available at www.sciencedirect.com

ScienceDirect

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

Effect of modern irrigation methods on growth and energy production of sweet sorghum (var. Keller) on a dry year in Central Greece

M. Sakellariou-Makrantonaki [a,*], *D. Papalexis* [a], *N. Nakos* [a], *I.K. Kalavrouziotis* [b]

[a] *University of Thessaly, School of Agricultural Sciences, Department of Agriculture, Crop Production and Rural Environment, Agriculture Hydraulics Laboratory, Volos, Greece*

[b] *Department of Environmental and Natural Resources Management, University of Ioannina, Seferi 1, 30100 Agrinio, Greece*

ARTICLE INFO

Article history:
Accepted 2 March 2007
Published on line 2 May 2007

Keywords:
Bio-ethanol
Drip irrigation
Growth and production analysis
Subsurface irrigation
Sweet sorghum
Water use efficiency

ABSTRACT

The subject of this project is to estimate the growth and productivity of sweet sorghum [*Sorghum bicolor* (L.)] var. Keller, under two different irrigation methods – the conventional surface drip method (two treatments) and the subsurface drip method – in a dry year in Central Greece, as an energy crop for the production of bio-ethanol. A field experiment was carried out on the experimental farm of the University of Thessaly during 2005, comprising of a completely randomized block design with four treatments in four blocks, including control (non-irrigated). In the treatments of surface drip method the evapotranspiration needs were satisfied by using full (100% ETm) and supplement (80% ETm) irrigation doses, while in the treatments of subsurface drip method only supplement irrigation water was used (80% ETm) with the aim of more efficient water conservation. Irrigation was fully automated, and application depths were determined, using a class A open evaporation pan for matching the evapotranspiration needs. The growth of the crop was measured by means of plant height and leaf area index, which were determined periodically throughout the growing period. Fresh and dry biomass productions were measured over six harvests covering the entire growth and production process of cultivation. The results of the first year demonstrated a clear superiority of the subsurface drip method on plant heights, leaf area index and total fresh and dry biomass production compared with the surface drip method for equal values of irrigation water. Maximum yield was attained by mid-September, before crop maturation, something which should be taken into consideration when choosing the best harvesting time of the crop. After late September, large negative growth rates were recorded, resulting in an appreciable drop in the final fresh and dry matter yield.

1. Introduction

In the last decade the scientific community has become interested in crops from which bio-diesel and bio-ethanol can be produced, because of the depletion of existing fuel reserves. Perhaps the greatest challenge of this century will be the development of sustainable alternatives to oil as a source from which liquid fuels can be made. The new agricultural policy of the E.U., stipulates that the production of energy from alternative (renewable) sources in Greece reach 5.75% by

* *Corresponding author*. Tel.: +30 4210 93059; fax: +30 4210 93060.
E-mail address: msak@agr.uth.gr (M.S. Makrantonaki).
0378-3774/$ – see front matter
doi:10.1016/j.agwat.2007.03.004

2010 (European Commission, 2000). Sorghum [*Sorghum bicolor* (L.) Moench] is one of many plant species that have potential for this purpose.

Sorghum, a C_4 plant of tropical origin (uses the ''malate'' cycle), is the fifth most important cereal crop and can be used for green fodder, thatch and silage and the production of syrup and fuel (ethanol). It is grown in 99 countries around the world on 44 million ha, mainly in poor and semi-arid areas which are too dry for maize. Domesticated possibly in Ethiopia between 5000 and 7000 years ago, it has high photosynthetic efficiency and low fertilizer requirements, making it greatly advantageous when used in a crop rotation scheme with its high biomass yields and dry matter accumulation rates, sorghum has received considerable attention during the last years as an alternative source for energy production. Previous research has stressed that the crop is well adapted to warm southern E.U. regions, especially in diverse geographic locations throughout Greece (Dalianis, 1996; Chatziathanassiou et al., 1998; Alexopoulou et al., 2000). Sorghum, compared to other crops is more environmentally friendly from the agronomic point of view (Dalianis, 1996), particularly because of its relatively low nitrogen needs (Dercas et al., 1995; Duarte et al., 2000) and water requirements (Mastrorilli et al., 1995; Curt et al., 1995). Sweet sorghum is characterized by high sugar content in the juice of the stalks, mainly sucrose and also fructose and glucose, which can easily produce ethanol used as fuel in vehicles. Sweet sorghum has also been called ⟨⟨a camel among plants⟩⟩ (FAO, 2002) because of its wide adaptability, its resistance to saline-alkaline soils and water-logging. It is for this reason that sweet sorghum has become a very popular energy plant throughout the world. More specifically, the Keller variety has high biomass and sugar productivity depending on the harvest time, about 8–11.5% total sugar content of fresh biomass yield (Kavadakis et al., 2000) or 9–14.5% total sugar content of fresh stalk yield (Dalianis et al., 1995; Alexopoulou et al., 1998). The Keller variety of sweet sorghum has proved to be the most adaptable and so the best producing energy plant for the Mediterranean climate. This is mentioned in experiments by Curt et al. (2000) in Spain (height of plants = 3.5 m, dry biomass 28.5 Mg ha^{-1} and percentage of sugar fermentation 43% by the total dry biomass of the plants), Dalianis et al. (1994) in different areas of Greece (height of plants >330 cm, fresh biomass 103.4 Mg ha^{-1} and sugar percentage by the total fresh biomass of the plants 11.1–13.2%), Alexopoulou et al. (1998) also in Greece (height of plants ≥3.5 m, dry biomass 30–39 Mg ha^{-1} and percentage of sugar fermentation 9.5–11.4% by the total fresh biomass of the plants), Roman et al. (1998) in their experiment in Rumania (dry biomass 28 Mg ha^{-1} and total fresh biomass 114 Mg ha^{-1}) and finally Foti et al. (2004) in their experiment in Italy—dry biomass 21–27 Mg ha^{-1}.

