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Impact of fertilisers on soil properties and biomass yield under a long-term sweet sorghum cropping system

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Abstract: A continuous long-term field experiment (2008–2018) was conducted in Xinjiang, north-western China, to assess the impact of farmyard manure (FYM) and inorganic fertilisers on the sustainable biomass yield of sweet sorghum cultivar (Xingaoliang No. 3) and soil chemical properties. Seven treatments, associated with nitrogen (N), phosphorus (P), potassium (K), FYM, and their different combination, were compared with the control plot (CK). As a result, the treatments NP, PK, NK, NPK and NPKM significantly increased the average biomass yields by 30–48% over CK. The 12 t/ha FYM per year with NPK (NPKM) increased both the yield and total soluble solids (T_{SS}) by 48% and 7.9%, respectively, while the 18 t/ha/year application rate of FYM had an adverse effect on yield. Stem T_{SS}, soil available N and K for all treatments decreased while soil organic carbon, soil total salt and the available P for FYM applied treatments increased over the years. The soil pH stabilised at 7.8–8.2 at the end. In conclusion, the 12 t/ha/year of FYM is the most efficient rate for a single application or incorporation with inorganic fertilisers. A more reasonable application rate of N and K fertiliser to increase the yield and irrigation rate to reduce soil salt needs for further investigation.

Keywords: soil nutrient; biological mass; *Sorghum bicolor* (L.) Moench; salinity; arid region

Manasi is one of the important agricultural regions in China's north-western Xinjiang and is located in an extremely arid and semi-arid region (Liu et al. 2012). Sweet sorghum (*Sorghum bicolor* (L.) Moench) is a common salt-tolerant grain sorghum crop suitable for arid land cultivation and shows several advantages, e.g., high biomass yield, rapid growth, wide adaptability to diverse climate and soil conditions, high resistance to drought and salinity, and good yield potential in marginal environments (Zhang et al. 2016). Therefore, sweet sorghum has been the most dominant forage crop cultivated in Xinjiang. Some experimental achievements conducted in this study area showed that the sweet sorghum cultivar Xingaoliang No. 3 was relatively more resistant to soil salinity and suitable for accumulating higher sugar content than other cultivars (Zaituniguli et al. 2012), and it has been cultivated for years with different fertilisation. The long-term application of farmyard manure (FYM) with balanced nitrogen (N), phosphorus (P), and potassium (K) fertiliser promotes soil microbial activity, prevents soil acidification and enhances crop production (Zhai et al. 2011, Chen et al. 2018). However, little attention has been paid to the change of soil fertility, the trend of annual crop yield, and the sugar contents of sweet sorghum for long-timescale in this region. Therefore, evaluating the fertilisation management for sustainable sorghum

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production with higher stem sugar and improving soil condition became necessary. Hence, a continuous fertilisation experiment in combination with FYM was conducted under the intensive long-term monocropping sweet sorghum system to examine the dynamics of biomass yield, stem sugar content, soil condition and available nutrients. The result will be useful for the cultivation in arid and semi-arid regions with similar soil and weather condition, e.g., the southern Xinjiang region and central Asia.

MATERIAL AND METHODS

Experimental site description. The field experiment was conducted for the sweet sorghum cv. Xingaoliang No. 3, the conventional early-maturing cultivar, continuously from 2008 to 2018 at the experimental station of Xinjiang Academy of Agricultural Sciences, located in Manasi county (44°31'N, 86°26'E, 470 m a.s.l.), Xinjiang Uyghur Autonomous Region, China. The soil texture can be classified (USDA 1987) as silty loam. The soil covers can be termed anthrosols according to the soil classification system (FAO 2006). Xingaoliang No. 3 was cultivated every year and remained fallow for the remainder of the year. This region has a typical dry continental climate and has an annual precipitation of 180–270 mm, and the mean annual temperature is 7.2 °C.

Experimental design. Eight different fertilisation treatments with three replicates were established: CK (control, without fertilisation); NK (application of N + K); NP (application of N + P); PK (application of P + K); NPK (application of N + P + K), and another three different treatments combined with dairy FYM (M, NPKM, and 1.5NPKM). The details are provided in Table 1. The area of each plot was set as 30 m^2 (5 m × 6 m). Sweet sorghum was planted at a density of approximately 8–9 plants per 1 m^2, with a spacing of 60 cm between rows and with a spacing of 20 cm between plants.

