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Miscanthus, switchgrass, giant reed, and bulbous canary grass as potential bioenergy crops in a semi-arid Mediterranean environment

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ABSTRACT

Perennial grasses have received particular attention as bioenergy crops in recent years due to their high biomass productivity and environmental benefits. The objective of the present study was to compare four perennial grasses: miscanthus (*Miscanthus x giganteus* Keng), switchgrass (*Panicum virgatum* L.), giant reed (*Arundo donax* L.), and bulbous canary grass (*Phalaris aquatica* L.) in terms of biomass yield, energy balance, and biomass quality under four nitrogen fertilization rates (0, 100, 150, 200 kg $ha^{-1}y^{-1}$) and 2 harvest times (autumn, winter) over three growing seasons in the Mediterranean environment of Turkey. The crop biomass and net energy yields were optimized with none or 100 kg ha^{-1} y^{-1} N input in the study. Although the winter harvest resulted in significant yield reductions in all of the grass species, it improved the biomass quality of miscanthus, switchgrass, and giant reed due to reduced moisture and ash contents. On the contrary, the autumn harvest resulted in a considerably lower moisture and ash contents in bulbous canary grass, mainly because of leaf defoliation the during summer dormancy period. Giant reed produced the highest average biomass yield (between 12.86 and 36.78 t ha^{-1}) over the three years, followed by miscanthus (between 12.75 and 23.54 t ha^{-1}), switchgrass (between 11.88 and 18.91 t ha^{-1}), and bulbous canary grass (between 5.21 and 10.83 t ha^{-1}). On the other hand, bulbous canary grass provided the highest average energy ratio (19.7–64.5) over the three years, due mainly to a lack of energy input for irrigation. These results suggest that satisfactory biomass production can be achievable from miscanthus, switchgrass, and giant reed in the semi-arid Mediterranean environment under adequate moist conditions, but the irrigation requirement increases the energy cost, thus decreasing the energy ratio. In this respect, bulbous canary grass may be evaluated as an alternative bioenergy crop in the dry marginal lands of Mediterranean for sustainable biomass production.

1. Introduction

The inevitable depletion of fossil fuel sources and their adverse effects on the environment, particularly greenhouse gas (GHG) emissions have dramatically raised the tendency toward renewable energy sources worldwide (Chen et al., 2012). The utilization of biomass for bioenergy production is an important form of renewable energy, which can substitute fossil fuels, and thereby allow GHG mitigation (Meyer et al., 2017; Xu et al., 2017). Among bioenergy crops, perennial rhizomatous grasses, such as miscanthus (*Miscanthus x giganteus*), switchgrass (*Panicum virgatum* L.), and giant reed (*Arundo donax* L.) have received much attention due to their many advantages, including higher biomass productivity and GHG saving potentials, efficient water and nitrogen uses, and lower input requirements in comparison to conventional crops (Lewandowski et al., 2003a; Pedroso et al., 2014). Miscanthus and switchgrass, which have a C_4 photosynthetic pathway, have been most extensively studied as dedicated bioenergy crops around the world (Pedroso et al., 2014). Miscanthus is currently cultivated in Europe on about 20,000 ha of land for local co-firing in heat and power plants (Don et al., 2012; Lewandowski et al., 2016). Switchgrass originated in North America and has been proposed as a prominent crop to be cultivated on marginal croplands and conservation reserve program lands in the USA, which may play an important role in achieving the USA government's 2030 bioenergy goal, predicting that 30% of the petroleum usage will be displaced by biofuels (Heaton et al., 2004; Dohleman et al., 2009). On the other hand, giant reed, a C_3 perennial grass, has been considered as a valuable biomass feedstock for temperate regions, like the Mediterranean, due to its higher biomass yield potential relative to miscanthus and switchgrass under adequate water availability conditions (Christou et al., 1999;

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Angelini et al., 2009; Mantineo et al., 2009; Kering et al., 2012; Burner et al., 2015). However, giant reed is considered as an invasive plant and has been included in the world's 100 worst alien invasive species (Lowe et al., 2000; Pilu et al., 2012). Therefore, its cultivation on a large scale for biomass production could result in multiple threats for agriculture, biodiversity, and riparian ecosystems in the future (Moran and Goolsby, 2009; Coffman et al., 2010).

Each of the crops accumulate their biomass mainly during the spring and summer in dry Mediterranean areas where the prolonged and severe summer drought frequently occurs, which may become the main bottleneck to maintain productivity and crop survival (Clifton-Brown et al., 2001; Vamvuka et al., 2010). This concern was clearly justified in previous studies that showed a remarkable decrease in the rhizome viability (Mann et al., 2013), number of tillers, leaf area index (Barney et al., 2009), and biomass productivity (Petrini et al., 1996; Christou et al., 2001; Vamvuka et al., 2010; Cosentino et al., 2014; Giannoulis and Danalatos, 2014), which became generally unavoidable in miscanthus, switchgrass, and giant reed as a consequence of prolonged severe drought. For this reason, irrigation support is generally necessary to ensure good establishment and high biomass productivity in the cultivation of these crops in large areas of the Mediterranean basin where crop growth is restricted by low water availability and high evapotranspiration rates during summer (Vamvuka et al., 2010; Zema et al., 2012). Unfortunately, irrigation is unlikely to provide any economic advantages due to its high cost for biomass production, which must be accomplished with minimum input (Bullard, 2001; Clifton-Brown et al., 2004). Additionally, irrigation support often requires large amounts of energy and has a negative impact on the CO_2 balance of energy crops and leads to higher N_2O emissions through increasing decomposition of nitrogen (Liebig et al., 2005; Prueksakorn and Gheewala, 2006; Zegada-Lizarazu et al., 2010). More importantly, the allocation of irrigation water to cereal crops instead of bioenergy farming in arid and semi-arid areas may provide more benefits with respect to global food security, considering the fact that worldwide useable water resources have been threatened by global climate change and the rapidly rising human population (Hanjra and Qureshi, 2010; Misra, 2014).

