*According to World Reference Base for Soil (FAO, 1998).

# Allometric equations for predicting mineralomass in high-forest chestnut stands in Portugal

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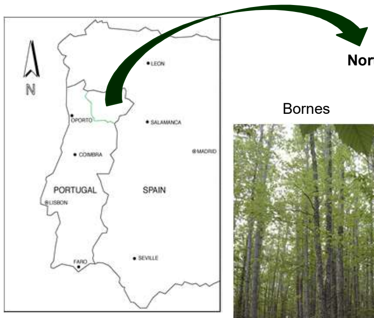
## Introduction

The information of the content of mineral elements in the tree-component biomass is essential to understand their status and flow in the whole system, as well as to assess the productive capacity of ecosystems and the management implications for forest sustainability. However, the evaluation of nutrients in biomass tree-components is a process time consuming and expensive, often involving tree felling, not always possible or desirable. On the other hand, the concentration of minerals in tree-biomass components for a given species varies considerably between tree-components, sites and it is not always available in the literature. Given the importance of the relationship of biomass and nutrients (mineralomass) for dynamic and sustainable management chestnut woodlands, aboveground mineralomass was studied in sweet chestnut (*Castanea sativa* Mill.) high-forest stands located in Northern Portugal.

**Objective**: To provide allometric equations for chestnut high-forest woodlands for estimating the mineralomass using the dendrometric variables diameter breast height (d) and total height (h) of the tree.



Northern of Portugal

Bornes

Marão

Padrela

## Materials and Methods

The present study was carried out in the three high-forest mature chestnut stands located in three mountains of Northern Portugal: Marão (41º 14’ 46” N, 7º 55’ 04” W), Padrela (41º 30’ 41” N, 7º 37’ 15” W) and Bornes (41º 29’ 42” N, 6º 55’ 12” W) which have been monitored over time. Sampling followed a west-to-east transect across to northern Portugal from a more-Atlantic-to-less-maritime influence.

In order to obtain biomass data, 34 trees were felled according to the existent diameter classes. The methodology of biomass collection was described by Patrício et al. (2005). These samples of tree-biomass components were analyzed to determine their mineral concentrations.

**Table1. General characteristics of the studied chestnut stands (Northern Portugal).**

| Chestnut stands | Marão | Padrela | Bornes |
|---|---|---|---|
| Altitude (m a.s.l.) | 900 | 850 | 800 |
| Slope (º) | 5-10 | 25-30 | 15-20 |
| Main soil type* | *Umbric Regosols* | *Dystric Regosols* | *Dystric Cambisols* |
| Mean annual temperature (ºC) | 11.5-12.0 | 12.5 | 11.9 |
| Mean annual precipitation (mm year$^{-1}$) | 2505 | 1132 | 1009 |
| Age (years) | 71 | 64 | 53 |
| Density (tree ha$^{-1}$) | 360 | 470 | 1260 |
| Mean DBH (cm) | 41.2±9.0 | 33.6±6.3 | 26.1±6.1 |
| Mean height (m) | 28.7±2.7 | 21.7±2.4 | 22.4±2.7 |

*According to World Reference Base for Soil (FAO, 1998).

- ✓ The collected samples of biomass of leaves, flowers and barks were dried in a stove at 70±2ºC, while the log samples and branches, were dried at 103±2ºC (until constant weight) for determining the water content and estimating the dry matter.
- ✓ After the drying process the biomass samples were finely ground. Sub-samples of these were taken for chemical analysis. The following elements were determined: N, P, K, Ca, Mg, S, B and C in all tree-components biomass above ground.
- ✓ We consider the following mineralomass of tree-components: bark (M_Bark), leaves and flowers (M_Ltot), live branches (M_Bliv), main stem under bark (M_Wood), main stem over bark (M_Stem) and the total aboveground mineralomass (M_Tot).

**Model selection:**

✓The models were evaluated in terms of measures of fit and prediction ability: modelling efficiency (EM), mean square error (MSE), models parameter significance, $R^2$ of prediction ($R^2$pred), mean of PRESS residuals (m_PRESS), and mean of the absolute values of the PRESS residuals (ma_PRESS) as well as the percentiles 95% (P95) and 5% (P5) of the PRESS residuals.