The field was ploughed to a depth of 25–30 cm, and most of the root residue was cleaned by raking before flattening the surface of the soil in April. The urea (46%), $Ca(H_2PO_4)_2$ (16% P_2O_5), and KCl (60% K_2O) were applied to represent the N, P, and K, respectively. The N, P and K were applied at a constant rate as basal and topdressing fertilisers every year. Organic manure was only applied as basal fertiliser. Basal fertilisers were applied before sowing (1^{st} May–10^{th} May), and topdressing was applied along the rows at the stem elongation (stage 3, BBCH-scale; first ten-day of July). The total N, P, and K contents of the farmyard manure were 26.5 g/kg, 7.9 g/kg, and 18.2 g/kg, respectively. An equal amount of groundwater was applied for irrigation during crop growth. The aboveground stalk was completely harvested from each plot for biomass and other measurements at the maturity date (stage 9, BBCH-scale, 1^{st} September–5^{th} September).

Sample analysis. Soil samples (0–20 cm depth) were collected in September after harvesting every year. In each plot, the soil was collected from ten points randomly and mixed into one sample. After carefully removing the surface organic materials and fine roots, the soil samples were air-dried and sieved using a 2-mm sieve before determining the soil chemical properties. Soil pH_{H_2O} and soil organic carbon (C_{tot}) were determined by the electrometric instrument (Mettler Toledo FE20, Shanghai, China) and the dichromate wet oxidation method, respectively. Soil total salt (S_{tot}) content was estimated by weighing the evaporation residue of the soil/water (1:5) extraction previously filtered on quantitative paper.

Table 1. The annual fertilisation rate and fertiliser type of each treatment

Treatment	Nitrogen		Phosphorus		Potassium		Manure
	basal	topdressing	basal	topdressing	basal	topdressing	basal
	(t/ha/year)						
CK	0	0	0	0	0	0	0
NK	108	72	0	0	27	27	0
NP	108	72	0	0	72	72	0
PK	0	0	27	27	72	72	0
NPK	108	72.0	27	27	72	72	0
M	0	0	0	0	0	0	12
NPKM	108	72.0	27	27	72	72	12
1.5NPKM	108	72.0	27	27	72	72	18

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Available nitrogen (AN) was determined by back-titrating the ammonia and nitrate nitrogen adsorbed in boric acid, which was extracted from the soil with NaOH hydrolysis. Available phosphorus (AP) was extracted by 0.5 mol/L $NaHCO_3$ method and determined colorimetrically using the molybdenum-blue method. Available K (AK) was extracted from the soil with NH_4OAc and determined by AAS (Pansu and Gautheyrou 2006).

The plant biomass yield was determined by weighing the fresh weights of the four middle-of-the-plot plants after harvest in 2008, 2009, 2010, 2011, 2013, and 2018. The final biomass yield was the average of the replicates and expressed in t/ha. The total soluble solids (T_{SS}) were determined by PAL-1digital Sugar Meter (ATAGO, Inc., Bellevue, USA) and averaged the T_{SS} of the upper, middle, and lower stem internodes of 5 stalks in each plot at harvest time in 2008, 2009, 2010, and 2018. Available N, P and K were analysed every year, but the biomass and T_{SS} were measured in some years due to the limited condition of labs.

Statistical analysis. Statistical analyses were performed using Excel 2013 (Microsoft, Redmond, USA) and SPSS 25.0 software (IBM, Armonk, USA). Statistically significant differences were identified using a one-way ANOVA with the least significant difference (*LSD*) tests at the 0.05 level of significance. Data obtained from the triplicate measurements are presented as the mean ± standard deviation (SD).

Weather data. Annual precipitation and temperature for Xinjiang were obtained at the China Meteorological Administration (http://data.cma.cn/).

