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Chip Quality as a Function of Harvesting Methodology

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The study aimed to evaluate the aboveground dry biomass production and the quality of fresh and dried chips obtained by eight different species grown under SRC culture and subjected to two harvesting systems and chipping devices.
The present study was part of a long project including different species and management regime of a SRC plantation, which was established in 2007 on a level soil at the Improsta experimental farm (Eboli, Salerno, Italy).
In 2015, It was realized a comparative test chipping eight different species grown under SRC system: Fraxinus oxyphylla, Robinia pseudoacacia, Salix alba, Populus nigra (Limatola) and four hybrid genotypes of Populus x euroamericana (Grimminge, Vesten, Hoogvorst, Muur), harvested at the end of the first three years rotation coppice (2012-2014).
The trees were chipped both fresh and dried. The fresh biomass was harvested and chipped in a single phase by a self-propelled forage harvester Claas Jaguar 880 (nominal power of 353 kW), equipped with GBE biomass head for trees cutting and harvester feeding. The dried biomass was chipped by a forestry wood disk chipper Farmi Forest CH 260, after two months of storage in the field.
The plantation mean of the standing aboveground dry biomass was greater for P. nigra Limatola, followed by F. oxyphylla. As consequences, they showed respectively a high mean annual increment of aboveground dry biomass of 14.38 and 10.16 t ha^{-1} $year^{-1}$. The first coppice rotation dry biomass yield was not significantly different for Hoogvorst and Vesten. In contrast to the biometric attributes clone Muur showed a low aboveground dry biomass production, followed by Grimminge and S. alba with a significantly lower production.
Moisture content of the fresh biomass ranged between 42.59 % and 56.84 % for black locust and willow, respectively. The dried biomass ranged, instead, between 17.32 % for willow and 36.80 % for Populus nigra. The average reduction of moisture content after storage was 43.97 % with the highest and lowest rate of dehydration for willow (69.53 %) and poplar Vesten (28.70 %).
Concerning the particle size distribution, the presence of large chips (63-45 mm) and oversized (> 63 mm) were extremely limited for the fresh chips, while it is considerably higher for the dried chips. Fractions ranging from 45 to 3 mm were the most represented for all species and treatment, accounting between 84.09 % and 90.65 % for the fresh chips, and 74.15 % and 85.68 % for the dried chips. The comminution carried out with the disk chipper on dried biomass always leads to a decrease in the percentage of accept (45-3 mm fractions) respect to the same fresh species chipped by drum chipper.

1. Introduction

The increasing global energy demand, the increasing prices and limited availability of fossil fuels, the environmental impacts and the need to reduce emissions of greenhouse gases are some of the issues that are driving the growth of biomass as a source of renewable and sustainable energy (Lo Monaco et al., 2011; Koseki, 2011). Fast growing trees planted as Short Rotation Coppice (SRC) are an important source of lignocellulosic biomass (Broeckx et al., 2012), due to their high yields, good combustion quality, ecological and social benefits (Groscurth et al., 2000; Hauk et al., 2014) and relatively low production costs (Kauter et al., 2003).

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Besides poplar (*populus* spp.), other species commonly used for SRC plantation are Salix Alba, Fraxinus augustifolia, Eucalyptus occidentalis and Robinia pseudoacacia (Civitarese et al., 2015b; Facciotto et al., 2007). Currently, chipped lignocellulosic biomass are used in power stations, combined heat and power plants (CHP), biogas stations, large heating plants and small combustion units (Abdallah et al., 2011; Verani et al., 2015). The quality of the wood chips is strictly correlated with the tree species considered, the harvesting system and the chipping device, mainly drum and disc chipper (Civitarese et al., 2015a).
Two different harvesting systems are currently available: single pass cut and chip, and whole stem (Mitchell and Angus-Hankin, 1996).
The single pass cuts and chips the fresh biomass (moisture content 55-60 %) by using large size forage harvesters.
The whole stem implies the use of forest chippers an intermediate stocking period between cutting (first step) and chipping (second step) (Pari, 1999), favouring the natural drying of the biomass.
Many parameters characterize the quality of the biomass as the moisture content and the particles size distribution. Particles size distribution influences the storage behavior (Jirjis, 2005, Barontini et al., 2013), the handling properties (Nati et al., 2010; Spinelli et al., 2012) and the combustion efficiency (Wu et al., 2011). The moisture content has a great influence toward the heating value and the storage behavior. In 2015, the Department of Agriculture of the University of Naples Federico II and the Consiglio per la ricerca in agricoltura e l'analisi dell'economia agraria (Crea), carried out a comparative test chipping both fresh and dried eight different species grown under SRC system: Fraxinus oxyphylla, Robinia pseudoacacia, Salix alba, Populus nigra (Limatola) and four hybrid genotypes of Populus x euroamericana (Grimminge, Vesten, Hoogvorst, Muur), harvested at the end of the first three years rotation coppice (2012-2014).
The study aimed to evaluate the aboveground dry biomass production and the quality of fresh and dried chips by analysing their particle size distribution and the moisture content, obtained by height different species grown under SRC culture and subjected to two harvesting systems and chipping devices.