✓The normality of the studentized residuals was analysed using normal QQplots. The presence of heterocedasticity associated with the error term of the models was checked by plotting the studentized residuals against the predicted values.

✓The regression assumptions departure was solved with non-linear iteratively re weighted least squares (IRWLS) using the Huber function with the maximum value of r=1 and weighting factors. The procedure was repeated for each mineral.

**Data analysis:**

- ✓ The mineralomass equations were fitted by the ordinary least squares method (OLS) associated with both the PROC REG (linear models) and PROC NLIN (non-linear models) procedures of SAS/STAT. The modified Gauss-Newton iterative method was applied in the non-linear model fitting.
- ✓ A simultaneous fit by SUR method using iterative seemingly unrelated regression (ITSUR) by PROC MODEL procedure of SAS/STAT was used for the final compatible selected models.

**Table2. Biometric variables of the 34 sampled trees**

| Variable | Minimum | Mean | Maximum | Stand. deviation |
|---|---|---|---|---|
| DBH (cm) | 10.25 | 33.98 | 64.20 | 14.14 |
| h (m) | 11.55 | 21.91 | 30.40 | 4.63 |

DBH, diameter breast height, h, total height

## Results and Discussion

✓ **To model the mineralomass (M) by tree-components, the following candidate allometric equations were tested:**

(1) $M = \beta_0 + \beta_1 d^2h$
(1.1) $M = \beta_1 d^2h$
(2) $M = \beta_0 + \beta_1 d + \beta_2 d^2$
(2.2) $M = \beta_1 d + \beta_2 d^2$
(3) $M = \beta_1 d^2$
(4) $M = \beta_1 d + \beta_2 h$
(5) $M = \beta_1 (d^2h)^{\beta 2}$
(6) $M = \beta_1 d^{\beta 2}$

→ *d* represent the DBH and *h* the total height of the tree

**Table 3. Mean value and respective standard deviation (in brackets) of the mineralomass (n=34 trees) for the minerals N, P, K, Ca, Mg, S, B and C**

| Mineral | M_Wood (kg) | M_Bark (kg) | M_Bliv (kg) | M_Ltot (kg) | M_Tot (kg) |
|---|---|---|---|---|---|
| N | 0.489 | 0.203 | 0.379 | 0.225 | 1.451 |
|  | (0.572) | (0.155) | (0.476) | (0.199) | (1.489) |
| P | 0.047 | 0.017 | 0.048 | 0.015 | 0.140 |
|  | (0.062) | (0.015) | (0.062) | (0.011) | (0.151) |
| K | 0.105 | 0.085 | 0.201 | 0.074 | 0.500 |
|  | (0.161) | (0.085) | (0.205) | (0.065) | (0.427) |
| Ca | 0.307 | 0.594 | 0.394 | 0.036 | 1.448 |
|  | (0.414) | (0.436) | (0.389) | (0.028) | (1.143) |
| Mg | 0.107 | 0.065 | 0.129 | 0.037 | 0.379 |
|  | (0.114) | (0.047) | (0.166) | (0.030) | (0.379) |
| S | 0.059 | 0.008 | 0.016 | 0.010 | 0.097 |
|  | (0.081) | (0.008) | (0.019) | (0.008) | (0.106) |
| B* | 0.977 | 0.461 | 0.904 | 0.116 | 2.703 |
|  | (1.966) | (0.360) | (1.084) | (0.100) | (2.623) |
| C | 226.714 | 26.034 | 73.731 | 5.289 | 354.902 |
|  | (179.350) | (18.832) | (92.717) | (4.446) | (310.320) |

*

* Mineralomass of B in (g), (M_Wood) mineralomass of main stem under bark, (M_Bark) minetalomass of stem bark, (M_Bliv) mineralomass of branches, (M_Ltot) mineralomass of leaves and flowers, (M_Tot) the total aboveground mineralomass.