Also, previous research showed that 1 Mg of dry biomass corresponds to 0.4 Mg of oil equivalent (Dolcioti et al., 1996) and 1 kg sucrose can give us 538–700 g or 648–843 l bio-ethanol ([1]S.G.$_{Ethanol}$ = 0.789–0.870 kg l^{-1}) (Wilhoit and Zwolinski, 1973; Bryan et al., 1981; Smith et al., 1987; Soldatos and Chatzidaki, 1999; U.S. Department of Energy, 2005). Ethanol, a great weapon in the fight against vehicular pollution because of its high oxygen content, helps complete the combustion of fuel and thus reduces harmful exhaust emissions and also reduces particular emissions that pose a health hazard.

Considering sweet sorghum as an alternative energy crop in the near future that requires (supplemental) irrigation under Greek conditions, the crop could be irrigated using existing irrigation methods and systems. Surface drip irrigation has been common practice in many orchards and vineyards since as early as the 1980's in Greece. A variation of the conventional surface drip irrigation method is subsurface drip irrigation, which is nowadays gaining ground in many irrigated areas in Central Greece (Sakellariou-Makrantonaki et al., 2001, 2003, 2005, 2006). According to this method the laterals are buried at a certain depth below the soil surface depending mostly on crop type and tillage practices. Many advantages of this method are reported in the bibliography. Firstly, since the drip system is buried, irrigation system performance is unaffected by surface infiltration characteristics. On the other hand, the upper soil has lower volumetric soil water content so that evaporation is practically eliminated. A relatively dry soil surface permits farm equipment access and movement during the whole irrigation period and eliminates weed growth; it restricts root rot and other soil diseases and prevents crust formation that inhibits soil aeration and rainfall water infiltration into the soil causing surface runoff (Phene et al., 1993). A subsurface irrigation system is not exposed to the sun and extreme weather conditions, meaning longer material life (7–12 years). Using such systems, irrigation water and injected fertilizers are delivered directly to the crop's rooting zone; this is particularly advantageous for nutrients with low mobility in the soil (Solomon, 1993). The permanent installation of this system below the plough layer, thus appreciably reducing the labor costs, is also very advantageous. The high installation cost and the difficulty of inspecting and repairing the system may be considered disadvantages to this method. Another concern is the ability of the system to provide adequate soil water conditions for germination. This necessitates the use of sprinkle systems for crop establishment.

Based on the above, and considering sweet sorghum [*S. bicolor* (L.) Moench] var. Keller as a possible alternative crop for biomass production in Central Greece in the near future, the present work focuses on the growth and biomass productivity of this crop as affected by the two existing irrigation methods, i.e. the surface drip and the subsurface drip, under full and supplementary irrigation schemes.

2. Materials and methods

The evolution of growth and the biomass productivity of the sweet sorghum [*S. bicolor* (L.) Moench] var. Keller, were studied under field conditions in Central Greece (experimental farm of the University of Thessaly in Velestino—latitude 39°23′, longitude 22°45′, altitude 50 m above sea level) in 2005 using a randomized block desing with four treatments (subsurface drip, 80% ETm; surface drip, 100% ETm; surface drip, 80% ETm and control, non-irrigated) in four replicates. The treatments comprise the two different irrigation methods, the surface drip and the subsurface drip, and a dry crop as control. In the

[1] Specific gravity of ethanol (at 20–28 °C).

treatments of the surface drip method the evapotranspiration needs were satisfied by using full (100% ETm) and supplement (80% ETm) irrigation doses, while in the treatments of the subsurface drip method only supplement irrigation water was used (80% ETm) with the aim of more efficient water conservation. The measurements of each experimental block were $10 \times 5 = 50\ m^2$ and the total surface of every treatment was 200 m^2. So, the total surface of the experimental field was 800 m^2, excluding, of course, the paths in between the sections in use and the central road of supervision.

The crop was sown on May 9th, 2005 at distances 0.8 m between the lines and 14.3 cm between the plants (total plant density 8.4 plants m^{-2}). All treatments received the amount of irrigation, at regular intervals, matching 80 and 100% of the evapotranspiration needs (approximated using the class A open evaporation pan method). According with the general consideration of introducing biomass crops and particularly sorghum, in low-input farming systems in Central Greece, fertilization was not applied.

The laterals of both the surface and subsurface drip systems were a 20 mm polyethylene pipe with in-line RAM self regulated emitters (Netafim Company) discharging at a constant low rate of 3.6 l h^{-1}. Surface and subsurface drip irrigations were applied in rows of 1.6 m apart and 0.6 m between the emitters, thus recharging 3.75 mm h^{-1}. The fully automatic subsurface irrigation system was placed at a depth of 0.45 m from the soil surface. It was additionally equipped with a vacuum breaker valve to prevent any water suction and consequently emitter clogging when irrigation pauses, and also with a disk filter enriched with triflouralin, which was injected during irrigation to prevent root intrusion. The irrigation control valves were connected to an irrigation controller (microcomputer miracle) in order to make irrigation fully automated. During the total irrigation period (first 10 days of June to the end of September) 32 application depths were accomplished with a total irrigation input of 659 mm in the treatments of full surface irrigation, and 527 mm in the treatments of supplement surface and subsurface irrigation, according to evapotranspiration needs. Considering the amount of rain falling during the irrigation period of 2005 (the first 10 days of May to the early days of October), which was 112 mm (see later Fig. 1), the total water input for full and supplement irrigation treatments were 777 and 637 mm, respectively (including soil water storage).

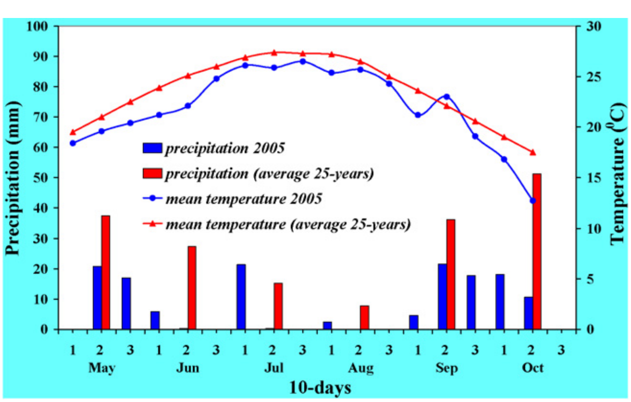

Fig. 1 – Temperature and precipitation (10-days mean values) occurring in the study area during the growing period of sweet sorghum in 2005 and in an average year.

