Energy production of poplar clones and their energy use efficiency

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Poplar clones "Robusta" and "I-214" (*Populus* × *euramericana)* are characterized by fast growth and high quality biomass production. In this investigation the calorific value of these clones was determined, and modeling of the calorific production of a whole poplar clone stands in relation to stand age and site index was performed. Eleven trees were sampled in four sites in the eastern and seven in the western part of Slovakia. Samples of bark, wood and small-wood with bark were excised from three points along the stem and from two parts of the crown. No significant differences were observed between clones with regard to either the biomass fraction or the excising location. The average calorific capacity of all biomass fractions was approximately 6.86-8.73 GJ m^{-3}, with the lowest bark values obtained for samples excised from the stem base. The mean annual calorific energy production for site index 20-40 was 320-380 GJ ha^{-1} y^{-1} after 17-26 years since plantation, with the clone "I-214" culminating 1-2 years earlier than "Robusta". Energy use efficiency of these clones was estimated approximately 0.4-1.6% of the incoming solar radiation.

Keywords: Biomass, Calorific Value, Energy Use Efficiency, Poplar Clones, *Populus* × *euramericana*

Introduction

A fairly large portion of agricultural lands in Europe is suitable for plants of fast-growing tree species. Poplars have proven their efficacy in restoring functional and structural attributes of agro-ecosystems (Fortier et al. 2010, Raslavičius et al. 2013, Updegraff et al. 2004). Since this species produces valuable biomass for energy production (Hansen 1991), it is necessary not only to know the calorific value of its individual components, but also to understand the formation processes occurring throughout the tree existence. Poplar clones have a great advantage over other woody species because they produce a large amount of above-ground biomass during their relatively short life-cycle. Solar energy drives photosynthetic assimilation stored as chemical bonds in the biomass structural components, though the accumulated energy content can remarkably vary, primarily depending on species growth over a determined time period. Moreover, stand age and site index affect the biomass production of forest tree species, influencing the obtainable volume and yield.

Yield tables for "Robusta" and "I-214" poplar clones published by Petráš & Mecko (2005) predict not only biomass volumes for whole trees, but also for their main parts including stem, large wood, under-bark components, etc. Such partition of the whole yield in its different fractions is essential for industrial processing purposes. The volume obtained from yield tables is then converted to weight units based on the density of its different components. Many studies have reported that bark has lower density than wood (Knige & Schultz 1966, Požgaj et al. 1997, Klašnja & Kopitovič 1999), and soft broadleaf species have registered the lowest wood density, followed by coniferous and hard broadleaf species. Petráš et al. (2010) derived average densities of above-ground biomass fractions in the range of 350-470 kg m^{-3} for two clones of *Populus* × *euramericana*, and a similar wood density of 306-367 kg m^{-3} was recorded for 4 clones of *Populus* × *deltoides* by Kord & Samdaliri (2011). In addition, wood density varies not only according to species considered but also to the excising location along the tree (Požgaj et al. 1997, Husch et al. 2003, Petráš et al. 2010).

Besides the evaluation of a species' calorific value, it is important to assess the relative efficiency of woody species in using the solar radiation. Pretzsch (2009) named this characteristic "energy use efficiency", defined as the ratio between the energy accumulated in the above-ground biomass and the incoming solar radiation. For example, the average annual sum of global radiation for Germany is approximately 36 000 GJ ha^{-1} y^{-1}. Since net biomass production for Norway spruce, European beach, Scots pine, Sessile and Common oak is in the range 0.005-0.009, their energy use efficiency is less than 1% (Pretzsch 2009). Indeed, Larcher (2003) and Körner (2002) reported that 50-60% of incoming radiation is outside the photosynthetically useful spectrum, and a further 10-20 % is reflected or transmitted, while most of the remainder is lost in the photosynthetic process.

The aims of this analysis were: (i) to determine the calorific values of above-ground biomass for poplar clones "Robusta" and "I-214"; (ii) to examine the above-ground biomass of wood, bark and small-wood with bark in order to establish which fraction has the highest calorific capacity; (iii) to derive the calorific energy content and energy use efficiency of clones at the stand level; and (iv) to establish the most appropriate exploitation strategy of poplar clones for energy production purposes.

