Australian Journal of Crop Science AJCS
AJCS 6(1):10-16 (2012) ISSN:1835-2707

Yield, quality and irrigation water use efficiency of sweet sorghum [*Sorghum bicolor* (Linn.) Moench] under different land types in arid regions

Tingting Xie[1*], Peixi Su[2], Lishan Shan[3] and Jianbin Ma[4]

[1]Linze Inland River Basin Research Station, Heihe Key Laboratory of Ecohydrology and Integrated River Basin Science, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China
[2]Linze Inland River Basin Research Station, Plant Stress Ecophysiology and Biotechnology Laboratory, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China
[3]Forestry Department, Gansu Agricultural University, Lanzhou 730070, China
[4]Plant pathology Department, University of Arkansas, Fayetteville, America

***Corresponding author: xieting1026@126.com**

Abstract

In order to evaluate changes in biomass, sugar content, ethanol yield as well as water use status of sweet sorghum [*Sorghum biocolor* (L.) Moench] a number of experiments conducted in marginal land arid region of Hexi Corridor in northwestern China, with the average rainfall of 116.8 mm, in three land types including loam land, saline-alkaline land and sandy land. The saline-alkaline land and sandy land possessed low total aboveground dry weights of 22.1 and 26.8 t ha^{-1} in 2009, respectively. In 2010, total soluble sugar yields for saline-alkaline land and sandy land varied from 11.00 to11.28 t ha^{-1}, which were significantly higher than loam land's total soluble sugar yield. Similarly, ethanol yield originated from sugar ranged from 6032.57 to 6193.02 L ha^{-1} for saline-alkaline land and sandy land, respectively, indicating a significant difference in comparison with ethanol yield in loam land. However, irrigation water use efficiency of aboveground biomass in 2009 were 3.93, 3.62 and 2.36 kg m^{-3} for loam land, saline-alkaline land and sandy land, respectively. The same trend was found in 2010. It is concluded that although loam land produced more biomass yield and irrigation water use efficiency, the higher sugar and ethanol yield of sweet sorghum was acquired in saline-alkaline land and sandy land. Considering the competition of production between food and energy crops, it is pragmatic and meaningful to develop sweet sorghum in saline-alkaline and sandy land. Meanwhile, the soil condition can be improved to adapt different cultivation modes in order to increase biomass yield or water use efficiency in saline-alkaline and sandy lands.

Key words: Land types; biomass yield; sugar, ethanol yield; irrigation water use efficiency.
Abbreviation: LSD-Least Significance Difference, IWUE-Irrigation Water Use Efficiency, SDW-stems dry weight, AGDW-aboveground dry weight.

Introduction

Plant biomass has been known for decades as one of the most promising renewable energy sources that can be used for production of biofuels, since it is an abundant resource with low CO_2 emissions and low cost (Berndes et al., 2003; Antonopoulou et al., 2008). Biomass derived from plants provides approximately 14% of the total world-wide energy needs (IEA, 1998), which acts as an important contributor to the world's economy (Parikka, 2004; Antonopoulou et al., 2008). Furthermore, plant biomass can contribute to stabilize farmers income, and maintain and improve ecological and social sustainability (Parikka, 2004; Xiong et al., 2008). One of the prime sources, investigated as energy crops, is sweet sorghum because of its higher photosynthetic rate that is two to three times higher than other crops such as soybean, beet and wheat. Currently, sweet sorghum is considered as one of the energy crops with higher biomass yield in the world (Yang, 2004). The cultivation of sweet sorghum enables not only to resolve the green feed problem in animal husbandry, but also enhances the Brix degree of stalk juices, containing high concentration of sucrose, fructose and glucose to produce ethanol used as fuel in vehicles (Ali et al., 2009). Sweet sorghum as an energy crop has received a worldwide concern especially under the scarcity of oil in recent years (Zhang et al., 2006). China is the second largest petroleum consumer in the world. However, due to the largest population pressure, bioethanol projects which bases on food crops such as corn or wheat have been suspended for fuel ethanol production. Instead, the main focus has been given to use non-grain materials which can be grown in marginal lands (The National Development and Reform Commission, 2007). It is well known that sweet sorghum is a tropic native, but it has been well adapted to temperate climates (Gnansounou et al., 2005; Kangama and Rumei, 2005). It is recognized as one of the most promising ethanol crops in China (FAO, 2002; Gnansounou et al., 2005; Kangama and Rumei, 2005). In the Northwestern region of China with the topographic attributes including larger area for arid hillside land, poor sandy land and low-lying saline-alkaline land, sweet sorghum is considered as an optimum option for energy crop because of its higher photosynthesis