The growth of the crop was measured by means of plant height and leaf area index, which were recorded in periodical samplings throughout the growth period. The leaf area index was measured using the LAI-COR detector of Biosciences (type LI-3100C area meter). Biomass production (above ground part) was measured in six harvests, during the whole growth period, specifically on the dates 16/7, 4/8, 27/8, 17/9, 1/10 and 22/10/2005. Leaf blades and stalks were harvested separately. All samples were dried at 90 °C until weight stabilization. For the measuring of volumetric soil water content, the time domain reflectometry method was used, which is especially accurate and completely safe. The volumetric soil water content readings were carried out before each irrigation and 1 day after, in all treatments up to depths of 1.2 m below the surface, with the aim of better irrigation efficiency. Meteorological data (daily maximum and minimum air temperature and precipitation rates) were recorded at in a fully automatic meteorological station, which was installed at a distance of approximately 50 m from the center of the experimental field. The evaporation A pan was installed inside the meteorological station in order that all the necessary equipment for research into climatic data were gathered under the same roof.

3. Results and discussion

3.1. *Weather data*

The study area of the experimental field in Velestino is characterized by a typical Mediterranean climate with hot and dry summers and cool-humid winters. The air temperature and precipitation (10-day average values) prevailing at the experimental site during the growing period of 2005 and in an average year, is schematically presented in Fig. 1. It can be seen that the air temperature during the study period did not fluctuate much from its values of an average year. It was slightly lower than average (up 1 or 2 °C) in early summer ranging from about 19 °C in mid-May to 25 °C in late June. It remained constant at about 25–26 °C during July and early August, and dropped in values between 19 and 23 °C from mid-August to early September and remained below 17 °C until the first fortnight of October. With the exception of May (total rainfall 38 mm), the growing period of 2005 was particularly dry with only 103 mm of rain falling during the period from the beginning of June until mid-October.

Under such conditions and more generally under the conditions in Central Greece, most summer crops, including sorghum, need irrigation to reach acceptable yields (Fig. 1).

3.2. *Growth analysis*

3.2.1. *Plant heights*

The growth analysis of sweet sorghum as reflected by means of plant heights for each treatment illustrated in Fig. 2. It can be observed that initially all treatments, except control, produced similar growth rates (1.8–2.4 cm d^{-1} in height) to reach a height of about 1 m by mid-July. This is apparently due

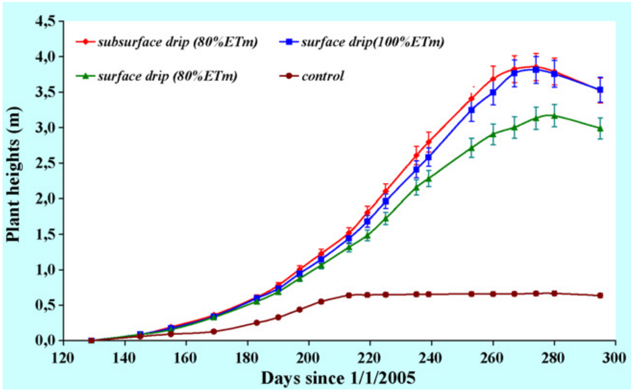

Fig. 2 – Plant height development of sweet sorghum under different irrigation methods in Central Greece in 2005 [vertical bars reflect L.S.D. ($^{*}P < 0.05$)].

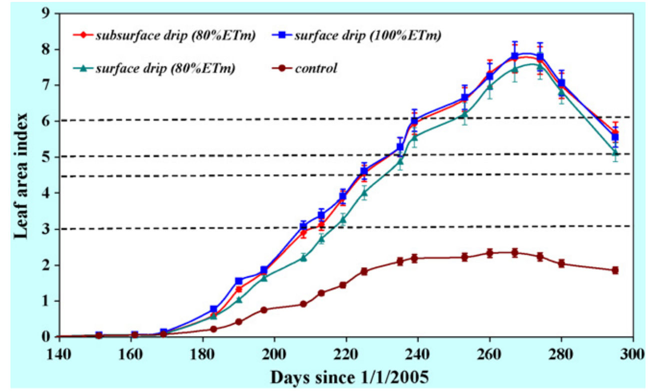

Fig. 3 – The development of leaf area index of sweet sorghum under different irrigation methods in Central Greece in 2005 [vertical bars reflect L.S.D. ($^{*}P < 0.05$)].

to the initial use of the water stored in the soil before the onset of irrigation (by late May, see earlier).

One and a half months after the initiation of the drip irrigation, full surface drip and supplement subsurface drip irrigated plants exhibited remarkable growth rates, e.g. 2.7–3.3 cm d^{-1}, in the period between the second half of July up to the end, respectively. A substantially smaller growth was observed in the sorghum plants receiving supplement surface drip irrigation (about 2.0–2.8 cm d^{-1}) so it was a little taller than 2 m by the end of August. It can also be observed that initially the plants subjected to all treatments, except control, exhibited high growth rates (4.3–5.0 cm d^{-1}), in the period between the second half of August up to the early days of September, reaching particularly great mean heights of 385, 381 and 316 cm for subsurface drip, full surface and supplement surface drip irrigation, respectively, by the early days of October (Fig. 2).

After the first days of August, a clear superiority in growth was noticed in the treatments that plants receiving supplement subsurface and full surface drip irrigation water, as opposed to the plants receiving only supplement surface drip water ($^{*}P < 0.05$) as can be seen in Fig. 2. On the contrary, there was no statistical significant difference found in growth rates of plant heights, final or mean, between the plants that were irrigated by subsurface and full surface drip water.

Taking these facts into account, the superiority of subsurface over the surface drip method, for equal water doses, owing to the direct access of water to the root zone the maintenance of acceptable rates of volumetric soil water content for 3–5 days after irrigation ends in the treatments of the subsurface drip irrigation method.