Materials and methods

Study sites

Eleven trees were sampled in poplar stands located in the southern area of western (7 stands) and eastern (4 stands) Slovakia, at elevations ranging from 100 to 300 m a.s.l. (Fig. 1). Average annual temperature in these regions is 9.0-10.0 °C, and vegetation period is approximately 180 days. Most poplar stands were affected by ground water from surrounding rivers.

The site index *q* indicates the fertility of a location based on the mean tree height after 30 years since the establishment (Petráš & Mecko 2005). For example, a site index of 40 indicates that a 30-years-old poplar stand attains a mean height of 40 meters. Additional characteristics of the sampled stands including age, diameter at breast height (*DBH*)

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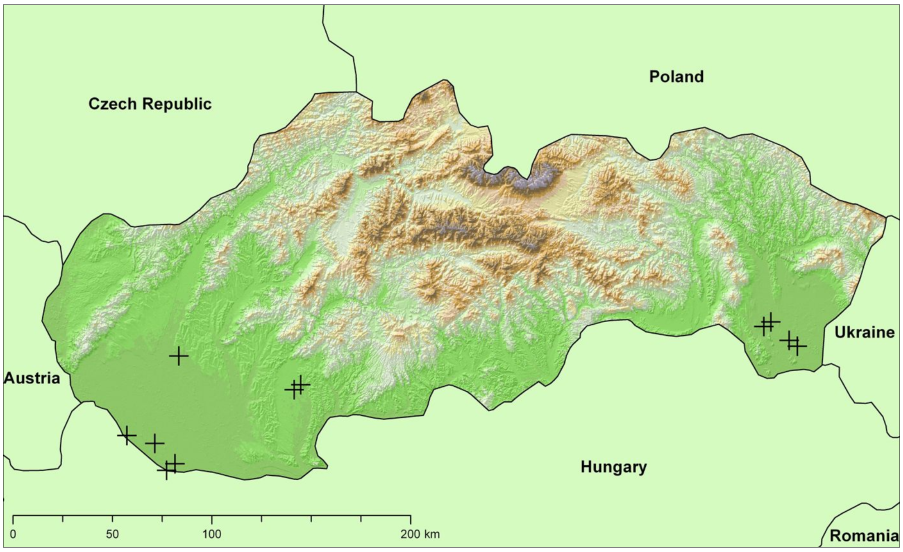


Fig. 1 - Location of study sites in western and eastern Slovakia, indicated by black crosses.

Tab. 1 - Basic growth characteristics of the sampled poplar trees. (DBH): diameter at breast height.

Clone	Number of trees	Age	DBH	Height	Site index
"Robusta"	5	22-44	35-49	30-41	24-34
"I-214"	6	19-47	34-56	25-40	22-40

Tab. 2 - Percentage distribution of annual global radiation in each months (1997-2002).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
%	2.5	4.3	7.6	10.6	13.9	14.8	14.7	12.8	8.6	5.7	2.6	1.9

and tree height are reported in Tab. 1.

Sampling and analysis

Samples were taken from the following five tree segments: (1) the base, middle and top part of each stem provided three wood and bark samples; and (2) two small-wood samples were taken from the crown, one 4-6 cm in diameter and the other < 4 cm. A total of 88 samples were obtained, of which 33 wood, 33 bark and 22 small-wood samples with bark. Fresh volume of samples was determined to the nearest 1 ml in a calibrated cylinder. Dry weight was measured after oven-drying at 105 °C using a 0.01g precision scale. Samples were then ground with a Retsch cutting mill (Gmbh, Germany) and homogenized by thorough mixing. The calorific values (as Higher Heating Values) of dry matter (*CVDM* - [J g^{-1}]) were determined by the C-200 calorimeter according to the Standard ISO 1928:2009 for solid mineral fuels. Four repetitions per sample were carried out.