RESULTS AND DISCUSSION

Annual average yield and stalk T_{SS}. The average biomass yields of the treated plots were significantly higher than that of CK (Figure 1A). The treatments NP, PK, NK, NPK and NPKM significantly increased the average biomass yields by 30–48%, without the marked differences between the years. Compared to CK, the average biomass of NPKM was the highest (94.06 t/ha), increased by 48.79%, but the average biomass yields of NP, PK and NPK were not significantly different from that of NPKM ($P > 0.05$). A significant difference ($P < 0.05$) in the average biomass yield among NPKM, 1.5NPKM, and M implies that 12 t/ha/year is the proper amount of manure for the combination with inorganic fertilisers to harvest higher yield.

T_{SS} is the weight percent of water-soluble solids in stem and is widely used as an approximation for sugar content due to its significant linear correlation with total sugar content. The T_{SS} of sweet sorghum stems is shown in Figure 1B. The NPKM and M increased the T_{SS} by 7.9% and 13.4% over CK, respectively, whereas no significant differences ($P > 0.05$) were observed among the average T_{SS} for CK, PK, NK, NPK, 1.5NPKM and NP. The treatments NPKM and M increased the sugar T_{SS} by 7.89% and 13.42%, respectively.

In conclusion, the 12 t/ha/year application rate of manure was recommended because NPKM emerged as the most efficient treatment in increasing the yield and T_{SS} simultaneously.

The tendency of annual biomass and T_{SS}. To get a more comprehensive understanding, the changes of biomass and T_{SS} were analysed over the study years. The biomass yields exhibited diverse tendencies in response to the different fertilisation and varying

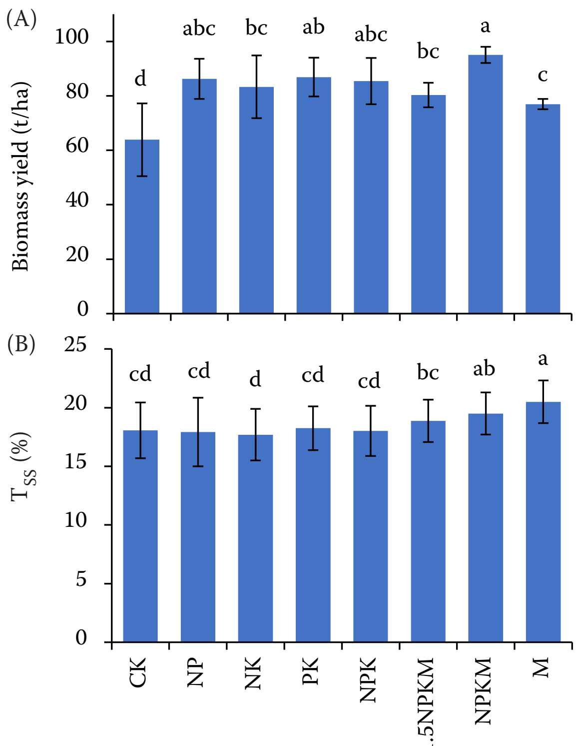

Figure 1. (A) Average biomass yield of six years and (B) average stem sugar total soluble solids (T_{SS}) of four years. The vertical bars indicate the standard deviation (SD). The different small letters at the top of the SD bars indicate significant differences between treatments ($P < 0.05$; *LSD* test). CK – control, without fertilisation; NK – application of N + K; NP – application of N + P; PK – application of P + K; NPK – application of N + P + K), and another three different treatments combined with dairy farmyard manure (M, NPKM, and 1.5NPKM)