3.2.2. *Leaf area index*

Fig. 3 illustrates the development of leaf area index under the various irrigation methods throughout the growing period of sweet sorghum, in 2005, in Central Greece.

Leaf area expansion is of great importance for light interception and photosynthesis; it varies according to the quantity of assimilation allocated to the production of leaves and the ratio of the leaf area produced per unit of leaf dry matter. Many studies consider maximum assimilation when the leaf area index reaches values above 4–5, whereas values relatively lower than three characterize open leaf canopies and considerable loss in photo-synthetically active radiation.

It can be observed that the leaf area index of the plants irrigated with the full surface drip and the supplement subsurface drip methods were always greater than the plants receiving supplement surface drip irrigation water throughout the growing period. There were statistical significant differences ($^{*}P < 0.05$) between the two irrigation methods, both with equal application doses, only for the period between the end of July to the mid-August and before these rates reached value 5. This difference did not last until the end of growing period of the crop (Fig. 3).

In 2005, the canopy results were already satisfactory by the end of August (leaf area index >6), so it might be interesting to determine for how long these rates of leaf area index were higher than values 3 and 5. So, the total time in subsurface drip treatment was 83 and 61 days, in full surface drip treatments 87 and 62 days, and in supplement surface drip treatments 79 and 57 days, respectively. This minor difference gave the plants that were irrigated with the subsurface drip method the opportunity to achieve higher productive rates against the other method under equal irrigation doses.

It should be noted that unpublished results on sweet sorghum (cv. Keller) by CRES justify maximum leaf area index values of about 4.5, under conditions of moderate (drip) irrigation and no fertilization.

It might thus be concluded that further reduction in water inputs (see Fig. 3, control values), i.e. matching less than half of the evapotranspiration needs, would enhance the risk of an open canopy and thus an appreciably greater loss in assimilation and productivity, and should be seriously taken into consideration under the xerothermic conditions of this study.

3.3. *Production analysis*

3.3.1. *Fresh and dry biomass production*

The evolution of dry biomass yield of sweet sorghum in 2005, under the two-irrigation methods plus control (non-irrigated) is schematically presented in Fig. 4. It can be observed that the

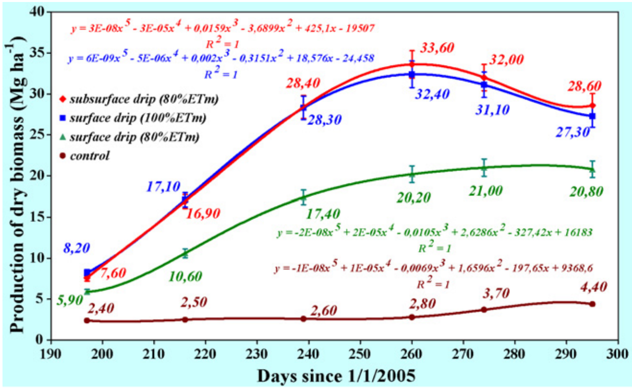

Fig. 4 – The development of the total (above ground) dry biomass of sweet sorghum under different irrigation methods in Central Greece in 2005 [vertical bars reflect L.S.D. ($^*P < 0.05$)].

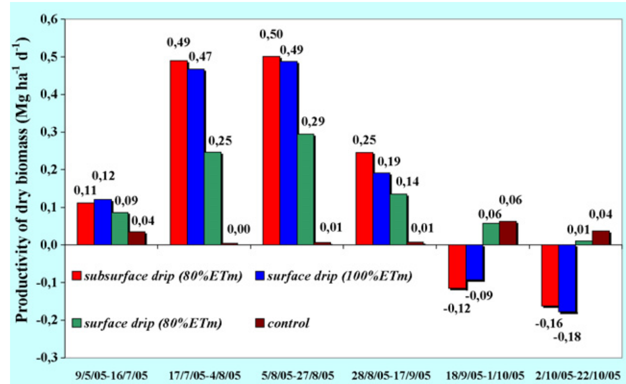

Fig. 5 – The development of dry biomass productivity of sweet sorghum under different irrigation methods in central Greece in 2005.

plants which received supplement subsurface and full surface irrigation water exhibited higher biomass rates than those which received supplement surface irrigation, demonstrating the clear superiority ($^*P < 0.05$) of the subsurface drip irrigation method, for equal irrigation inputs, on the growth and productivity of the crop. This should be attributed both to the supply of the water directly to the root zone and to the effectiveness of the irrigation, with respect to the minimization of evaporation losses from the soil surface which remained dry in the case of subsurface drip irrigation, as mentioned earlier.

Maximum dry biomass production was attained for subsurface and full surface drip treatments by the second half of September and for supplement surface drip treatments about 2 weeks later, and it was 33.6, 32.4 and 21.0 Mg ha^{-1}, respectively. As far as the total fresh biomass production is concerned, it was achieved during the same period for all treatments except control and it reached the rates of 148.2, 138.2 and 85.1 Mg ha^{-1} for subsurface drip, full surface drip and supplement surface drip treatments, respectively. On the other hand, the maximum fresh and dry biomass production of control treatments was attained by the end of October and it reached the rates of 14.1 and 4.4 Mg ha^{-1}, respectively (Fig. 4).

More specifically as one can observe in Fig. 5 during the period between 5/8 and 27/8 the following productivity rates were reached 0.50 Mg ha^{-1} d^{-1} for subsurface drip and 0.49 Mg ha^{-1} d^{-1} for full surface drip treatments. Maximum productivity rate for supplement surface drip treatments was attained in the same period and it was 0.29 Mg ha^{-1} d^{-1}. Such productivity values are particularly high and should seriously be considered in future studies of farming systems with low inputs (Fig. 5 presents the productivity rates of all growing periods). During the period between 2/10 and 22/10 water limited biomass production decreased at appreciable negative rates, especially in the treatments of subsurface and full surface drip irrigation (approximately 0.16–0.18 Mg ha^{-1} d^{-1}). On the contrary, in supplement surface drip (80% ETm) and control treatments negative rates of growth throughout the duration of developmental activity were not observed. This of course is the best proof for the characterization ⟨⟨amel among plants⟩⟩ (Fig. 5).

