



Review

Review of the technology for high-yielding and efficient cotton cultivation in the northwest inland cotton-growing region of China

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ABSTRACT

The northwest inland is currently the most dominant cotton-growing region in China. In 2015, the region measured 2.3 million hectares with a total output of 4.28 million tons of cotton. The unit yield was 1900 kg hm⁻², which was not only 21, 41 and 121% higher than the national averages of China, Brazil and the United States, respectively, but also 2.37 times as much as that of the world's average. Enhanced cotton production, particularly the high unit yield, can largely be attributed to the adoption of a series of key cultivation techniques. These techniques, including earliness-stimulating cultivation for full utilization of accumulated heat, close planting and short plant height for adequate use of light energy, and drip irrigation under plastic mulching for water saving and yield improvement, have been recently established and applied in the northwest inland of China. At the same time, a series of labor and cost-saving technologies or practices have been adopted to increase net production returns. Mechanization and precision seeding has greatly reduced labor inputs, rational high-density planting techniques combined with chemical regulation has simplified plant pruning and harvesting, and the integrated application of water and fertilizer has reduced the inputs and costs in field management. In particular, the integration of these agronomic techniques and material equipment has not only enhanced yields, but is also convenient, cost-effective and simple. These factors have all led to the establishment of the northwest inland as the largest predominantly cotton-growing area in China. However, the region is currently facing major issues including stagnated cotton yields, serious plastic film pollution, continuous degradation in fiber quality, substantial increases in the cost of cotton production and continuously declining profits. These factors necessitate that cotton cultivation strategies in the region need to be further optimized. Yields can be enhanced by exploring heat and water potential, while quality and economic benefits can be improved by exploring light potential, fertigation and integrating agronomic techniques with mechanization. Greater attention should be paid to seed quality and seeding processes to further reduce costs and improve efficiency. Comprehensive steps for improving the cultivation system at all stages of production should also be taken to enhance the quality of the cotton fiber.

1. Introduction

China is one of the world's largest producers and consumers of cotton (Mao, 2013). The northwest inland cotton region is China's major concentrated growing area. Since the mid-1990s, the northwest inland has gradually developed into one of three dominant cotton-growing regions in China, and in recent years it has substantially developed and became the largest cotton-growing region in China in terms of yield, total production and planting acreage (Appiah et al., 2014; Tian et al., 2016). In 2015, the region measured 2.3 million

hectares with a total output of 4.28 million tons, accounting for 58% of the entire cotton planting acreage and 69% of the total output of the nation. The yield per unit area was 1900 kg hm⁻², which is 21% higher than the national average for the same year. The contribution and status of the area to cotton production and agriculture has rendered it to be the biggest and most successful in the country (Fig. 1). Compared with the world's major cotton-producing countries, cotton yields in this region were 25% and 96% higher than those of Brazil and the United States respectively during the past five years. In addition, cotton yield of this region was 2.37 times as much as that of the world's average