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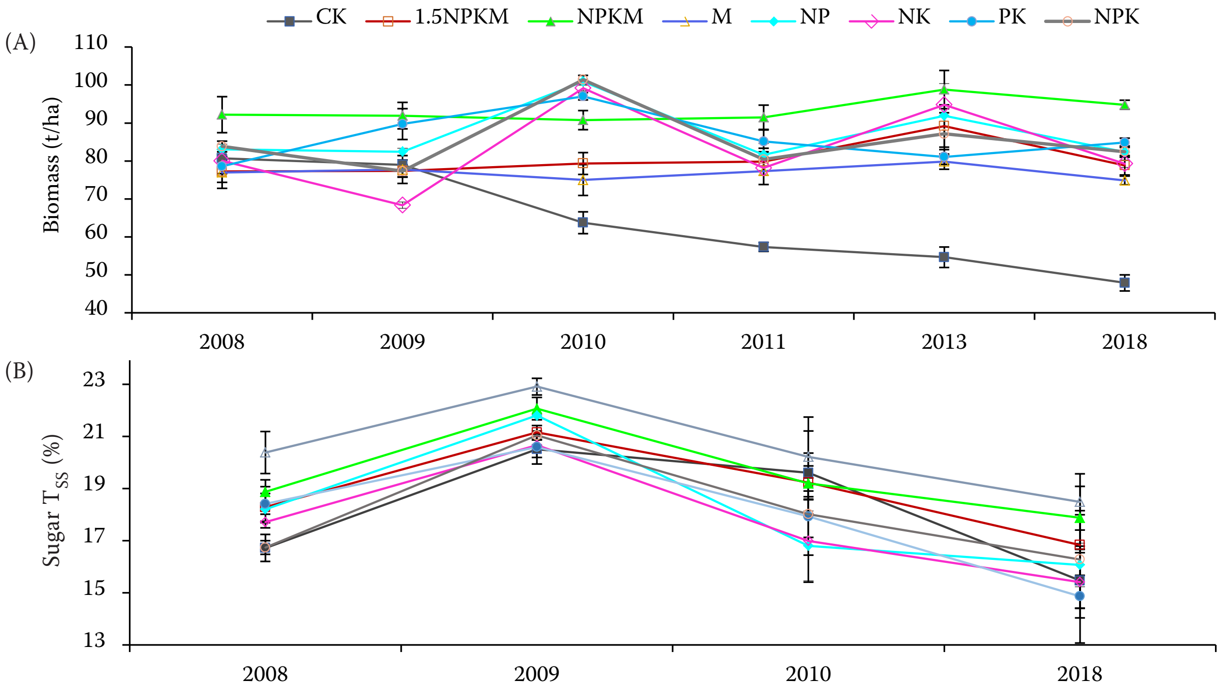

Figure 2. (A) Changing tendency of biomass yield and (B) sugar total soluble solids (T_{SS}) of sweet sorghum. Vertical bars represent the standard deviation. CK – control, without fertilisation; NK – application of N + K; NP – application of N + P; PK – application of P + K; NPK – application of N + P + K, and another three different treatments combined with dairy farmyard manure (M, NPKM, and 1.5NPKM)

weather course (Figure 2A). The biomass of CK significantly decreased with years, while the biomass of other treatments fluctuated over the years without showing a clear increasing trend.

The yield of CK significantly decreased by 40.66%, from 80.71 t/ha to 47.89 t/ha ($P < 0.05$). The biomass for the inorganically fertilised treatments (NP, NK, PK, and NPK) was extraordinarily high in 2010 and declined to a stable level in the following years. However, the biomass for the treatments with FYM and inorganics changed slightly. The biomass for NPKM kept the highest values during the later years.

The changing of the T_{SS} illustrated the same trend for all treatments over the years (Figure 2B). It increased from 2008 to 2009 and then decreased until 2018. At the end of the experiment, the highest T_{SS} content was achieved with M, followed by NPKM and 1.5NPKM with slight differences. This result indicates that some nutrient sources from FYM can increase the T_{SS}.

Soil pH_{H_2O} and S_{tot}. Figure 3 represents the change in soil pH_{H_2O} and S_{tot} during 2008–2018. Soil pH_{H_2O} for the treatments with FYM exhibited a steady increasing trend at the beginning of the experiment, whereas a quick decrease was observed for the other treatments. The pH_{H_2O} for all treatments decreased sharply from 2012 to 2015 and then began to increase again (Figure 3A). In 2018, the pH_{H_2O} for CK was highest, with slight differences with the other treatments, and the pH_{H_2O} for all treatments stabilised at 7.8–8.2. Treatment M decreased the soil pH_{H_2O} value to a noticeable level.

As illustrated in Figure 3B, the S_{tot} was affected by different fertilisation; first, the S_{tot} for all treatments showed an upward trend, then declined dramatically, followed by a relatively stable level, and a similar trend was also observed for CK. After being stabilised, no significant differences across the treatments were observed in S_{tot}; the S_{tot} for treatment M was the lowest and reached a clear stabilised level.

