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Research paper

Relationship between soil chemical composition and potential fuel quality of biomass from poplar short rotation coppices in Portugal and Belgium

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ABSTRACT

Soil-woody biomass interactions are relevant for the productivity of bioenergy plantations and biomass quality. In this context, the main objective of this study was to evaluate and to quantify possible relationships between chemical variables of the soil and the produced biomass through a multivariate approach. This latter approach allows to overcome the complex issue of multi-collinearity among variables. Soil and woody biomass samples were collected from two poplar short rotation coppices in Santarém (Portugal) and in Lochristi (Belgium). The results from the analyses of those samples were integrated into three databases with soil, woody biomass and site plots as cases, and 23 physical and chemical properties as variables. The databases were subjected to a multivariate sequence of calculations, which included correlation, principal components, factorial and hierarchical clustering analyses. The calculations showed that the site plots and the woody biomass of genotypes in Lochristi were more homogeneous as compared to Santarém; they also confirmed the high interconnection between soil and woody biomass variables. The higher heating value of the woody biomass correlated well with the soil concentrations of P_2O_5, Mg, Ca, Na and organic C. Linear equations related the higher heating value to the most important soil and woody biomass variables. Finally, the results suggest that the annual monitoring of soil and biomass in SRC systems should be performed to optimize both productivity and woody biomass quality as a fuel.

1. Introduction

Short rotation coppice (SRC), an intensively managed agroforestry system to assure that biomass productivity ranges between 10 and 20 tons dry matter (DM) ha^{-1} y^{-1} [1], is an option for the efficient production of woody biomass for bioenergy. Productive cycles are generally between two to five years and the plants are replaced when productivity starts to decrease [2–5]. In Europe, poplar is one of the main species used for SRC because of its high plasticity to different latitudes and climatic conditions, high growth rates, high potential for genetic improvement [6–9] and limited requirements for irrigation, herbicides and fertilisers [10,11]. Under medium or poor site conditions, irrigation and fertilisation should be implemented in SRC plantations for improving soil fertility and biomass yield [3,12]. The biomass heating value is determined by the chemical energy inherent to its structure, that is converted to heat by combustion [13].

The most important properties of woody biomass for energy are the ratio of bark/wood, the moisture content, the heating value, the contents of cellulose, lignin and extractives, as well as the content and composition of the ash. Around 70% of the heat released during the combustion of woody biomass is associated with the oxidation of the volatile matter. Cellulose, lignin and xylan in woody biomass contain about 91%, 66% and 77% of volatile matter, respectively. Amounts of 84% of volatile matter, 15% of fixed C and 1% of ashes are typical for poplar wood [14].

One issue that should be addressed for the improvement of management techniques of SRC sites is the impact of soil chemical and physical characteristics on the fuel quality of the produced

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biomass. Literature suggests that soil structure and soil properties have an influence on biomass characteristics [15–17]. Despite the vast amount of research on SRC, studies of the influence of soil chemical and physical characteristics on the fuel quality of SRC biomass are still lacking. At the stand level, mineral nutrients and nutrient cycling processes play a crucial role in soil sustainability [16,18]. At SRC sites mineral nutrient recycling from canopy to roots and to the soil occurs during the dormant season of poplar [16]. An advantage of SRC compared to annual crops is the more efficient nutrient cycling and lower nutrient losses: as harvesting is performed after leaf fall, fewer nutrients are removed and the high amounts of nutrients in leaves are annually recycled [19]. High biomass yields are linked to good soil fertility, possibly ameliorated by fertilisation [17]. In this context, Di Matteo et al. [3] in Southern Italy, suggested fertilising poplar SRC sites with 100 kg P_2O_5 and 100 kg K_2O ha^{-1} in the first year of the rotation. SRC soils also sequester vast amounts of atmospheric CO_2, usually up to 30 cm deep [20].

Plant metabolism is affected by changes in the mineral composition of the soil, giving rise to differences in the woody biomass composition. For example, potassium (K) in plants is known for balancing the ionic charges of organic acids and it is associated with 50 enzymatic reactions in chlorophyll synthesis, photosynthesis and carbohydrate metabolism [21–24]. Fertilisation with base cations on acid soils increases the electron transport rate in forest species that are intolerant to acidification and soil cation imbalances [25].

Data on higher and lower heating values (HHV and LHV, respectively) have been thoroughly examined, mainly using least squares regression methods, in order to relate the fuel HHV with its proximate and ultimate analyses [13,26,27]. Despite many advantages, least square regression methods have some drawbacks related to the strict requirement of normality and multi-collinearity conditions. Indeed, the evaluation of woody materials for bioenergy, should consider empirical biomass properties that are certainly correlated [26,28,29]. These complex issues increase with the addition of soil properties to the analysis. Multivariate analyses can overcome the restrictions of the least square regressions by addressing the sources of correlation and interconnectedness of different variables [29–32]. The literature on multivariate analyses on plant-soil interactions is, however, too scarce to address a thorough analysis of these interconnections.