Table 1. The ion content of water-soluble salt at different land types

Land types	Depth (cm)	Ion composition ($mg.kg^{-1}$)							
		CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	Na^+	K^+
Loam land	0-20	30	400	50	20	90	50	110	110
	20-40	20	300	50	20.00	80	40	130	70
Saline-alkaline land	0-20	70	380	330	500	200	170	1610	340
	20-40	60	500	120	20	60	80	1290	60
Sandy land	0-20	20	240	10	20	40	40	180	20
	20-40	20	240	10	20	40	40	110	20

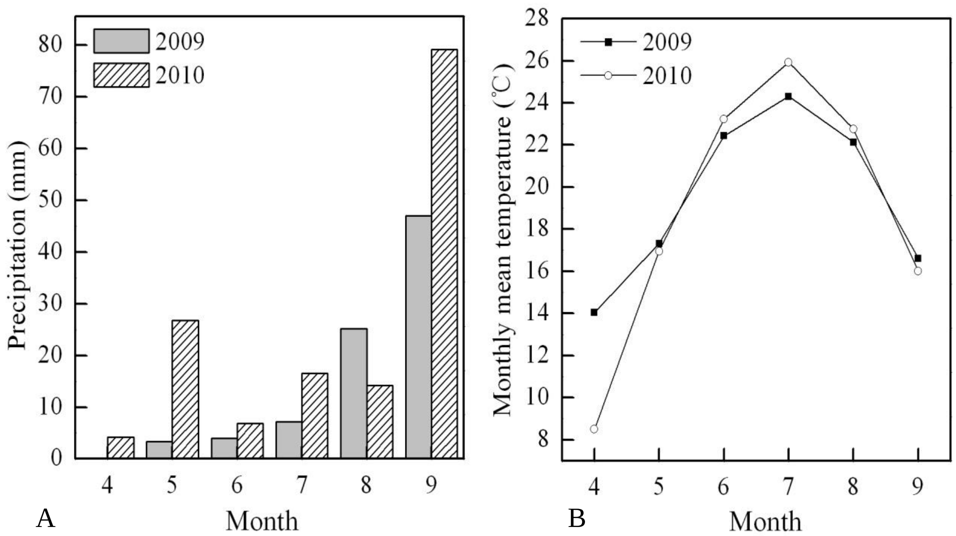

Fig 1. Meteorological factors in the study area during the growth period of sweet sorghum in 2009 and 2010.

rate. Nonetheless, little is known about the development potential of sweet sorghum in arid region of temperate climates. In this study, we conducted a two-year field experiment cultivating sweet sorghum in different land types in the middle of Hexi corridor in China. The objective of this study was to investigate the productive capacity and water use efficiency of sweet sorghum that adapted to different land types. This effort will provide a theoretical base and practice guidelines for utilizing marginal land effectively to produce sweet sorghum in the arid regions.

Results

Climate factors

The experimental field in Hexi is characterized by a typical arid desert climate with hot and dry summers and cool-humid winters. The precipitation and temperature, prevailing at the experimental site during the growing period in 2009 and 2010, is schematically presented in Fig 1. This figure shows that how the precipitation in the experimental region was little in the early growth periods of sweet sorghum (7.2 mm) in July but increased significantly in later growth period, with 25.2 and 47 mm in August and September of 2009, respectively. In 2009, the growth season was particularly dry with only 86.8 mm of total precipitation from early April to September. However, there was more precipitation in 2010, which rose to 26.8 mm and 79.2 mm in May and September, respectively (Fig. 1A). The total precipitation in all growth season was 147.8 mm in 2010. The air temperature presented an increasing trend (Fig. 1B) and the highest air temperature reached in July. The monthly average temperature was 24.3 ºC in 2009 and 25.9 ºC in 2010, respectively. These characteristics of climate determined that crops will experience a high temperature and strong radiation period in July.

