WATER CONSUMPTION AND BIOMASS YIELDS RELATION IN SHORT ROTATION POPLAR COPPICE

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ABSTRACT

The plantations of short rotation coppice (SRC) usually based on poplar or willow species are promising source of biomass for energy use. To contribute to decision-making process where to establish the plantations we evaluated the water consumption and its relation to biomass yields of poplar hybrid clone (*Populus nigra x P. maximowiczii*) in representative conditions for Czech-Moravian Highlands. Water availability is usually considered as the main constraint of well profiting SRC culture and therefore we focused on analyzing the linkage between the aboveground biomass increments and the total stand evapotranspiration (ET) and thus on so called water use efficiency (WUE). During the seasons 2008 and 2009 the total stand ET measured by Bowen ratio system constructed above poplar canopy and the stem diameter increments of randomly chosen sample trees were examined. The stem diameters were subsequently converted to total above ground biomass by allometric equation obtained by destructive analysis at the beginning of 2010. The biomass volume and its increment of particular trees were subsequently transformed to the whole canopy growth and correlated with the ET values. Our results revealed that there was a statistically significant relation between water lost and biomass growth with coefficients of determination r^2 0.96 and 0.57 in 2008 and 2009 respectively. The dynamic of seasonal WUE varied from 4 to 0 g kg^{-1} and from 6 to 0 g kg^{-1} with means 2.8 and 3.4 g kg^{-1} in both executed years respectively. These values are comparable with other broadleaved tree species of temperate climate zone and suggest that economically profitable plantation (defined by yield at least in the range of 10 – 12 Mg ha^{-1} $year^{-1}$ of dry matter content) will consume more than 400 – 450 mm per year and thus will demand a locality with higher and adequately temporally distributed amount of precipitation especially in rain feed areas such as the discussed Czech-Moravian Highlands.

Key words: Short rotation coppice, biomass increment, water consumption

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INTRODUCTION

The term short rotation coppice (SRC) is generally used for any high-yielding woody species managed in a coppice system usually grown at arable land for energy use. Typically, these crops are harvested on a 3–7 year rotation and remain viable for 15–30 year. The SRC plantations are in conditions of middle Europe usually based on poplar or willow species and has recently represented promising source of bio-energy. The replacement of fossil fuel with biomass in the generation of energy has recently been an important strategy promote by the European Union (EU) to mitigate effect of climate change an enhance the security of the supply and diversification of energy sources (IEA, 2003). Biomass, and in particular energy crops, have attracted attention as a promising, renewable and local energy source (EU commission, 2005, Gasol et. al 2007), which could help the EU reduce its dependency on external energy sources, i.e., the main oil-exporting and gas-exporting countries. Within the biomass option, short-rotation coppice (SRC) plantations feature several environmental advantages. Of all the raw materials, such as winter rape oil, sugarcane, sorghum, soy and palm oil, wood chips show the best performance as biofuel with respect to the total environmental impact and greenhouse gas emissions (Scharlemann and Laurance, 2008). Only biofuels produced from waste materials (manure, whey) show a better performance. Furthermore, the life cycle assessment for poplar SRC plantations in Germany (Rödl, 2008) confirms the very low CO_2 emissions resulting from energy production using biomass from SRC. It produces just 0.015 kg CO_2-equivalent per kWh generated electricity. At the other extreme, lignite-fired power plants discharge 1.1 kg CO_2-equivalent per kWh. According to results of many research papers, SRCs has additionally positive impacts on their surround; e.g. on water cycle, carbon cycle, biodiversity, liveliness of the countryside, and also except the energetic independence also higher employment rate (Isebrands and Karnosky, 2001). Despite these facts, the areas of SRC plantations in the Czech Republic are still low compared with the neighbouring countries (Weger et al., 2009), however, higher popularity of SRCs and vote to plant them has been recorded during a few of last years. For successful establishing and choosing the new suitable localities for growing of SRC, the deep knowledge of their ecological demands is necessary. According to empirical and modelled results, the water availability constitutes the main constraint for SRC grown on arable land (Braatne et al., 1992, Cienciala and Lindroth, 1995, Deckymn et al., 2004, Lindroth and Båth, 1999). By relating the water use to the plant productivity we obtain so called water use efficiency (WUE, sometimes the reciprocal transpiration, evaporation or assimilation ratio is used) describing the increase in growth per unit of water use. WUE can be instantaneously measured at leave or stand levels as the rate of CO_2 uptake by photosynthesis per unit of water lost in transpiration or whole evapotranspiration (Lindroth and Cienciala, 1996, Linderson et al., 2007). More related to forestry practices is long term WUE which is estimated on the basis of dendrometric measurements and the water lost (Cienciala and Lindroth, 1995). Depending on which method is used, factors such diurnal variation in root respiration, relative carbon allocation to roots and turnover of fine roots and leaves influence in resulting WUE (Dickamn et al., 2001, Lindroth et al., 1994).