The aforementioned considerations indicate that soil physical and chemical properties influence the biomass quality and quantity, in particular its heating value, and ash and volatile matter contents. The quantification of the interactions between soil properties, chemical composition and biomass output can also be relevant for improving the management of SRC systems.

This contribution aims to evaluate and to quantify relationships between the soil and characteristics of biomass as-a-fuel at two sites (in Portugal and Belgium) through a sequence of multivariate techniques including correlation, principal components, factorial and hierarchical clustering analysis. To this purpose, it was also tested if the number of variables necessary to discriminate the different plots that constitute a site or different poplar genotypes, could be reduced. Lastly, partial least squares (PLC) modelling was applied to test the effects of the soil and of the plot on the quality of biomass-as-fuel.

2. Materials and methods

2.1. Site description and sample collection

In the present study, soil and woody biomass were sampled at two SRC sites located in Santarém (Portugal; Mediterranean climate) and in Lochristi (Belgium; temperate Atlantic climate). In Santarém, two plots cultivated with the genotype AF_8 (*Populus generosa* x *P. trichocarpa*) and one plot with the genotype AF_2 (*P. deltoides* x *P. nigra*) were examined. Here, twenty soil samples per plot were collected in 2014 with a vertical probe at 30 cm depth. We assumed that the chemical composition of the soil 30 cm upper layer as representative of the bulk of soil-plant interaction. We also considered that this soil layer was in a quasi-steady equilibrium, under the overall context of the soil dynamics, thereby excluding the litterfall component, which in SRC areas can be regarded as under a transient condition of continuous changes. In Lochristi, eight plots cultivated with four genotypes [Grimminge (G; *P. deltoides x (P. trichocarpa x P. deltoides)*), Skado (S; *P. trichocarpa x P. maximowiczii*), Wolterson (W; *P. nigra*), and Bakan (B; *P. trichocarpa x P. maximowiczii*)] on two previous land uses were examined. The two previous land uses were agricultural land (postfix Agr) and pasture land (postfix Pas) resulting in eight combinations (G_Agr, S_Agr, W_Agr, B_Agr, G_Pas, S_Pas, W_Pas and B_Pas). In Lochristi, 10 soil samples per plot were sampled in 2013, also with a vertical probe at 30 cm depth. For this study woody biomass samples were obtained in the form of wood chips for each genotype after harvesting both SRC sites in 2014 [33,34].

2.2. Soil and woody biomass characterization

The soil samples were chemically analysed according to the methodologies described in Ref. [35]. In brief, the soil extractable P and K were determined using the Egner-Riehm method, followed by flame atomic emission (for P) and absorption (for K) spectrometry. The soil extractable Ca, Mg and Na were determined with a 1 M solution of ammonium acetate (pH = 7), followed by atomic absorption spectrometry. To determine the organic C content, a soil solution was enriched with potassium dichromate ($K_2Cr_2O_7$) and concentrated sulphuric acid (H_2SO_4) to first obtain the organic matter content by UV-Vis spectrophotometry. The soil organic C content was then obtained by multiplying the organic matter content by 0.58 [35]. Finally, soil pH was determined by potentiometry on an aqueous soil solution.

The woody biomass samples were characterised in terms of HHV, LHV, proximate and ultimate analyses following the standard procedures ASTM-E-870, EN 14918 and EN 14775 as well as in terms of ash composition using X-ray fluorescence spectroscopy.

To relate the soil and the woody biomass characteristics, a database with 18 cases and six common variables was constructed. The six common soil and woody biomass chemical variables were the concentrations of P_2O_5, K_2O, Mg, Ca, Na and C. Six out of the 18 cases were derived from the Santarém plots: three cases corresponding to woody biomass from one plot planted with clone AF_2 (b_AF_2) and two plots planted with AF8 (b_AF_{8b} and b_AF_{8m}) and three cases corresponding to soils in the same plots (s_AF_2, s_AF_{8b} and s_AF_{8m}). From the remaining 12 cases, four were linked to the woody biomass of the four studied genotypes planted in Lochristi: Grimminge (b_G), Skado (b_S), Wolterson (b_W), and Bakan (b_B). The last eight cases were linked to the soil corresponding to the genotypes planted in Lochristi, taking into consideration the previous land use of the SRC: s_G_Agr, s_S_Agr, s_W_Agr, s_B_Agr, s_G_Pas, s_S_Pas, s_W_Pas and s_B_Pas.

For plot comparisons a matrix with 11 cases was considered, which were the three plots in Santarém (AF_2, AF_{8b} and AF_{8m}) and the eight plots in Lochristi (G_Agr, S_Agr, W_Agr, B_Agr, G_Pas, S_Pas, W_Pas and B_Pas). This matrix had 23 variables corresponding to the whole set of physical and chemical variables of the soil and of the woody biomass. There were six chemical variables common to the soil and the woody biomass (prefixes s and b, respectively): s_C, b_C, s_Ca, b_Ca, s_Na, b_Na, s_Mg, b_Mg, s_K, b_K, s_P_2O_5 and b_P_2O_5. One variable was associated exclusively with the soil (s_pH) and 10 chemical variables were associated exclusively with the woody biomass: HHV, LHV, volatile matter (Vol), fixed carbon (FC), b_Al, b_Si, b_SO_3, b_Fe, b_ZnO and b_Cl.