Growth analysis

The growth analysis of sweet sorghum as reflected by means of plant heights for each land type illustrated in Fig 2A. It indicates the high growth rates in plant height in early growth period until 130 days after germination with the values of 4.24, 3.68 and 3.78 cm d^{-1} for loam, saline-alkaline and sandy lands, respectively. However, the growth rates showed slightly decrease about 0.52, 0.12, 0.23 cm d^{-1} for loam, saline-alkaline and sandy lands, respectively. The plant height in loam land reached 345.3 cm in harvest time which was 18.0% and 14.1% higher than those in saline-alkaline (283.3 cm) and sandy lands (296.6 cm), respectively. The ANOVA analysis shows that the plant height in loam land was significantly higher than saline-alkaline and sandy land ($P < 0.05$). Fig. 2B illustrates the development of stem diameter under different land types throughout the growing season of sweet sorghum in 2009.

Table 2. Soil mechanical composition of different land types

Land types	Depth (cm)	Sand	Silt	Clay
Loam land	0～20	46.5	45.45	8.05
	20～40	34.15	55.5	10.35
Saline-alkaline land	0～20	65.9	26.05	8.05
	20～40	32.45	44.45	23.1
Sandy land	0～20	81.3	14	4.7
	20～40	99.87	0.13	

The method of soil texture classification was defined as follows: sand, 0.05–2.0 mm; silt, 0.002–0.05 mm; clay, <0.002 mm.

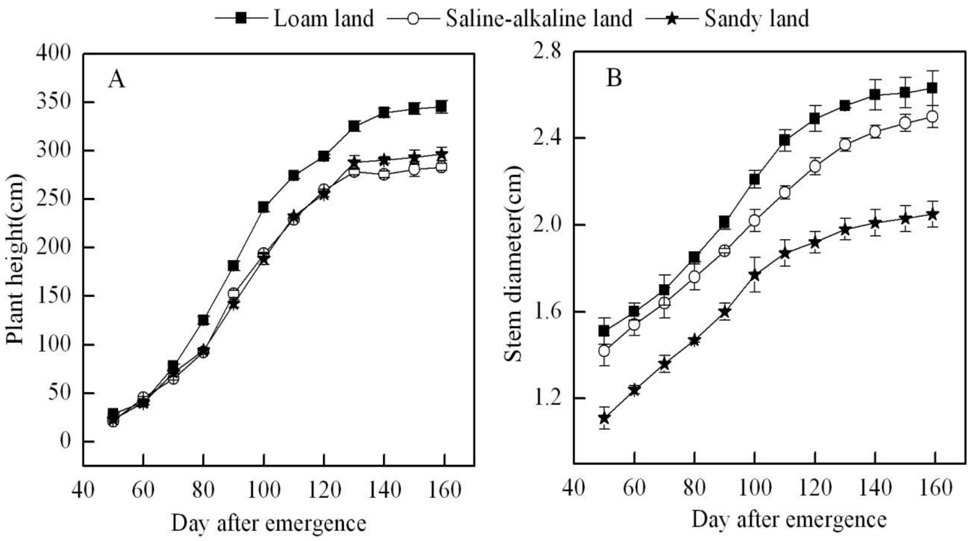

Fig 2. Development of plant height and stem diameter of sweet sorghum under different land types in 2009. Point shows averages of three replications and vertical bars are standard errors.

The stem diameter increased quickly 50 days after germination but this growth rate reduced 130 days after germination. The stem diameter land was the largest in loam soil during the growth season while it was smallest in sandy land. At harvest time, the average of plant's stem diameter grown in loam land was 2.63 cm. The average stem diameter was 2.50 and 2.05 cm for sweet sorghum grown in saline-alkaline and sandy land, respectively, which was 4.94% and 22.05% less in comparison with average stem diameter of sweet sorghum grown in loam land. Average stem diameters of sweet sorghum for loam land, saline-alkaline land and sandy land were significantly different ($P < 0.05$).