The results provided favourable evidence for preventing soil salinisation and alkalisation with a single FYM application.

Soil nutrient. The quantity of N, P and K distributed in each kilogram of topsoil was calculated according to the natural soil bulk density of this region 1.45 g/cm (Wang et al. 2016), the calculated inorganic N, P and K per kilogram of soil were 0.062 g/kg, 0.049 g/kg and 0.019 g/kg, respectively. The amounts of distributed nutrients in each kilogram of topsoil from 12 t/ha of FYM were 0.110 g/kg N, 0.033 g/kg P, and 0.075 g/kg K, respectively.

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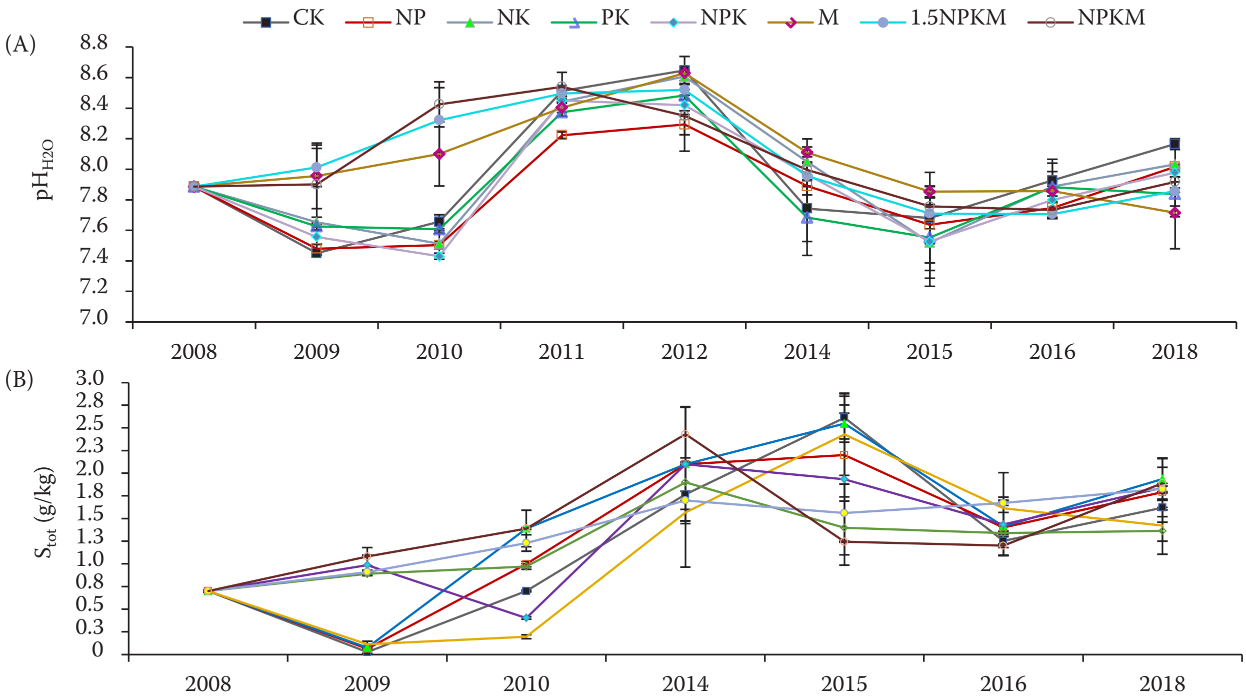

Figure 3. Annual changes of (A) soil pH and (B) total salt (S_{tot}) during 2008–2018. Vertical bars represent the standard deviation. CK – control, without fertilisation; NK – application of N + K; NP – application of N + P; PK – application of P + K; NPK – application of N + P + K, and another three different treatments combined with dairy farmyard manure (M, NPKM, and 1.5NPKM)

Soil organic carbon. C_{tot} for the treatments ranged from 10.00 to 22.00 g/kg with years (Figure 4A). The C_{tot} for CK decreased gradually, whereas the C_{tot} for other treatments showed a wavy increasing tendency. The differences in C_{tot} between the CK and other treatments became more significant with years. At the end of the trial, the C_{tot} for 1.5NPKM was the highest, followed by NPKM with a slight difference. 1.5NPKM and NPKM increased the soil organic carbon by 46.25% and 44.23%, respectively. The C_{tot} for the treatments only with inorganic fertilisers also increased due to root biomass left in the soil.