Calculation procedures

The calorific production of the above-ground biomass for clones was derived by recalculation from its volume production. This was achieved using the yield tables' model for the "Robusta" and "I-214" poplar clones (Petráš & Mecko 2001, 2005), their biomass densities (Petráš et al. 2010) and the calorific value of the biomass dry matter.

Tab. 3 - Density, calorific dry matter and calorific capacity of the "Robusta" and "I-214" poplar clones analyzed. Mean values (± standard deviation) of calorific content are reported.

Characteristics	Clone	Bark	Wood	Small-Wood
Density (kg m^{-3})	"Robusta"	389.39 ± 29.99	427.47 ± 37.45	468.98 ± 39.36
	"I-214"	385.25 ± 33.79	392.96 ± 58.49	456.72 ± 22.49
Calorific value of dry matter (J g^{-1})	"Robusta"	17975 ± 547	18350 ± 468	18589 ± 553
	"I-214"	17801 ± 473	18492 ± 359	18307 ± 348
Calorific value capacity (GJ m^{-3})	"Robusta"	7.01 ± 0.65	7.85 ± 0.76	8.73 ± 0.93
	"I-214"	6.86 ± 0.61	7.27 ± 1.10	8.36 ± 0.51

Yield tables predict the biomass volume (*VB* - m^3 ha^{-1}) based on age *t* and site index *q* as follows (eqn. 1):

$$VB = f(t, q)$$

Biomass volume was thus obtained for whole-tree wood components, stem and large wood elements. All volumes (over-bark and under-bark) were given for mixed coppice, main stand, secondary crop, total production and also for total current annual and total mean periodic increments.

The calorific value capacity (*CVC* - GJ m^{-3}) was calculated from measured density values (*D* - kg m^3) and *CVDM* (J g^{-1}) as follows (eqn. 2):

$$CVC = D \cdot CVDM \cdot 10^{-6}$$

The calorific energy content of whole stand (*CEC* - GJ ha^{-1}) was then derived by replacing in eqn. 2 the average value of calorific capacity (eqn. 3):

$$CEC = VB \cdot CVC$$

The final model then predicts the calorific energy production (*CEP* - GJ ha^{-1}) of poplar clone stands based on age *t* and site index *q* (eqn. 4):

$$CEP = f(t, q)$$

The energy use efficiency throughout the life-cycle (*EUE* - %) was derived according to Larcher (2003) and Pretzsch (2009), as the ratio of the energy accumulated in the above-ground biomass (*AGTB* - GJ ha^{-1}) and the incoming solar energy as follows (eqn. 5):

$$EUE = \frac{CEP_{AGTB}}{R_{May-Sep}}$$

where CEP_{AGTB} is the calorific energy production in the above-ground trees biomass (GJ ha^{-1}), and $R_{May\text{-}Sep}$ is the incoming global radiation (GJ ha^{-1}) over the vegetation period (May-September).

Data for annual global radiation were taken from the meteorological observatory at the Geophysical Institute of the Slovak Academy of Science in Mlynany, Slovakia (long. 18° 20' E, 48° 19' N), at an approximate elevation of 195 m a.s.l. Recorded average annual global radiation was 436 212 kJ cm^{-2} y^{-1} (43 621.2 GJ ha^{-1} y^{-1}) for the period 1970-2002 (Ostrožlík 2003). The incoming radiation for the period considered in this study (May to September) represents the 64.8% of the annual total radiation (Tab. 2).

Statistical analysis

Analysis of variance was applied to test for differences in calorific value capacity obtained from eqn. 2, using the following three factors: (1) the clone ("Robusta" and "I-214"); (2) the excising location on the tree (base, middle and top of the tree stem plus 4-6 cm and < 4 cm small wood); and (3) the biomass fraction (wood, bark and small-wood with bark). Tukey's *post-hoc* HSD test was applied to test for differences in mean values (α = 0.05).