**Table 4. Fitting and prediction statistics of the models with the best performance for the mineralomass by tree-component and by mineral, after weighting.**

| Min | Model | Comp. | MSE | EM | mPRESS | maPRESS | $R^2_{pred}$ | P95 | P5 |
|---|---|---|---|---|---|---|---|---|---|
| N | (1.1) | M_Bark | $0.507\ 10^{-7}$ | 0.957 | -0.003 | 0.033 | 0.862 | 0.065 | -0.101 |
|  | (3) | M_Ltot | $0.718\ 10^{-5}$ | 0.837 | 0.007 | 0.076 | 0.715 | 0.264 | -0.163 |
|  | (3) | M_Bliv | $0.2357\ 10^{-4}$ | 0.767 | 0.043 | 0.181 | 0.477 | 0.832 | -0.260 |
|  | (3) | M_Wood | $0.284\ 10^{-4}$ | 0.830 | 0.054 | 0.180 | 0.417 | 0.530 | -0.286 |
|  | (3) | M_Stem | $0.257\ 10^{-3}$ | 0.944 | 0.096 | 0.611 | 0.803 | 2.853 | -1.168 |
|  | (1.1) | M_Tot | $0.536\ 10^{-5}$ | 0.900 | 0.083 | 0.431 | 0.720 | 1.929 | -0.829 |
|  | (3) | M_Bark | $0.216\ 10^{-7}$ | 0.895 | $0.522\ 10^{-3}$ | 0.005 | 0.632 | 0.016 | -0.010 |
|  | (3) | M_Ltot | $0.372\ 10^{-7}$ | 0.831 | $0.665\ 10^{-3}$ | 0.005 | 0.672 | 0.015 | -0.008 |
| K | (3) | M_Bliv | $0.786\ 10^{-5}$ | 0.752 | 0.016 | 0.096 | 0.524 | 0.274 | -0.135 |
|  | (1.1) | M_Wood | $0.156\ 10^{-3}$ | 0.428 | 0.025 | 0.078 | 0.088 | 0.192 | -0.143 |
|  | (1.1) | M_Stem | 0.002 | 0.868 | 0.034 | 0.393 | 0.618 | 1.034 | -0.753 |
|  | (3) | M_Tot | 0.036 | 0.925 | 0.023 | 0.171 | 0.719 | 0.398 | -0.274 |
| Ca | (3) | M_Bark | $0.392\ 10^{-4}$ | 0.852 | -0.009 | 0.224 | 0.242 | 0.580 | -0.629 |
|  | (3) | M_Ltot | $0.337\ 10^{-6}$ | 0.749 | 0.002 | 0.016 | 0.451 | 0.049 | -0.021 |
|  | (3) | M_Bliv | $0.359\ 10^{-4}$ | 0.707 | 0.027 | 0.198 | 0.401 | 0.631 | -0.492 |
|  | (1.1) | M_Wood | $0.352\ 10^{-3}$ | 0.773 | 0.023 | 0.148 | 0.538 | 0.673 | -0.258 |
|  | (1.1) | M_Stem | 0.088 | 0.891 | 0.119 | 2.260 | 0.498 | 5.256 | -6.362 |
|  | (1) | M_Tot | $0.414\ 10^{-5}$ | 0.882 | 0.020 | 0.286 | 0.870 | 0.687 | -0.565 |
| Mg | (3) | M_Bark | $0.752\ 10^{-6}$ | 0.779 | $0.408\ 10^{-3}$ | 0.024 | 0.357 | 0.064 | -0.048 |