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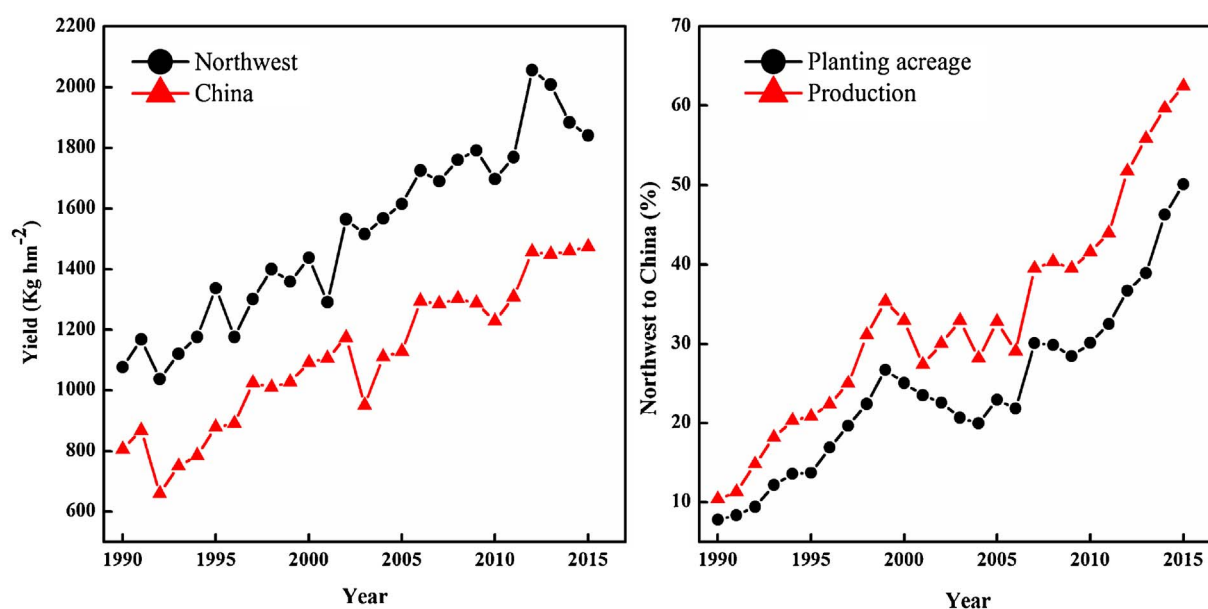


Fig. 1. Variation in the proportion of the northwest inland cotton yield, total production and acreage with respect to the entire country (China).

(Table 1). The cotton yield per unit area was only lower than that of Australia during the same period, but comprises a far larger cotton-growing area than Australia. Furthermore, the main cotton-producing areas of Australia have sufficient light (average light intensity of 5807 MJ m⁻²), longer growing periods (greater than 300 d) and good irrigation conditions (80–90% of total cotton-growing areas receive good irrigation) (Mao and Li, 2016). In contrast, the natural ecological conditions of the northwestern inland vary, suffering from extreme low light intensities and periods, major seasonal water shortages, low temperatures, frost and frequent natural disasters (Mao, 2013; Shen et al., 2013b). Thus, the cotton production achieved in this region is commendable under the circumstances (Table 2). The majority of researchers in the industry have recently come to believe that cultivation techniques such as close planting (high plant density), dwarfing (reduced plant height) and early maturation stimulating as well as plastic mulching are the main contributors to the high yields and efficiency of the northwest inland cotton region (Mao, 2013; Wang and Zhang, 1995; Tian et al., 2000; Chen et al., 2001b). Furthermore, some scholars consider the enhanced productivity to be the result of a number of introduced strategies, including high density planting, wide plastic film mulching, drip irrigation under mulching, the integration of water and fertilizer application and the integrated use of agricultural mechanization technologies (Yu et al., 2015; Ma and Li, 2006; Li et al., 2015; Xin, 2013). In our opinion, the above-mentioned measures are all factors contributing to the high yield and efficiency of the northwest inland cotton region, but do not fully elucidate the reasons and mechanisms for the sustained high yields and efficiency achieved over

the years. We believe that the high cotton yield of the region can be attributed to the full utilization of heat, light and water resources, and the continued high efficiency can be attributed to the high-level integration of agronomic techniques and mechanization. An in-depth analysis of the causes and mechanisms of continued high yields and efficiency of northwest inland cotton will not only provide guidance for the sustainable development of the region's cotton production, but will also act as an important reference for global cotton production.

2. Promotion of early maturation and full utilization of accumulated heat

The northwest inland cotton growing region essentially includes the Xinjiang and Gansu regions, in which poor thermal conditions and insufficient accumulated heat are the main limiting factors for cotton production (Table 2). In the northwest inland, the northern Xinjiang cotton-growing areas suffer from a shortage of heat resources during the seedling and boll-opening stages (Li et al., 2010; Chen et al., 2014a). Crops are prone to chilling injury during the early stages, as well as late fast cooling which renders them vulnerable to frost in autumn. Early frost in southern Xinjiang generally occurs from early October to mid October, while in northern Xinjiang it occurs from the end of September to early October (Pan et al., 2011). In response to the climatic characteristics, particularly the insufficient heat resources, the region has adopted a series of earliness-stimulating measures to accelerate the process of cotton growth and development, such that the majority of cotton fields can meet the requirements for the growth