For woody biomass comparisons, a matrix was considered with seven cases related with the three plots in Santarém and with four plots in Lochristi. This matrix had 16 variables, namely: b_P_2O_5, b_K_2O, b_Mg, b_Ca, b_Na, b_C, b_Al_2O_3, b_SiO_2, b_Fe_2SO_3, b_SO_3, b_ZnO, b_Cl, HHV, LHV, Vol and FC.

2.3. Statistical analysis

The soil and woody biomass data were grouped into three matrix databases. Exploratory and analytical statistics were performed with multivariate techniques consisting of: i) correlation analyses; ii) PCAs; iii) factorial analyses; iv) hierarchical clustering analysis by the unweighted pair group method with arithmetic mean (UPGMA); and v) the construction of a minimum length spanning tree (MST) and linear regression through partial least squares (PLS). The clustering analysis and the MST allowed an evaluation of the homogeneity of plots and biomasses in both sites through the calculated values of the Euclidian distances shown in the phenograms and in projections of the MSTs on the planes of the two principal components of the databases. The calculations were performed with packages Statistica, version 6 Statsoft, NTSYSpc version 2.1 (Exeter software) and PROC PLS v9.4 (SAS Institute) [36]. All multivariate analyses were made considering standardized variables with nil mean and unit variance. From the UPGMA calculations, the cophenetic correlation coefficients (CCC) were obtained. A correlation matrix of the CCC's indicated the distortion in the Euclidean distances between the data points caused by the clustering of these points.

The evaluation of PLS regressions was done through R^2 values and one-a-time cross validation, which was implemented to choose the number of extracted factors in such a way that the predicted residual sum of squares (PRESS statistic) was minimized. The results of the multivariate analyses enabled using a lower number of variables to adequately parameterize the datasets and distinguish the differences between the plots and the woody biomass cases.

3. Results and discussion

3.1. Comparative analysis of soil and woody biomass

Overall, biomass results for proximate and ultimate analyses, ash composition, HHV and LHV were within the reported ranges for poplar [14,28,37]. The concentrations of P_2O_5, K_2O, Mg, Ca, Na and organic C were higher in the woody biomass than in the soil at all plots (Table 1). The average soil nutrient concentrations and organic matter in Lochristi were higher than in Santarém and the woody biomass concentrations of P_2O_5, K_2O, Mg and Na were higher in the Santarém plots than in the Lochristi plots. The woody biomass Ca concentration was higher in Lochristi than in Santarém. Considering the previous land use of the Lochristi plots, the data suggest that the P_2O_5 and K_2O concentrations in the soil were higher in the plots which were previously used as agricultural land than those that were previous pasture land. The average soil pH in the Santarém plots (6.3) was higher than in the Lochristi plots (5.2). The concentrations of the woody biomass ash components (Al_2O_3, SiO_2, Fe_2SO_3, SO_3, ZnO and Cl) were also higher in the Santarém plots than in the Lochristi plots. The Vol in the biomass from the Santarém plots was higher than that in the Lochristi plots, in contrast with the FC.

The comparative multivariate analysis of the soil and biomass variables showed that C was significantly correlated to Ca (0.90), P_2O_5 to K_2O (0.94), and Mg to K_2O (0.97). In addition, P_2O_5 was significantly correlated (p values < 0.05) with the other five chemical elements. These correlations were 0.94 (K_2O), 0.87 (Ca), 0.78 (Na), 0.88 (C) and 0.87 (Mg).

Soils from all plots clustered among themselves (average Euclidean distance = 0.2), with two distinct subgroups for the Santarém soils and for the Lochristi soils (Fig. 1). Biomass from all plots was also clustered together, although average Euclidean distances were higher (0.7) as compared to soil clusters. The only exception was bAF_2, which was separated from all other soil and biomass cases. Lochristi biomass cases were more homogeneous than Santarém biomass cases (average Euclidean distances of respectively 0.39 and 0.92). Projection of the MST in the plane of the two main principal components confirmed that a relatively similar soil chemical composition was associated with a much higher heterogeneous biomass chemical composition.

The factorial analysis showed that two factors were enough to explain 94% of the total variance. The first factor was related to P_2O_5, K_2O and Mg (respectively 0.77, 0.91 and 0.90) while the second factor was related to C and Ca (respectively 0.90 and 0.87). The database was adequately parameterized by the factorial analysis (the average value of the specific factors was -0.001 ± 0.04). These results reflect the prominent role of P_2O_5, K_2O and Mg in the dynamics of chemical properties of soil and biomass in both sites.