Results and discussion

Calorific values of biomass fractions

Density (kg m^{-3}), calorific values of dry matter (J g^{-1}) and calorific value capacity (GJ m^{-3}) were obtained for each of the three biomass fractions considered for each clone (Tab. 3). Results of the analysis of variance carried out may be summarized as follows: (1) overall, the influence of the factors explored in the analysis was statistically significant ($p<0.001$ - Tab. 4); (2) the influence of the individual factors considered on biomass calorific value was statistically significant except for the clone (Tab. 5); (3) the *post-hoc* test applied confirmed that differences in the average calorific content do exist among the three biomass fractions analyzed ($p<0.05$ - Fig. 2); and (4) significant differences in the calorific value capacity were detected only between the three crown parts and the other two parts of the stem (the base and the middle). The above results indicate that stem wood from these poplar clones can be advantageously utilized for mechanical and chemical purposes.

Energy content in plant tissues is proportional to their carbon content. Larcher (2003) asserted that the greatest energy content in plant tissues is due to lignin (26.4 kJ g^{-1}), lipids (38.9 kJ g^{-1}), and terpenes (46.9 kJ g^{-1}). Accordingly, in this study the highest calorific content was found for small-wood, likely depending on the higher abundance of the above-mentioned tissues in this biomass fraction.

Tab. 4 - Results of the ANOVA on the poplar clones' calorific value using the clone, the excising location on the tree and the biomass fraction as factors.

Source of variability	Sum of Squares	F-statistic	p-value
Total	89.66	-	-
Explained	51.74	2.36	3.72E-05
Residual	37.92	-	-

Tab. 5 - Results of the one-way ANOVA carried out to test the influence of individual factors on poplar clones' calorific value.

Factors	Sum of Squares	F-statistic	p-value
Biomass fraction	34.12	26.11	1.32E-09
Excising Location on the tree	42.74	18.90	3.25E-11
Clone	2.90	2.87	0.094

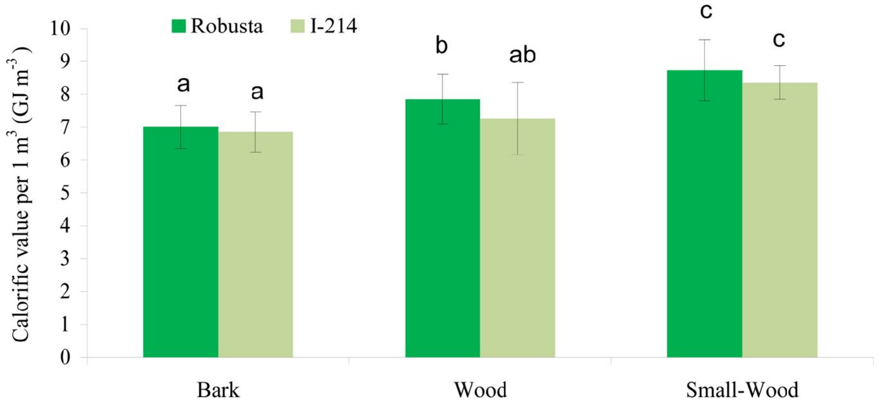


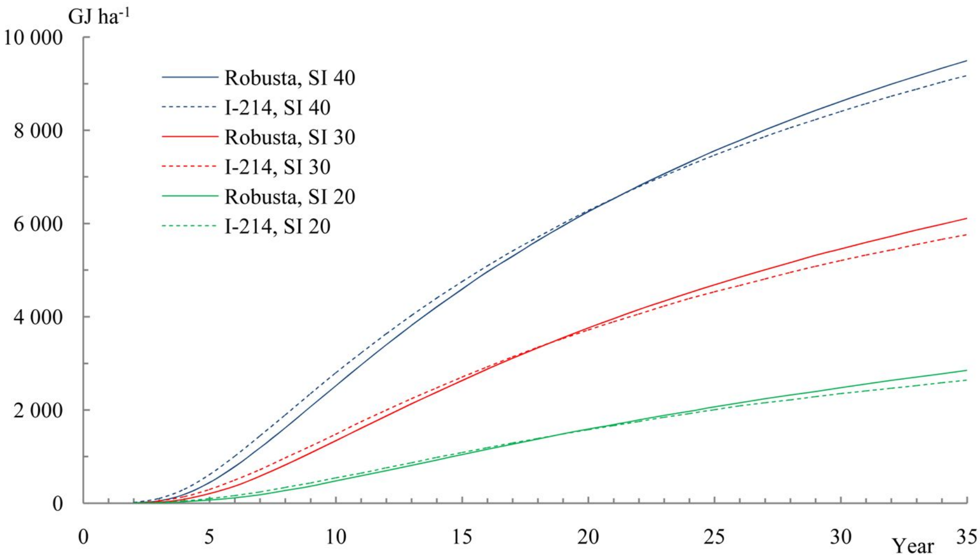
Fig. 2 - Mean (± SE) calorific capacity of basic biomass fractions in "Robusta" and "I-214" poplar clones. Different letters indicate significant differences among the means ($P < 0.05$) according to the *post-hoc* Tukey HSD test.

