, respectively. The mineral soil accounted for the larger proportion of the total amount of stored C and also for the significant differences observed between regions. Phosphorous was at low concentrations in the soils of all the regions and K was also at low to very low levels. This is reflected in the nutrient concentration of the plant dry matter. Calcium and magnesium were found at moderate levels in the understory vegetation and in the forest floor (leaves) from Sines. These levels statistically differed from Tâmega and Minho where soils are more acid and lower levels of these nutrients were found. Nitrogen concentration in soil significantly decreased in the order Minho > Tâmega > Sines. The importance of downed dead wood as a C pool in these managed stands was very small as well as was its contribution to the nutrient status of the ecosystem. The basic density of dead wood decreased along the decomposition stage.

The percent of carbon in the plant material (forest floor, understory and dead wood) ranged between 52% and 54%, slightly above the value 50% commonly used in many practical applications.

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References

APA, 2007. Atlas do Ambiente Digital. Agência Portuguesa do Ambiente, Ministério do Ambiente, do Ordenamento do Território e do Desenvolvimento Regional [www.iambiente.pt/atlas/est/index.jsp].

BALBINO L.R., 1968. O método de Égner-Riehm na determinação do fósforo e potássio assimiláveis em solos de Portugal. Rev Agron 51, 47-63.

BARFORD C.C., WOFSY S.C., 2001. Factors controlling long and short-term sequestration of atmospheric CO_2 in a mid-latitude forest. Science 294, 1688-1691.

BIRDSEY R.A., 1992. Carbon storage and accumulation in United States forest ecosystems. GTR WO-59, USDA Forest Service, Washington, DC. 51 pp.

BOWEN G.D., NAMBIAR E.K.S., 1984. Nutrition of plantation forests. Academic Press. 516 pp.

BRAVO F., BRAVO-OVIEDO A., DÍAZ-BALTEIRO L., 2007. Carbon sequestration in Spanish Mediterranean forests under two management alternatives: a modeling approach. Eur J Fores Res 127(3), 225-234. doi: 10.1007/s10342-007-0198-y.

CARDOSO J.V.J DE CARVALHO, 1965. Os solos do Portugal. Sua classificação, caracterização e génese. 1. A sul do rio Tejo. Secretaria de Estado da Agricultura, Direcção Geral dos Serviços Agrícolas, Lisboa.

CARMONA M.R., ARMESTO J.J., ARAVENA J.C., PÉREZ C.A., 2002. Coarse woody debris biomass in successional and primary temperate forests in Chiloé Island, Chile. For Ecol Manage 164, 265-275. doi: 10.1016/S0378-1127(01)00602-8.

CHAPMAN H.D., 1965. Total exchangeable bases. In: Methods of soil analysis. Part 2: Chemical and microbiological properties (Black C.A. *et al.,* eds). Madison, Wisconsin, USA. American Society of Agronomy, Inc, Series Agronomy nº 9. pp. 902-904.

CORREIA A., 2004. Metodologias para quantificação do balanço de carbono nas florestas em Portugal. Master's thesis. Universidade Técnica de Lisboa, Instituto Superior de Agronomia, Lisboa. 62 pp.

DAVIS M.R., ALLEN R.B., CLINTON P.W., 2003. Carbon storage along a stand development sequence in New Zealand *Nothofagus* forest. For Ecol Manage 177, 313-321. doi: 10.1016/S0378-1127(02)00333-X.

ESRI INC, 2009. ArcGis version 9.1.3. New York Street, Redlands, Calif.

FAIAS S., 2009. Analysis of Biomass Expansion Factors for the most important tree species in Portugal. Master's thesis. UTL-ISA, Lisboa.

FERNANDES P., LOUREIRO C., BOTELHO H., FERREIRA A., FERNANDES, M., 2002. Avaliação indirecta da carga de combustível em pinhal bravo. Silva Lusitana 10(1), 73-90. ISSN 0870-6352.

FRIDMAN J., WALHEIM M., 2000. Amount, structure, and dynamics of dead wood on managed forestland in Sweden. For Ecol Manage 131, 23-36. doi: 10.1016/S0378-1127(99)00208-X.

