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Carbon assimilation and water use efficiency of a perennial bioenergy crop (*Cynara cardunculus* L.) in Mediterranean environment

G. Rana[a], R.M. Ferrara[a,*], D. Vitale[b], L. D'Andrea[a], A.D. Palumbo[a]

[a] Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria (CREA)—Research Unit for Cropping Systems in Dry Environments (CREA-SCA), via C. Ulpiani, 5, Bari 70125, Italy

[b] DIBAF, Dipartimento per l'Innovazione nei sistemi Biologici, Agroalimentari e Forestali, University of Tuscia, via C. de Lellis, Viterbo 01100, Italy

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ABSTRACT

Here we investigate how cardoon (*Cynara cardunculus* L.), energetic crop cultivated under Mediterranean climate in rainfed conditions, is adapted to the environment. Two main resources used for producing biomass are analysed in detail: water (H_2O) and carbon dioxide (CO_2). Following micrometeorological approach, the eddy covariance technique has been used for monitoring H_2O and CO_2 exchanges between canopy and atmosphere in order to investigate the dynamics of the cardoon growth at field level and to compute the Gross Primary Production (GPP). The dynamics of canopy CO_2 assimilation in terms of GPP, evapotranspiration (ET) and water use efficiency (WUE_{GPP}, as ratio between seasonal GPP and seasonal ET and WUE_{agro} as ratio between yield and seasonal ET) were analysed during three successive growth seasons in a south Italy site. The environmental drivers of CO_2 assimilation and ET were analysed at instantaneous scale. The crop showed increasing resource use efficiency along the three seasons of experiment for all considered resources: in particular, for the last two seasons cumulated GPP increased and cumulated ET decreased. It seemed to require a season for its establishment to the environment, improving the use of water and CO_2 assimilation in the second and third season.

1. Introduction

The European Community perceives bioenergy as a mean to reduce its dependence on external energy supplies and to mitigate pressing issues of climate change. In fact, directive 2009/28/EC of 23 April 2009 on the promotion of the use of energy from renewable sources (http://ec.europa.eu/energy/renewables/biofuels/biofuels) established mandatory national targets consistent with a 20% share of energy from renewable sources in energy consumption by 2020.

Among energy from renewable source, the increasing biomass and biodiesel uses are key tools proposed to reduce the dependence on imported oil and oil products, thus improving the security of energy supply in the medium and long term, also through the cultivation of dedicated species, the so called energy crops. Among these, *Cynara cardunculus* L. var *altilis* D.C. was proposed as bioenergy crop, especially in the biofuel and lignocellulosic chains for heating or power production. Rather, cultivated cardoon is considered as one of the most promising first generation bioenergy crops, also in marginal rural locations with limited resources. In fact, it is a drought tolerant herbaceous perennial plant (Curt et al., 2002) and it can be easily propagated by seed with important advantages for crop management. Thus, it can be cultivated without irrigation (rainfed), hence it is particularly adapted to the Mediterranean environments, where the major limiting production factor is just water.

Cardoon was proved to carry out high yields (Foti et al., 1999; Piscioneri et al., 1999; Grammelis et al., 2008; Fernández et al., 2006; Ierna et al., 2012). Several works were published on its agronomics in Mediterranean region, demonstrating the strong potentiality of this crop as energetic source, both as biomass and biofuel from seeds (Raccuia and Melilli, 2007; Ierna and Mauromicale, 2010; Gominho et al., 2011) or, more marginally, for industrial and animal use (Christaki et al., 2012). After a long trial in Mediterranean region, Angelini et al. (2009) found that the average biomass yield of two cardoon cultivars obtained with 860 mm mean annual rainfall was 14 and 15 Mg ha^{-1} $year^{-1}$. In this case the maximum yield was reached at the third year for both cultivars. Gherbin et al. (2001) reported a decreasing cardoon yield from the first to the last (fifth in this case) season for all the 17 cultivars grown under Mediterranean climate. In this work the authors found that the yield of the different cardoon cultivars had a very large variability, ranging between 5 and 14 Mg ha^{-1} $year^{-1}$, with

* Corresponding author. Tel.: +39 0805475007; fax: +39 0805475023.
E-mail address: rossana.ferrara@entecra.it (R.M. Ferrara).

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500 mm mean annual rainfall. In all these previous studies the cardoon crop was cultivated in small plots (about 100 m^2), the typical ones for agronomic purpose investigations. Actually, there are no surfaces specifically dedicated to cardoon for energy in Italy.

However, to evaluate the adaptability of a crop to an environment, yield and its partitioning analysis is not enough (Fernández et al., 2005; Richardson et al., 2012). Conversely, it is essential to give information about the use of natural resources in forming biomass to assess agronomic benefit and environmental impact in a changing world. Long-term studies on CO_2 and water vapour exchange in agricultural ecosystems can improve the understanding on the biophysical factors affecting changes in the functionalities of this kind of cropping system (Beer et al., 2009; Suyker and Verma, 2010). For bioenergy crops, similar recent studies were carried out on reed canary grass in Finland (Shurpali et al., 2009, 2013), on young switchgrass in the northeastern USA (Skinner and Adler, 2010), on switchgrass in Oklahoma, USA (Wagle and Kakani, 2014), on miscanthus and switchgrass in Central Illinois, USA (Zeri et al., 2011).

Furthermore, present climate changes and climate variability impose that experimental investigations would be carried out in order to actualise the biological and physiological relationships among natural resources, climatic variables and agricultural crops (Fischer et al., 2007; Giannakopoulos et al., 2009; Espadafor et al., 2011).