Modeling of calorific energy content

Since the yield tables used in this study predict only the volume for wood, bark and small-wood with bark, a simplification in the calculation of the calorific energy production was applied according to eqn. 4.

The life-time calorific energy production obtained from the model applied as a function of stand age and site index is displayed in Fig. 3. The growth curves starts with values accrued from the second year of the growth tables, given that values before that age are close to zero. However, after 35 years and at site indexes of 20, 30 and 40,

Fig. 3 - The calorific energy production in poplar clone biomass, dependent on stand age and site index (SI) 20, 30 and 40.



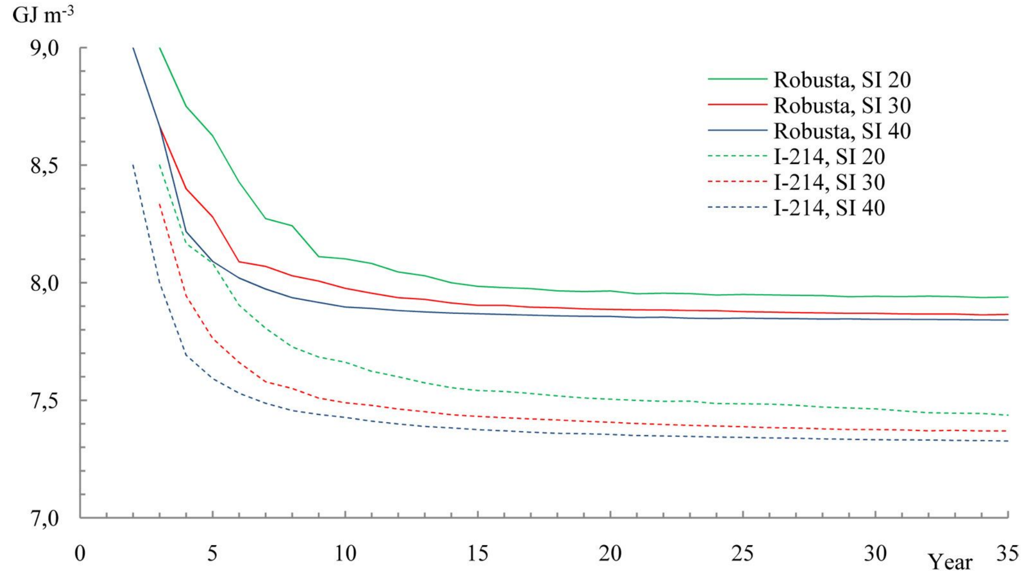


Fig. 4 - The average calorific capacity in 1 m^3 of poplar clone biomass, dependent on stand age and site index (SI) 20, 30 and 40.