Table 1
Cotton productivity in the main cotton growing regions and countries.*

Region or country	Planting area ($\times 10^3$ hm ²)			Total output ($\times 10^3$ t)			Lint yield (kg hm ⁻²)		
	1991–2000	2001–2010	2011–2015	1991–2000	2001–2010	2011–2015	1991–2000	2001–2010	2011–2015
Northwest§	819	1368	1801	1047	2245	3481	1335	1649	1806
China	5075	5175	4573	4458	6134	6476	899	1183	1420
Australia	360	273	411	544	479	832	1506	1823	2077
Brazil	1147	1000	1080	556	1205	1559	546	1212	1447
USA	5201	4672	3541	3738	4038	3266	721	868	921
World	33107	32920	33589	19181	23884	25597	579	725	761

§Northwest includes Xinjiang and Gansu.

* Data sourced from United States Department of Agriculture and Agricultural Statistics in China.

Table 2
Comparison of ecological conditions among the major cotton sub-regions.

Sub-region	The number of days $\geq 10^{\circ}\text{C}$ (d)	$\geq 10^{\circ}\text{C}$ degree days ($^{\circ}\text{C}$)	Annual sunshine hours (h)	Rain fall (mm)	Major weather disasters
Southern Xinjiang	190–210	3800–4400	2600–3400	25–98	Cold and dry spring, dry hot wind in summer
Northern Xinjiang	160–180	3100–4100	2600–3000	100–200	Freezing in spring and chilly in autumn
Gansu	160–180	2901–3574	3033–3259	40–110	Freezing in spring and chilly in autumn

and development processes of seeding in April, squaring in May, flowering in June, boll-setting in July and boll-opening in August in northern Xinjiang and in September in southern Xinjiang.

2.1. Early sowing

The northwest inland possesses relatively inadequate heat resources, and the temperature in spring is variable. To meet the reproductive process requirements of full emergence in April, early sowing must be conducted (Chen et al., 2014a; Pan et al., 2011). Generally, when the temperature of 5 cm soil layer depth under the film reaches $12\text{--}14^{\circ}\text{C}$, seeding can be started. In terms of time, the optimum sowing period for southern Xinjiang is generally from April 4 to April 15 (Zhu, 2004), and sowing should be completed before April 20. The optimum sowing period for northern Xinjiang is generally from April 10–20, and sowing should be completed before April 25 (Chen, 2013). In order to conserve water and avoid lowering the ground temperature, in recent years the region has been implementing a technique of dry seeding and wet emergence (i.e. cotton is sown in dry soil in early spring and not irrigated until the temperature reaches $12\text{--}14^{\circ}\text{C}$), which has achieved good water-saving, plant-protecting and earliness-stimulating effects (Chen, 2013).

2.2. Plastic film mulching

Plastic film mulching significantly increases soil temperature, preserves soil moisture, reduces the impact of soil salinity on plants and controls the growth of weeds, which not only promotes early sowing and emergence, but also seedling growth and development (Dong et al., 2008, 2009). Additionally, it also adjusts the cotton flowering and boll stages in accordance with local optimum photothermal periods (Dong et al., 2014). It is an essential technology for the northwest inland cotton production area to achieve emergence of a full stand from a single seeding, and promotes early emergence for early maturation. According to records in the northwest inland cotton regions of Shache, Moyu and Kuqa, the temperature at 5 cm depth in film-mulched cotton fields was $2.5\text{--}3.29^{\circ}\text{C}$, and the accumulated heat at depths of 5 cm and 10 cm was 239°C and 162°C higher than that of open cotton fields from April to June (Tian et al., 2000). The greater the percentage coverage of mulched land, the higher the temperature and the greater the accumulated heat was (Zhang et al., 1997). The main stem leaves of plastic film-mulched cotton crops emerged faster and the square emerged seven to ten days in advance compared to open field crops, and cotton yield was greatly improved by 51.3% in wide film-mulched cotton fields compared to open cotton fields (Hu and Tian, 2003). Through continuous improvement and optimization, the northwest inland cotton region has created a variety of coverage patterns, including one film with four rows (that is, four rows of cotton crops are planted on one mulched film), five rows, six rows, eight rows and other models, as well as double films that act as better preservers of temperature and soil moisture (Wen et al., 2010). It should be noted that the increased heat load is not always a positive effect, particularly in July and August when air and soil temperature is too high under plastic mulching, but comprehensive benefits of plastic mulching is greater than the disadvantage.

