Gaziosmanpaşa Üniversitesi Ziraat Fakültesi Dergisi
Journal of Agricultural Faculty of Gaziosmanpasa University
http://ziraatdergi.gop.edu.tr/

Araştırma Makalesi/*Research Article*

JAFAG
ISSN: 1300-2910
E-ISSN: 2147-8848
(2017) 34 (1), 229-237
doi:**10.13002/jafag4215**

Effects of Row Spacing on Growth, Yield and Quality Parameters of Sweet Sorghum

Chris CAVALARIS*[1] Odisseas MERKOURIS[1] Christos KARAMOUTIS[1] Serap AKDEMİR[2] Diomi MAMMA[3] Dimitrios KEKOS[3] Theofanis GEMTOS[1]

[1]University of Thessaly, Faculty of Agricultural Sciences, Department of Agriculture, Crop Production and Rural Environment, Fytokou str., 38446, Volos, Greece
[2]Namık Kemal University, Technical Sciences Vocational School, Tekirdag, Turkey
[3]National Technical University, School of Chemical Engineering, 9, Iroon Polytechneiou st., Zografou 157 80, Athens, Greece
*e-mail: chkaval@uth.gr

Alındığı tarih (Received): 05.02.2017 Kabul tarihi (Accepted): 20.03.2017
Online Baskı tarihi (Printed Online): 25.04.2017 Yazılı baskı tarihi (Printed): 02.05.2017

Abstract: A two-year field experiment was conducted in Thessaly, Central Greece, in order to evaluate the effect of row spacing on several growth and yield parameters of sweet sorghum. In particular, two row spacings were tested: wide row spacing (WRS) at 0.75m and narrow row spacing (NRS) at 0.375m. During the growing period, crop growth in terms of plants' emergence, plants' height, panicle appearance, while stalk sugar content, dry biomass and total sugar yield were also evaluated. In addition, plant material was analysed to assess the potential effects of the treatments on stalk quality. The results showed that with the appropriate cultural practices, sweet sorghum can yield over 40 Mg ha-1 of dry matter and over 18 Mg ha-1 of total sugar yield under Greek conditions. Narrow row spacing resulted to higher plant population and productivity in terms of dry matter and total sugar yield (61% and 37% increase, respectively) in the first year, but without any statistical significant difference compared to the wide spacing in the second year. The compositional analysis of the crop samples revealed significant effects of row spacing on water soluble matter, cellulose and hemi-cellulose content revealing a beneficial effect of narrow row spacing on the quality and consequently ethanol production.

Keywords: Sweet sorghum, row spacing, yield; quality, ethanol

1. Introduction

Sweet sorghum (*Sorghum bicolor* L. Moench) is a sugar crop with high potential as energy crop for bioethanol production (Smith *et al*., 1987). It also produces lignocellulosic material that could serve as feedstock for second generation biofuels (Anfinrud *et al*., 2013). Sorghum also serves as good feedstock for methane digesters (Chynoweth, 1993). On the other hand, it can be used as silage or as a direct feed for ruminants (Reddy *et al*., 2009). In fact, sweet sorghum with its high productivity and ability to adapt to marginal growing conditions is considered as one of the most suitable crops that could potentially provide significant amounts of feed stuff and energy to cover human needs in the near future. In particular, sweet sorghum is considered to be one of the best alternative crops to grow in the saline and semi-arid Mediterranean regions (Habyarimana *et al*., 2004). It could easily substitute maize due to its higher ability to extract water from deeper soil layers (Farré and Faci, 2006). Due to its short growing period, it could also be introduced in annual double cropping rotations with food or feed crops such as cereals and legumes, allowing the use of sustainable crop management practices and provide a supplementary income to the farmers (Mahmood and Honermeier, 2012).

Regarding productivity, stem weight ranging from 21 to 54 Mg ha^{-1} has been reported across five sorghum cultivars with juice Brix values ranging from 14% - 19% (Rutto *et al*., 2013). In optimized growing conditions, Wight *et al.* (2012) found sorghum dry biomass yields exceeding 25 Mg ha^{-1}, while aboveground dry matter up to

30.1Mg ha^{-1} has been reported by Rocateli *et al.* (2012). By comparing eight sorghum varieties Cifuentes *et al.* (2014) reported fresh stalk and dry grain yield of 42.15 Mg ha^{-1} and 2.36 Mg ha^{-1}, respectively.