3.2. Comparative analysis of plots

As mentioned above, the database for the second multivariate analysis included 11 cases and 23 variables. Soil and biomass variables were highly correlated, as the variables s_P_2O_5, s_Mg, s_Ca, s_C, s_pH, b_P_2O_5, b_K_2O, b_Mg, b_Al_2O_3, b_SO_3, b_Cl, HHV, LHV and Vol were all significantly correlated (correlation coefficient > 0.6) with at least seven other soil and biomass variables.

The PCA showed that three eigenvalues were responsible for 81% of the variability. The factorial analysis with the varimax criterion showed that four factors explained 90% of the variance. The specific factors had a very low average (0.0064 ± 0.007), showing that the factorial analysis extracted most of the correlations of the dataset. The first factor (55% of the variance) corresponded to (i.e. loadings lower than -0.5 or higher than 0.5) s_P_2O_5, s_Mg, s_Ca, s_Na, s_C, s_pH, b_P_2O_5, b_K_2O, b_C, b_Al_2O_3, b_SO_3, b_Cl, LHV, HHV and Vol. The second factor (16% of the variance) corresponded to b_P_2O_5, b_K_2O, b_Mg, b_Al_2O_3, b_SiO_2, b_Fe_2SO_3, b_SO_3, b_ZnO and Vol. The third factor (10% of the variance) corresponded to b_C and FC. The fourth factor (9.5% of the variance) corresponded to s_C, s_pH, b_Ca, b_Na and b_ZnO. Overall, the first two factors confirm the correlations discussed above, pointing out the distinct role of the variables s_P_2O_5, s_Mg, s_Ca, s_C, s_pH, b_Cl, LHV, HHV, b_SO_3, b_Mg, b_K_2O, b_Al_2O_3, Vol and b_P_2O_5 in the dynamics of soil and biomass in the 11 plots.

There was a high cophenetic correlation coefficient (0.97) between the 11 plots and a clear distinction between the Santarém site (average Euclidean distance = 1.46) and the Lochristi site (average Euclidean distance 0.68; Fig. 2). Lochristi genotypes were more homogeneous (maximum Euclidean distance = 1.1) than Santarém genotypes (minimum Euclidean distance = 1.2), regardless of former land use. In Lochristi there was a closer relationship among genotypes than between previous land use (Fig. 2). This confirms earlier findings that showed the previous land use had no significant impact on overall productivity [33].

A projection of the MST for the database with 11 plot cases in the plane of the two main principal components was made, with the variable coordinates in arrows (Fig. 3). This MST: i) confirmed the dissimilarity of the Santarém and Lochristi plots; ii) identified the positive and negative correlations between the variables and the

Table 1
Soil and woody biomass data from the 11 plots in Santarém and Lochristi. Prefixes s and b refer to soil and woody biomass, respectively. Postfixes Agr and Pas refer to the previous land use of the plots in Lochristi: agricultural and pasture land, respectively. G, S, W, B, AF_2 and AF_8 refer to genotypes Grimminge, Skado, Wolterson, Bakan, AF_2, AF_{8b} and AF_{8m} (postfixes b and m refer to two plots with clone AF8 in Santarém).

	s_P_2O_5 (ppm)	s_K_2O (ppm)	s_Mg (ppm)	s_Ca (ppm)	s_Na (ppm)	s_C (%)	s_pH	b_P_2O_5 (ppm)	b_K_2O (ppm)	b_Mg (ppm)	b_Ca (ppm)	b_Na (ppm)	b_C (%)	b_Al_2O_3 (ppm)
G_Agr	285.0	160.0	115.0	892.5	10.0	1.2	5.2	952	328	496.8	3840	41.6	49.7	64
S_Agr	290.0	190.0	117.5	853.8	10.5	1.1	5.3	1215	576	553.5	4003	46.8	48.4	80
W_Agr	177.5	110.0	132.5	1113	9.8	1.2	5.3	1364	737	609.4	5192	31.9	48.3	55
B_Agr	312.5	155.0	127.5	1048	30.0	1.4	5.6	1136	408	501.6	3600	56.0	48.9	56
G_Pas	256.3	122.5	131.3	1051	9.6	1.3	5.3	952	328	496.8	3840	41.6	49.7	64
S_Pas	213.8	107.5	120.0	838.8	11.4	1.2	5.1	1215	576	553.5	4003	46.8	48.4	80
W_Pas	165.0	77.5	117.5	675.0	14.8	1.6	4.7	1364	737	609.4	5192	31.9	48.3	55
B_Pas	200.0	62.5	157.5	1303	13.0	1.3	5.6	1136	408	501.6	3600	56.0	48.9	56
AF_2	200.0	164.0	87.0	436.9	6.9	1.0	5.8	2470	1995	2578	5174	77.9	49.1	197
AF_{8b}	61.0	188.0	102.0	513.0	9.2	0.7	6.2	1496	944	810.4	2081	68.0	46.7	214
AF_{8m}	80.0	99.0	54.0	346.7	2.3	0.4	7.0	2695	1353	1101	2696	52.8	49.0	138