2. Materials and methods

The research was conducted at "Improsta" experimental farm, located in the rural area of the town Eboli, in Southern Italy (40°33'32.18''N; 14°58'15.6''E; 20 m above sea level).
The plantation was established in March 2007 and it includes nineteen genotypes, on a total surface of 4.6 ha (6667 plants per ha). Overall, the following eight genotypes with 9 years of roots and 3 years of stems (R9S3) were selected for the purpose of this study: Muur and Vesten (P. deltoides x P. nigra), Hoogvorst (P. thichocarpa x P. deltoides) Grimminge (P. deltoides x P. thichocarpa x P. deltoides), Limatola (P. nigra), Salix alba, Robinia pseudoacacia and Fraxinus oxyphylla.
The aboveground dry weight of coppice stand was assessed by measuring stool volume and wood basic density. The volume (V_s, m^3) of individual standing stool was estimated with Eq(1) applying the trees felled method (La Marca, 2004; van Laar and Akça, 2007)

$$V_s = g \cdot h_g \cdot f \tag{1}$$

where g (m^2) is the stool basal area, h_g (m) is the mean regressed height of quadratic mean diameter and f is the non-dimensional absolute form factor (van Laar and Akça, 2007). Wood basic density was calculated on three wood samples collected along the stem of the felled shoots. Finally, the respective yields were evaluated multiplying the mass of the stool by the effective density of the stool for each monoclonal plot.
Differences in stand biometric attributes among studied species and varieties were analyzed by applying a non-parametric Kruskal – Wallis test for independent samples (Analysis of variance by ranks), followed by a non-parametric multiple comparison Dunn test for unequal sample size (Zar, 2010). All the above-mentioned statistical analysis were carrying out considering statically significant a p-value less than 0.05. The Kruskal-Wallis test was done on the data with the kruskal.test function of the native 'stats' package, while the Dunn test was performed with the posthoc.kruskal.dunn.test function of the PMCMR package (Pholert, 2014).
The fresh biomass was harvested and chipped in a single phase in April, utilizing a self-propelled forage harvester Claas Jaguar 880 (nominal power of 353 kW), equipped with the GBE biomass head. The dried biomass was chipped, at the end of May, with a Farmi Forest CH 260 forestry chipper. Ten trees per each species were cut manually in April, simultaneously with the single-phase harvesting, and stocked in the field for 56 days before comminution.
Fresh and dried chips produced respectively by Claas Jaguar forage harvester and Farmi Forest wood disk chipper were collected and examined in order to assess the moisture content and the particle size distribution, according to the standardized characterization procedures EN 14774-2 and EN 17225-4. Moisture content was determined by collecting five samples of about 500 g for each specie and treatment (80 samples for a

total mass of 40 kg approximately). The samples, transported to the laboratory in non-breathable bags, were dried in a forced air convection oven at 103 ± 2 °C, until reaching a constant weight.
Five samples of 8 L for each species and treatment were collected for the particle size analysis (80 samples for a total volume of 640 liters). Sub-samples of 2.5 - 3 L were used for the sieving in order to avoid overloading of the mechanical sieve shaker. Four sieves (normalized in accordance with ISO 3310-1) were used in order to separate the five following chip length classes: 100–63 mm, 63–45 mm, 45–16 mm, 16–3.15 mm and <3.15 mm. For a better understanding, the fractions were grouped into four functional classes: oversize particles (>63 mm), large chips (63 – 45 mm) accepts (45 – 3.15 mm) and undersize particles (<3.15 mm).
The 50–50 MANOVA was used for the particle size distribution analysis. The moisture content were analysed using ANOVA and Duncan's post hoc test. All statistics were computed by using Past, Statistics and R software (R Core Team, 2014).