|  | (3) | M_Ltot | $0.229\ 10^{-6}$ | 0.822 | 0.002 | 0.014 | 0.719 | 0.040 | -0.022 |
|  | (3) | M_Bliv | $0,283\ 10^{-5}$ | 0.759 | 0.016 | 0.059 | 0.465 | 0.232 | -0.083 |
|  | (1.1) | M_Wood | $0.229\ 10^{-4}$ | 0.874 | 0.006 | 0.037 | 0.681 | 0.151 | -0.071 |
|  | (3) | M_Stem | 0.001 | 0.893 | 0.025 | 0.243 | 0.637 | 0.845 | -0.540 |
|  | (1) | M_Tot | $0.479\ 10^{-6}$ | 0.818 | 0.023 | 0.125 | 0.642 | 0.326 | -0.203 |
| S | (1.1) | M_Bark | $0.321\ 10^{-9}$ | 0.835 | $0.128\ 10^{-4}$ | 0.003 | 0.510 | 0.010 | -0.009 |
|  | (3) | M_Ltot | $0.155\ 10^{-7}$ | 0.852 | $0.143\ 10^{-3}$ | 0.003 | 0.692 | 0.009 | -0.009 |
|  | (3) | M_Bliv | $0.351\ 10^{-7}$ | 0.797 | 0.001 | 0.007 | 0.619 | 0.036 | -0.010 |
|  | (1.1) | M_Wood | $0.260\ 10^{-4}$ | 0.616 | 0.008 | 0.036 | 0.314 | 0.183 | 0.054 |
|  | (1.1) | M_Stem | $0.956\ 10^{-4}$ | 0.775 | 0.008 | 0.074 | 0.461 | 0.239 | -0.126 |
|  | (1.1) | M_Tot | $0.397\ 10^{-7}$ | 0.827 | 0.008 | 0.034 | 0.631 | 0.159 | -0.060 |
| B* | (3) | M_Bark | $0.119\ 10^{-4}$ | 0.915 | 0.004 | 0.129 | 0.780 | 0.273 | -0.292 |
|  | (3) | M_Ltot | $0.491\ 10^{-5}$ | 0.684 | 0.001 | 0.055 | 0.507 | 0.236 | -0.090 |
|  | (3) | M_Bliv | $0.125\ 10^{-3}$ | 0.786 | 0.088 | 0.397 | 0.562 | 1.154 | -0.513 |
|  | (3) | M_Wood | $0.150\ 10^{-3}$ | 0.806 | 0.011 | 0.407 | 0.576 | 0.997 | -1.191 |
|  | (3) | M_Stem | $0.168\ 10^{-3}$ | 0.927 | 0.083 | 1.475 | 0.822 | 4.063 | -3.473 |
|  | (1.1) | M_Tot | $0.237\ 10^{-4}$ | 0.915 | -0.006 | 0.831 | 0.819 | 2.335 | -2.487 |
| C | (5) | M_Bark | $0.437\ 10^{-3}$ | 0.963 | 0.071 | 3.074 | 0.950 | 8.348 | -7.686 |
|  | (3) | M_Ltot | 0.004 | 0.838 | 0.152 | 1.976 | 0.712 | 5.862 | -3.541 |
|  | (3) | M_Bliv | 0.887 | 0.757 | 8.031 | 35.974 | 0.5602 | 188.415 | -52.166 |
|  | (5) | M_Wood | 0.012 | 0.978 | -1.141 | 26.027 | 0.933 | 64.273 | -40.100 |
|  | (5) | M_Stem | 0.090 | 0.982 | -3.611 | 52.653 | 0.946 | 156.171 | -103.883 |
|  | (6) | M_Tot | 0.860 | 0.984 | -0.942 | 34.370 | 0.972 | 66.810 | -107.667 |