In Greece, Alexopoulou *et al.* (1998) found dry biomass production to be 30-39 Mg ha^{-1} and percentage of sugar of 9.5-11.4% of the total fresh biomass. Sakellariou-Makrantonaki *et al.* (2007) suggested sweet sorghum as a promising alternative crop for biomass and energy production in Greece with fresh biomass yield of 148.2 and 138.2 Mg ha^{-1} under supplemental subsurface and full surface drip irrigation, respectively.

Row distances affect population density and consequently crop productivity. Nowadays, with the availability of a variety of herbicides and the development of appropriate harvesting machinery, narrow row spacing has been adopted in crops like soybean (Ethredge *et al.*, 1988), cotton (Keren *et al.*, 1983) or wheat (Gemtos *et al.*, 1997), while little research has been done with sorghum. Research carried out by Sawargaonkar *et al.*, (2013) revealed that row spacing of 60 or 45 cm had no influence on the performance of various cultivars of sweet sorghum. Other researchers (Broadhead and Freeman, 1980; Kaushik *et al.*, 2005) have studied row distances ranging from 50 to 105 cm with benefits mainly for the narrower rows.

Although sweet sorghum appears to be a suitable crop for many regions and also for Greece, data on the appropriate cropping practices are rather limited. In order to optimize crop productivity additional research is needed under the specific conditions of some areas. The objective of the present study was to evaluate the effects of row spacing (and especially very narrow distances) on several growth, yield and quality parameters of sorghum under the conditions of Thessaly, Central Greece.

2. Methodology

Experimental details

A field experiment was carried out for two years (2013 and 2014) in Thessaly, Central Greece (Velestino: 39°23′39.52″ N, 22°45′10.30″ E, altitude 85 m) and particularly in the Farm of University of Thessaly. The soil was a sandy clay loam with 53% sand, 22.9% silt and 21.4% clay. The pH was 7.86 and the EC 0.16 ms cm^{-1}. The soil organic matter was 1.31% and the P and K concentration 9.84 and 217 mg kg^{-1}, respectively. Meteorological data for air temperature and precipitation were retrieved from the Farm weather station. The mean air temperature and rainfall during the two years of the study period are shown in Figure 1. The total precipitation during the growing period (May to December) was 179 mm and 384 mm for 2013 and 2014, respectively.

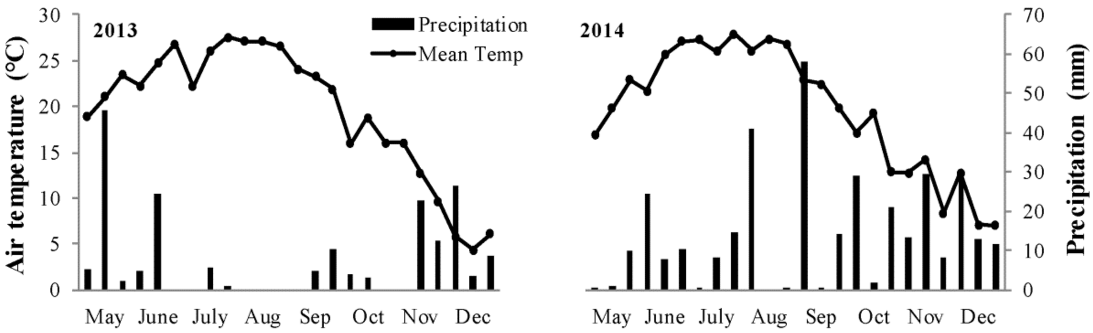

Figure 1. Air temperature (10 days mean values) and precipitation (10 days cumulative values) during the growing period for 2013 and 2014.