Available potassium. The soil AK contents for some treatments, except for CK, NP and PK, increased steadily for the first 7 years, then decreased to stabilised level in 2016, and maintained till the end of the trial (Figure 4B).

Available nitrogen. The AN for all treatments increased in the early years of this trial (Figure 4C); CK had the minimum AN during this period. Then AN for all treatments decreased drastically until the end of the study period.

Available phosphorus. The annual variation in soil AP differed for the different treatments (Figure 4D). The AP for all treatments showed a steady increase for the first several years. Then only the two treatments M and NPKM, maintained the increasing trend while AP for the other treatments began to decline. Interestingly, AP for PK and NP decreased to relatively low values, although they were applied with phosphorus every year.

Weather impact. The annual precipitation, air temperature and their values for the growing season over the study period were plotted in Figure 5. Annual precipitation and precipitation in the growing season in 2010 and 2016 were higher. The more water supply in 2010 might give rise to the biomass yield for the inorganically fertilised treatments (Figure 2A) by elevating the water solubility of inorganic fertilisers; the effect of precipitation on yield was not further confirmed due to the absence of biomass data in 2016. No significant trend was revealed for the annual air temperature and temperature in the growing season.

DISCUSSION

Soil pH$_{H_2O}$. Soil pH$_{H_2O}$ affects nutrient availability to plants. Some components in the soil buffer against the pH$_{H_2O}$ changes caused by natural and

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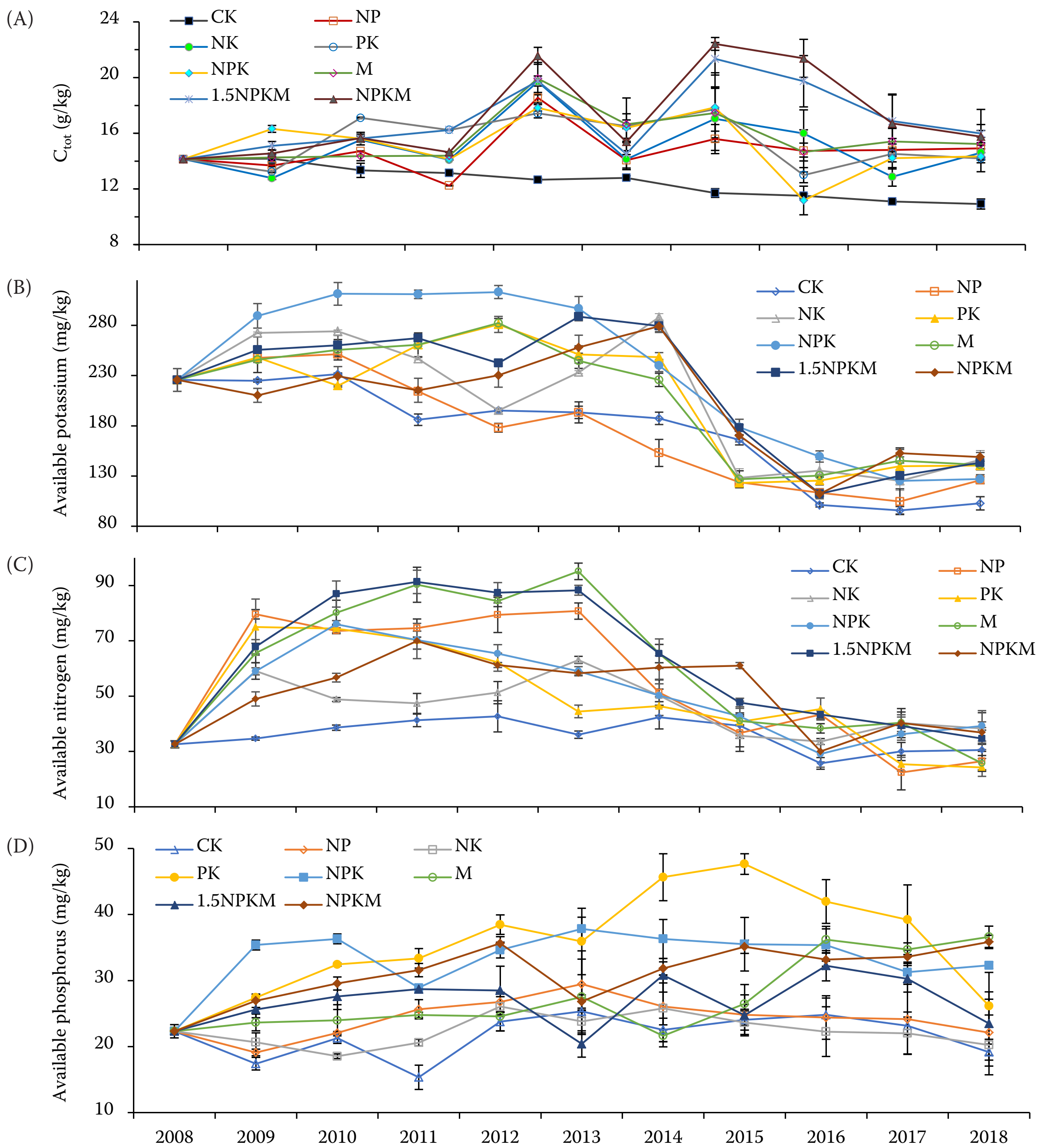