Production analysis

Aboveground dry biomass production

The stems dry weight (SDW) and aboveground dry weight (AGDW) of sweet sorghum grown in loam land was largest with the values of 18.9 and 24 t ha^{-1} in 2009 and 24.5 and 29.6 t ha^{-1} in 2010. The SDW in sandy land was similar to loam land with the value of 18.5 t ha^{-1} in 2009 and 22.5 t ha^{-1} in 2010. The smallest values of both SDW and AGDW occurred in saline-alkaline land, which were 16.9 and 22.1 t ha^{-1} in 2009 and 22 and 26.8 t ha^{-1} in 2010, respectively (Fig. 3A, B). Sorghum exhibited higher SDW and AGDW values in 2010 compared to 2009, in all land types. The AGDW decreased by 7.92% and 4.58% in 2009 and 6.75% and 9.53% in 2010 for saline-alkaline and sandy land, respectively in comparison with loam land. Effects of each factor of land types, year and land types × year interaction on SDW and AGDW were significant ($P < 0.05$)(Fig. 3A, B).

Belowground dry biomass production

The plants in loam land exhibited higher belowground biomass than those in saline-alkaline and sandy land both years (Fig. 3C, D). Comparing with loam land, the dry weight of plants decreased by 21.89% in 2009, and 24.78% in 2010 in sandy land but only decreased by 3.39% in 2009, and 7.08% in 2010 in saline-alkaline land. Each factor of land types, year and land types×year interaction had significant effect on belowground biomass ($P < 0.05$)(Fig. 3C, D).

Energy production

Total soluble sugar

The largest amount of total soluble sugar content in the stems and leaves occurred in sand land with the values of 492.07 and 55.68 g kg^{-1}, respectively. But the lowest values measured in loam land, which were 437.81 and 41.10 g kg^{-1} for stems and leaves (Fig. 4A), which increased 12.39% and 35.47%, respectively. The same trends were found among total soluble sugar content in leaves and this differences were significant among different land types ($P < 0.05$). Total soluble sugar yield was greatest in sand land with the value was 11.28 tha^{-1}. However, the loam land had lowest value of 10.89 t ha^{-1} (Fig. 4B). These differences were significant among different land types ($P < 0.05$).

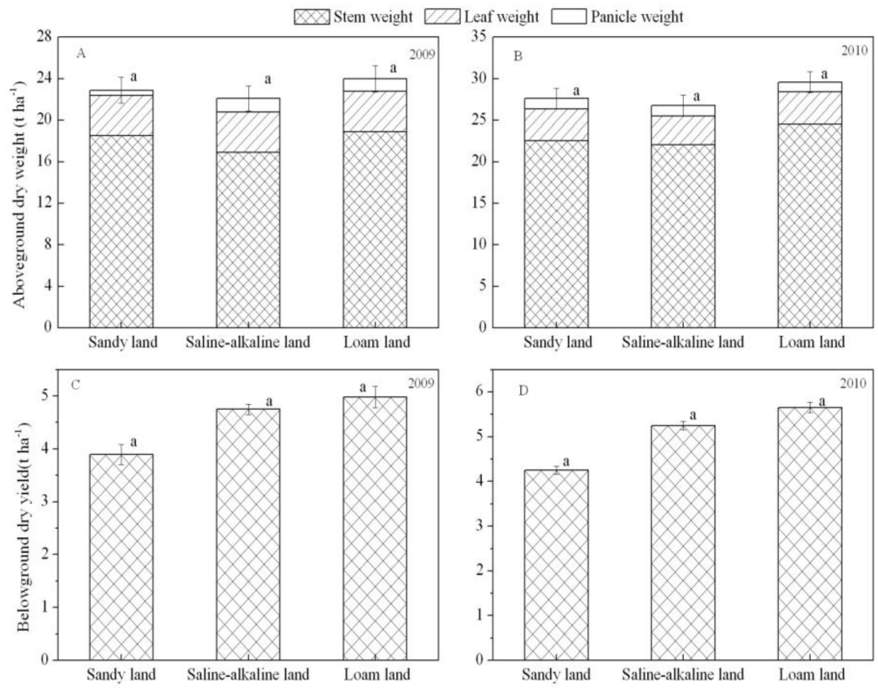

Fig 3. Changes in biomass yield of sweet sorghum under different land types in 2009 and 2010. Vertical bars are standard errors. The same lowercase letter indicates no significant differences (P＜0.05).