The experiment was carried out to assess the effect of two row spacings, 0.75m and 0.375m on sweet sorghum establishment, development, final dry matter and sugar yield as well as on tissue quality. The cultivar "Sugargraze" (*Sorghum bicolor* L. Moench) was used in both years. On a previous three year study, the specific cultivar was tested and compared with four other genotypes and was found to be the most productive one with the highest dry matter and total sugar yield (Gemtos *et al*., unpublished data). The experimental design was a randomized complete block with 4 replications. In the first year ploughing at 25 cm depth was applied and seedbed preparation by two passages with a rotary cultivator at 8 cm. The experimental site was under fallow during the previous year. Fertilizer application of 48kg ha^{-1} N, 33 kg ha^{-1} of P_2O_5 and 52 kg ha^{-1} of K_2O was conducted just before sowing. Another 204 kg ha^{-1} of N was applied through drip irrigation during the growing season. The crop was sown on June 11 of 2013 with a Monosem planting machine at seed density of 8.8 seeds m^{-2} for both row distances. The intra row distances of the seed were 15.15cm and 30.3cm for the wide and the narrow row spacing respectively. All treatments received 650 mm irrigation water during the summer, by a surface drip irrigation system. Each plot was 3 x 9 m with four rows for the wide row spacing planting (0.75 m) and eight rows for the narrow row spacing planting (0.375 m). The crop was harvested on November 7 of 2013, at 149 days after planting (DAP) with one row silage machine. In the second year, soil tillage included ploughing at 25 cm depth and seedbed preparation by one passage with a medium cultivator at 10 cm depth, 2 passages with a disk harrow at 8 cm depth and 3 field passages with a light cultivator at 8 cm depth. Sowing was on May 15 of 2014 for both row distances (0.75 and 0.375 m) using the above mentioned Monosem planter. Harvest was on December 4 of 2014, at 203 DAP (delayed harvest was because of the extremely wet conditions of the second year).

Samplings and measurements

During the growing period the following measurements were taken and determinations were made for both years:

i) Crop emergence every 3-4 days after planting by counting the emerged plants of two marked 2 m rows on each plot.
ii) Plant growth during the growing period by measuring the plants height every week. Five randomly selected plants were marked and measured. The growth measurements stopped when over 90% of the plants (for each individual experimental plot) had developed panicles.
iii) Physiological maturity by counting the panicles appearance and estimating the percentage of the panicles every two to three days.
iv) Sugar content in the juice (Brix %) with a hand-held refractometer. The juice was extracted from three plants in each plot by squeezing the stalks at 1 m above the ground. The measurements were taken every 8-12 days, starting after the completion of flowering.
v) Fresh matter yield (panicles, stalks, leaves) in Mg ha^{-1}. A one row silage machine was used to harvest the two inner rows of the plots.
vi) Dry matter and juice yield. After harvesting and measuring the fresh weight, 5 plants (from each plot) were dried in an oven for 72 hours at 80° C in order to estimate the water content % and the total dry mass yield (DMY) in Mg ha^{-1}
vii) Total sugar yield (TSY) in Mg of sugars ha^{-1}.The total sugar yield is estimated by using the following equation proposed by Uchino *et al.* (2013):

$$TSY\ (Mg\ ha^{-1}) = [(Brix\ (\%) \times 0.8746) + 0.1516]/100 \times juice\ yield\ (m^3\ ha^{-1})\quad [1]$$

Compositional analysis of sorghum samples

During the second year, samples were taken from the experimental plots and sent to the Biotechnology Laboratory (School of Chemical Engineering) of the National Technical University of Athens for compositional analysis in order to assess the potential effects of the row distances to the quality of the plant material and to their potential for ethanol production. The stalks from three random plants from each plot were cut at 0.25 m pieces, leaves were removed, and the stalks were marked and placed immediately in a deep freezer. Samplings were taken on September 9 of 2014 and on October 22 of 2014, in order to detect any compositional differences between the early and late maturity stages.

Dry matter content of the samples was determined by drying duplicate samples for 16 h in an oven at 105◦C, according to the National Renewable Energy Laboratory (NREL) standard method for determination of total solids in biomass (Sluiter *et al.*, 2008). Extractives, cellulose, hemicellulose and lignin were determined according to NREL standard method (Sluiter *et al.*, 2012).

Statistical analysis

A combined over years analysis of variance (ANOVA) was conducted for all data and differences between means were compared at the 5% level of significance using the Fisher's Protected LSD test. Before ANOVA, data were analysed to test for the normality and homoscedasticity assumptions. All statistical analyses were conducted using the SPSS software package (SPSS 15.0, Chicago, Illinois: SPSS Inc. 2006).

3. Results and Discussion

In 2013, over 85% emergence was completed 15 days after planting, while in 2014 emergence was significantly delayed. Sorghum seeds germinate when soil temperature is above 10 ^{o}C, but emergence is slow. The optimum temperature for fast seed germination is considered to be 25^{o}C (Patanè *et al.*, 2009). In the early 2014 planting, the low soil temperature delayed the germination in contrast to the late 2013 planting that favoured a faster crop establishment. As a result, even though there was almost one month difference on the planting dates between the two years, the actual starting of the crops differed only 15 days. For both years, higher plant population was found for the NRS plots (Figure 2).