The main aim of this paper is the short insight into water and biomass relation by using long term WUE based on stand aboveground biomass increment and water lost by evapotranspiration, and description of its seasonal variation in conditions representative for Czech-Moravian Highland where mostly only the precipitation is the source of available soil water.

MATERIALS AND METHODS

In April 2002, a high-density experimental field plantation for verification of the performance of poplar clone J-105 (*Populus nigra x P. maximowiczii*) with the total area of 4 ha was established in Domanínek (Czech Republic, 49° 32´ N, 16° 15´ E and altitude 530 m a.s.l.). The plantation was established on agricultural land previously cropped predominantly for cereals and potatoes. Hardwood cuttings were planted in a double row design with inter-row distances of 2.5 m and spacing of 0.7 m within rows accommodating a density of 10,000 trees/ha. Soil conditions at the location are representative of the wider region with deep luvic Cambisol influenced by gleyic processes and with a limited amount of stones in the profile. The site itself is situated on a mild slope of 3° with an eastern aspect and is generally subject to cool and relatively wet temperate climate typical for this part of Central Europe with mingling continental and maritime influences. Although the area does not provide optimal conditions for SRC based on Populus sp. clones, the site itself is highly suitable for planting due to deep soil profile (Trnka et al., 2008).

In May 2008, 14 m high mast with system for estimating actual evapotranspiration (ET_a) by measuring Bowen ratio (EMS Brno, Czech Republic) was placed in the centre of the poplar plantation. At the same place below ground, three sensors EC - 20 (Decagon Devices, USA) for measuring volumetric water content of soil and six gypsum blocks (EMS Brno) to measure soil water potential were accommodated in the depths 0.1 m, 0.3 m and 0.9 m. All sensors were connected to datalogger ModuLog 3029 (EMS Brno) and measuring step was adjusted to measure each 2 minutes and to store each 10 minutes. At the same time, the tipping bucket rain gauge MetOne 370 (MetOne Instruments, USA) was placed next to the poplar plantation. For estimating biomass increment and its reaction to soil water availability an array of 15 mechanical - DB 20 and 3 automatic dendrometers - DRL 26 (EMS Brno) were fixed to trunks at the breast height at beginning of 2008. The values from DB 20 were usually read in a week period and the DRL 26 were adjusted to hourly measuring step. These measurements were updated by adding another 15 DB 20 and 1 DRL 26 dendrometers at start of the season 2009. These dendrometers are designed for long-term registration of tree trunk circumference via stainless tape that encircles the tree trunk. The values of increment of stem circumferences or diameters are very useful because they could be subsequently converted through the allometric equation to increment of biomass (e.g. Al Afas, 2008, Cienciala et al., 2005, Fajman et al., 2009). Moreover, in summer 2009 the plantation inventory took place and diameters at breast height (DBH) of 702 trees were measured with calliper at the area of cca 800 m^2 around the mast with Bowen ratio measuring system. Finally, destructive measurements of 42 randomly chosen trees, where the dendrometers were placed and another randomly selected 80 trees, were carried out during the harvesting at the beginning of 2010 – the end of first eight years long rotation period. This procedure followed the same methodology as described by Fajman et al. (2009). From these measurements, the allometric relationship between DBH and the dry matter content (DMC) of aboveground biomass (AB) without leaves was analysed and the common biometric exponential function AB = a x DBH^b was parameterized. Secondarily, also the dependence of tree length on DBH and the seasonal stem radius increment on DBH were investigated to get more parameters for up-scaling the sampled trees biomass increments into the whole stand and additionally to reveal the competitive interactions between the trees of different social position. By using the plantation inventory and the above mentioned allometric equation together with exponentially expressed dependence of increment rates on DBH, the growth of 42 regularly monitored trees were extrapolated in to the whole canopy and also convert to biomass increment per area of 1 m^2.