	b_SiO_2 (ppm)	b_Fe_2SO_3 (ppm)	b_SO_3 (ppm)	b_ZnO (ppm)	b_Cl (ppm)	HHV (MJ kg^{-1})	LHV (MJ kg^{-1})	Vol (%)	FC (%)
G_Agr	120.0	48.0	128.0	8.0	0.0	17.7	16.4	48.5	14.4
S_Agr	162.0	54.0	153.0	27.0	0.0	17.8	16.5	54.3	6.5
W_Agr	132.0	55.0	154.0	55.0	0.0	19.1	17.8	51.3	8.3
B_Agr	160.0	48.0	88.0	24.0	0.0	17.8	16.5	52.7	6.2
G_Pas	120.0	48.0	128.0	8.0	0.0	17.7	16.4	48.5	14.4
S_Pas	162.0	54.0	153.0	27.0	0.0	17.8	16.5	54.3	6.5
W_Pas	132.0	55.0	154.0	55.0	0.0	19.1	17.8	51.3	8.3
B_Pas	160.0	48.0	88.0	24.0	0.0	17.8	16.5	52.7	6.2
AF_2	1191	155.8	657.4	61.0	18.4	18.9	17.5	82.7	4.2
AF_{8b}	276.8	46.2	494.4	35.0	40.8	20.5	19.2	84.7	2.9
AF_{8m}	376.2	59.3	485.1	30.6	32.8	20.3	18.9	76.7	11.0

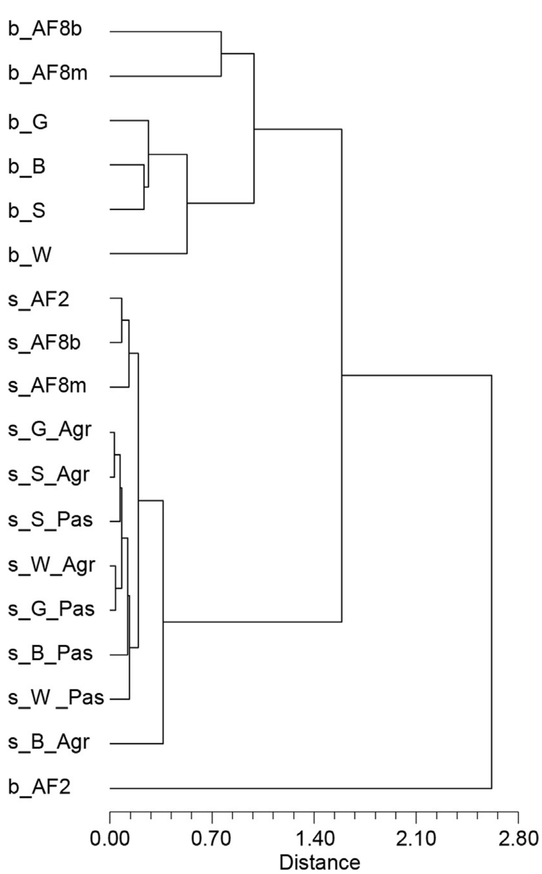

Fig. 1. Phenogram for the 18 soil and biomass cases. Prefixes s and b refer to soil and woody biomass, respectively. Postfixes Agr and Pas refer to the previous land use of the plots in Lochristi: agricultural and pasture land, respectively. G, S, W, B, AF_2 and AF_8 refer to genotypes Grimminge, Skado, Wolterson, Bakan, AF_2, AF_{8b} and AF_{8m} (postfixes b and m refer to two plots with clone AF8 in Santarém).

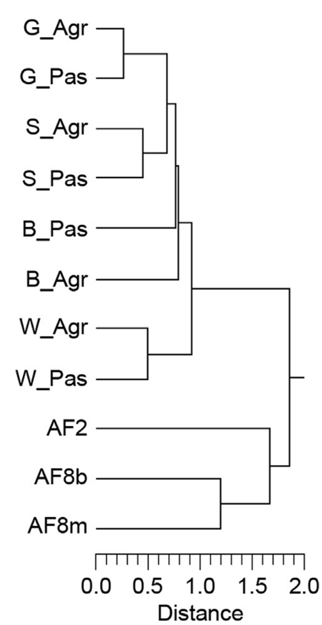

Fig. 2. Phenogram for the 11 plot cases. Postfixes Agr and Pas refer to the previous land use of the plots in Lochristi: agricultural and pasture land, respectively. G, S, W, B, AF_2 and AF_8 refer to genotypes Grimminge, Skado, Wolterson, Bakan, AF_2, AF_{8b} and AF_{8m} (postfixes b and m refer to two plots with clone AF8 in Santarém).

plots; and iii) showed the most influential variables for the HHV and thereby the potential as a fuel.