It can be seen that the final yield dropped to 28.6 Mg ha^{-1} for subsurface drip treatments and 27.3 Mg ha^{-1} for full surface drip treatments, about 5.0 Mg ha^{-1} lower than the peak attained a month earlier. Such negative growth rates and considerable yield decreased at late crop growth were attributed to leaf senescence as well as the increased respiration losses which could not be matched by crop assimilation late in the season. Obviously, the time that maximum yield of sorghum is attained should be taken into consideration for choosing the best harvesting time of the crop (about 120–130 days after sown).

Quite a high performance rate, which fluctuated from 16.1 to 31.9 Mg ha^{-1} of dry biomass of the Keller variety, was noticed in an experiment conducted in the area of Piacentza, Italy, the purpose of which was research on tolerance and productivity levels of sweet sorghum in cooler Mediterranean climates (Habyarimana et al., 2002). Respectively, high productivity and growth rates were noticed in an experiment carried out in the Peninsular area of Portugal, using three different nitrogen fertilization rates (Duarte et al., 2000). In addition, high productivity in fresh biomass (90.3–121.7 Mg ha^{-1}), dry biomass (26.1–35.3 Mg ha^{-1}) and the height of the plants (283–310 cm) was established in experiments conducted in five different areas of Northern Greece using two different irrigation rates, three plant populations and two nitrogen fertilization rates (Alexopoulou et al., 2000). Also, high yield of dry biomass were noticed in different areas of Europe. In Central Spain 16–40 Mg ha^{-1} (Curt et al., 1995), 25 Mg ha^{-1} in France (Tayot et al., 1995), 30.4 Mg ha^{-1} in Southern Italy (Perniola et al., 1996) and 22.9 Mg ha^{-1} in Hungary (Hunkar, 1996).

3.3.2. *Energy production*

As previously discussed (see Section 1), there is high sugar content in the juice of the sweet sorghum stalks. Sucrose, fructose and glucose are the main components of the sugar in the sweet sorghum stalks that produce alcohol fuel (bio-ethanol). The sucrose content in the sweet sorghum stalk juice

Table 1 – Theoretical maximum, minimum and average of ethanol yield (l ethanol ha^{-1}) of sweet sorghum (var. Keller) under different irrigation methods in Central Greece

Parameters	Subsurface drip (80% ETm)	Surface drip (100% ETm)	Surface drip (80% ETm)	Control
Total fresh biomass (Mg ha^{-1})	148.20	138.20	85.10	14.10
Percentage of stalks on total fresh biomass (%)	85.0	83.0	82.0	59.0
Theoretical ethanol yield (10% sugar)-Formula 1 (l ha^{-1})	8,180	7,630	4,690	770
Theoretical ethanol yield (12% sugar)-Formula 1 (l ha^{-1})	9,810	9,150	5,640	930
Theoretical ethanol yield-Formula 2 (l ha^{-1})	10,190	9,280	5,650	670
Theoretical ethanol yield (538 g ethanol kg^{-1} sucrose)-Formula 3 (l ha^{-1})	8,150	7,420	4,520	540
Theoretical ethanol yield (700 g ethanol kg^{-1} sucrose)-Formula 3 (l ha^{-1})	10,600	9,660	5,880	690
Theoretical ethanol yield (5.2 g ethanol 100^{-1} g^{-1} fresh biomass)-Formula 4 (l ha^{-1})	6,540	5,960	3,620	430
Theoretical ethanol yield (8.4 g ethanol 100^{-1} g^{-1} fresh biomass)-Formula 4 (l ha^{-1})	10,570	9,620	5,850	690
Maximum ethanol yield (l ha^{-1})	10,600	9,660	5,880	930
Minimum ethanol yield (l ha^{-1})	6,540	5,960	3,620	430
Average ethanol yield (l ha^{-1})	9,150	8,390	5,120	670

is dominant and it remains relatively stable throughout the growth stages, in contrast to the glucose and fructose contents, which were found to be higher or lower depending mainly on the harvest time (Table 1).

A theoretical way of calculating the production of ethanol from the fresh biomass of sweet sorghum was expressed by Lipinski (1978) and is formulated as: total ethanol production (l ha^{-1}) = total sugar content (%) in fresh matter × 6.5 (a conversion factor) × 0.85 (the process efficiency) × fresh biomass in Mg ha^{-1} [Formula 1].

In the measurings which took place (Pari and Ragno, 1998), it was found that 1 kg fresh biomass of sweet sorghum can produce 0.081 l of ethanol [Formula 2].

In another evaluation work (Soldatos and Chatzidaki, 1999), the ethanol production was calculated by this formula: 64.8–84.3 l ethanol × total fresh biomass (Mg ha^{-1}) × percentage of stalks in total fresh biomass (%) [Formula 3].

Finally, Mamma et al. (1996) mention that the modifications in the chemical composition of the sweet sorghum plants (Keller variety), depending on the time of harvest, reflect corresponding changes in the final ethanol production (the best production: 5.2–8.4 g ethanol per 100 g of fresh biomass or 36%, w/v) [Formula 4].

Fig. 6 schematically illustrates the maximum, minimum and average production, depending on the total sugar content, of ethanol during the growing period of sweet sorghum in 2005, in Central Greece (the best harvest time for subsurface drip, full and supplement surface drip methods; 17/9/2005). The mean values of ethanol production correspond to 9150, 8390, 5120 and 670 l ha^{-1} for subsurface drip, full surface drip, supplement surface drip and control treatments, respectively. It is obvious that in subsurface treatments the production of ethanol was higher than the other two treatments of full and supplement surface drip, corresponding to the relation of total fresh and dry biomass production.

Proportional fresh, dry and energy production values had been observed in previous researches in Greece (Kavadakis et al., 2000; Sakellariou-Makrantonaki et al., 2005) and more generally in the Mediterranean region (Curt et al., 1995). Also, in the experiments which took place from 1990 to 1993 (Dalianis et al., 1995), in various areas of Greece, the Keller variety of sweet sorghum among others, proved to be the best product as far as fresh and dry biomass with a percentage of sugar by the total fresh biomass which is contained in the stalks of the plants (9–13.2%) (Fig. 6).

