Forest Ecology and Management 409 (2018) 749–756

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Precision subsurface drip irrigation increases yield while sustaining water-use efficiency in Mediterranean poplar bioenergy plantations

Pierluigi Paris[a], Giovanni Di Matteo[b,*], Massimo Tarchi[c], Luca Tosi[a], Luciano Spaccino[a], Marco Lauteri[a]

[a] Consiglio Nazionale delle Ricerche, Istituto di Biologia Agroambientale e Forestale (CNR-IBAF), Porano, Italy
[b] Council for Agricultural Research and Economics (CREA), Research Centre for Agriculture and Environment, Rome, Italy
[c] W2 Agency, Osimo, Ancona, Italy

ARTICLE INFO

Keywords:
Drought
Irrigation scheduling
Precision agriculture
Soil moisture
Carbon stable isotopes

ABSTRACT

Bioenergy production in poplar Short Rotation Coppice plantations (SRC) is strongly limited in drought prone areas due to the high crop water requirement. Appropriate scheduling of subsurface drip irrigation (SDI) could be a practice for ensuring adequate biomass production with reduced water inputs while maintaining high water-use efficiency. We tested SDI in a commercial SRC cultivated with the hybrid poplar clone *Monviso* under Mediterranean environmental conditions. We applied two irrigation treatments during the summer season, i.e. a control irrigation treatment with an average amount of 115 mm (CI) and a double irrigation treatment for an average amount of 239 mm (DI) over two growing seasons of the second triennial rotation. We analyzed tree growth, yield, shoot diameter increments (PDI) and carbon isotope composition ($\delta^{13}C$) in both litterfall and tree-rings. We also measured soil moisture at 10, 20, 30, 40, 60 and 100 cm soil depths to explore more efficient irrigation scheduling. The results showed that CI and DI recovered 23–49 and 43–90% of the April-September precipitation deficit over the two growing seasons, respectively. We observed higher yield increments in DI compared to CI, with mean yields of 11.4 and 20.4 Mg ha^{-1} for CI and DI respectively. DI significantly affected biomass quality (biomass allocated to shoots with greater dimensions); however, stem moisture and shoot basal density did not significantly change after the irrigation treatments. $\delta^{13}C$ in tree-rings showed non-significant differences after CI and DI applications for two growing seasons. Congruently, the analysis of litterfall $\delta^{13}C$ did not show significant differences comparing the two irrigation regimes. Thus, the isotopic analyses indicate a constancy of intrinsic water-use efficiency (iWUE), irrespective of the watering regime. We found significant positive linear relationships (R^2 from 0.89 to 0.96) between PDI and soil moisture at 30 and 40 cm soil depths for both CI and DI when compared to the rest of the monitored soil layers. We suggest, therefore, the monitoring of soil moisture at 30–40 cm as a reference for scheduling irrigation practices during the growing season. In conclusion, DI significantly increased the overall plantation yield while sustaining the same iWUE observed in the deficit irrigation regime (CI).

1. Introduction

Bioenergy feedstocks are widely recognized as valid alternatives to fossil fuels in mitigating global climate change (IPCC, 2014).

In the European Union (EU) the share of renewable energies is expected to increase from 14% in 2010 to 20% in 2020 and up to 27% by 2030 (Mantau et al., 2010). Yet, by 2030, about 26 Million ha of plantations dedicated to bioenergy productions will be required to meet the EU bioenergetics needs. Bioenergy coppice plantations, managed under short rotation cycles of 2–5 years and characterized by high planting densities (i.e., up to 10,000 trees per ha) (SRC), have received much attention worldwide due to their large biomass productivity for bioenergy purposes (Morhart et al., 2014; Sixto et al., 2015).

Hybrid poplars are the most common species used in SRC (Zamora et al., 2015) because of their high yield potential (i.e., up to 25 Mg dry matter ha^{-1} year^{-1}) (Paris et al., 2011), depending on site conditions, cultivar choice and rotation cycle duration. However, under Mediterranean conditions, water availability represents the most limiting factor affecting poplar yield due to its hydrophilic behavior, which requires constant soil moisture throughout the growing season. Therefore, it is essential to take into account irrigation practices to increase poplar SRC yield.