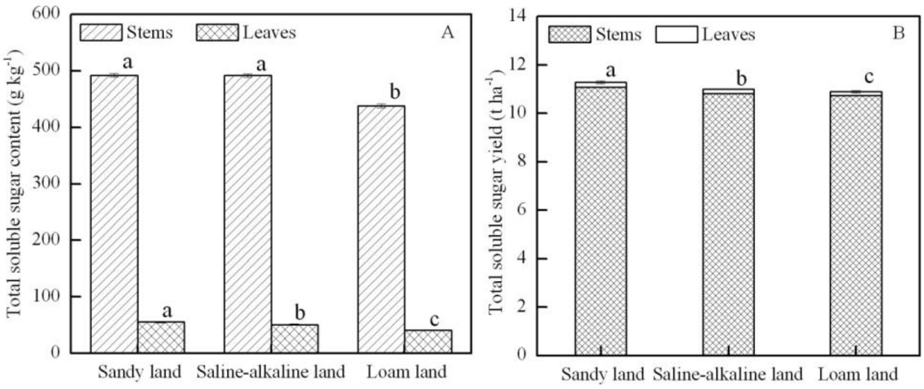

Fig 4. Changes in total soluble sugar content and total soluble sugar yield in the stems and leaves of sweet sorghum under different land types in 2010. Vertical bars are standard errors. The different lowercase letter indicates significant differences (P＜0.05).

Ethanol yield from sugar

Similarly to the pattern of changes in sugar content of stem, the largest calculated ethanol yield from stem sugar was 6193.02 L ha^{-1} for sandy land. The loam land had lowest ethanol yield with the value of 5973.88 L ha^{-1}. There was significant difference among different land types (P＞0.05).

Irrigation water use efficiency

The irrigation water use efficiency of sweet sorghum under different land types is presented in Fig 8. The figure indicates that sweet sorghum, grown in loam land, exhibited higher irrigation water use efficiency with the values of 3.93 kg m^{-3} in 2009 and 4.85 kg m^{-3} in 2010. The lowest irrigation water use efficiency measured in sandy land with the values of 2.36 kg m^{-3} in 2009 and 2.85 kg m^{-3} in 2010. Comparing with loam land, irrigation water use efficiency decreased by 7.89 % in 2009 and 9.48% in 2010 in saline-alkaline land and it decreased by 39.94% in 2009 and 41.24% in 2010 in sandy land. The differences of irrigation water use efficiency among loam land, saline-alkaline and sandy land were significantly different (P<0.05).

Discussion

As an important energy crop, stems of sweet sorghum are the most important organ for bioethanol production. We found that stem biomass was the highest portion of the total aboveground biomass yield but the panicles possessed the lowest dry weight in the arid region of Northwestern China. This result is in close agreement with previous studies conducted on the sweet sorghum cultivars of Wray (Dolciotti et al., 1998) and Keller (Amaducci et al., 2004) in North Italy where the climatic conditions are much different than those to our study and with the results concluded on five cultivars in the North China (Zhao et al., 2009).

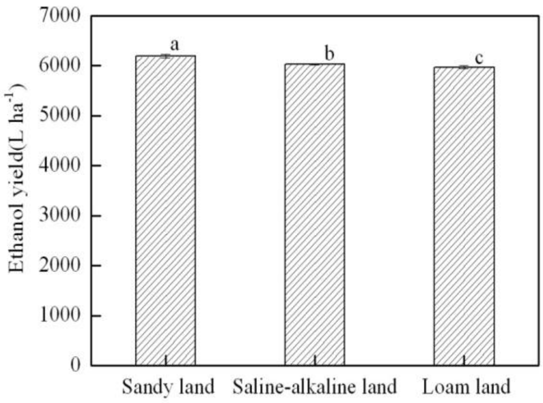

Fig 5. Changes in calculated ethanol yields from sugar of sweet sorghum under different land types in 2010. Vertical bars are standard errors. The different lowercase letter indicates significant differences (P＜0.05).