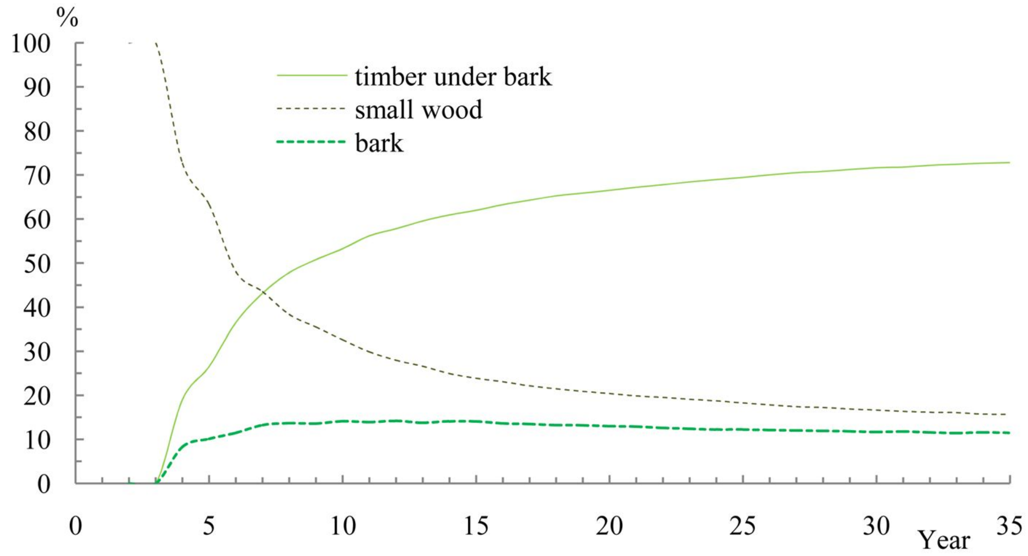


Fig. 5 - The proportion of calorific energy production in wood, bark and small-wood for the "Robusta" clone at site index 30.

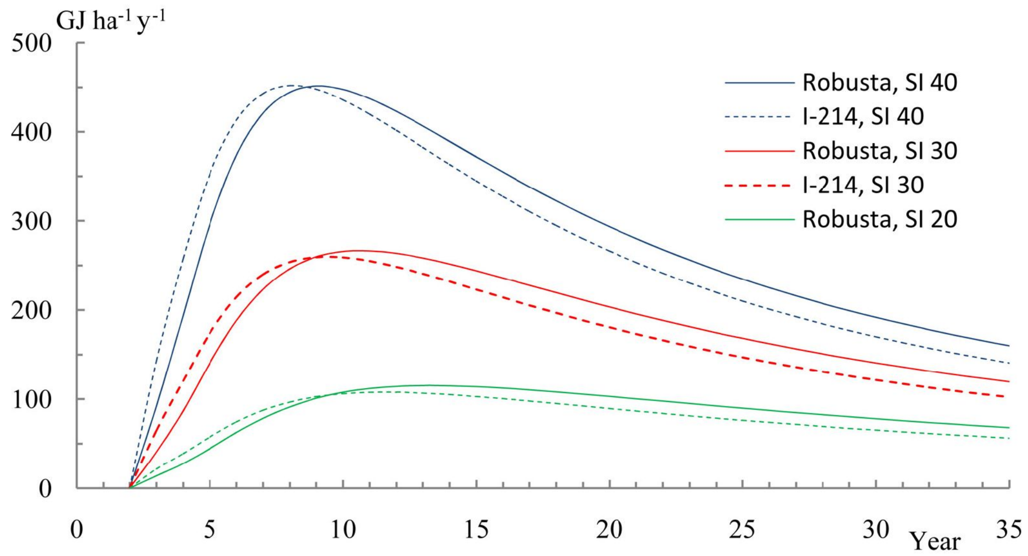


Fig. 6 - Annual increments in poplar biomass calorific energy, dependent on stand age and site index (SI) 20, 30 and 40.

Fig. 7 - Average annual biomass calorific energy production, dependent on stand age and site index (SI) 20, 30 and 40.