* Mineralomass of B in (g), Mineralomass of the remaining minerals in (kg). (MSE) mean square error, (EM) modelling efficiency, (m_PRESS) mean of PRESS residuals, (ma_PRESS) mean of the absolute values of the PRESS residuals, ($R^2$pred) $R^2$ of prediction, (P95) and (P5) percentiles 95% and 5% of the PRESS residuals.

✓ **The analysis**

**for each tree component:**

✓ **Final mineralomass equations fitted by OLS method**

**Nitrogen:**
$N\_Bark = 0.6260\ 10^{-5}\ d^2 h;$
$N\_Ltot = 0.1768\ 10^{-3} d^2;$
$N\_Bliv = 0.2505\ 10^{-3}\ d^2;$
$N\_Wood = 0.3232\ 10^{-3}\ d^2;$
$N\_Tronc = 0.00193\ d^2;$
$N\_Tot = 0.4138\ 10^{-4}\ d^2 h;$
$P\_Bliv = 0.3070\ 10^{-4}\ d^2;$
$P\_Wood = 0.3217\ 10^{-4} d^2;$
$P\_Tronc = 0.1713\ 10^{-3}\ d^2;$
$P\_Total = 0.1030\ 10^{-3} d^2;$
**Potassium:**
$K\_Bark = 0.2400\ 10^{-5}\ d^2h;$
$K\_Ltot = 0.6220\ 10^{-4}\ d^2;$
$K\_Bliv = 0.1370\ 10^{-3}\ d^2;$
$K\_Wood = 0.2430\ 10^{-5}\ d^2h;$
$K\_Tronc = 0.3036\ 10^{-4}\ d^2h;$
$K\_Total = 0.4060\ 10^{-3}\ d^2;$
**Calcium:**
$Ca\_Bark = 0.4152\ 10^{-3} d^2;$
$Ca\_Ltot = 0.2824\ 10^{-4}\ d^2;$
$Ca\_Bliv = 0.2671\ 10^{-3}\ d^2;$
$Ca\_Wood = 0.8670\ 10^{-5}\ d^2h;$
$Ca\_Tronc = 0.2041\ 10^{-3}\ d^2\ h;$
$Ca\_Total = 0.1062+0.3777\ 10^{-4}\ d^2h;$

**Magnesium:**
$Mg\_Bark = 0.4750\ 10^{-4}\ d^2;$
$Mg\_Ltot = 0.2991\ 10^{-4}\ d^2;$
$Mg\_Bliv = 0.8383\ 10^{-4}\ d^2;$
$Mg\_Wood = 0.3080\ 10^{-5} d^2\ h;$
$Mg\_Tronc = 0.2325\ 10^{-4} d^2\ h;$
$Mg\_Total = 0.0336+0.9950\ 10^{-5}\ d^2\ h;$
$S\_Bliv = 0.1063\ 10^{-4}\ d^2;$
$S\_Wood = 0.1550\ 10^{-5}\ d^2h;$
$S\_Tronc = 0.4420\ 10^{-5}\ d^2h;$
$S\_Total = 0.2580\ 10^{-5}\ d^2\ h;$
**Boron:**
$B\_Bark = 0.3386\ 10^{-3}\ d^2;$
$B\_Ltot = 0.9340\ 10^{-4}\ d^2;$
$B\_Bliv = 0.6070\ 10^{-3}\ d^2;$
$B\_Wood = 0.7160\ 10^{-3}\ d^2;$
$B\_Tronc = 0.00438\ d^2;$
$B\_Total = 0.9437\ 10^{-4}\ d^2\ h;$
**Carbon:**
$C\_Bark = 0.0076\ (d^2\ h)^{0.7880};$
$C\_Ltot = 0.0045\ d^2;$
$C\_Bliv = 0.0490\ d^2;$
$C\_Wood = 0.0138\ (d^2\ h)^{0.9360};$
$C\_Tronc = 0.0342\ (d^2\ h)^{0.9299};$
$C\_Total = 0.0630\ d^{\ 2.3754}.$

✓ **The selected final models were simultaneously fitted by SUR method with the ITSUR procedure for each mineral.**

