Contents lists available at ScienceDirect

Field Crops Research

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

Planting density and sowing date strongly influence growth and lint yield of cotton crops

Aziz Khan[a], Ullah Najeeb[b], Leishan Wang[a], Daniel Kean Yuen Tan[b], Guozheng Yang[a,*], Fazal Munsif[c], Saif Ali[a], Abdul Hafeez[a]

[a] MOA Key Laboratory of Crop Eco-physiology and Farming System in the Middle Reaches of the Yangtze River, Huazhong Agricultural University, Wuhan, 43007, PR China

[b] Faculty of Science, Plant Breeding Institute, Sydney Institute of Agriculture, School of Life and Environmental Sciences, The University of Sydney, Sydney, NSW 2006, Australia

[c] Department of Agronomy, Amir Muhammad Khan Campus Mardan, The University of Agriculture, Peshawar, Khyber Pakhtunkhwa, 23200, Pakistan

ARTICLE INFO

Keywords:
Cotton lint yield
Sowing date
Planting density
Photosynthesis
Nitrogen partitioning
Assimilation

ABSTRACT

This study assesses the effects of plant population density (PPD) and sowing date (SD) on growth, physiology and lint yield of a cotton crop. Seedling transplanting is one of the most dominant cotton production systems in China. But on the other hand, the net benefit is decreasing because the system is labor intensive. Therefore, a shorter cotton growing season is urgently needed to reduce the production costs through management practices such as adjusting sowing date and PPD. The following hypothesis was tested; would cotton yield and physiology

high density planting system (HDPS) has become popular in the cotton production systems worldwide. However, dense populations (> 10 plants m^{-2}) and subsequent shading may lead to disease infestation, reduced boll size, fruit shedding, delayed maturity and decreased individual plant development (Yang et al., 2014a,b; Bednarz et al., 2006). Current recommended PDD in China was is 22.7 plants m^{-2} in the Northwest (Han et al., 2009), 5.3–7.5 plant m^{-2} in the Yellow River Valley (Dong et al., 2012) and 3.0 plants m^{-2} in the Yangtze River Valley (Yang et al., 2014a,b).

Similar to PPD planting time is an important determinant of lint yield and quality in cotton farming systems. Timely planting of crops is essential for root penetration and proliferation, and vegetative growth for optimum harvesting of available soil nutrients and solar radiation (Soler et al., 2007). Early planted crops may experience some challenges of seedling establishment due to low temperatures and high insect pest incidence (Pettigrew and Adamezyk, 2008). Late planting, in contrast, usually reduces cotton yield due to delayed physiological maturity and carbohydrate deficiency (Gwathmey and Clement, 2010). Both PPD and planting time strongly influence N status in cotton leaves, which is positively associated with canopy photosynthetic capacity (Poorrter and Evand, 1998). Synchronization of crop N demands with its supply is crucial for improving crop nitrogen use efficiency (NUE). N demand for a crop is strongly related to yield potential, which in turn is associated with N supply and crop management (Yousaf et al., 2016). Since nutrient uptake and PPD are strongly associated, increasing plant density may lead to an increased N uptake in reproductive tissues. High plant population favors high N uptake and N translocation from vegetative structures to reproductive organs (Jiang et al., 2013).

A leaf with a history of low light has lower photosynthetic saturation relative to an illuminated leaf, and this is particularly important when the cotton crop is grown under dense PPD (Landivar et al., 2010). The affinity of the enzymes involved in carbon fixation e.g., rubisco increases under low light conditions (Jenson, 1986), which imbalances ethylene/sugar ratio and can lead to abscission of the reproductive structures (Zhao and Oosterhuis, 2000). The rubisco has high affinity with O_2 and CO_2 (Jenson, 1986), and photorespiration is increased under low light conditions. This increased ethylene/sugar ratio can lead to abscission of reproductive structures (Guinn, 1974), and cotton yield reduction (Zhao and Oosterhuis, 2000). Thus, time of sowing and plant density can be an important determinant of growth cycle of a cotton crop phenology, growth and development. However, limited information is available on their combined effects on nutrient dynamics, growth, leaf photosynthetic capacity and lint yield of cotton crop. This study explores, the role of plant density and sowing date on (1) cotton growth, lint yield, leaf photosynthetic capacity and nutrient dynamics at different phenological stages; and (2) elucidates the quantitative relationship between planting density and planting date. These data will provide crop management guidelines to cotton growers.