Furthermore, the AB increment was divided by the amount of ET_a [mm] and thus the long term WUE_{ET} was obtained. Because in this work, the WUE is defined only from part of above ground biomass (stems and branches - the growth of leaves and roots is not considered) which is divided by ET_a (not only transpiration), the term gross WUE_{ET} is used in order to point out the differences against typical view on WUE.

RESULTS

Figure 1 depicts the seasonal patterns of gross WUE_{ET} with means 2.78 and 3.39 $g*kg^{-1}$ in 2008 and 2009 respectively. Apparently, there are systematically higher values during the second investigated season which also showed much higher variability which is in fact rather the consequence of higher number of measured values than the effect of the different conditions.

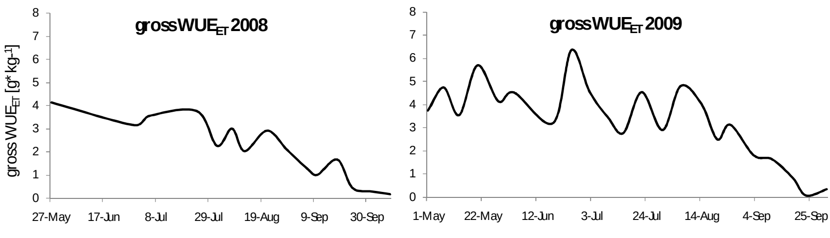


Fig. 1 The seasonal patterns of gross water use efficiency as the ratio of total evapotranspiration and allometrically defined aboveground biomass increments.

At the next figure 2, the water lost and change of allometrically defined biomass are correlated. There is narrower relationship in the year 2008 with the coefficient of determination 0.96 compared to lower 0.56 in 2009. On the other hand, again the correlation in 2009 was generated with higher number of the data and thus the other inherent factor like the root-shoot carbon allocation and the stem shrinking and swelling linked with the precipitation were not “hidden” in the long term course. With application of multiple linear regressions by adding the precipitation as another independent variable, much higher coefficient of determination 0.73 was obtained. The reasonable and statistically best resulted was the separation of the precipitation simply into the two categories: amount lower and higher than 10 mm.

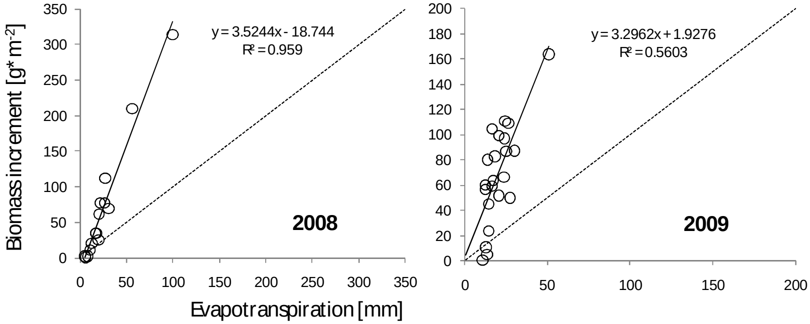
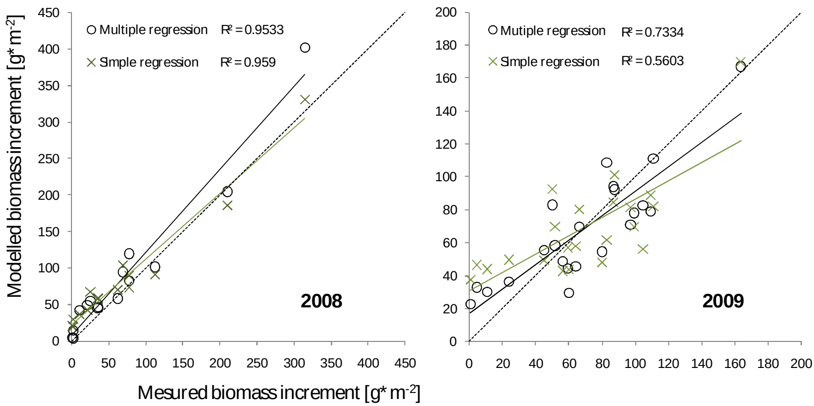