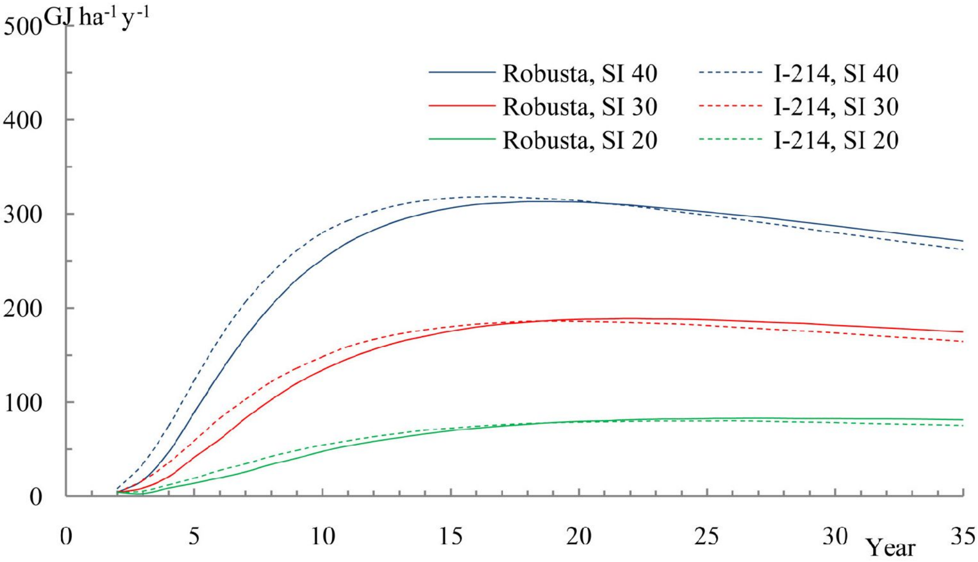
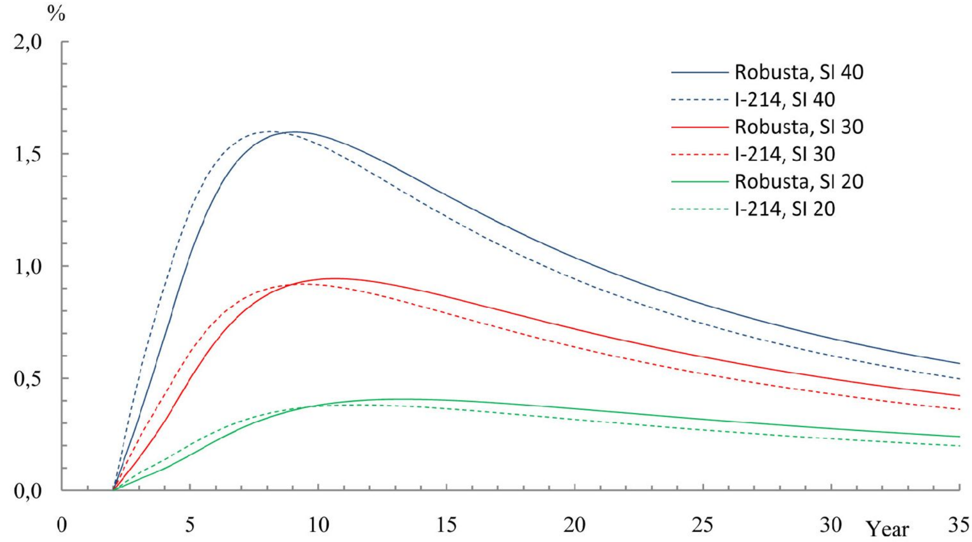


Fig. 8 - Energy use efficiency of poplar clone biomass calorific production, dependent on stand age and site index (SI) 20, 30 and 40.



the estimated calorific energy productions are approximately 2 700, 6 000 and 9 300 GJ ha^{-1}, respectively. Clone "I-214" had a slightly higher calorific production than "Robusta" during the first half of its rotation time, the latter clone recording 7.8-8.0 GJ m^{-3} in the middle-late years and site indexes 40-20, while "I-214" clone had just 0.5 GJ m^{-3} less.

However, larger differences between the clones analyzed were observed when the calorific value per m^3 of biomass at lower site indexes was considered (Fig. 4). Indeed, a significant reduction in the calorific value from the 2nd to the 5th year of growth was observed.