2. Materials and methods

2.1. Experimental site and cultivar

Field studies were conducted in 2014 and 2015 on the experimental farm of Huazhong Agricultural University, Wuhan, China (30° 37′ N latitude, 114° 21′ E longitude, 23 m above sea level). Soil of the experimental site was yellowish brown and clay loam comprising of 1.2% organic matter, 81.7 mg kg^{-1} alkaline N, 21.3 mg kg^{-1} P_2O_5, and 78.4 mg kg^{-1} K_2O. Mean air temperature was higher during seedling establishment, vegetative growth and remained relatively lower during reproductive periods of both years. On average, 2014 was relatively cooler than 2015. Relative humidity was associated with air temperatures during earlier crop stages. It was low during early growth phases and increased as canopy gets closer (Table 1). A cotton cultivar Huazamian H318 (*G. hirsutum* L.) having moderate maturity was used for the present study.

Table 1
Description of climatic parameters during 2014 and 2015.

Month	2014				2015			
	Max°C	Min°C	Mean°C	RH%	Max°C	Min°C	Mean°C	RH%
May	26.8	17.1	22.0	80.6	27.0	18.4	22.7	82.4
June	30.1	21.4	26.0	65.7	31.2	22.5	26.9	68.7
July	41.0	26.5	34.0	62.2	43.3	28.1	31.2	63.1
August	40.2	23.4	31.8	69.1	41.5	24.6	33.1	70.0
September	31.5	21.1	26.3	75.5	33.4	22.7	28.1	75.6
October	28.4	15.3	21.9	70.3	29.3	17.2	23.3	71.2
Average	33.0	20.8	27.0	70.5	34.3	22.3	28.0	71.8

2.2. Experimental design, treatment and crop management

The experiment was conducted in a split-plot arrangement e.g. three plant densities (D_1, low; 7.5 × 10^4; D_2, moderate; 9.0 × 10^4 and D_3, high; 10.5 × 10^4 ha^{-1}) randomly assigned (sub plot) with two planting dates (S1, early May 20; S2, late June 04) (main plot). The split-plot arrangement with four independent replicates was used to increase the precision of comparisons. The experimental sub plot was size consisted of a 12 m long and 3.04 m wide with total plot size of 36.48 m^2. Row spacing of the experimental treatment consisted of narrow row spacing (25 cm) and wide row spacing (76 cm). Plant spacing was adjusted according to the corresponding plant population density. Each sub plot was consisted of four rows with narrow row and wide row space. Cotton seeds were sown on raised bed by hand in respective plots. Seedlings were thinned two weeks after emergence to the required plant density (75,000, 90,000 and 105,000 ha^{-1}). Fertilizer, at the rate (kg ha^{-1}) of 180 N, 54 P_2O5, 180 K_2O, 1.5 B with urea (46% N), superphosphate (12% P_2O_5), potassium chloride (59% K_2O) and borate (10% B), were applied at early flowering (66 days after emergence). Cultural management practices such as irrigation, weeding, hoeing and pesticide application were implemented to reduce competition for nutrient, light, water and spacing for a better crop stand. Mepiquat chloride was applied as a growth regulator in order to speed up boll opening and reduce excessive vegetative growth.

2.3. Observations

2.3.1. Cotton plant growth characteristics

At peak boll stage (74 days after emergence), fifteen plants per plot were randomly selected to measure plant height using a specially designed ruler. Cotton fruiting branch length was measured from the point of attachment to the end of the branch. Number of fruiting branches nodes and leaves were counted from fifteen randomly selected plants in each plot. Fruiting branch length data were divided by fruiting branch number to obtain fruiting branch length to fruiting branch numbers ratio (FB/FN).

2.3.2. Yield and yield contributors

Seed cotton yield (fiber and seed) was recorded three times from the manually harvested plants in each sub plot. The boll was sun dried to ≤ 11% water content (Dong et al., 2010), and ginned to obtain lint yield. Prior to second harvest one hundred fully matured open bolls were picked from each plot dried and ginned to calculate individual boll weight and lint%. Individual boll weight was calculated by total seed cotton yield of 100 bolls divided by total boll number. Lint% was assessed from the ratio of lint yield derived from 100 bolls divided by seed cotton weight of 100 bolls.