* Corresponding author at: Council for Agricultural Research and Economics (CREA), Research Centre for Agriculture and Environment, Via della Navicella 2-4, I-00184 Rome, Italy.
E-mail address: giovanni.dimatteo@crea.gov.it (G. Di Matteo).

https://doi.org/10.1016/j.foreco.2017.12.013
Received 22 August 2017; Received in revised form 5 December 2017; Accepted 6 December 2017
0378-1127/

Poplar water requirement under SRC conditions is particularly relevant due to high evapotranspiration rates (Fischer et al., 2013). Yet, Fisher et al. (2013) noticed a mean annual crop coefficient (K_c) value of 0.91, ranging between 0.42 and 1.51, depending on site conditions. By studying the poplar SRC water requirement in a lysimetric trial under Mediterranean conditions, Guidi et al. (2008a) found that K_c value peaked at 3, with daily evapotranspiration (ET_0) values ranging between 5 and 10 mm.

European SRC plantations cover an estimated area of 50,000–70,000 ha, with about 12,000 ha in Sweden, and 10,000 ha in Italy and Hungary, respectively (Facciotto et al., 2015). In Italy, most poplar SRC plantations are cultivated across northern continental areas as these are particularly suitable due to their climatic and edaphic conditions (Paris et al., 2011). Conversely, southern Mediterranean areas are particularly exposed to prolonged drought periods (four months or more without adequate rainfall). These site conditions strongly limit poplar SRC cultivation, mainly due to water shortages (Di Matteo et al., 2012). Efficient irrigation systems are, therefore, urgently required to ensure the cultivation of bioenergy plantations (Navarro et al., 2015).

Poplar SRC in Europe is mostly irrigated via gravity-fed and sprinkler systems. Drip irrigation systems are sometimes used, mainly in research plots and for evaluating the performance of additional tree species to be cultivated under SRC conditions (Bianconi et al., 2011; Cañellas et al., 2012; Perez et al., 2014; Pérez-Cruzado et al., 2014). Subsurface drip irrigation (SDI) is an advanced irrigation system that minimizes the water losses by evapotranspiration from soil and weeds and by soil drainage below the root system. SDI has been successfully tested on several crops under Mediterranean conditions (Ayars et al., 1999, 2015). It seems particularly suitable for perennial woody crops since its high installation costs could be amortized within multi-annual plans. SDI could be a very promising irrigation system for poplars under SRC conditions and its application could optimize the overall plantation water-use efficiency, with positive economic and environmental benefits. To the best of our knowledge, no study has reported the use of SDI in poplar SRC in drought prone areas. Therefore, we carried out a pilot experiment in a Mediterranean poplar SRC in central Italy by applying the SDI system with different irrigation levels, according to the operational guidelines required by commercial plantations.

SDI can result in an increase of the agronomic water-use efficiency (WUE), the ratio of crop yield to total water consumption, when compared with other irrigation systems (Najafi and Tabatabaei, 2007). Intrinsic water-use efficiency (iWUE) is, at the leaf level, the ratio between net CO_2 assimilation rate (A) and stomatal conductance to water vapor (g_s). In poplar, the leaf carbon isotope composition ($\delta^{13}C$) has been often used as an indicator of iWUE along the period of accumulation of leaf structural carbon (Ripullone et al., 2003, 2004), while $\delta^{13}C$ in the tree-rings reflects long-term tree physiological responses, in interaction with phenological, environmental and anthropogenic factors (McCarrol and Loader, 2006; Di Matteo et al., 2014, 2017). An isotope composition (e.g., $\delta^{13}C$) is the deviation from the unit of the ratio of the isotope ratio of a sample to that of the standard. Whenever the $\delta^{13}C$ value of atmospheric CO_2 can be assumed as constant among the treatments, the value of carbon isotope composition of photo-assimilates is controlled by stomatal conductance and photosynthetic capacity, which determine the intercellular to atmospheric CO_2 partial pressure ratio (p_i/p_a). Since iWUE is negatively related to p_i/p_a, carbon stable isotope analysis is a reliable proxy of iWUE itself (Farquhar et al., 1989). For instance, iWUE seasonal fluctuations in poplar were associated to variations in soil water availability, which potentially affect the photosynthetic operational point via the p_i/p_a value (Broeckx et al., 2014).