As mentioned above, calorific capacity accumulated differently in the different biomass fractions as a function of a varying proportion of lignin, terpenes and essential oils contained in the tissues (Fig. 5). After 35 years since plantation, 73% of the calorific value was stored in the wood, 16% in the small-wood component, and 11% in the bark. It is should be noted here that the decrease in bark calorific capacity was quite low, reducing only from 15% to 11% over a twenty year period.

Annual increment estimates in calorific energy content culminated approximately at age 8-13 in the 20-40 site indexes, with a value of 110-450 GJ ha^{-1} y^{-1} (Fig. 6), the "I-214" clone culminating 1-2 years earlier than "Robusta". The calorific value then markedly decreased with increasing age to approximately 60-160 GJ ha^{-1} y^{-1} after 35 years. As a comparison to hard broadleaf species, Bublinec et al. (2011) found that the average annual increment of energy content in aboveground biomass in a 75 years-old beech stand was approximately 176 GJ ha^{-1} y^{-1}.

The estimated average annual production of calorific energy content (Fig. 7) for site indexes 20-40 culminated approximately 17-26 years after plantation, with values of 80-320 GJ ha^{-1} y^{-1}, the "I-214" clone culminating again 2-3 years earlier than "Robusta". This value can be compared with the highest annual increment of 450 GJ ha^{-1} y^{-1} recorded for 8-9 years-old poplar stands on above-average site indexes in the temperate climatic zone in Central Europe. According to the above evidence, it is recommended to harvest the poplar clone stands at this age, since the average annual energy production under these conditions is lower both before and after this time.

Energy use efficiency

The energy use efficiency calculated by eqn. 5 for "Robusta" and "I-214" poplar clones has a similar relationship to their annual calorific production increments (Fig. 8). Poplar clones stands achieve their maximum solar radiation usage (approximately 1.6%) at 8-9 years after plantation at the highest site indexes. This value, however, markedly decreases with lower site index and higher age, attaining only 0.2-0.6% by age 35. As for comparison, Bublinec et al. (2011) report that beech ecosystems in Central Europe effectively utilize less than 1% during the photosynthetic activity period (May to September). Moreover, Pretzsch (2009) reported energy use efficiency values of 0.8-0.9% for spruce and pine in Germany and 0.5-0.6% for broadleaf species.

Based on our estimates, poplar clones received 28 267 GJ ha^{-1} solar radiation during the period May to September, while Pretzsch (2009) calculated 36 000 GJ ha^{-1} over the entire year. The above difference may be due to the fact that the latter estimate is based only on the marketable wood quantities from the national forest inventory. However, it is widely accepted that total above-ground biomass volume is much larger, exceeding 8-10% for coniferous species and 12-15% for broadleaves. Although Larcher (2003) reported similar energy use efficiency values, with a 2% limit for forest stands, the solar radiation usage reported for most woody species was less than 1%.

Conclusions

The poplar clones "Robusta" and "I-214" poplar clones have high above-ground biomass production, eminently suitable for biofuel energy. Crown small-wood provided 0.8 GJ m^{-3} higher calorific value capacity than stem wood, and wood from the base and the middle of the poplar stems had 1 GJ m^{-3} less than the crown parts. Moreover, the bark registered only approximately a 0.61 GJ m^{-3} lower calorific capacity than the wood. The above findings are especially valuable in the light of industrial exploitation of the poplar clones' biomass, since industrial energy utilization efficiency must include costs for both production and transport to the consumption point.

A calorific energy content of approximately 5 000 GJ ha^{-1} is available from the burned biomass of poplar clones at above-average site indexes, with a 25% decrease below-average sites. Therefore, the energy content of a 30 years-old poplar stand is similar to the 5 137 GJ ha^{-1} reported by Bublinec et al. (2011) for a 75 years-old beech stand.

In addition to their fast growth, large biomass and high calorific production, poplar clones "Robusta" and "I-214" also exhibited a particularly high energy use efficiency compared to other wood species. Moreover, most poplar stands in this study accumulated more than 1% of the solar radiation.

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