In 2013, the differences were clear from the beginning (10-15 DAP), while in 2014 the differences presented statistical differnce only at the end of the growing period. Given that the target population was 60 to 80,000 plants per ha, WRS reached that target only in the second year while NRS reached it in 2013 and exceeded it in 2014. This is a noticeable observation, since the same amount of seed was used in both treatments. One possible explanation is that during the second pass for planting in between the 0.75 m rows in order to achieve the narrow row spacing, the tractor weels were passing over the already planted rows. This additional passage probably improved the seed-soil contact (as the conditions were dry) and probably contributed to a better emergence. The assumption was evidenced by the visual observations in the field (data not shown). One could easy recognize a better crop emergence on those rows that the tractor wheels had passed for second time and worse emergence on the rows where the seed was not pressed by the tractor wheels. Plants' growth expressed by means of height measurements was similar for the two treatments (Figure 3).

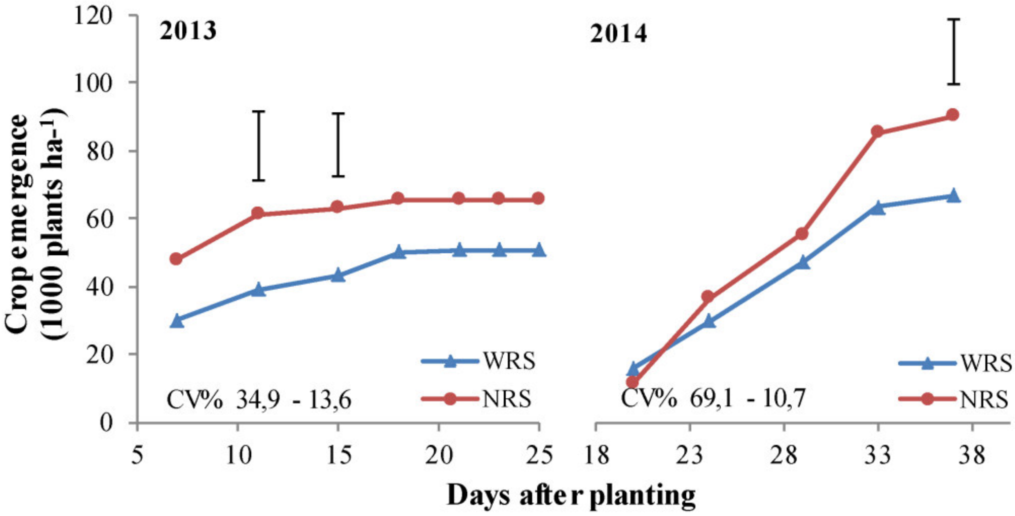

Figure 2. Effect of wide row spacing (WRS) and narrow row spacing (NRS) on crop emergence.

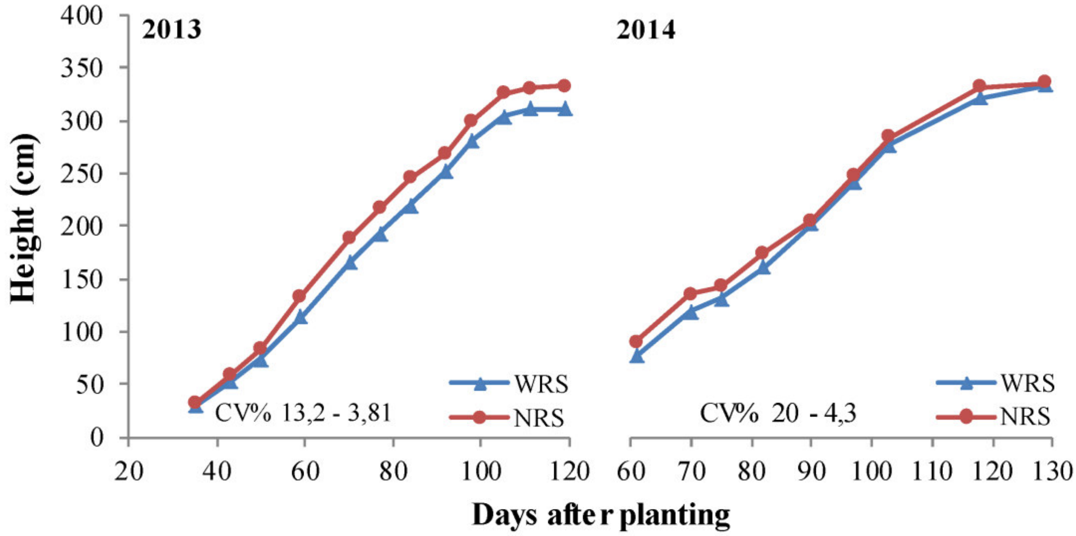

Figure 3. Effect of wide row spacing (WRS) and narrow row spacing (NRS) on plant height.