The tree iWUE might be enhanced by scheduling proper irrigation practices according to the actual crop water consumption. Thus, monitoring the physiological responses in relation to phenology, soil moisture availability and atmospheric evapotranspiration demand, would suggest the best management for a sustainable plant carbon and water economy. Three methods can be used to accomplish this target, based on the monitoring of: i) soil moisture, ii) tree water status via leaf water potential or crop water stress indices by remote sensing (Bellvert et al., 2013; Gago et al., 2015), and iii) soil water budget according to FAO recommendations (Allen et al., 1998). The most promising drip irrigation system in terms of irrigation efficiency considers soil moisture monitoring by using sensors positioned at different soil depths (Soulis et al., 2015). A key-issue in this method is the choice of representative crop rooting volume points in order to place the soil probes properly and, consequently, to measure the crop soil moisture as accurately as possible.

However, little is known about these experimental practices, as no study has been conducted to clarify these issues, especially in poplar SRC managed with SDI systems. This is because few experiments have considered soil moisture probes at different soil depths to investigate the relationships between tree growth and soil moisture profile (Intrigliolo and Castel, 2006).

The aims of this study are: i) to determine the effects of SDI regimes applied during the summer season on yield and growth in poplar SRC, under Mediterranean conditions; ii) to estimate poplar iWUE responses to SDI regimes via $\delta^{13}C$ analysis in litterfall and tree-rings; iii) to quantify the effect of SDI system on soil moisture at different soil depths; iv) to examine the relationships between tree growth and soil moisture at different soil depths, in order to identify the soil layers where moisture content significantly affects tree growth.

2. Materials and methods

2.1. Site descriptions

The experiment was carried out in central Italy, at the *Risiere* locality, in the municipality of Viterbo (42°22′48″ N; 12°01′45″ E, elevation 204 m a.s.l.). The main land-use surrounding the study area is arable agriculture, the main crops being rain-fed wheat, alfalfa and clover. Secondary crops are irrigated corn and vegetables.

The climate is typically Mediterranean (i.e., dry summer-subtropical climate, type *Csa*, Köppen climate) with dry summers and cool and wet winters. Mean annual temperature and annual total precipitation are 13.25 °C and 736 mm, respectively. The coldest month is January (mean temperature: 5.6 °C), and the hottest month is August (mean temperature: 22.8 °C). The precipitation pattern is bimodal, i.e. it peaks in autumn (263 mm), followed by wet and rainy late winters and early springs (almost 175 mm in each season), and dry summers (121 mm) (30 years average data, 1971–2000, for the city of Viterbo. Source: Italian Air Force-Meteorological Service). In order to schedule the irrigation treatment during the experiment, we monitored the site precipitation patterns by using meteorological data from a meteorological station located near the experimental plantation (Table 1). Summer precipitation (i.e., June, July and August) was 119, 12 and 115 mm for 2011, 2012 and 2013, respectively. The year 2012, therefore, was drier than the average.

The soil originates from limestone volcanic deposits which characterize the three horizontal layers, with a clay loam texture and a significant percentage of gravel, up to 25% in the deepest layer, and a low water holding capacity of around 15% (Table 2).

2.2. Plant material and plantation management

Experimental plots are part of a 40 ha poplar commercial plantation managed under SRC conditions (Table 3). The tested poplar clone is "*Monviso*" [(*P.* X *generosa* Henry) X *P. nigra* L.], which is registered in the Italian Registry of Forestry Clones for biomass production and recorded as having a very high tolerance to Poplar rust. We planted the stem cuttings mechanically at 2.5 × 0.66 m spacing with an overall plantation density of 6,060 cuttings ha^{-1}. In the establishment year, i.e.