Environmental and economic challenges associated with biomass production from high-yielding bioenergy crops (miscanthus, switchgrass, and giant reed) in semi-arid areas have generated notable interest on the biomass utilization of perennial C_3 grasses, also called 'cool-season grasses' (Maletta et al., 2012). The vegetative growth of most C_3 grasses occurs during rainy seasons (autumn, winter, and spring) and they complete seed setting until the end of the June, when their aboveground biomass becomes senescent in the Mediterranean environment. Hence, this growing method enables them to cope with severe summer drought via summer dormancy and dehydration tolerance (Ofir and Kigel, 1999; Volaire et al., 2009). Eventually, some cool-season grasses may produce satisfactory biomass yields in arid and semi-arid areas under rain-fed or less watered conditions with low cost and high benefits, unlike miscanthus, switchgrass, and giant reed (Maletta et al., 2012; Monono et al., 2013; Porensky et al., 2014).

In this context, bulbous canary grass (*Phalaris aquatica* L.), a *phalaris* species, has currently been under consideration as a biomass feedstock, particularly in the Mediterranean environment, due to its high biomass productivity potential and drought tolerance (Pappas et al., 2012, 2014; Maletta et al., 2012). It is native to the Mediterranean environment and has been utilized as a traditional forage crop, especially in Southern Australia, where rainfall is very low and unreliable (Norton and Volaire, 2012). Summer dormancy traits and deep rooting (up to 2.3 m) behaviour are particularly important under drought persistent conditions, which allow the crop to survive in regions receiving only 200–250 mm of annual rainfall (Neal-Smith, 1955). The crop can produce a dry biomass yield exceeding 20 t ha^{-1} and grow up to 250-cm in Mediterranean regions receiving more than 400 mm of rainfall during its vegetative growth period (approximately between October and May) (Saglamtimur et al., 1986; Tansı, 2009; Alexopoulou et al., 2013; Pappas et al., 2014). Therefore, investigation of bioenergy crop performance of the crop in rain-fed Mediterranean areas is essential to examine whether it can be considered as a promising biomass feedstock for the dry marginal land of the Mediterranean where miscanthus, switchgrass and giant reed require irrigation support to produce satisfactory biomass yields.

For a species to be considered as an energy crop, it must provide a combination of high biomass yield and good combustion quality (o Di Nasso et al., 2010). The ash and moisture contents are the important factors when determining biomass quality. A high moisture content impedes the ignition of biomass, reduces the calorific value, and increases storage losses (Lewandowski and Kicherer, 1997). Hence, the moisture content at the time of harvest should not exceed 25% to enable the long-term storage of the biomass without molding, provided that natural ventilation is provided (Lewandowski et al., 2000). A high ash content reduces the calorific value of the biomass, just as a high moisture content does, and also causes slagging, corrosion, and fouling during combustion (Lewandowski and Kicherer, 1997).

Despite the fact that a considerable amount of research (Christou et al., 1999; Alexopoulou et al., 2008; Angelini et al., 2009; Mantineo et al., 2009; Zema et al., 2012; Giannoulis and Danalatos et al., 2014; Pedroso et al., 2014) has comprehensivelyrevealed the biomass and energy productivity of miscanthus, switchgrass, and giant reed in the Mediterranean environment so far, side-by-side comparisons between these crops and rain-fed cool-season grasses are scarce in the peer reviewed literature. Therefore, the objective of the present study was to compare four perennial rhizomatous grasses (miscanthus, switchgrass, giant reed, and bulbous canary grass) with regards to their biomass yield, biomass quality, and energy balance under four nitrogen fertilization rates (0, 100, 150, 200 kg ha^{-1} y^{-1}) and two harvest times (autumn, winter) in this study, in order to reveal their bioenergy crop performance for solid biofuel production in a semi-arid Mediterranean environment.

2. Materials and methods

2.1. Crop culture

Some details of the agronomic techniques implemented in this study were described previously by Nazli et al. (2015). The field experiment was conducted between November 2013 and February 2017, covering 3 growing seasons for each crop at an Experimental site at the Agricultural Faculty of Cukurova University in Adana (370 01′N, 350 18′E), Turkey. The soil at the site had a clay-loam texture and a low level (1.11%) of organic matter (Table 1). Four different rhizomatous perennial grasses were compared in the study: miscanthus (provided by Energiepflanzen Oberhofen, Austria), switchgrass (Alamo), giant reed (local ecotype), and bulbous canary grass (local ecotype). Rhizomes of giant reed and vegetative clones of bulbous canary grass were mechanically extracted from the soil, while cleaning and partition phases were compulsorily based on manual practices in the study, due to lack of essential technological equipment. Tillage was carried out in two

Table 1
Initial chemical and physical properties of the soil.

Property	Depth (0–30 cm)
Texture	Clay-loam
Organic matter (%)	1.11
pH	7.8
Salt (mmhos cm^{-1})	0.04
Lime (%)	12.76
Available P (mg kg^{-1})	36
Available K (mg kg^{-1})	2847

mg: milligram, kg: kilogram, mmhos: milliMhos, cm: centimetre.