A slightly higher plant growth was detected in the NRS in 2013, but the differences were not significant. In both years, the plants achieved an average height of 320-330cm around 105 - 120 DAP in 2013 and 2014, respectively.

Panicles emerged at about 90 and 120 DAP in 2013 and 2014, respectively. The duration of this stage was about 15 and 20 days for 2013 and 2014, respectively (Figure 4). Plants earliness (crop maturity) expressed by means of panicles' appearance presented no significant differences. Juice sugar content measurements started after the panicle apearence and continued until harvesting. Mean sugar content in 2014 was significantly lower than 2013 (Figure 5). Brix values in 2013 reached over 20%, while in 2014 they were about 11.5% lower.

As shown in Table 1, narrow row spacing gave higher yield (fresh and dry matter) in 2013 but not in 2014. One reason might be the low crop population achieved in 2013 with WRS that also resulted to a less efficient weed competition (visually observed especially at the early stages of the crop, data not shown). Furthermore, mean fresh and dry matter was significant lower in 2013 compared to 2014. This difference could be plausibly attributed to the lower mean population (Figure 2) and to the shorter growing period due to the late sowing in 2013. Wortman *et al.* (2010) also found that sweet sorghum sugar yield was improved by increasing sowing rate above 75,000 viable seed ha^{-1}.

The crop was harvested at about 71,7% How could be 1% moisture content of stalks, though in hay there is 12-14% moisture???? moisture content (MC) in both years but no differences were detected between the row spacing treatments. The extracted sugars (Brix) were significantly higher for the WRS treatment in 2013 and for the first year. This indicates that probably higher populations have a negative effect on sugar concentration. Total sugar yield (TSY) was higher in 2014. No statistical differences were found between the row spacing treatments, even though the interactions show a significant effect for 2013 (Table 1).

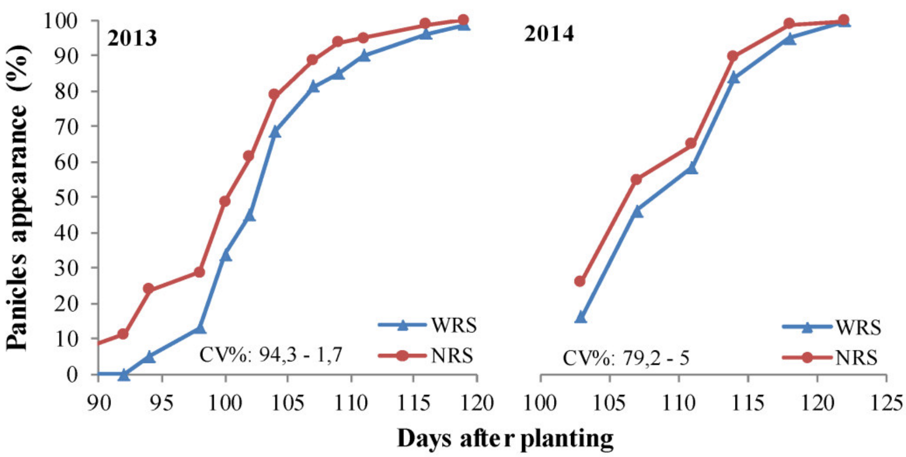

Figure 4 Effect of wide row spacing (WRS) and narrow row spacing (NRS) on panicles appearance.

In 2013, NRS presented 4.6 Mg ha^{-1} higher sugar yield than WRS. Sawargaonkar *et al.* (2013) found that row spacing of 45 and 60 cm had no effect on sugar content or juice yield although the wide spacing increased grain and green stalk yield; however the populations used in their experiment were significantly higher compared with our study.