In contrast, in 1995, in Spain, Curt et al., calculated the average percentage of fermented sugar by the total dry plant biomass of sweet sorghum (41.4%, w/w).

In conclusion, it can be reported that, in Greece, on average the percentage of fermented sugar of the Keller variety of sweet sorghum, fluctuates between the amount of 10–12% of the total fresh biomass of the plants or at the amount of 35–40% of the total dry plant biomass. Finally, the production of bio-ethanol can fluctuate between 6500 and 8000 l ha^{-1} in case of fermentation of the sugar content by the total fresh plant biomass and can surpass the limit of 10,000 l ha^{-1} in the case of fermentation of the corresponding amount of cellulose which it contains (Boukis et al., 1995).

Such productivity energy values are particularly high, proving that this crop seems to be a very promising alternative

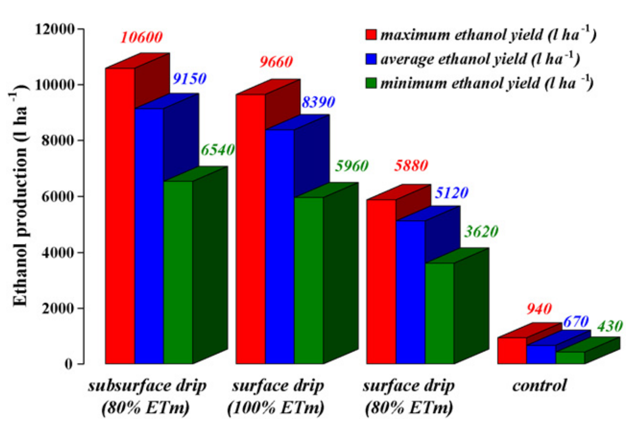

Fig. 6 – Theoretical maximum, minimum and average of ethanol yield (liters ethanol ha^{-1}) of sweet sorghum (var. Keller) under different irrigation methods in Central Greece in 2005 [best harvest time for subsurface and surface drip; 17/9/2005-for control; 22/10/2005].

commodity for biomass production in Greece in the near future.

3.3.3. *Water use efficiency*

The water use efficiency, as proposed by Monteith (1993) (ratio of dry biomass which was divided by the total amount of water inputs: irrigation, precipitation and water storage), of sweet sorghum in 2005, between the irrigation methods under full and supplement application depths, is schematically presented in Fig. 7 (water runoff and deep drainage was excluded).

The evapotranspirated water was estimated using the class A open evaporation pan on daily base and the water storage was calculated using the time domain reflectometry method measuring the volumetric soil water content at four depths (0–30, 30–60, 60–90, 90–120 cm).

It can be observed that the plants which received subsurface drip irrigation water exhibited higher water use efficiency values than those receiving surface drip irrigation, demonstrating the clear qualitative superiority of the subsurface irrigation method against the surface drip method, for equal dry biomass productions.

More specifically, the largest percentage differences between subsurface drip and full surface drip treatments were observed in the period ranging from mid-September to the end of October (approximately 21%) (Table 2).

Moreover, the differences between the subsurface and the supplement surface drip treatments were higher at almost 38%. On the contrary, the differences between full and supplement surface drip treatments oscillated at reasonable levels, corresponding with their differences in the application of water doses (approximately 21%). Finally, the difference between the supplement surface drip treatments (80% ETm) and control treatments (non-irrigated) was almost equal to zero.

In experiments in Spain (Curt et al., 1995) it was proven that a high rate of water use efficiency was attributed to the Keller variety of sweet sorghum. The large amount of water use efficiency fluctuated from 3.74 to 5.43 g aerial biomass dm^{-3}.

In Sicily, the growth and production capacity of sweet sorghum (Keller variety) was researched, together with the water efficiency at three different irrigation levels. It was found that a reduction of irrigation water of about 38% brought a reduction of the total amount of productivity by 22% and an increase in water efficiency from 4.05 to 5.00 $g\,l^{-1}$ (Foti et al., 2004) (Fig. 7).

According to their experiments on sweet sorghum (Keller variety), in Bari, Italy, in 1995, Mastrorilli et al., concluded that

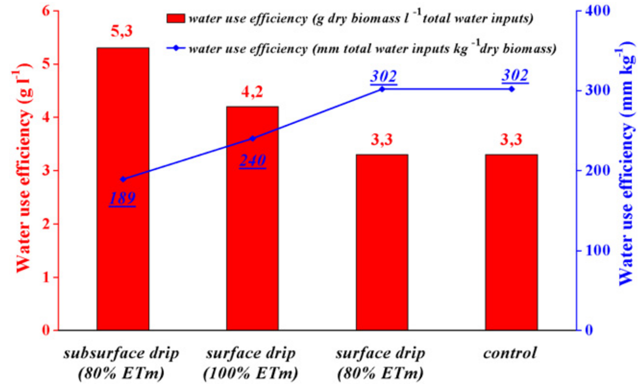

Fig. 7 – Water use efficiency (ratio of dry biomass production divided by the water used: "irrigation, precipitation and soil water storage") of sweet sorghum under different irrigation methods in Central Greece in 2005.

not only was there a high productivity of dry biomass, but that this particular plant is also the most efficient as far as irrigation water use is concerned, on the basis of the produced biomass (water use efficiency = 193 $mm\,kg^{-1}$) in comparison to the other plants studies, and that the production of this plant in the Mediterranean is at low risk and constitutes an excellent opportunity for investment.

Finally, high rates of water use efficiency was noticed by Dercas et al., in 1995, in Central Greece (62–80 $kg\,ha^{-1}\,mm^{-1}$ ET).

Under these circumstances the subsurface drip irrigation method seems very promising and should seriously be considered for future studies of farming systems with low inputs such as those including bio-energy crops.

4. Conclusions

Based on our 1-year study, we conclude that the subsurface drip method excels the surface drip method in quantitative and qualitative characteristics of growth, productivity and the water use efficiency of the sweet sorghum (var. Keller) cultivation in Central Greece.