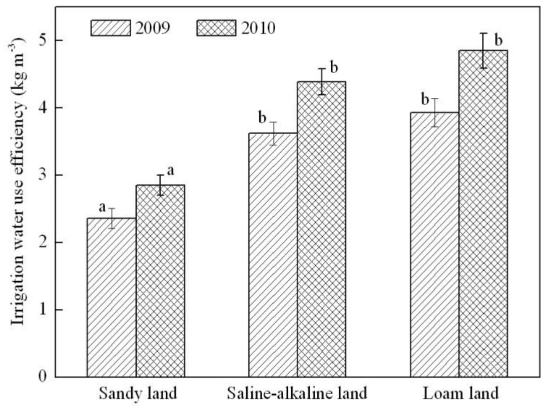

Fig 6. Changes in irrigation water use efficiency of sweet sorghum under different land types. Vertical bars are standard errors. The different lowercase letter indicates significant differences (P＜0.05).

We found the stem and aboveground biomass yield were higher when sweet sorghum grown in loam land but decreased to some extent when plant grown in saline-alkaline and sandy land. The possible reason is the better water holding capacity and nutrition in loam lands due to several decades of cultivation practices rather than the other studied soils. It provides a more suitable environment for the crop growth. Due to the high water-soluble salt content in saline-alkaline land, the soil was easy to harden which suppresses the absorption of nutrition and water from soil, producing lower biomass yield. The sandy lands have weak capability in maintaining water and nutrition because of the soil mechanical composition of fine sand and leads to a lower biomass yield, comparing with loam land. Zhao et al. (2009) noted that the variation ranges of stem dry weight for five sweet sorghum hybrids was 8.2–16.4 t ha^{-1} in 2006 and 9.5–23.9 t ha^{-1} in 2007. Guo, (2005) documented stem biomass yield in ten sweet sorghum hybrids in China and reported that the variation range of stem fresh weight is 35.1–58.8 t ha^{-1}. We found that the stem fresh weight were 61-70.7 t ha^{-1}, and the dry weight was 16.9-22.5 t ha^{-1} in saline-alkaline and sandy land, respectively. It shows that the higher biomass yield also can be acquired in saline-alkaline and sandy land in arid regions. Therefore, considering the competition between food and energy crops, it is benefited to cultivate sweet sorghum in saline-alkaline and sandy land. Meanwhile, the soil condition can be improved and different cultivated modes can be adopted in saline-alkaline and sandy land, which increases biomass yield. The aims of sweet sorghum cultivation were not only to accomplish higher biomass yield, but also to obtain higher quality. Previous studies found total soluble sugar content of the cultivar Keller was 401-422g kg^{-1} in Madird, Spain (Curt et al., 1995). The cultivar Wray was reported to have 436g kg^{-1} of total soluble sugar content at maturity stage in Italy (Dolciotti et al., 1998). Zhao et al. (2009) documented a range of total soluble sugar content of sorghum stems about 305-503 g kg^{-1} in North China. We found the total soluble sugar content in stems was 437.81-492.07 g kg^{-1} from loam to the sandy land, and it was significantly higher in saline-alkaline land and sandy land, in comparison with loam land. This result demonstrates the higher total soluble sugar content can be acquired in the arid region of Northwestern China. Some previous studies focused on the ethanol yield from sugar in sweet sorghum. Smith and Buxton (1993) found the ethanol production from sugar in sweet sorghum was between 3100 and 5235 L ha^{-1} in the temperate zone of the USA. In the temperate site of North China, the ethanol yield from sugar in five sweet sorghum cultivars was 2252-5414 L ha^{-1} (Zhao et al., 2009). We found the ethanol yields from sugar in three land types were 5973.88-6193.02 L ha^{-1}, and the ethanol yield in saline-alkaline and sandy was significantly higher than loam land. Water use efficiency is a synthetical index which is being used to evaluate the relationship between water consumption and material production (Wang et al., 1997). It can be divided into three levels including leaf, canopy and yield. The water use efficiency in yield level is the aim of agriculture production (Wang and Liu, 2000). We found that irrigation water use efficiency has the highest rate in the loam land while it was lowest in sandy land. The reason maybe is that the total water input was less in loam land due to the good capacity in holding water and nutritions. However due to the poor ability in keeping water and nutrition in sandy land, more water in soil was lost by soil evaporation and drainage and then resulted in higher water input in the growth season of sweet sorghum. Thus, irrigation water use efficiency was lowest.