FUJIMORI T., 2001. Ecological and Silvicultural Strategies for Sustainable Forest Management. Elsevier, Amsterdam. 398 pp.

GANJEGUNTE G.K., CONDRON L.M., CLINTON P.W., DAVIS M.R., MAHIEU N., 2004. Decomposition and nutrient release from radiata pine (*Pinus radiata*) coarse woody debris. For Ecol Manage 187, 197-211. doi: 10.1016/S0378-1127(03)00332-3.

HARMON M.E., CROMACK K. Jr., SMITH B.G., 1987. Coarse woody debris in mixed-conifer forests, Sequoia National Park, California. Can J For Res 17, 1265-1272. doi: 10.1139/x87-196.

IDOL T.W, FIGLER R.A., POPE P.E., PONDER F.J., 2001. Characterization of coarse woody debris across a 100 year chronosequence of upland oak-hickory forests. For Ecol Manage 149, 153-161. doi: 10.1016/S0378-1127(00)00536-3.

IPCC, 2007. Climate Change 2007: synthesis report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on

Climate Change (Core Writing Team, Pachauri R.K., Reisinger A., eds). IPCC, Geneva, Switzerland. 104 pp.

IUSS Working Group WRB, 2006. World reference base for soil resources, 2nd ed. World Soil Resources Reports No. 103. FAO, Rome.

KAVVADIAS V.A., ALIFRAGIS D., ALEXANDROS T., BROFAS G., STAMATELOS G., 2001. Litterfall, litter accumulation and litter decomposition rates in four forest ecosystems in norhern Greece. For Ecol Manage 144, 113-127. doi: 10.1016/S0378-1127(00)00365-0.

LAIHO R., PRESCOTT C.E., 1999. The contribution of coarse woody debris to carbon, nitrogen, and phosphorus cycles in three Rocky Mountain coniferous forests. Can J For Res 29, 1502-1603. doi: 10.1139/X03-241.

LARCHER W., 2007. Physiological plant ecology. Ecophysiology and stress physiology of functional groups, 4th ed. Springer. 513 pp.

LEMAY V., KURZ W.A., 2008. Estimating carbon stocks and stock changes in forests: linking models and data across scales. In: Managing forest ecosystems: the challenge of climate change (Bravo F. *et al.,* eds). Springer. pp. 63-81.

LOPES D., ARANHA J., 2006. Avaliação do conteúdo de carbono na matéria seca de diferentes componentes de arvores de *Eucalyptus globulus* e de *Pinus pinaster*. Silva Lusitana 14(2), 149-154. ISSN 0870-6352.

LQARS, 2000. Manual de fertilização das culturas. INIA, Lisboa, Portugal.

MARSCHNER H., 1986. Mineral nutrition of higher plants. Academic Press. 612 pp.

MARTINS A., COUTINHO J., COSTA S., FONSECA F., MADEIRA M., 2007. A folhada de quatro povoamentos florestais no Norte de Portugal: produção e concentração e quantidade de nutrientes devolvidos ao solo. Rev de Ciências Agrárias 30(2), 201-216. ISSN 0871-018X.

MARTINS A., RAIMUNDO F., DUARTE J., FARROPAS L., MANO R., SOUSA V., LOURENÇO M., ARANHA J., MADEIRA M., 2009. O carbono nos solos florestais de Portugal continental e relações com factores ambientais. In: Proceedings of 6º National Forest Congress. Sociedade Portuguesa de Ciências Florestais, Ponta Delgada, Azores. pp. 91-99.

MCCARTHY B.C., BAILEY R.R., 1994. Distribution and abundance of coarse woody debris in a managed forest landscape of the central Appalachians. Can J For Res 24, 1317-1329. doi: 10.1139/x94-172.

MONTERO G., RUIZ-PEINADO R., MUÑOZ M., 2005. Producción de biomasa y fijación de CO_2 por los bosques españoles. Monografías INIA, Serie Forestal, nº 13, Madrid.

OLIVEIRA A.C., PEREIRA J.S., CORREIA A., 2000. A silvicultura do pinheiro bravo. Centro Pinus, Porto. 112 pp.

OLIVER C.D., LARSON B.C., 1990. Forest stand dynamics. John Wiley and Sons, New York. 467 pp.