This superiority is mainly owing to the reduction of the losses because of the evaporation and the best water distribution in the depth of the rooting zone.

Table 2 – Water use efficiency (ratio of dry biomass production divided by the water used (irrigation, precipitation and soil water storage) of sweet sorghum (var. Keller) under different irrigation methods in Central Greece

Parameters	Subsurface drip (80% ETm)	Surface drip (100% ETm)	Surface drip (80% ETm)	Control
Total dry biomass ($Mg\,ha^{-1}$)	33.6	32.4	21.0	4.4
Irrigation water (mm)	527.0	659.0	527.0	0.0
Precipitation (mm)	112.0	112.0	112.0	141.0
Soil water storage (mm)	−2.0	6.0	−5.0	−8.0
Total water inputs (mm)	637.0	777.0	634.0	133.0
Water use efficiency (g of dry biomass l^{-1} of total water inputs)	5.3	4.2	3.3	3.3
Water use efficiency (mm of total water inputs kg^{-1} of dry biomass)	189.0	240.0	302.0	302.0

Furthermore, in the subsurface drip treatments 189 l of irrigation, water was used for the production of 1 kg dry biomass, whereas in full and supplement surface drip treatments 240 and 302 l of water was used for proportionally equal values of total dry weights.

Finally, the conservation of water, calculated as water use efficiency, was higher initially than estimated (20%) when compared with the amount used for surface drip irrigation (approximately 38%).

This irrigation method (subsurface) seems very promising and should seriously be considered in future studies of farming systems with low inputs such as those including bio-energy crops.

Furthermore, considering the attained maximum fresh biomass and average ethanol yield of sweet sorghum under supplemental subsurface drip irrigation (148.2 t ha^{-1} to 9150 l ha^{-1}) or under full surface drip irrigation schemes (138.2 t ha^{-1} to 8390 l ha^{-1}), this crop seems a very promising alternative commodity for biomass and energy production in Greece in the near future.

REFERENCES

Alexopoulou, E., Kipriotis, E., Zafiris, Ch., Christou, M., 1998. Adaptability and productivity of sweet sorghum in northern Greece. In: Proceedings of the 10th European Conference on Biomass for Energy and Industry, Wurzburg, Germany, 8–11 June, pp. 939–942.

Alexopoulou, E., Chatziathanassiou, A., Panoutsou, C., Koutoukidis, A., Tsakiris, S., Drimaki, E., 2000. Yields and public perception of sweet sorghum growth in demonstrative fields of northern Greece. In: Proceedings of the 1st World Conference on Biomass for Energy and Industry, Sevilla, Spain, 5–9 June, pp. 1638–1641.

Boukis, I., Christou, M., Sooter, Ch., Zafiris, Ch., Vassilatos, V., 1995. Non Technical Barriers to the Development of Liquid Biofuels in Greece. NTB Net, Paris.

Bryan, W., Monroe, G., Nichols, R., Gascho, G., 1981. Evaluation of sweet sorghum for fuel alcohol. In: Proceedings of Winter Meeting of ASAE. paper No. 81-3571.

Chatziathanassiou, A., Christou, M., Alexopoulou, E., Zafiris, C., 1998. Biomass and sugar yields of sweet sorghum in Greece. In: Chartier, et al. (Eds.), Proceedings of the 10th European Conference. C.A.R.M.E.N. Press, Germany, pp. 209–212.

Curt, M.D., Fernandez, J., Martinez, M., 1995. Productivity and water use efficiency of sweet sorghum (*Sorghum bicolor* (L.) Moench) cv. ‘‘Keller’’ in relation to water regime. Biomass Bioenergy 8 (6), 401–409.

Curt, M.D., Fernandez, J., Gonzalez, J., Gil, J.L., 2000. Comparative growth analysis of two sorghum cultivars in Badajoz, Spain. In: Proceedings of the First World Conference on Biomass for Energy and Industry, Sevilla, Spain, 5–9 June, pp. 1877–1880.

Dalianis, C., 1996. Adaptation, productivity and agronomic aspects of sweet sorghum under EU conditions. In: Proceedings of the First European Seminar on Sorghum for Energy and Industry, held in France, 1–3 April, pp. 15–25.

Dalianis, C., Christou, M., Sooter, S., Kyritsis, S., Zafiris, Ch., Samiotakis, G., 1994. Growth and productivity of sweet sorghum in Greece. In: Hall, et al. (Eds.), Proceedings of the Seventh E.U. Biomass Conference on Biomass for Energy and Industry. Ponte Press, Bochum, Germany, pp. 636–642.

Dalianis, C., Sooter, C., Christou, M., 1995. Sweet sorghum (*sorghum bicolour* (L.) Moench) biomass productivity sugar yields and enhanol potential in Greece. In: Chartier, et al. (Eds.), Proceedings of Eighth E.U. Biomass Conference on Biomass for Energy, Environment, Agriculture and Industry. Pergamon Press, Oxford, UK, pp. 622–628.

Dercas, N., Panoutsou, C., Dalianis, C., Sooter, C., 1995. Sweet Sorghum (*Sorghum bicolor* [L.] Moench). In: Chartier, et al. (Eds.), Proceedings of the Eighth E.C Conference on Response to four irrigation and two nitrogen fertilisation rates. Biomass for Energy, Environment, Agriculture, vol. 1. Pergamon Press, UK, pp. 629–639.

Dolcioti, A., Mambelli, S., Grandi, S., Venturi, G., 1996. Comparison of two Sorghum genotypes for sugar and fiber production. Ind. Crops Prod. 7, 265–272.

Duarte, M.P., Fernando, A.L., Guimaraes, H., Amparo, V., Alves, L., Santos Oliveira, J.F., 2000. Study of sweet and fiber surghum in Portugal. Effect of climatic conditions and sowing date on the final productivity and on quality of the biomass. In: Proceedings of the First World Conference on Biomass for Energy and Industry, Sevilla, Spain, 5–9 June, pp. 361–364.

European Commission Biomass, 2000. An Energy Resource for the European Union. Office for Official Publications of the European Communities, Luxembourg.

FAO Production, 2002. Sweet Sorghum in China.