Figure 4. Annual change of (A) soil organic carbon (C_{tot}), (B) available potassium, (C) available nitrogen, and (D) available phosphorus during 2008–2018. Vertical bars represent the standard deviation. CK – control, without fertilisation; NK – application of N + K; NP – application of N + P; PK – application of P + K; NPK – application of N + P + K, and another three different treatments combined with dairy farmyard manure (M, NPKM, and 1.5NPKM)

anthropogenic inputs of acidic and basic fertilisers. Long-term fertilisation of soil and cultivation of different crops may result in different consequences in different regions. In a cotton-chickpea cropping system in India's Vertisols, FYM combined with inorganic fertiliser markedly lowered the soil pH_{H_2O} (Meena et al. 2019). Organic manure application contributed to the soil organic acids and caused a reduction in soil pH_{H_2O} due to humic and fulvic acids from the microbial decomposition of organic manures (Liang et al. 2012), releasing of CO_2 in the soil (Walker et al. 2004) and to the nitrification of NH^{4+} (Chang et al. 1991). The phenolic groups in the soil also buffer pH_{H_2O} at pH > 8.5 (Huang et al.

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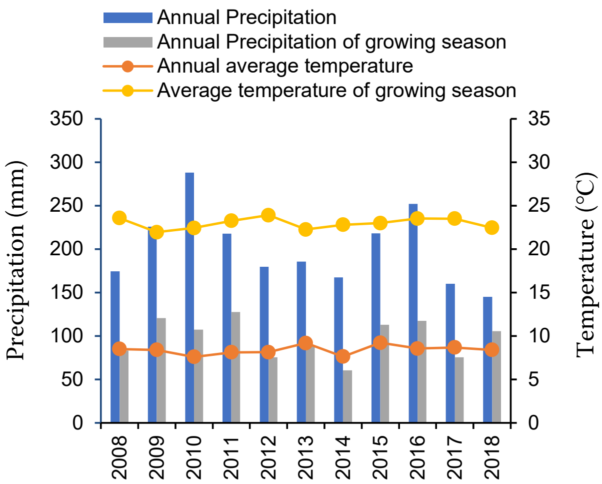

Figure 5. Precipitation and temperature during 2008–2018 at the experiment site

2011). In this study, the pH for all treatments undulated during the trial, and treatment only applied organic manure had the lowest soil pH_{H_2O} at the end of this trial. The decrease in pH_{H_2O} for the manured soil was in close agreement with the above findings. The role of FYM in reducing soil pH_{H_2O} was clearly demonstrated after 11 years, possibly because of the slowness of organic manure decomposition in this arid experimental region.