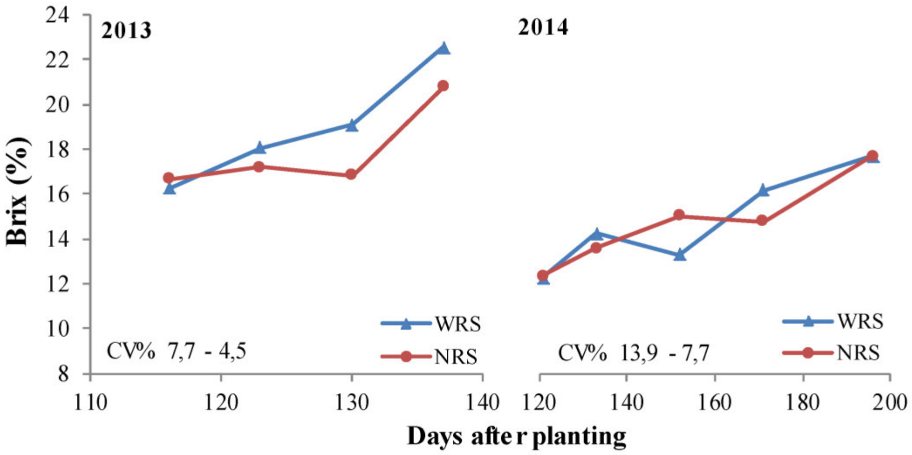

Figure 5. Effect of wide row spacing (WRS) and narrow row spacing (NRS) on the sugar content in the extracted juice.

The percentage of water soluble materials (WSM), cellulose (C), hemicellulose (HC) and lignin (L) derived from the sorghum samples were recorded upon completion of flowering at 120 DAP and 40 days later in order to determine the compositional differences between early and late maturity stages, under different row spacing treatments. There was a significant superiority of WSM in the case of narrow row distance at the second sampling date (Figure 6). The percentage of cellulose and hemicellulose under narrow row spacing are significantly higher ($p<0.005$) for the early measurement, while no significant differences were found for the late measurement. Amaduci et al., (2000) have found that cellulose and hemicellulose decrease with the delay of harvesting. Probably the differences disappear as the crop matures.

Table 1. Harvesting parameters of sweet sorghum for two years under two row spacing treatments (WRS: Wide row spacing, NRS: Narrow row spacing).

Treatments			***FMY*** *Mg ha^{-1}*	***DMY*** *Mg ha^{-1}*	***MC*** *%*	***Brix*** *%*	***TSY*** *Mg ha^{-1}*
Years	2013		96.7	26.8	72.3	21.65	14.9
	2014		143.8	41.4	71.2	17.48	17.9
			*	*	*	*	*
Row Spacing	WRS		110.5	30.9	72.0	20.40	15.7
	NRS		130.0	37.3	71.3	18.73	17.1
			*	*	ns	*	ns
Years X Row Spacing							
	2013	WRS	76.4^{a}	20.6^{a}	73.0	22.54	12.6^{a}
		NRS	117.1^{b}	33.1^{b}	71.7	20.75	17.2^{b}
	2014	WRS	144.7^{c}	41.3^{c}	71.5	18.25	18.9^{b}
		NRS	143.0^{c}	41.5^{c}	71.0	16.71	17.0^{b}
			*	*	ns	ns	*
CV%			8.8	8.6	1.23	6.5	9.4

**= significant differences at P≤0.05, ns= no significant differences, values followed by the same letter do not significantly differ at p≤0.05*

The differences found in the quality parameters may be associated with the presence of a denser crop for the NRS because of the better emergence. This finding is not in agreement with the ones reported at another study from Amaduci *et al.*, (2004), who reported no significant effect of plant density on any of the quality parameters of sweet sorghum.