2.3. Close planting to promote early maturation

It is believed that close planting (super high plant density) and the stimulation of earliness are correlated and complement each other. Considering the arid climate and short frost-free period in the region, it is necessary to cultivate a high-yielding population that is dense and uniform to ensure the establishment of a high leaf area index (LAI) as quickly as possible. Particularly, taking full advantage of the available light energy in the early and middle stages of growth and development is one of the best ways to promote early maturation in the region (Li, 2002). It is recommended that the number of harvested plants in southern Xinjiang should be $16.5\text{--}19.5/\text{m}^2$, and the number of harvested plants in northern Xinjiang should be $18\text{--}22.5/\text{m}^2$ (Bai et al., 2017). Close planting can promote early maturation, but when the density is too high it delays earliness of cotton. According to experimental results and practice, when the density is higher than $22.5/\text{m}^2$, boll setting at the middle and lower parts of a plant is severely inhibited, resulting in severe boll rotting and abscission, with the result that there is more reliance on the formation of upper bolls for yield, resulting in delayed maturation (Bai et al., 2017). In addition, the greater the density, the lower the plant height, which is not conducive to mechanized harvesting (Chen et al., 2014a). Recently, the continued promotion of cotton harvesting mechanization in the region has presented a downward trend in plant density, whereby an average decrease of 2 plants/ m^2 or so has been recommended (Bai et al., 2017). Furthermore, the region also supports early tillage, early fertilization, early topping, the timely management of irrigation and other earliness-stimulating measures to further tap the thermal potential.

2.4. Use of appropriate cotton varieties

During the selection of suitable cotton varieties in the northwest inland, the first consideration is growth period as cotton varieties with very short growth periods have small yield potential, which easily leads to premature senescence and is not likely to produce high yields. Conversely, if the growth period is too long, the crops are susceptible to early frost, resulting in reduced earliness. Based on this, it is important to consider aspects of yield, quality and resistance of a cotton variety. Generally, to achieve $\geq 85\%$ harvestable yield prior to the onset of frost in normal years, the early-maturing cotton varieties with a growth period of about 125 d should be planted in northern Xinjiang (Bao et al., 2014), while the middle and early maturing varieties with a growth period of about 135 d should be planted in southern Xinjiang (Hu and Hu, 1997). In some areas of southern Xinjiang that offer better heat resources, long-staple cotton varieties can be planted (Hu and Hu, 1997). In addition, in order to facilitate simplified cultivation and mechanized harvesting, the cotton variety should also possess traits favorable for machine harvesting, such as a relatively compact plant type, strong lodging resistance, steady and robust plant growth and development, concentrated flowering and boll-setting, good fiber quality with length ≥ 30 mm and strength ≥ 30.0 cN/tex and a micronaire value of 4.5 or less, as well as sensitivity to defoliant to ensure good ripening and defoliation (Bao et al., 2014; Zhao, 2013).

3. Optimizing plant population and making full use of light energy

Close planting is an important means of promoting early maturation

for cotton yield improvement. However, highly dense populations are subject to the increased mutual influence and mutual competition of individuals and might adversely affect individual development, leading to an irrational population structure, which is economically disadvantageous in terms of yield and quality. Therefore, the full use of light energy and heat potential should be a priority when designing an optimal population structure (Chen et al., 2014a).