✓ **Final compatible mineralomass equations**

| Nitrogen: | EM |
|---|---|
| $N\_Bark = 0.5877\ 10^{-5}\ d^2\ h;$ | 0.8871 |
| $N\_Ltot = 0.1700\ 10^{-3} d^2;$ | 0.7266 |
| $N\_Bliv = 0.2930\ 10^{-3}\ d^2;$ | 0.5437 |
| $N\_Wood = 0.3660\ 10^{-3}\ d^2;$ | 0.4609 |
| N_Total | 0.7209 |
| Phosphorus: |  |
| $P\_Bark = 0.1400\ 10^{-4}\ d^2;$ | 0.6318 |
| $P\_Ltot = 0.1200\ 10^{-4}\ d^2;$ | 0.6954 |
| $P\_Bliv = 0.3400\ 10^{-4}\ d^2;$ | 0.3639 |
| $P\_Wood = 0.3800\ 10^{-4} d^2;$ | 0.2128 |
| P_Total | 0.4951 |
| Potassium: |  |
| $K\_Bark = 0.2812\ 10^{-5}\ d^2h;$ | 0.5853 |
| $K\_Ltot = 0.6600\ 10^{-4}\ d^2;$ | 0.6634 |
| $K\_Bliv = 0.1480\ 10^{-3}\ d^2;$ | 0.5638 |
| $K\_Wood = 0.7100\ 10^{-4}\ d^2;$ | 0.0932 |
| K_Total | 0.7427 |
| Calcium: |  |
| $Ca\_Bark = 0.4730\ 10^{-3} d^2;$ | 0.2546 |
| $Ca\_Ltot = 0.2600\ 10^{-4}\ d^2;$ | 0.4772 |
| $Ca\_Bliv = 0.2491\ 10^{-3}\ d^2;$ | 0.4221 |
| $Ca\_Wood = 0.8796\ 10^{-5}\ d^2h;$ | 0.5882 |
| Ca_Total | 0.7998 |
| Magnesium: |  |
| $Mg\_Bark = 0.4300\ 10^{-4}\ d^2;$ | 0.4369 |
| $Mg\_Ltot = 0.3000\ 10^{-4}\ d^2;$ | 0.7398 |
| $Mg\_Bliv = 0.9700\ 10^{-4}\ d^2;$ | 0.5323 |
| $Mg\_Wood = 0.3100\ 10^{-5} d^2\ h;$ | 0.7125 |
| Mg_Total | 0.7246 |
| Sulfur: |  |
| $S\_Bark = 0.2441\ 10^{-6}\ d^2h;$ | 0.5537 |
| $S\_Ltot = 0.7388\ 10^{-5}\ d^2;$ | 0.7147 |
| $S\_Bliv = 0.1100\ 10^{-4}\ d^2;$ | 0.6622 |
| $S\_Wood = 0.1872\ 10^{-5}\ d^2h;$ | 0.3827 |
| S_Total | 0.5925 |
| Boron: |  |
| $B\_Bark = 0.3330\ 10^{-3}\ d^2;$ | 0.8000 |
| $B\_Ltot = 0.9200\ 10^{-4}\ d^2;$ | 0.5354 |
| $B\_Bliv = 0.655\ 10^{-3}\ d^2;$ | 0.6128 |
| $B\_Wood = 0.7940\ 10^{-3}\ d^2;$ | 0.6011 |
| B_Total | 0.7830 |
| Carbon: |  |
| $C\_Bark = 0.010008\ (d^2\ h)^{0.760258};$ | 0.9491 |
| $C\_Ltot = 0.004172\ d^2;$ | 0.7175 |
| $C\_Bliv = 0.041554\ d^2;$ | 0.5124 |
| $C\_Wood = 0.010784\ (d^2\ h)^{0.960756};$ | 0.9314 |
| C_Total | 0.9103 |

- ✓ We present the modeling efficiency (EM) of the equations, a measure similar to the adjusted $R^2$ in linear models. The *EM* obtained by *SUR* method is generally lower than that obtained by *OLS*, but with a smaller standard error of the coefficients and with the guarantee of the additivity of the mineralomass of the tree-components to obtain the total mineralomass of the tree.

## Conclusions

✓At the end of this study we available equations of mineralomass by tree-components and mineral for the sweet chestnut high-forest management. The information obtained with these mineralomass equations, applicable to data of individual trees, can be applied to the forest inventories as well as to a great variety of ecological problems, like wildfire studies, the carbon sequestration and to evaluate the harvesting impact on site nutrient export and site sustainability.

**References:** FAO. (1998). World reference base for soil resources. World Soil Resources Reports, Rome, 84.
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