PORTÉ A.J., SAMALENS J.C., DULHOSTE R., Du CROS R.T., BOSC A., Meredieu C., 2009. Using cover measurements to estimate aboveground understorey biomass in Maritime pine stands. Ann For Sci 66(3), 307. doi: 10.1051/forest/2009005.

PRÉVEL P.M., GAGNARD J., GAUTIER P., BENTON J., HOLMES M.R.J., 1984. Plant analysis as a guide to the nutrient requirements of temperate and tropical crops (Martin-Prevel *et al.,* eds). Lavoisier Publishing Inc, New York.

RAVINDRANATH N.H., OSTWALD M., 2008. Carbon inventory methods handbook for greenhouse gas inventory, carbon mitigation and roundwood production projects. Advances in Global Change Research Series, Vol. 29, Martin Beniston Ed, Springer. 304 pp.

SAARSALMI A., STARR M., HOKKANEN T., UKONMAANAHO L., KUKKOLA M., NORJD P., SIEVANEN R., 2007. Predicting annual canopy litterfall production for Norway spruce [*Picea abies* (L.) Karst.] stands. For Ecol Manage 242, 578-586. doi: 10.1016/j.foreco.2007.01.071.

SANTOS J.Q., 1996. Fertilização. Fundamentos da utilização de adubos e correctivos. Publicações Europa América. Colecção Euroagro n.º 30.

SEVINK J., 1991. Soil development in the coastal dunes and its relation to climate. Landscape Ecology 6, 49-56.

SIITONEN J., MARTIKAINEN P., PUNTTILA P., RAUH J., 2000. Coarse woody debris and stand characteristics in mature managed and old-growth boreal mesic forests in southern Finland. For Ecol Manage 128, 211-225. doi: 10.1016/S0378-1127(99)00148-6.

SOLLINS P., 1982. Input and decay of coarse woody debris in coniferous stands in western Oregon and Washington. Can J For Res 2, 18-28. doi: 10.1139/x82-003.

TOMÉ M., BARREIRO S., CORTIÇADA A., PAULO J.A., MEYER A., RAMOS T, MALICO P., 2007. Inventário florestal 2005-2006. Áreas, volumes e biomassas dos povoamentos florestais. Resultados Nacionais e por NUT's II e III. Publicações GIMREF. RT 5/2007. Universidade Técnica de Lisboa, Instituto Superior de Agronomia, Centro de Estudos Florestais, Lisboa.

VAN WAGNER C.E., 1968. The line intersect method in forest fuel sampling. For Sci 14, 20-26.

WARNCKE D., BROWN J.R., 1998. Potassium and other basic cations. In: Recommended chemical soil test procedures for the North Central Region, Missouri Agricultural experiment station SB 1001 (Brown J.R. *et al.,* eds). North Central Regional Research Publication No. 221. pp. 31-33. [Revised].

WARREN W.G., OLSEN P.F., 1964. A line intersect technique for assessing logging waste. For Sci 10, 267-276.

WILCKE W., HESS T. BENGEL C., HOMEIER J., VALAREZO C., ZECH, W., 2005. Coarse woody debris in a montane forest in Ecuador: mass, C and nutrient stock, and turnover. For Ecol Manage 205, 139-147. doi: 10.1016/j.foreco.2004.10.044.

WOLDENDORP G., SPENCER R.D., KEENAN R.J., BARRY S., 2002. An analysis of sampling methods for coarse woody debris in Australian forest ecosystems. Report for the National Greenhouse Strategy, Module 6.6 (Criteria and Indicators of Sustainable Forest Management). Commonwealth Department of Agriculture, Fisheries and Forestry-Australia. 84 pp.

WOLDENDORP G., KEENAN R.J., BARRY S., SPENCER R.D., 2004. Analysis of sampling methods for coarse woody debris. For Ecol Manage 198, 133-148. doi: 10.1016/j.foreco.2004.03.042

YATSKOV M., HARMON M.E., KRANKINA O.N., 2003. A chronosequence of wood decomposition in the boreal forests of Russia. Can J For Res 33, 1211-1226. doi: 10.1139/x03-033.