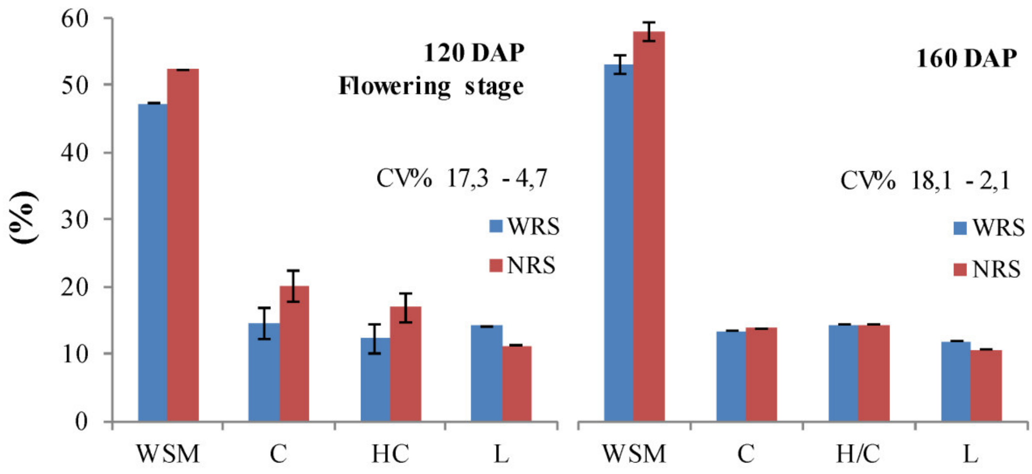

Figure 6. Effect of row spacing (WRS and NRS) on the percentage of Water Soluble Materials (WSM), Cellulose (C), Hemicellulose (HC) and Lignin (L) in the fresh stalks on flowering stage (left) and 40 days after flowering (right).

4. Conclusions and Recommendations

Our results revealed that under Greek conditions and with the adoption of the appropriate cultural practices, sweet sorghum can yield over 40 and 18 Mg ha^{-1} of dry matter and total sugar yield, respectively. Average dry matter yield for the first year with a short growing period (due to late sowing) was 26.8 Mg ha^{-1}. In the second year, the earlier sowing and most favourable conditions resulted up to 61% higher yields. The higher productivity of sorghum under the narrow row spacing could be attributed to the significant higher plant population achieved, as well as the earlier soil coverage (canopy closure) and the better competition with the weeds. Moreover, our study revealed that narrow row spacing resulted to products of higher quality. Conclusively, our study revealed that row distance is among the factors which are strongly correlated with higher yield and quality of sorghum, while further research is required to rank the productivity of more sorghum cultivars under a wide range of conditions. Such information could be useful for extension personnel, in order to recommend the ideal agronomic practices to the farmers and optimize crop's productivity.

Acknowledgements

The paper is based on data collected by the project entitled "The Sustainable Integrated Method for the Production of Lignocellulosic Ethanol". This research has been co-financed by the European Union (European Social Fund – ESF) and Greek national funds through the Operational Program the National Strategic Reference Framework (NSRF) 2007-2013.

References

Alexopoulou, E., Kipriotis, E., Zafiris, Ch. and 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, p. 939-942.

Amaducci, S., Amaducci, M.T., Benati, R., Venturi, G., (2000). Crop yield and quality parameters of four annual fibre crops (hemp, kenaf, maize and sorghum) in the North of Italy. Ind. Crops Prod. 11, 179–186.

Amaducci, S., Monti, A. & Venturi, G. (2004). Non-structural carbohydrates and fibre components in sweet and fibre sorghum as affected by low and normal input techniques. *Industrial Crops and Products* 20 (1):111-118.

Anfinrud, R., Cihacek, L., Johnson, B. L., Ji, Y. and Berti, M. T. (2013). Sorghum and kenaf biomass yield and quality response to nitrogen fertilization in the Northern Great Plains of the USA. *Industrial Crops and Products* 50:159-165.

Broadhead, D. M. and Freeman, K. C. (1980). Stalk and sugar yield of sweet sorghum as affected by spacing. *Agronomy Journal* 72 (3):523-524.

Chynoweth, D. P., Turick, C. E., Owens, J. M., Jerger, D. E. and Peck, M. W. (1993). Biochemical methane potential of biomass and waste feedstock. *Biomass and Bioenergy* 5(1):95-111.

Cifuentes, R., Bressani, R. and Rolz, C. (2014). The potential of sweet sorghum as a source of ethanol and protein. *Energy for Sustainable Development* 21(1):13-19.

Ethredge ,W. J., Ashley, D. A. and Woodruff, J. M. (1988). Row spacing and plant population effects on yield components of soybean. Agronomy Journal 81(6):947-951.

Farré, I., Faci, J.M., 2006. Comparative response of maize (Zea mays L.) and sorghum (Sorghum bicolor L. Moench) to deficit irrigation in a Mediterranean environment. Agric. Water Manag.

Gemtos T. A., Galanopoulou, St. and Kavalaris, Chr. (1997). Wheat establishment after cotton with minimal tillage. *European Journal of Agronomy* 8:137-147.