2.3.3. Net photosynthetic rate (Pn)

Net photosynthetic rate (Pn) was measured at various reproductive growth stages e.g. squaring (47 days after emergence) (DAE), first bloom (66 DAE), peak bloom (74 DAE) and boll opening (121 DAE) from the functional 4th leaf on the main stem from the apex using a gas-exchange meter (Li-6400, Li-COR Inc., NE, USA). These measurements were carried out on sunny days between 10:00 and 12:00 am in each treatment in the following conditions; light intensity of 1800 μ mol m^{-2} s^{-2}, the ambient CO_2 concentration was 366 μmol - mol^{-1} and the vapor pressure was 3.5 kPa during different phenological stages at field temperatures. Three readings per leaf were replicated on three plants in each sub plot.

2.3.4. Nitrogen uptake

Three plants in each plot were randomly harvested at each growth stage of the crop, e.g. squaring (47 DAE), fist flowering (66 DAE), peak flowering (74 DAE) boll opening (121 DAE) and plant removal (151 DAE). The plants were dissected into vegetative structures (root, stem, leaves, fruiting branch) and reproductive organs (squares, flowers, bolls). Samples were placed in an electric fan-assisted oven for quick cell killing at 105 °C for 30 min to stop N consumption by respiration and dried at 70 °C for at least 48 h to constant weight. The dried samples were milled with a Wiley mill and screened through a 0.5 mm sieve. Total N concentration was determined according to the micro-Kjeldahl method (

crops at peak bloom, boll opening and withdrawal (plant removal) stages, respectively. Among different PDD, D_2 plants had higher RON at all growth stages followed by D_1 and D_3 plants.

3.5. Simulation of nitrogen accumulation

Simulation of N accumulation with cotton growth stages was calculated using Formula (1). The function of logistic was followed by N accumulation as a normal sigmoidal growth pattern since all P values were < 0.005 (Table 5).

Data obtained by Formula (2)–(4), based on Table 5 exhibited the beginning and termination day of cotton plant nitrogen (CPN) uptake for earlier (S_1) and later (S_2) sowing are presented in (Table 6). S_1 plants had higher rates of CPN acquisition in average and maximum than S_2 plants during the whole growing period. Further, S_1 plants with higher density (S_1D_3) showed fast CPN accumulation at 64 days after emergence (DAE) and terminated at 83 DAE 7-d, 6-d later compared with earlier and moderate (S_1D_2) and earlier and lower (S_1D_1) density, respectively. Further, both average (6.7 V_M kg ha^{-1} d^{-1}), and maximum (7.7 V_M kg ha^{-1} d^{-1}) CPN accumulation rate in S_1D_3 crops were higher than S_1D_1 and S_1D_1. A similar trend was observed in S_2 sowing, S_2 D_3 had maximum rate (4.8 V_M kg ha^{-1} d^{-1}), CPN accumulation during FAP compared with S_2D_2

highest average (3.8 V_T kg ha^{-1} d^{-1}) and maximum (5.0 V_M kg ha^{-1} d^{-1}) rate than that of other combinations S_1 D_1 and S_1D_2, respectively. S_2 D_1, S_2 D_2 and S_2 D_3 showed starting and ending days of the 31-d FAP for VON, averaged across the treatments were 61 and 92 DAE, respectively (Table 6). Moreover, S_2 D_3 was superior to other treatments in average and maximum rate in FAP (2.6 V_M kg ha^{-1} d^{-1}) and (2.9 V_M kg ha^{-1} d^{-1}) terminated at 73 DAE.

Averaged across the treatments, the FAP for reproductive organ nitrogen (RON) uptake began at 22-d in S_1 crop and 26-d in S_2, respectively (Table 6). Among the treatments S_1D_2 RON accumulation initiated the FAP at 80 DAE and ended at 102 DAE with relatively higher average (3.5VT kg ha^{-1} d^{-1}) and maximum (4.5VM kg ha^{-1} d^{-1}) rates to $S_1D_1$and S_1D_3, respectively. RON accumulation in S_2 started day of FAP at 94.7 DAE and ended at 120.3DAE, with higher average and maximum speed of FAP. However, S_2D_2 had the highest average (2.1VT kg ha^{-1} d^{-1}), and maximum (3.1VT kg ha^{-1} d^{-1}) rates of RON uptake compared with other treatments. Significant differences existed between sowing dates for RON accumulation. S_1 crops had higher RON acquisition rate in both average and maximum compared with S_2 crops.