3.1. Close planting lays the foundations for a high-yield base population

Plant density and LAI are closely associated. The leaf area of a sufficiently dense population can increase quickly, resulting in a suitable LAI being reached earlier, thus laying a foundation for the optimal use of early light energy and increased early boll formation (Zhang et al., 2004; Liu et al., 2013; Wu et al., 2016). Under the constraints of low rainfall and very limited freshwater resources in the northwest inland, it is essential to effectively use light energy to establish a large foundation population as early as possible (Li et al., 1999; Zhou et al., 1999). Therefore, row spacing of 66 cm + 10 cm or 64 cm + 12 cm or 68 cm + 8 cm strip planting pattern has been adopted in the machine-harvested cotton fields. In recent years, some farmers in the region have explored a 72 cm + 4 cm strip planting pattern in an attempt to ensure maximal cotton planting and a high cotton net picking rate (Chen et al., 2014a,b).

3.2. Integrative measures to shape a highly light-efficient population structure

The population structure determines the spatial distribution of the leaves in the population and therefore its light-receiving potential, which directly affects photosynthetic capacity (Wang et al., 2002). A large population alone is not sufficient to ensure the effective utilization of light energy. It is necessary to adopt a series of other measures to help establish a high light use efficiency (LUE) population for high cotton yield. A high LUE population is one whereby the temporal and spatial distribution of leaf area maximizes the use of light energy at a minimal respiratory consumption (Chen et al., 2014a; Wang et al., 2002).

3.2.1. Requirements for a high LUE population structure index

Specifically, a high LUE population structure should meet several requirements as listed below.

The LAI should be appropriate, specifically, the minimum value necessary for the population to obtain maximum dry matter accumulation. At a less than appropriate range, the photosynthetic production would be reduced and the yield would be low (Chen et al., 2001a). Shade would initiate from the middle part of the canopy with a density beyond the optimum, resulting in a lower value both in canopy photosynthetic rate and cotton yield (Zhang et al., 1999; Du et al., 2009a). The range of the maximum LAI varies for different population structure types. The high density population type in the northwest inland cotton region has a maximum LAI of 3.7–4.0, while this value is 3.5–3.8 for the medium density type in the Yellow River Basin, and 3.7–4.3 for the low density type in the Yangtze River cotton-growing area (Bai et al., 2017).

LAI dynamics should be appropriate. Leaf area growth is promoted

in the seedling stage and the LAI is required to grow steadily from squaring to full flowering, so that the maximum suitable LAI appears at the peak boll-setting stage, after which growth tends to decline (Chen et al., 2001b). In order to prevent premature senescence, measures should be taken to promote a steady decrease of LAI (Table 3) (Tan, 1992). According to a study in Aksu in the northwest inland from 2008 to 2009, high-yielding cotton plants were taller before flowering, the squaring rate increased more rapidly and plant height reached 55 cm at the flowering stage compared with low-yielding cotton (Guo et al., 2011). For the high-yielding cotton, the LAI increased rapidly from the squaring stage to the flowering stage, and peaked at the full flowering stage. Additionally, the photosynthetic rate of high yielding cotton was maintained at a relatively high level and declined more slowly during the boll-opening period, and maintained a relatively larger photosynthetic active area in later growth stages than that of low-yielding cotton (Guo et al., 2011).

Plant height should be appropriate. In the northwest inland region with a lint yield greater than 1875 kg/hm², the plant height should be maintained at about 70 cm, with 8–11 fruit branches per plant and a main stem internode length of 4–5 cm. Based on related studies and local practices as well as the requirements of mechanical harvesting (Zhang et al., 1999; Guo et al., 2011), a plant height ranging from 65 to 70 cm for northern Xinjiang and 70–75 cm for southern Xinjiang seems to be conducive for the collaborative improvement of yield, quality and economic benefits.

Nodes/branches ratio should be appropriate. When the plant density or the number of fruiting branches is the same, the ratio of the number of fruiting nodes to the number of branches is relatively low, indicating that there are too few fruiting nodes on the branch. The plant is therefore slender and not conducive for the formation of a high-yielding plant type. When the nodes/branch ratio is too high as a result of too many fruiting nodes per fruit branch, the lateral growth is too large, which results in serious shading, thereby hampering yield. For the high-density population structure in the northwest inland cotton region, a suitable nodes/branches ratio is approximately 2.5 (Bai et al., 2017).