Fig. 2 The relationships between the total evapotranspiration and aboveground biomass increments during two consecutive seasons.

The multiple regression model created from the data of the season 2009 was subsequently compared with the first simple linear model as well as with the measured biomass increments for



both investigated seasons (Fig.3).

Fig. 3 The comparison of measured biomass increment with simple and multiple linear regression models based on water lost and aboveground biomass increment relationship.

The comparison of two linear regression functions with the measured data revealed that the models in both cases overestimated within the range of low values. The first simple linear function fitted quite well with the higher values in the case of 2008, whereas the multiple regression model systematically overestimated. For the 2009, there is quite equable under and over estimation ratio, except the low values which are overestimated by both models. For the simple linear function the Root mean square error (RMSE) was equal to 9.3 and 16.5 g*m^2; the Mean bias error (MBE) was equal to -14.9 and -3.8 g*m^2 of AB in 2008 and 2009 respectively. Multiple linear regression model amounted RMSE 29.7 and 19.7 g*m^2 an MBE -17.9 and -4.8 g*m^2 of AB for both consecutive years 2008 and 2009.

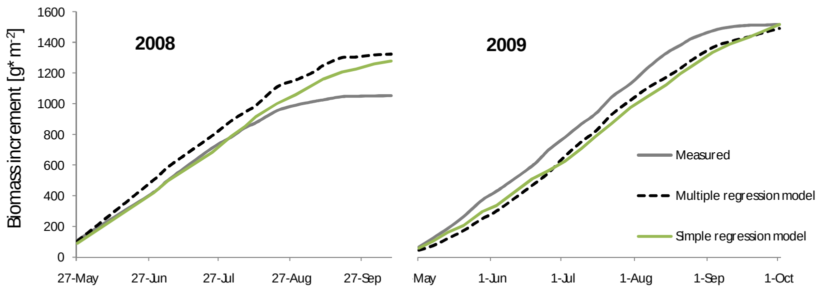


Fig. 4 Cumulative comparison of measured biomass increment with simple and multiple linear regression models based on water lost and aboveground biomass increment relationship.

At the last picture, the same comparison of modelled and measured AB increment is expressed in cumulative way. This graph is indicating that most problematic periods for expressing the biomass increment are the beginnings and the ends of the seasons when the antinomy of WUE is significant.

