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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,