Leaf angle and angular distribution of fruiting branches should be appropriate. Under similar LAI conditions, the leaf angle is an important factor affecting light intensity in a population. Leaf angle and light transmittance have been found to be negatively correlated. In the northwest inland, the canopy leaf inclination of the high yielding cotton population changes with LAI from small to large, then from large to small. During the boll opening period, leaf inclination (angle against the main stem) from the top to the bottom canopy is from large to small. The leaf angle in the upper canopy is 76°–61°, which is 17°–12° and 36°–25° larger than the central and lower canopy, respectively (Li et al., 1999; Du et al., 2009a). The angular distribution of fruit branches directly affects the leaf angle distribution, in that the smaller the angle between the fruit branch and main stem, the smaller the angle between the leaf and main stem will be; therefore the fruit branch angle and leaf angle distribution are positively correlated. If the leaf angle is small, then light transmittance below the canopy and boll rate per plant will be high. Therefore, light transmittance into the canopy can be improved by narrowing the angle between the fruit branches and the main stem, further narrowing the leaf angle (Du et al., 2009b; Feng et al., 2012).

An appropriate harvest index is also important. It was found that the

Table 3
Cotton demand structure proportion of China and the northwest inland cotton supply structure proportion from 2011 to 2015.*

	Fiber length (mm)				Micronaire value				
	25–27 mm	28 mm	29 mm	≥30 mm	A (3.7–4.2)	B1 (3.5–3.6)	B2 (4.3–4.9)	C1 (≤3.4)	C2 (≥5.0)
Fiber Type									
Demand proportion	2.3	67.2	24.4	6.1	31.7	12.0	55.1	0	1.2
Supply proportion	18.3	48.5	29.9	3.2	15.3	1.2	60.0	1.4	22.2

* Source: China fiber inspection bureau (2011–2015).

ratio of seed cotton to stalks was positively correlated with harvest index ($y = 4.6251x - 0.8496$, $R^2 = 0.9603^{**}$) (Dong et al., 2010). Improving the ratio of seed cotton to stalks is an important way to increase cotton yield, however, an excessively high ratio of seedcotton to stalks may result in the premature senescence of cotton, which is not conducive to high yield and quality. A ratio of seedcotton to stalks ranging from 0.75 to 0.85 seems to be appropriate for the northwest inland, while the appropriate ratios for the Yellow River Basin and the Yangtze River Basin are 0.8–0.9 and 0.9–1.0, respectively (Bai et al., 2017).

3.2.2. Main measures for shaping high LUE population structures

Firstly, plant density and row spacing configuration is important, as an optimal canopy structure provides the basis for obtaining high yields and can improve the ventilation and light transmission conditions in the field (Liu et al., 2013). Too narrow or too wide spacing will lead to an inefficient relationship between population and individuals, resulting in reduced yield. Adjusting the row spacing configuration is also an important means of facilitating mechanization for cotton production. The planting mode for mechanic harvesting being applied in the northwest inland results in high utilization of light energy, because in the mode LAI increases quickly at the early growth stage and declines slowly at the later stage (Bai et al., 2017). Researchers in Xinjiang recently designed a cultivation mode for several hybrid cotton varieties, including 76 cm row spacing; a harvesting plant density of 12–15 plants/m²; plant height of 80–90 cm and possession of 10–11 fruit branches and good ventilation (Yao et al., 2011; Chen et al., 2014b). Secondly, comprehensive regulations for shaping the population are necessary. In accordance with indicators of high LUE populations, the population regulation means in the northwest inland mainly include the integrative use of irrigation, fertilizer, tillage and chemical controls (Bai et al., 2017). First of all, irrigation and fertilizer management should be timely and appropriate to avoid excessive vegetative growth in the middle stage and premature senescence in the late stage. Secondly, chemical regulation should be properly conducted to promote a timely transformation from vegetative growth to reproductive growth, to ultimately achieve a relatively compact plant structure with relatively shorter main-stem internodes and fruiting branches. Thirdly, the combination of timely topping, tillage and other measures is also important. Through the rational application of these measures, it is possible to establish a high LUE cotton population in the northwest inland (Bai et al., 2017).