Habyarimana, E., Bonardi, P., Laureti, D., Di Bari, V., Cosentino, S. and Lorenzoni, C. (2004). Multilocational evaluation of biomass sorghum hybrids under two stand densities and variable water supply in Italy. *Industrial Crops and Products* 20(1):3-9.

Kaushik, M. K. and Shaktawat, M. S. (2005). Effect of row spacing, nitrogen and weed control on growth, yield and nutrient uptake of sorghum. *Indian Journal of Agronomy* 50(2):140-142.

Keren R., Meiri, A. and Kalo, Y. (1983). Plant spacing effect on yield of cotton irrigated with saline waters. *Plant and Soil* 74 (3):461-465.

Mahmood, A. and Honermeier, B. (2012). Chemical composition and methane yield of sorghum cultivars with contrasting row spacing. *Field Crops Research* 128:27-33.

Patanè, C., Cavallaro, V. and Cosentino, S. L. (2009). Germination and radicle growth in unprimed and primed seeds of sweet sorghum as affected by reduced water potential in NaCl at different temperatures. *Industial Crops and Products* 30:1-8.

Reddy, B. V. S., Rao, P. S., Kumar, A. A., Reddy, P. S., Rao, P., Sharma, K. K., and Blummel, M. (2009). Sweet sorghum as a biofuel crop: Where are we now? In *Sixth Winrock International Workshop on Biofuels*, 1-13.

Rocateli, A. C., Raper, R. L., Balkcom, K. S., Arriaga, F. J., and Bransby, D. I. (2012). Biomass sorghum production and components under different irrigation/tillage systems for the southeastern U.S. *Industrial Crops and Products* 36(1):589-598.

Rutto, L. K., Xu, Y., Brandt, M., Ren, S. and Kering, M. K. (2013). Juice, ethanol, and grain yield potential of five sweet sorghum (*Sorghum bicolor* [L.] Moench) cultivars. *Journal of Sustainable Bioenergy Systems* 3(2):113-118.

Sakellariou-Makrantonaki, M., Papalexis, D., Nakos, N. and Kalavrouziotis, I. K. (2007). Effect of modern irrigation methods on growth and energy production of sweet sorghum (var. Keller) on a dry year in Central Greece. *Agriculture Water Management*, 90(3):181-189.

Sawargaonkar, G., Wani, S., Pavani, E., Reddy, B. and Marimuthu, S. (2013). Nitrogen response and water use efficiency of sweet sorghum cultivars. *Field Crops Research* 149:245-251.

Sluiter, A., Hames, B., Hyman, D., Payne, C., Ruiz, R., Scarlata, C., Sluiter, J., Templeton, D., and Wolfe, J. (2008). Determination of total solids in biomass and total dissolved solids in liquid process samples. *Laboratory Analytical Procedure (LAP), Technical Report NREL/TP-510-42621* Revised January 2008.

Sluiter, A., Hames, B., Ruiz, R., Scarlata, C., Sluiter, J., Templeton, D. and Crocker, D. (2012). Determination of structural carbohydrates and lignin in biomass. *Laboratory Analytical Procedure (LAP), Technical Report NREL/TP-510-42618,* Revised August 2012.

Smith G. A., Bagby M. O., Lewellan R. T., Doney D. L., Moore P. H., Hills F. J., Campbell, L. G., Hogaboam, G. J., Coe, G. E. and Freeman, K. (1987). Evaluation of sweet sorghum for fermentable sugar production potential. *Crop Science* 27(4), 788-793.

Uchino, H., Watanabe, T., Ramu, K., Sahrawat, K. L., Marimuthu, S., Wani, S. P. and Ito, O. (2013). Effects of nitrogen application on sweet sorghum (*Sorghum bicolor* (L.) Moench) in the semi-srid tropical zone of India. *JARQ, Japan Agricultural Research Quarterly* 47(1):65-73.

Wight, J. P., Hons, F. M., Storlien, J. O., Provin, T. L., Shahandeh, H. and Wiedenfeld, R. P. (2012). Management effects on bioenergy sorghum growth, yield and nutrient uptake. *Biomass and Bioenergy* 46:593-604.

Wortmann C. S., Liska, A. J., Ferguson, R. B., Lyon, D. J., Klein, R. N. and Dweikat, I. (2010). Dryland performance of sweet sorghum and grain crops for biofuel in Nebraska. *Agronomy Journal* 102(1):319-326.