3. Results

3.1 Yield and size characteristics of the crops

The genotypic means of aboveground dry biomass production, taken at the end of the first rotation coppice, are exhibited in Table 1. The plantation mean of the standing aboveground dry biomass was greater for Limatola, followed by F. oxyphylla. As a consequence, they showed high mean values for annual aboveground dry biomass increments of 14.38 and 10.16 Mg ha^{-1} y^{-1}, respectively. The first coppice rotation dry biomass yield was not significantly different for Hoogvorst and Vesten. Clone Muur showed a low aboveground dry biomass production, followed by Grimminge and S. alba with a significantly lower production. Additionally, R. pseudoacacia has showed a biomass production not significantly different from hybrid poplar clones.

3.2 Moisture content

Moisture content of the fresh biomass ranged between 42.59 % (± 1.23) and 56.84 % (± 0.56) for black locust and white willow, respectively. The dried biomass ranged, instead, between 17.32 % (± 0.67) for willow and 36.80 % (± 1.34) for Limatola. The average reduction of moisture content after storage was 43.97 % (± 13.25) with the highest and lowest rate of dehydration for willow (69.53 % ± 1.19) and poplar Vesten (28.70 % ± 2.13). Welch F test showed the existence of statistically significant differences in moisture content among the species, both for fresh and dried treatment.
For the fresh biomass, Duncan post hoc revealed significant differences among these species or groups of species: black locust; Vesten, Grimminge, Hoogvorst, Muur, Limatola, narrow-leaved ash and white willow (Figure 1).
For the dried biomass, Duncan post hoc test did not reveal significant differences among poplar hybrid clones Muur, Vesten and black poplar Limatola. Significant differences there were among the mentioned group of species and all other species considered (Figure 1).

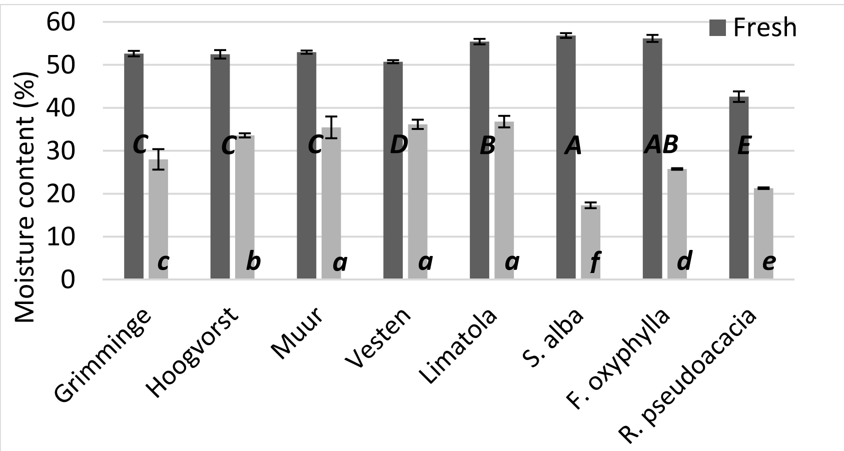

Figure 1: Moisture content (Mean ± SD) of the species considered, both fresh and after storage. Welch F test of fresh biomass: df: 13.53, F: 104.2, p: 0.000. Welch F test of dried biomass: df: 13.14, F: 555, p: 0.000*. Duncan's post hoc test: different letters indicate statistically significant differences at the 5 % level.*

*Table 1: Mean dry biomass yields at the end of the first three-year coppice rotation (2012-2014). In brackets are showed first standard deviation. Values sharing the same letters are statistically not different following post-hoc Dunn test (*Kruskall-wallis test: KW=24.73, df=7, p-value<0.01).*

Species	Genotype	Yield* (Mg ha^{-1})
P. x euroamericana	Grimminge	17.41 (5.67) *cd*
	Hoogvorst	25.45 (11.06) *bc*
	Muur	20.64 (6.67) *c*
	Vesten	25.79 (10.55) *bc*
P. nigra	Limatola	43.16 (13.11) *a*
S. alba	-	14.92 (2.17) *d*
F. angustifolia	-	30.50 (14.56) *b*
R. pseudoacacia	-	19.02 (4.79) *c*

3.3 Particle size distributions

Concerning the particle size distribution (Table 2), it is apparent that the presence of large chips (63-45 mm) and oversized (> 63 mm) were extremely limited for the fresh chips, while it is considerably higher for the dried chips. The undersize particles, instead, were very high both for fresh and dried chips ranging from an average value of 11 % and 18 % respectively for fresh and dried chip particles. Accepts chips fraction was the most represented for all species and treatment, accounting over 84 % and 75 % for the fresh and dried chip respectively. The results of 50–50 MANOVA (Table 3) showed a statistically significant difference of the particle size distributions among the species, the harvesting systems and their interaction (p<0.001).