4. Discussion

In this 2-year field study, we investigated the effects of plant density and sowing date on growth and physiology of a cotton crop. Increased PPD is practiced to maintain the number of bolls per unit area but it reduces individual plant yields. This pattern is essential when the crop growing season is short. Late planted crop with high density has the potential to increase lint yield under intensive field management (Dong et al., 2006). Late planted short season cotton with moderate plant density produced higher yields than other combinations (Dong et al., 2010). In the present study, cotton lint yield was significantly greater in D_2 compared with D_1 and D_3. No significant increase in lint yield beyond D_2, suggests that increasing that PPD may increase number of bolls per unit area without contributing to the total lint yield due to poor boll filling (Mao et al., 2015; Rossi et al., 2004). In contrast, to lower seeding rates, farmers tend to reduce input costs, which delays crop maturity and reduces overall lint yield (Yang et al., 2014a,b; Zhao et al., 2012; Siebert et al., 2006). Recent research has suggested that, cotton yield can be increased by increasing the PPD (Bartimote et al., 2017; Liu et al., 2015 Venugopalan et al., 2014; Ali et al., 2011; Brodrick et al., 2013).

Increased lint yield in D_2 crop was primarily attributed to higher root growth and activity in the soil, which in turn promoted N uptake and translocation to the developing bolls. Further, this promoted fruiting retention capacity. In contrast, poor light penetration to the lower canopy in D_3 crop accelerated photorespiration, leading to an increase ethylene/sugar ratio and higher abscission rate of reproductive structures (Echer and Rosolem, 2015). Elevated ethylene concentration in cotton tissues has been linked with poor yield performance (Najeeb et al., 2015) and can be regulated by blocking ethylene biosynthesis through aminoethoxyvinylglycine application (Najeeb et al., 2016). In higher density systems cotton plants produce smaller bolls due to poor boll filling compared with conventionally planted cotton (Wright et al., 2011). This suggests that, increasing lint yield is possible with high to moderate PPD but further increase in PPD may lower lint yield.

Sowing date is also an important determinant for cotton production. In this study, early planted crop produced significantly higher lint than late sown crop, which can be explained by the fact that S_1 crop took advantage of soil moisture and nutrients for longer growing season and produced more bolls. In contrast, S_2 crop experienced a shorter reproductive period due to increased air temperatures and reduced canopy photosynthesis due to less radiation interception. The reduction in lint yield in S_2 crop in 2014 was the result of many unopened bolls at harvesting. Although defoliation and tipping was practiced to enhance boll opening of late bolls in S_2 crop 2015, lint yield remained significantly lower than S_1 crop. The reproductive development in S_2 crop was also affected by cooler temperature and low light, which reduced photosynthetic activity carbohydrates transition to fruit structures (Gormus and Yucel, 2002; Liu et al., 2015; Zhang et al., 2014).

In this study, S_1 crops achieved photosynthesis9(-55011TfmjETBT7.9racticed)

(Table 1). Carbon assimilation in the S_2 crop was further impaired due to reduced day length and radiant energy (Bauer et al., 2000). This indicates that leaves on the main stem plays a pivotal role in cotton growth and development through light interception and radiation use efficiency. Lower Pn was expected in plants with higher PPD due to self-shading, which inhibited light penetration to the lower leaves, which also occurred in the present study (Zhang et al., 2012; Echer and Rosolem, 2015; Pettigrew and Adamezyk, 2008). The absorption of CO_2 in leaves of D_1 and D_2 was greater than D_3 PPD. The CO_2 absorption of cotton leaves was 2.2 times greater when cotton was grown under higher radiation (361 μ mol CO_2 $m^{-2} s^{-1}$) relative to low radiation (63 μ mol CO_2 $m^{-2} s^{-1}$) as reported by (Xie et al., 2016; Smith and Longstreth, 1994). We suggest that later sowing and higher PPD can potentially suffer photosynthesis reduction due to shorter day length, increased competition for resources more leaf senescence and poor light penetration to lower canopy leaves which in turn lower lint yield. This

2011). Our data are in good agreement with Ehdaie and Waines (2001), who also reported that early planted crop increase macro nutrients accumulation, distribution and utilization. Our data showed that higher reproductive organ N accumulation resulted in the efficient translocation of photosynthates during boll filling which led to higher yield. Higher density has the potential to increase total plant N acquisition but on the other hand decrease N partitioning to reproductive organs.

5. Conclusions

The present study proved that cotton lint yield significantly increased with moderate planting density under two sowing dates. Moderate density significantly altered plant architecture and consequently increased net photosynthesis and N accumulation and lint yield, for both sowing dates. This increment in lint yield was associated with higher N uptake, which promoted canopy photosynthetic capacity and assimilate translocation towards developing fruits. It is concluded that 9.0 plants m^{-2} could be optimum plant density under both sowing dates in Hubei province China. Ethylene management in cotton canopy could promise higher lint yield by controlling fruit shedding in dense cotton population, however, further studies are needed to confirm this hypothesis.