Soil total salt. The topsoil salinity is highly variable, and the correlation between the salt concentration and the soil pH_{H_2O} varies for the soils. In this study, the similar changing tendency of S_{tot} for all treatments, including CK, presented that S_{tot} was not affected by fertilisation and sweet sorghum cultivation. Cotton cultivation without fertilisation for 16 years resulted in a steady decrease in pH_{H_2O} and salinity in this experimental region (Liu et al. 2016). The wavy fluctuation in S_{tot} was not in good agreement with the abovementioned result. The S_{tot} can be leached to below ground along with the irrigation and rainfall. Compared with the strong soil salt deposit caused by strong evaporation, the effects of irrigation, fertilisation and cultivation on S_{tot} were relatively weak in this experiment. However, in 2016, the decrease in S_{tot} was probably caused by the relatively higher precipitation. More irrigation amount of water may be needed to overcome the strong evaporation.

Soil organic carbon. As reported by Mapfumo et al. (2007), C_{tot} can be increased with the application of extra organic fertilisation. However, the C_{tot} varies for the different soils mainly due to the decomposition rate of the organic matter. García-Ruiz et al. (2012) showed that the application of organic fertiliser resulted in no remarkable changes in C_{tot} for a short period due to the slow rate of the decomposition of organic matter. In the case of long-term organic fertilisation. Kouyaté et al. (2000) found that the effects of manure and crop residue on yield and soil organic carbon reached a significant level when sorghum was continuously cultivated for 8 years. In this experiment, significant differences in C_{tot} were observed for all fertilisation treatments at the end of the trial in comparison with that of the CK. The increasing C_{tot} for the treatments only with inorganic fertilisers might be attributed to the residual effect caused by the slow humification of roots and plant residue. Similar results have been previously reported, e.g., the C_{tot} increased with the long-term application of inorganic fertilisers in maize-wheat-cowpea cropping system in the semi-arid region of India (Kanchikerimath and Singh 2001).

Biomass and stem T_{SS}. Soil nutrients need to be available for the plants for greater yield. All treatments increased the yield over the unfertilised control without showing an increasing trend over the years. The insignificant differences between the initial and final yields indicated that there are potentials for increasing the yields. The high sugar content of the sorghum stem is an important factor in assessing sorghum quality. The T_{SS} for the treatments in this trial ranged from 14.87% to 22.92%, but the highest T_{SS} was not obtained with the highest biomass yield. The treatment M accounted for the greatest $T_{SS,}$ followed by NPKM with a slight difference. The effect of fertilisers on the sweet sorghum sugar content varies with the environment and gene type, e.g., Holou and Stevens (2012) found that the application of nitrogen increased the sugar content in sweet sorghum. In contrast, another study (Almodares et al. 2009) observed that nitrogen's application decreased sugar content under the same conditions. In this trial, a relatively higher average value of T_{SS} was observed in the treatments related to manure. The combination of extra manure with inorganics had a negative effect on the T_{SS} in the case of 1.5NPKM, indicating that the amount of FYM in NPKM was proper for the soil type and cultivation of sweet sorghum in this experimental region.

Available potassium and nitrogen. The soil K^+ availability is highest above soil pH of 6.0, and the proper pH range for N availability is 6.0–9.0 (Weil and Brady 2016). The soil pH during the overall experimental period held above 7.4–8.6, which was at the

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interval of highly available K and N for plants. Thus, the gradual decrease in soil K and N was probably caused by the absorption by sorghum plants while the limited rainfall was not able to leach the soil N and K. The hardly increased biomass yields with years under decreasing available N and K condition requested for a more reasonable inorganic fertiliser application rate.

Available phosphorus. The phosphorus availability generally declines between 7.5 and 8.5 (Weil and Brady 2016). The pH for all treatments varied at 7.4–8.6 during 2008–2018, which indicated the less unavailability of phosphorus to a plant. The steady increase in available phosphorus in the previous years might be caused by the accumulation of P at this pH range. The reason for the subsequent decline in phosphorus for treatments, except for M and NPKM, needs further investigation.

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