Materials and methods

Study site

A two-year field study was conducted in the northern part of Linze in the middle reach of Hexi Corridor in Gansu Province, China. It possesses a typical arid desert climate where the mean annual precipitation is 116.8 mm. The mean annual evaporation is 2390 mm, which is 20 times higher than the precipitation. The average daily temperature is 7.6 °C, with a total range of 39.1 °C to -27 °C. The accumulated annual temperature of ≥10 °C is around 3088 °C and the frost-free period is 165 d. The main wind is northwestern and the windy season is from April to May with an annual wind velocity of 3.2 m s^{-1} and there are about 15 days with heavy winds per year. The annual total number of sunlight hours is 3045 hrs. The depth of frozen soil is about 10 m. The drought, high temperature and strong wind are the main climate characteristics. Three land types including loam land (39° 16′ 59″ N, 100° 11′30″ E), saline-alkaline land (39° 20′57″ N, 100° 07′ 47″ E) and sandy land (39° 20′ 20″ N, 100° 08′01″ E) with the area of 1334 m^2 of each were selected for. Soil samples were collected at the beginning of growing season from three land types. The water-soluble salt ion content and mechanical composition of the soils in 2009 are presented in Table 1 and 2.

Plant material

A sweet sorghum [*Sorghum bicolor* (Linn.) Moench] hybrid "BJ0601" were sown on March 18th of 2009 and March 25th in 2010 and planted at 60×40×20 cm spacing (100050 plants per ha). Basal fertilizer of 110 kg N ha^{-1} as urea and 45 kg P_2O_5 ha^{-1} as diammonium phosphate were applied just before planting. 75 kg N ha^{-1} as urea and 22 kg K_2O ha^{-1} as potassium sulfate were applied at elongation stage, and 25 kg N ha^{-1} as urea were applied at anthesis stage. Sweet sorghum was overplanted and thinned to one plant in each hole when they had three leaves after germinated. The water input times for loam land, saline-alkaline land and sandy land were 5, 5 and 10 times and the total water input were 6100, 6100 and 9700 m^3 ha^{-1}, respectively.

Sampling and measurements

Three quadrates (2×2 m for each) were selected randomly from three land types in a CRD experimental design, 50 days after sweet sorghum germinated. Plant heights and stem diameters in each quadrate were measured every 10 days and the growth of sweet sorghum during the whole growth period was analyzed as well. The aboveground portions of sweet sorghum in each quadrate were harvested on September 27. Each plant was detached into stems, leaves and a panicle for biomass estimation and the fresh weight was measured. After being placed in an individual paper bag, it was oven dried at 80 ºC to constant weight in order to gravimetrically estimate plant biomass. IWUE (kg m^{-3}) was calculated by taking the quotient of the aboveground biomass yield of sweet sorghum (kg ha^{-1}) and the total water input during the growth period (m^3 ha^{-1}).

Measurement of total soluble sugar content

About ten dried plant tissues of each quadrate for different land types were ground with a Wiley mill and mixed, and then passed through a 0.5mm mesh for measuring total soluble sugar following the Anthrone method (Hewitt, 1958).

Calculation and statistical analysis

A theoretical calculation of ethanol yield from the total soluble sugar was formulated as follows:
Ethanol yield from sugar (L ha^{-1}) = total sugar content (%) in dry matter × dry biomass (t ha^{-1}) × 0.51 (conversion factor of ethanol from sugar) × 0.85 (process efficiency of ethanol from sugar) × 1000/0.79 (specific gravity of ethanol, g mL^{-1}) (Institution of Japan Energy, 2006).