The six variables selected as independent variables, to construct a PLS regression for HHV, were sP_2O_5, sCa, sC, bK_2O, bSO_3 and Vol, according to the results of the correlation and factorial analyses described above. The empirical equation had an R^2 of 0.89 and a minimal PRESS statistic of 0.75 (Eqn. (1)).

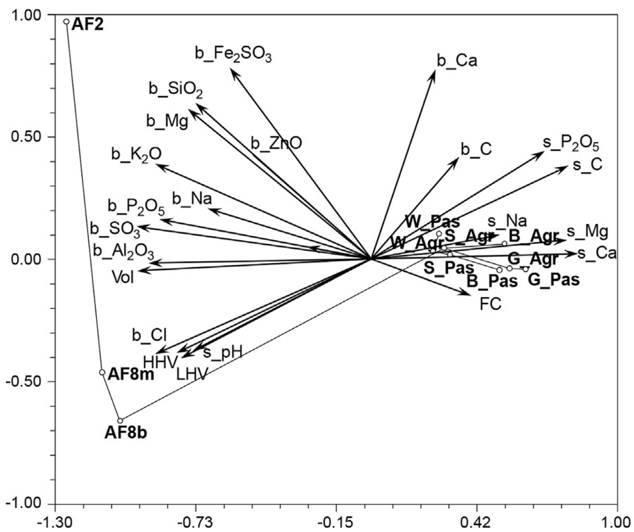

Fig. 3. Projection of the minimum length spanning tree of the 23 variables corresponding to 11 plot cases on the plane of the two principal components, with the variable coordinates in arrows. Cases are in bold. Prefixes s and b refer to soil and woody biomass, respectively. Postfixes Agr and Pas refer to the previous land use of the plots in Lochristi: agricultural and pasture land, respectively. G, S, W, B, AF_2 and AF_8 refer to genotypes Grimminge, Skado, Wolterson, Bakan, AF_2, AF_{8b} and AF_{8m} (postfixes b and m refer to two plots with clone AF8 in Santarém).

$$HHV = -0.65\ s\_P_2O_5 - 0.12\ s\_Ca - 0.18\ s\_C - 0.05\ b\_K_2O + 0.01\ b\_SO_3 + 0.11 Vol \quad (1)$$

To our knowledge, no information is available about possible relations between HHV and soil and biomass. The main advantage of Eqn. (1) is that the PLS technique with six independent variables can avoid collinearity problems, typical of ordinary least squares (as mentioned in the Introduction).

3.3. Comparative analysis of biomass

A third correlation matrix considering only biomass from Lochristi and Santarém was established with seven cases (b_G, b_S, b_W, b_B, b_AF_2, b_AF_{8b} and b_AF_{8m}) and 16 variables. The variables b_P_2O_5, b_K_2O, b_Mg, b_Al_2O_3, b_SiO_2, b_Fe_2SO_3, b_SO_3, b_Cl, HHV and Vol were significantly and positively correlated with at least one variable ($p < 0.05$ and correlation coefficient > 0.9). From the set of 16 variables b_P_2O_5 (4), b_K_2O (7), b_Mg (5), b_Na (4), b_Al_2O_3 (4), b_SiO_2 (5), b_SO_3 (8), b_Cl (5) and Vol (8) presented correlations higher than 0.75 with at least four variables. The number of these variables is in curved brackets. The variable bCl showed high significant correlations with HHV (0.91) and Vol (0.92).

The principal component and factorial analyses showed that two eigenvalues and three factors accounted for respectively 82% and 91% of the variance of the dataset. The specific factors were very low, as in the plot cases above, averaging 0.0002 ± 0.0007. For the first factor, accounting for 58% of the variance, the higher positive loadings were related to b_P_2O_5 (0.68), b_K_2O (0.86), b_Mg (0.96), b_Na (0.8), b_Al_2O_3 (0.65), b_SiO_2 (0.98), b_Fe_2SO_3 (0.94), b_SO_3 (0.78) and Vol (0.64). For the second factor, accounting for 24% of the variance, the variables with higher loadings were b_P_2O_5 (0.55), b_Ca (−0.56), b_C (−0.55), b_Al_2O_3 (0.62), b_SO_3 (0.61), b_Cl (0.88), LHV (0.98), HHV (0.98) and Vol (0.69). For the third factor, accounting for 9.6% of the variance, the variables with higher loading were b_Na (0.45), b_C (−0.76) and FC (−0.94). From the correlations and the loadings of the first and second factors it can be concluded that the variables b_P_2O_5, b_K_2O, b_Mg, b_SiO_2, b_Al_2O_3, b_Cl, b_Fe_2SO_3, b_SO_3 and Vol played a major role in the dynamics of the 16 variables and 7 woody biomass cases of this dataset.