Foti, S., Cosentino, S., Patane, C., Mantineo, M., 2004. Sweet sorghum in Mediterranean environment. In: Proceedings of the Second World Conference on Biomass for Energy, Industry and Climate Protection, Rome, Italy, 10–14 May, pp. 391–394.

Habyarimana, E., Laureti, D., Bonardi, P., Lorenzoni, C., 2002. Field evaluation of cold tolerence biomass and sugar yields in Sorghum. In: Proceedings of the 12th European Conference on Biomass for Energy, Amsterdam, The Netherlands, Industry and Climatic Protection, 17–21 June, pp. 369–371.

Hunkar, M., 1996. Productivity of sorghum in Huhgary. In: Proceedings of First European Seminar on Sorghum for Energy and Industry, Toulouse, pp. 177–187.

Kavadakis, G., Nikolaou, A., Alexopoulou, E., Natioti, H., Mitsiou, C., Panoutsou, C., Danalatos, N., 2000. Growth, productivity and sugar yields of sweet sorghum (var Keller) in central Greece. In: Proceedings of the Second National Conference of Agricultural Engineers (HelAgEng). Volos, Greece, (in Greek), pp. 205–212.

Lipinski, E.S., 1978. Sugar crops as a source of fuels, vol. II. Processing and Conversion, Research Dept. of Energy. Final Report. Battelle Columbus Labs, OH.

Mamma, D., Koulias, D., Fountoukidis, G., Kekos, D., Macris, B.J., Koukios, E., 1996. Bioethanol from sweet sorghum: simultaneous saccharification and fermentation of carbohydrates by a mixed microbial culture. Process Biochemistry, 31 (4). Elsevier Science Ltd., UK, pp. 377–381.

Mastrorilli, M., Katerji, N., Rana, G., Steduto, P., 1995. Sweet sorghum in Mediterranean climate: radiation use and biomass water use efficiencies. Ind. Crops Prod. 3, 253–260.

Monteith, J.L., 1993. The exchange of water and carbon by crops in a Mediterranean climate. Irrigation Sci. 14, 85–91.

Pari, D., Ragno, I., 1998. Biomass crop energy balance. In: Proceedings of the 10th European Conference on Biomass for Energy and Industry, C.A.R.M.E.N., Wurzburg, Germany, 8–11 June, pp. 819–823.

Perniola, M., Tartaglia, G., Tarantino, E., 1996. Radiation use efficiency of sweet sorghum and kenaf under field conditions. In: Abs. Book 9th Eur. Bioenergy Conference, Copenhagen, p. 156.

Phene, C.J., Hutmacher, R.B., Ayars, J.E., 1993. Subsurface drip irrigation: Realizing the full potential. In: Proceeding Workshop, Visalia, California.
Roman, G.V., Mitroi, A., Roman Ana, M., Ion, V., Dumbrava, M., 1998. Sweet sorghum an energetical crop of the future in Romania. In: Proceedings of the 10th European Conference on Biomass for Energy and Industry, C.A.R.M.E.N., Wurzburg, Germany, 8–11 June, pp. 1039–1041.
Sakellariou-Makrantonaki, M., Kalfountzos, D., Vyrlas, P., 2001. Irrigation water saving and yield increase with subsurface drip irrigation. In: Proceedings of the Seventh International Conference on Environmental Science and Technology Ermoupolis, Syros Island, Greece, pp. 466–473.
Sakellariou-Makrantonaki, M., Papalexis, D., Danalatos, N., Vultsanis, P., Nakos, N., 2003. The effect of surface and subsurface drip irrigation methods on growth and yield of fiber sorghum in Central Greece. In: Proceedings of Ninth National Cong. Hellas, Salonika, 2–5 April, (in Greek), pp. 183–190.
Sakellariou-Makrantonaki, M., Papalexis, D., Danalatos, N., 2005. The effect of irrigation methods on growth and yield of fiber sorghum in central Greece. In: Proceedings of the Sixth International Conference of European Water Resources Association (EWRA) Sector: Decision Support Systems, Menton, France, No. 021.
Sakellariou-Makrantonaki, M., Papalexis, D., Nakos, N., Dassios, S., Chatzinikos, A., Papanikos, N., Danalatos, N., 2006. Potential and water-limited growth and productivity of fiber sorghum in central Greece irrigated by surface and subsurface drip methods on a rainy and a dry year. In: Proceedings of the Sixth International Conference of IASME/WSEAS International Conference on Energy and Environmental Systems, Chalkida, Greece, May 8–10, pp. 49–54.
Smith, G.A., Babgy, M.O., Lewellan, R.T., Doney, D.L., Moore, P.H., Hills, F.J., Campell, L.G., Hogaboam, G.J., Ceo, G.E., Freeman, K., 1987. Evaluation of sweet sorghum for fermentable sugar production potential. Crop Sci. 27, 788–793.
Soldatos, P., Chatzidaki, M., 1999. Economic evaluation of biofuel production in Greece. The case of ethanol. In: Proceedings of ‘‘AgEnergy 99, vol. 2. pp. 973–980.
Solomon, K., 1993. Subsurface drip irrigation: product selection and performance. In: Jorgensen, G.S., Norum, K.N. (Eds.), Subsurface Drip Irrigation: Theory Practice and Application. CATI Publication, No. 921001.
Tayot, X., Chartier, M., Varlet-Grancher, C., Lemaire, G., 1995. Potential above-ground dry matter production of miscanthus in North Centre France compared to sweet sorghum. In: Chartier, Ph., Beenackers, A.A.C.M., Grassi, G. (Eds.), Proceedings of Eighth E.C. Conference on Biomass for Energy, Environment Agriculture and Industry, vol. 1. Pergamon, Oxford, pp. 556–564.
U.S. Department of Energy, 2005. Office of Energy Efficiency and Renewable Energy. Alternative Fuels Data Center, http://www.eere.energy.gov/afdc/fuel_properties.html.
Wilhoit, R.C., Zwolinski, B.J. (Eds.), 1973. Physical and thermodynamic properties of aliphatic alcohols. J. Phys. Chem. 2 (Suppl. no. 1) Reference data.