Acknowledgements

We are thankful to funding by The National Natural Science Foundation of China (311716600 and 31360248).

References

Ali, H., Afzal, M.N., Ahmad, F., Ahmad, S., Akhtar, M., Atif, R., 2011. Effect of sowing dates plant spacing and nitrogen application on growth and productivity on cotton crop. Int. J. Sci. Eng. Res. 2, 2229–5518.

Bange, M.P., Milroy, S.P., Thongbai, P., 2004. Growth and yield of cotton in response to waterlogging. Field Crops Res. 88, 129–142.

Bartimote, T., Quigley, R., Bennett, J.M., Hall, J., Brodrick, R., Tan, D.K.Y., 2017. A comparative study of conventional and controlled traffic in irrigated cotton: II. Economic and physiological analysis. Soil Tillage Res. 168, 133–142.

Bauer, J. Philip, James, R., Frederick Judith, M., Bradow, E., John Sadler Dean Evans, E., 2000. Canopy photosynthesis and fiber properties of normal-and late-planted cotton. Agron. J. 92, 518–523.

Bednarz, C.W., Nichols, R.L., Brown, S.M., 2006. Plant density modifications of cotton within-boll yield components. Crop Sci. 46, 2076–2080.

Bremer, J.M., Mulvaney, C.S., 1982. Nitrogen total. Methods of Soil Analysis. Part 2: Chemical and Microbiological Properties. American Socity of Agronomy Inc., Soil Science Society of America Inc., Madison, Wisconsin, pp. 595–624.

Briggs, R.E., Patterson, L.L., Massey, G.D., 1967. Within and Between-row Spacing of Cotton. Arizona Annual Report. Univ. of Arizona Agric. Ext. Service, Arizona, pp. 6–7.

Brodrick, R., Bange, M.P., Milroy, S.P., Hammer, G.L., 2013. Physiological determinants of high yielding ultra-narrow row cotton: canopy development and radiation use efficiency. Field Crops Res. 148, 86–94.

Caviglia, O., Melchiori, R.J.M., Sadras, V.O., 2014. Nitrogen utilization efficiency in maize as affected by hybrid and N rate in late-sown crops. Field Crops Res. 168, 27–37.

Constable, G.A., Bange, M.P., 2015. The yield potential of cotton (*Gossypium hirsutum* L.). Field Crops Res. 182, 98–106.

Constable, G.A., Oosterhuis, D.M., 2010. Temporal dynamics of cotton leaves and canopies. In: Stewart, J., Oosterhuis, D., Heitholt, J., Mauney, J. (Eds.), Physiology of Cotton. Springer, Netherlands, pp. 72–79.

Dong, H., Li, W., Tang, W., Li, Z., Zhang, D., Niu, Y., 2006. Yield: quality and leaf senescence of cotton grown at varying planting dates and plant densities in the Yellow River Valley of China. Field Crops Res. 98, 106–115.

Dong, H., Li, W., Xin, C., Tang, W., Zhang, D., 2010. Late planting of short-season cotton in saline fields of the Yellow River delta. Crop Sci. 50, 292–300.

Dong, H.Z., Li, W.J., Eneji, A.E., Zhang, D.M., 2012. Nitrogen rate and plant density effects on yield and late-season leaf senescence of cotton raised on a saline field. Field Crops Res. 126, 137–144.

Echer Fábio, Fábio R., Rosolem, Ciro A., 2015. Cotton yield and fiber quality affected by row spacing and shading at different growth stages. Eur. J. Agron 65, 18–26.

Ehdaie, B., Waines, J.G., 2001. Sowing date and nitrogen rate effects on dry matter and nitrogen partitioning in bread and durum wheat. Field Crops Res. 73, 47–61.

Gao, Y., Lynch, J.P., 2016. Reduced crown root number improves water acquisition under water deficit stress in maize (*Zea mays* L.). J. Exp. Bot. 67, 4545–4557.

Garnett, T., Conn, V., Kaiser, B.N., 2009. Root based approaches to improving nitrogen use efficiency in plants. Plant Cell Environ. 32, 1272–1283.

Gormus, O., Yucel, C., 2002. Different planting date and potassium fertility effects on cotton yield and fi