Means and standard errors were calculated for three replicates from each treatment. ANOVA was conducted using SPSS. The statistical significance of the difference between means was determined by LSD test. All graphical constructions were completed using the Origin 7.0 software package.

Conclusions

Compared with loam land, water use efficiencies were lower in saline-alkaline and sandy lands. However, the higher sugar content and ethanol yield of sweet sorghum can be acquired in saline-alkaline and sandy lands. Therefore, considering the competition between food crop and energy crop, it is benefited to cultivate sweet sorghum permanently in saline-alkaline and sandy lands in the arid region of Northwestern China. Meanwhile we think that soil conditions can be improved and different cultivated methods can be adopted in saline-alkaline and sandy lands, which increase biomass yield and higher water use efficiency.

Acknowledgements

This work was financially supported by the National Natural Sciences Foundation of China (31070359 and 91025026) and the CAS (Chinese Academy of Sciences) Action Plan for West Development Project (KZCX2-XB2-09-01).

References

Ali MA, Niaz S, Abbas A, Sabir W, Jabran K (2009) Genetic diversity and assessment of drought tolerant sorghum landraces based on morph-physiological traits at different growth stages. Plant Omics J 2(5):214-227

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. Ind Crop Prod 20:111-118

Antonopoulou G, Gavala HN, Skiadas IV, Angelopoulos K, Lyberatos G (2008) Biofuels generation from sweet sorghum: fermentative hydrogen production and anaerobic digestion of the remaining biomass. Bioresour Technol 99:110-119

Berndes G, Hoogwijk M, Broek R (2003) The contribution of biomass in the future global energy supply: a review of 17 studies. Biomass Bioenerg 25:1-28

Curt MD, 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 Bioenerg 8:401-409

Dolciotti I, Mambelli S, Grandi S, Venturi G (1998) Comparison of two sorghum genotypes for sugar and fiber production. Ind Crop Prod 7:265- 272

FAO (2002) Sweet sorghum in China. In: World Food Summit, Five Years Later, Agriculture Department, Food and Agriculture Organization of the United Nations (FAO).

Gnansounou E, Dauriat A, Wyman CE (2005) Refining sweet sorghum to ethanol and sugar: economic trade-offs in the context of North China. Bioresour Technol 96:985-1002

Guo HY (2005) Characteristic on growth and pole brixs of sweet sorghum hybrids. Dissertation, China: Henan Agricultural University.

Hewitt BR (1958) Spectrophotometric determination of total carbohydrate. Nature 182:246-247

Institution of Japan Energy (Ed.), 2006. In: Hua, Z.Z., Shi, Z.P. (Translators). Biomass Handbook. Chemistry Industry Press, Beijing, p 166-167, 172

International Energy Agency (IEA).1998. World Energy Outlook, 1998 edition. http: //www.iea.org

Kangama CO, Rumei X (2005) Introduction of sorghum (*Sorghum bicolor* (L.) Moench) into China. Afr J Biotechnol 4:575-579

Parikka M (2004) Global biomass fuel resources. Biomass Bioenerg 27: 613-620

Smith GA, Buxton DR (1993) Temperate zone sweet sorghum ethanol production potential. Bioresour Technol 43:71-75

The National Development and Reform Commission (2007) Mid-Long Term Development Plan for Renewable. China.

Wang HX, Liu CM (2000) Advances in Crop Water Use Efficiency Research. Advance Water Sci 11:99-104

Wang MY, Li SK, Zhao M (1997) Relationship between water use efficiency and leaf photosynthesis of maize. Acta Agron Sin 23:345-352

Xiong S, Zhang Q, Zhang D, Olsson R (2008) Influence of harvest time on fuel characteristics of five potential energy crops in northern China. Bioresour Technol 99:479-485

Yang WH (2004) Importance of sweet sorghum in Chinese green energy. Sugar crop China 3:57-59

Zhang FY, Zhao WJ, Ping JA (2006) Macroergic crop-sweet sorghum. Rev China Agric Sci Technol 8:14-17

Zhao YL, Dolat A, Steinberger Y, Wang X, Osman A, Xie GH (2009) Biomass yield and changes in chemical composition of sweet sorghum cultivars grown for biofuel. Field Crop Res 111:55-64