DISCUSSION

Gross WUE_{ET} based on synchronous measuring of AB increment and the canopy ET_a showed high seasonal variability in both of the evaluated years. The seasonal patterns were typical with the highest rates of gross WUE_{ET} at beginning of the season and with the decreasing at the end of summer. Lindroth et al. (1994) described the similar seasonal trends of WUE in willow SRC in Sweden, where the last most marked fall of WUE was linked with reducing LAI (leaf area index) at the end of summer. Our results confirmed this coherency with LAI dynamic since the pronounced decline of gross WUE_{ET} was observed around the mid August, when the period of LAI culmination in the investigated poplars culture was recorded. Lindroth et al. (1994) described the maxima in WUE, which was defined as the ratio of AB increment and transpiration, as an effect of rainy weather and thus with considerably amounts of evaporation of intercepted water and thus lower transpiration rates. However in our research taking in account with the gross WUE_{ET} based on total evapotranspiration, the maxima were also found during the rainy events. The higher gross WUE_{ET} as a consequence of precipitation could be explained by two reasons. Firstly, by using the long-term water use efficiency based on AB increment and not on CO_2 uptake and transpiration ratio, the relative carbon allocation to roots or AB can play important role (Dickmann et al., 2001, Lindroth et al., 1994). During the period with reduced soil water availability, the assimilated carbohydrates are directed away from shoots and towards root growth. After alleviated of such conditions by replenish the soil water status with rains or irrigation, the temporary carbon allocation toward the roots is compensated by a later increase in shoot growth (Kramer, 1983, Lindroth et al., 1994). The similar effect caused by mobile carbon pools influences also the seasonal variation with high WUE in the spring characteristic with so called spring flush (strong upward translocation of starch and sugars produced in assimilation during the end of previous season), and conversely with the drop to zero at the end of season linked with downward accumulation (Dickman et al., 2001) . By the way, the high accumulation of root reserves has great significance to coppicing. Secondly, growth is the biological phenomenon of increase in size with time. Growth involves the formation, differentiation and expansion of new cells, tissues or organs. The sudden increase in tree diameter often observed after rain is not necessary due to growth but reflects the saturation of shrunk xylem and other stem tissues with water after previous drier period (Herzog et al., 1995, Offenthaler et al., 2001). Within this context, the term WUE is very disputable and the using gross $WUE_{ET\ (T)}$ (either based on total evapotranspiration or just on pure transpiration) seems to be more reasonable and competent. Comparing the both executed years, there was notably higher gross WUE_{ET} during 2009. Similar situation was described also by Lindroth et al. (1994) where the authors explained the contrast in the consecutive seasons by different age of culture and with this linked different root-to-shoot ratio. The decreasing root-to-shoot ratio with ontogenically aging is well known phenomenon in SRC and also other tree species culture (Coleman et al., 2004, Ovington, 1957, Reynolds and D'Antonio 1996) and could provide an interpretation of higher AB increment during 2009. The heterogeneity in carbon allocation during the particular ontogenetic phases and also during the particular parts of the season causes difficulties to predict the yields with some simplified method based on evapotranspiration and biomass relation, but on the other hand such information could provide some general and gross estimation of the SRC production in condition of Czech-Moravian highland. Modelling the seasonal and yearly dynamic of root-to-shoot allocation could be key point to improve such approach.

Finally, considering that resulted values of gross WUE_{ET} with means 2.78 and 3.39 $g*kg^{-1}$ in 2008 and 2009 respectively are calculated from total evapotranspiration which is in SRC usually around 30% higher than pure transpiration, the WUE of poplars is comparable and rather higher than other broadleaved tree species of temperate climate zone. The estimated economically profitable yields range at least from 10 to 12 Mg ha^{-1} $year^{-1}$ of dry matter content which, according to our calculations, will consume more than 400 – 450 mm per year and thus will demand a locality with higher and adequately temporally distributed amount of precipitation especially in rain feed areas such as the discussed Czech-Moravian Highlands.

CONCLUSION

The gross WUE_{ET} for poplar SRC was charakteristic with high variability in both of the investigated years 2008 and 2009 with means 2.78 and 3.39 $g*kg^{-1}$ respectively. These values are situated in higher range comparing to the other broadleaved tree species of temperate zone and suggest that for well economically profiting biomass yields more than 400 – 450 of water per season will be consumed by the SRC plantation.

The relationship between AB increment and ET_a was investigated, and with considering that other factors like especially rains (soil water potential and stem water potential) are influencing the AB increment and volume, the multiple linear equation, with precipitation and ET_a as independent input variables, was proposed with yielding a satisfactory coefficient of determination 0.95 and 0.73 in 2008 and 2009 respectively.

Since the gross WUE_{ET} is influenced by seasonal and ontological variation caused by changing of allocation of mobile carbon pool, the modeling approach has to be updated by including this process to fit better the real seasonal and yearly dynamic of gross WUE_{ET}.

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