Non-invasive and continuous measurements of energy and mass flow between a crop and its environment are essential for understanding crop growth and its interactions with the environment over time, and to compare and evaluate cropping systems (i.e. Asseng and Hsiao, 2000). The micrometeorological method eddy covariance (EC) is considered the most direct approach for measuring canopy gas exchange at ecosystem scale and, thus, the results can be more easily generalised.

This study was conducted in a field submitted to Mediterranean semi-arid climate, in order to understand how cardoon spends and uses water and CO_2 during three successive growth seasons. In particular, the analysis has been carried out by detailing the dynamics of canopy CO_2 assimilation, of evapotranspiration (ET) and water use efficiency (WUE), from emergence up to harvest, using an EC system for measuring H_2O and CO_2 fluxes at hourly scale. In our knowledge this is the first study on the topic for a bioenergy crop in Mediterranean climate.

2. Materials and methods

2.1. The site and the crop

The field site for monitoring carbon (C) and water fluxes of cardoon was the CREA-SCA Research Unit experimental farm located in southern Italy (Rutigliano-Bari, 41°01′N, 17°01′E, altitude 147 m a.s.l). The site is characterised by typical Mediterranean semi-arid climate, with mild winters and warm-dry summers. On average, the rain is 535 mm $year^{-1}$ mainly distributed between the autumn and the late winter. The annual water deficit (reference evapotranspiration (ET_0)—Rain) is 560 mm (Campi et al., 2009). The soil, classified as "Lithic Rhodoxeralf", is characterised by clay texture, stable structure, shallow profile (0.6–1 m), because of a cracked limestone subsoil, and fast drainage. On average, its Total Organic Carbon (TOC) content is 12.0 g kg^{-1}. Such a low value is due to high temperatures reached during the spring–summer seasons. The field capacity and the permanent wilting point water contents on dry soil weight are equal to 30 and 18%, respectively. Therefore, with a bulk density of 1.15 Mg m^{-3}, the available soil water ranges from 80 to 140 mm because the soil profile depth is affected by high spatial variability (De Benedetto et al., 2012).

The cardoon, selected at the Polytechnic University of Madrid for the adaptability to semi-arid environments, was sown on 31th October 2009 on an area of about 2 ha, with a plant density of 30,000 plants ha^{-1} and an inter-row spacing of 1.2 m. Main tillage was conducted in the autumn 2009 as medium-depth ploughing (0.3 m). Seed bed preparation was conducted immediately before sowing, by a pass with a disk harrow. Pre-plant fertiliser was distributed at a rate of 100 kgP_2O_5 ha^{-1} (triple superphosphate). Starting from the second growing season, the crop was managed with low inputs, by avoiding soil tillage and mineral fertilisation. No water was applied as irrigation so that the cardoon regrew immediately after the first rain in autumn.

During the seasonal growing cycle, plants were picked up every month with randomised samples. On each sample, the fresh and dry weight of biomass, the leaf area index (LAI) and the height were measured.

The aboveground biomass was harvested in summer (August 2010, 2011 and 2012) when the crop was completely dry (about 70–80% of dry matter (DM)). The plants were placed in a thermo-ventilated oven at 65 °C until constant weight. The production was finalised to extract the oil for energy purposes. The percentage of C in the harvested biomass content was determined in triplicate using an elemental analyzer (EA-1108 model, Fisons Instruments, Crawley, UK).

The phenological stages of the cardoon crop were registered according to Archontoulis et al. (2010), by recording the first day of each phase. In the spring of the fourth vegetation cycle (2013), the crop was fully destroyed by the insect *Cassida deflorata* Suffr. (order *Coleoptera*) which compromised once and for all the leaves and stems, interrupting the photosynthetic function of the plants. As a consequence, neither harvest occurred in the summer 2013 nor data could be collected. For this reason the experiment was limited to three successive crop growth seasons.

The results here presented are for 1009 days, from the sowing to the third cut and harvest of cardoon crop. In this work three growth seasons were considered as following: (1) first season, from sowing up to first harvest (1 November 2009–19 August 2010); (2) second season, from the first day after the first harvest up to second harvest (20 August 2010–9 August 2011); (3) third season, from the first day after the second harvest up to third harvest (10 August 2011–6 August 2012).

2.2. The setup

The EC flux tower was established in the field in November 2009 for making continuous measurements and the setup consisted of a three-dimensional sonic anemometer (USA-1, Metek GmbH, Germany) for acquiring the three wind component and sonic temperature and in a fast-responding open-path infrared gas analyser (IRGA, LI-7500, Li-COR Inc., Lincoln, NE, USA) in order to measure atmospheric CO_2 and H_2O concentrations. The sonic anemometer was positioned at 1 m above the top of the crop and was adjusted to follow its growth, the maximum height of the EC sensors was 2.8 m; the gas analyser was placed at 0.3 m to the side of the anemometer in order to ensure measurement of the same air particles and to avoid airflow distortions.

Micrometeorological measurements were recorded every 0.1 s (10 Hz) on an Industrial Computer (Advantech, USA) by a resident software (MeteoFlux, Servizi Territorio, S.n.c., Cinisello Balsamo, Italy) and were collected on a continuous hourly basis. Net radiation, R_n in W m^{-2}, was measured by means of two net radiometers (model Q*6, REBS, USA) 1 m above the top of the canopy. Soil heat flux, G in W m^{-2}, was measured by means of two heat flux plates (FP-1, Campbell Sci., USA), placed at 0.1 m depth into the soil. R_n and G were collected by a CR10X (Campbell Sci., USA) data logger at a frequency of 0.1 Hz and stored for 1 h on average. Soil