Table 2: Percentage particle size distribution of the fresh and dried wood chips. Data were grouped in four functional classes: oversize particles (>63 mm), large chips (63–45 mm) accepts (45–3.15 mm) and undersize particles (<3.15 mm).

Species	Fresh				Dried			
	>63	63-45	45-3	<3	> 63	63-45	45-3	<3
P. x eur. Grimminge	1.27	0.47	87.23	11.03	6.61	2.20	75.14	16.05
P. x eur. Hoogvorst	0.56	0.11	89.44	9.89	2.40	0.43	77.71	19.46
P. x eur. Muur	0.56	0.21	89.42	9.81	3.35	1.05	79.97	15.63
P. x eur. Vesten	0.40	0.31	90.60	8.70	1.25	0.94	76.18	21.63
P. nigra Limatola	0.36	0.00	88.83	10.81	2.93	0.89	82.84	13.34
S. alba	0.12	0.28	84.09	15.51	2.90	1.21	77.39	18.50
F. angustifolia	0.63	0.00	87.16	12.21	2.03	0.76	85.68	11.53
R. pseudoacacia	0.24	0.00	90.63	9.13	1.63	2.80	80.95	14.62

Table 3: Results from the 50–50 Manova (for each species and harvesting system n. = 20). DF: Degrees of Freedom; exVarSS: explained variances based on sums of squares; nPC: number of principal components used for testing; nBu: number of principal components used as buffer components; exVarPC: variance explained by nPC components; exVarBU: variance explained by (nPC+nBU) components; p-Value: the result from 50–50 MANOVA testing.

Source	DF	exVarSS	nPC	nBu	exVarPC	exVarBU	p-Value
Species	7	0.148618	3	1	1.000	1.000	<0.001
Harvesting system	1	0.374301	2	2	0.898	1.000	<0.001
Species* Harv. syst.	7	0.125616	3	1	1.000	1.000	<0.001
Error	64	0.351465	-	-	-	-	-

4. Conclusions

The yield of a biomass plantation is an important factor due its implications on economic and energetic sustainability of the supply chain. Several studies showed a high variability in biomass production of Short Rotation Coppice plantations. Usually it ranged between 3 - 4 Mg ha^{-1} y^{-1} and 15 – 20 Mg ha^{-1} y^{-1} of dry biomass (Dillen et al., 2007; Ceulemans and Deraedt, 1999; Facciotto et al., 2005; Mareschi et al., 2005;

Bergante et al., 2010; Vande Walle et al., 2007; Di Matteo et al., 2012), strongly related to management system of plantation (Njakou Djomo et al., 2015).

The aboveground dry biomass productions are included in the above-mentioned range with values between 4.97 Mg ha^{-1} y^{-1} and 14.38 Mg ha^{-1} y^{-1}, with an average productivity of 9 Mg ha^{-1} y^{-1}. In SRC water supply strongly determine biomass yield of plantation, especially in a low-inputs management system (Aylott et al., 2008; Hauk et al., 2014). Therefore, the different biomass yields exhibited by tested species are most probably due to different tolerance to water stress.

The wood species and the harvesting system affect the moisture content and the chip size. The average moisture contents of the trees chipped fresh and dried were 52.47 % and 29.30 % respectively, with significant differences even among the species of the same treatment. The particle size distribution analysis revealed that, independently from the species and the harvesting system, the most represented class size was 45 to 3 mm. Anyway, the comminution of the dried trees leads to a decrease of the chips quantity in this fraction and an increase of the larger size and oversize.

The results of this study underline the differences between various species and genotypes in terms of yield productivity and point out how the biomass quality can change as function of the treatment and the species. The large variability observed suggest the possibility to choose the best species or different species mix wood chips or different treatment in order to offer a better product in the commercial biomass marketing, improving the overall efficiency of biomass combustion process.

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