The cophenetic correlation coefficient obtained for the seven woody biomass cases was very high (0.93). The phenogram (not shown) confirmed the higher homogeneity of the Lochristi woody biomass of genotypes comparatively to those of Santarém. The MST confirmed these tendencies and resulted in average Euclidean distances of 0.71 and 1.25 for the Lochristi and Santarém woody biomass samples, respectively (Fig. 4). This approach of cluster analysis, with calculation of a cophenetic correlation coefficient, for the characterization of calorific value and ultimate analysis of woody and non-woody biomass (as performed in Ref. [29]), allowed obtaining a cophenetic correlation coefficient of 0.91 and clusters of biomass types with different burning characteristics.

The PLS regression with this database was made to obtain relationships between the HHV and the woody biomass variables as independent variables (Eqn. (2); $R^2 = 0.84$ and minimal PRESS statistic = 1.069). For the regression, five woody biomass variables (b_K_2O, b_Mg, b_Fe_2SO_3, b_SO_3 and Vol) were selected, according to the results of multivariate analysis shown above.

$$HHV = 0.19\ b\_K_2O - 0.23\ b\_Mg - 0.51\ b\_Fe_2SO_3 + 0.45\ b\_SO_3 + 0.64\ Vol \quad (2)$$

The main advantage of Eqn. (2) is that, similar to Eqn. (1), the PLS technique could avoid collinearity problems between the five independent variables [30,31].

3.4. Analysis of reduced datasets of plot and woody biomass cases

Two further multivariate analyses were repeated with a reduced number of variables in the plot and woody biomass datasets in order to explore the possibility of using a reduced number of

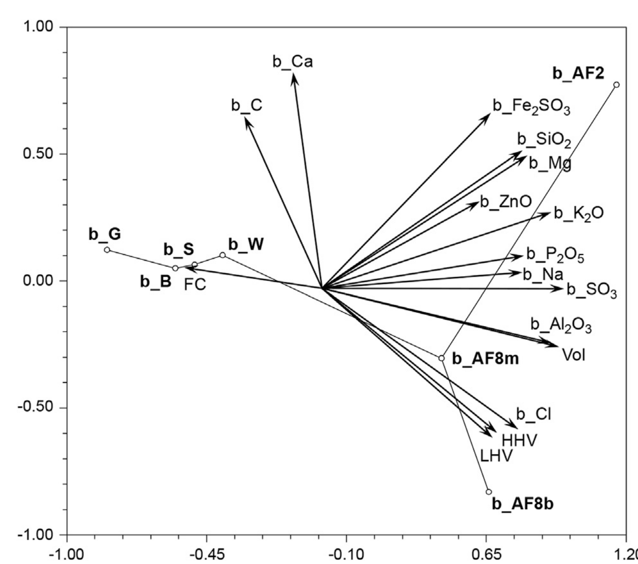

Fig. 4. Projection of the minimum length spanning tree of the 16 variables corresponding to 7 woody biomass cases on the plane of the two principal components, with the variable coordinates in arrows. Cases are in bold. Prefix b refer to woody biomass. G, S, W, B, AF_2 and AF_8 refer to genotypes Grimminge, Skado, Wolterson, Bakan, AF_2, AF_{8b} and AF_{8m} (postfixes b and m refer to two plots with clone AF8 in Santarém).

variables to distinguish the plot and the woody biomass cases. This reduced number of variables was obtained taking the above multivariate results in account. The new datasets for the plot and the woody biomass cases included only eight (s_P_2O_5, s_Ca, s_C, b_K_2O, b_Al_2O_3, b_SO_3, b_Cl and Vol) and six variables (b_P_2O_5, b_K_2O, b_Al_2O_3, b_Fe_2SO_3, b_SO_3, and Vol), respectively. For the new plot cases database, the cophenetic correlation coefficient was 0.98 and the average MST distances were 0.52 for Lochristi and 1.19 for Santarém. The projection of the MST for the reduced plot database allowed discriminating between the 11 plots of Santarém and Lochristi (Fig. 5). The specific factors of the factorial analysis were very low (0.0003), indicating that a factorial analysis extracted most of the correlations from the dataset.

These results indicated that the reduced dataset was convenient to explain the differences between the plots at both sites. The validity of the reduced database with six variables for the woody biomass cases was also validated: the new cophenetic correlation coefficient was 0.9 and the projection of the MST confirmed the above analysis (Fig. 6). The average MST distances were 0.49 and 1.14 for the Lochristi and Santarém woody biomass of genotypes, respectively. The specific factors of the dataset were very low (0.0002).

4. Conclusions

Multivariate analyses including correlation, principal components, factorial and clustering analysis, projection of minimum spanning trees in the planes of the two principal components and partial least squares modelling allowed to distinguish sites and woody biomass samples from poplar SRC plantations in Santarém

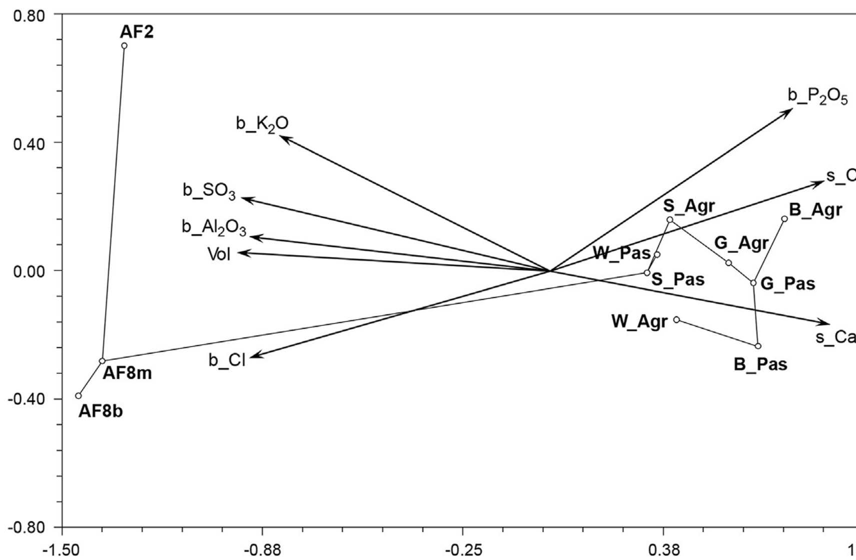

Fig. 5. Projection of the minimum length spanning tree of the reduced plot database with 8 variables on the plane of the two principal components with the variable coordinates in arrows. Cases are in bold. Prefixes s and b refer to soil and woody biomass, respectively. Postfixes Agr and Pas refer to the previous land use of the plots in Lochristi: agricultural and pasture land, respectively. G, S, W, B, AF_2 and AF_8 refer to genotypes Grimminge, Skado, Wolterson, Bakan, AF_2, AF_{8b} and AF_{8m} (postfixes b and m refer to two plots with clone AF8 in Santarém).

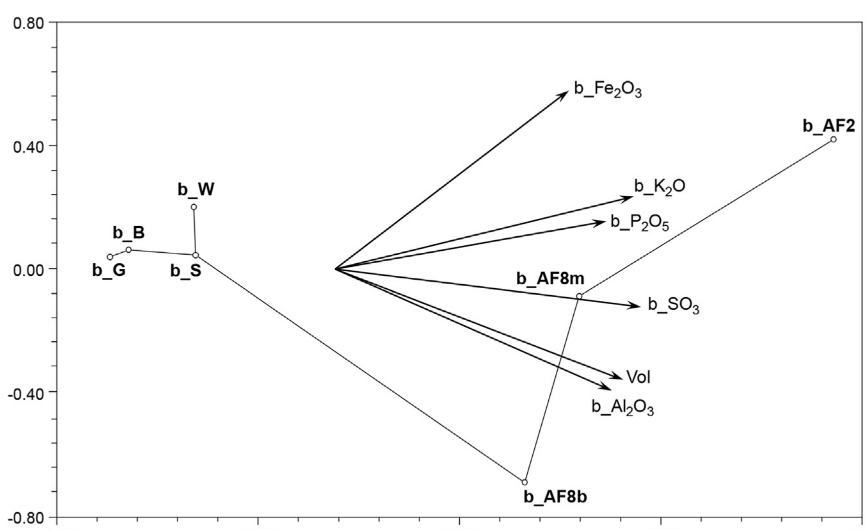

Fig. 6. Projection of the minimum length spanning tree of the reduced woody biomass database with 6 variables on the plane of the two principal components, with the variable coordinates in arrows. Cases are in bold. Prefix b refer to woody biomass. G, S, W, B, AF_2 and AF_8 refer to genotypes Grimminge, Skado, Wolterson, Bakan, AF_2, AF_{8b} and AF_{8m} (postfixes b and m refer to two plots with clone AF8 in Santarém).

(Portugal) and Lochristi (Belgium). The homogeneity between sites and woody biomass samples could also be evaluated with a reduction of the number of variables from 23 to 8 and from 16 to 6 in the site and biomass datasets, respectively. The Lochristi plots and woody biomass fuels (four poplar genotypes on two previous land uses) were more homogeneous than the Santarém plots and woody biomass fuels (two poplar genotypes). Significant correlations between soil and woody biomass variables enabled to evaluate the influence of these variables on the properties of the woody biomass samples, such as the HHV and the volatile matter content. The HHV, in particular, showed significant correlations with five soil variables. Two equations from site and biomass datasets, using PLS modelling, were obtained relating the HHV of the woody biomass with the soil and biomass variables. The results showed the usefulness of multivariate approach techniques for disentangling the relationships between soil and woody biomass, which has implications for the future establishment and management of SRC plantations. The results suggest that the annual monitoring of soil and biomass in SRC systems should be performed for optimizing productivity and woody biomass quality as a fuel. These objectives should thereby be achieved through a planning of management activities related to nutrient supply and nutrient recycling, as fertilisation or cutting the excessive shoots per stump, thus reducing competition for nutrients.

Further research is needed to obtain and to consolidate our knowledge on agro-forestry systems that are crucial for a sustainable and carbon neutral global economy.

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