4. Water-saving irrigation for efficient use of limited fresh water resources

The northwest inland is drought prone and experiences limited rainfall. The annual precipitation of the main cotton-growing area in southern Xinjiang is only about 70 mm, and water resources are very limited (Appiah et al., 2014; Wang et al., 2014). Therefore, water-saving irrigation is very important technology for maximizing the limited potential of the fresh water resources.

4.1. Drip irrigation under mulching technology

A unique under-mulching drip irrigation technology has been established and applied in the region through the combination of drip irrigation and plastic mulching (Wang et al., 2014; Zhang et al., 2016). The drip irrigation under plastic mulching system is laid during seeding in the cotton field by means of a specific seeder in which drip irrigation pipe laying, seeding and plastic mulching can be completed simultaneously. Usually under each piece of plastic film are two or three drip irrigation bands. Before irrigating for the first time, the branch and auxiliary pipes are laid by hand on the surface and connected to the main pipe, and the capillary inlet is connected with the corresponding branch pipe and auxiliary equipment. Cotton is drip-irrigated through

the system 8–12 times throughout the entire growth and development period, and each irrigation application consumes 225–300 m³ hm⁻² water (Ma and Li, 2006). The duration and amount each irrigation can be further optimized in accordance with growth monitoring, which not only improves ground temperature and reduces evaporation between plants, but also reduces deep leakages and balances water application and yields (Shen et al., 2013a,b).

4.2. Dry sowing and wet emergence technology

Water consumption in the northwest inland has been increasing as a result of continued cotton acreage increases in the region. Winter and spring irrigation water is increasingly scarce. In response to this, the region, especially the north, has widely implemented dry sowing and wet emergence technology. That is, neither winter irrigation nor spring irrigation is applied prior to sowing, but following soil preparation, plastic film and drip irrigation bands are directly laid and seeds are sowed. Once the optimal emergence temperature has been reached, a small amount of water is applied with drip irrigation for seed emergence (Chen, 2011). This technology requires a high standard of field preparation and timely sowing (Xiao and Yao, 2013). In these fields, water consumption is only about 20% compared to traditional sowing techniques, which significantly alleviates the stress from water shortages in the region (Wang and Wang, 2006).

4.3. Water and fertilizer integration technology

The climatic and agricultural characteristics of the northwest inland region require the use of water and fertilizer integration technology for cotton production (Li et al., 2015; Liang, 2015). Fertigation technology relies on soluble solid or liquid fertilizer being dissolved in the tank water, with a controlled pressure piping system for water and fertilizer application through the pipeline and emitter to form a uniform, regular and quantitative drip irrigation system (Zhou et al., 2012). High-yield drip irrigation has been widely implemented in the region to promote fertigation for the precise management of water and fertilizers. This technology can provide timely application of water and fertilizer and is easy for cotton crops to absorb. Furthermore, it also reduces fertilizer volatilization and loss, and in particular, effectively avoids the volatilization and loss of ammonium and urea nitrogen fertilizers. Additionally, it also simplifies the fertilization process and saves labor and other costs.

4.4. Regulated deficit irrigation techniques

Regulated deficit irrigation (RDI) is based on the physiological water requirements of crops, whereby a certain degree of man-made water stress is imposed during the crop growth and development period to save water without reducing (or increasing) the yield (Zhang et al., 2016). Based on years of research and practice, the techniques of wide-film mulching, drip irrigation, moderate planting density and full irrigation in southern Xinjiang have been widely used. Plant density is generally 18 plants/m² and drip irrigation amounts to approximately 5000 m³ hm⁻² over 12 irrigation applications (Shen et al., 2010). However, it was recently found that under full irrigation, the use of 18–24 plants/m² density can achieve relatively high yields. The use of regulated deficit irrigation under high plant density, corresponding to a water reduction of 20%, produced an economic yield equal to that of full irrigation (Zhang et al., 2016). From the perspective of saving water and improving water use efficiency, the use of regulated deficit irrigation along with an appropriate increase in plant density is a viable water-saving cultivation method for cotton planting in the northwest inland arid area.

5. The integration of agronomic techniques and mechanization to simplify cotton cultivation

Simplified cotton cultivation refers to the integration of agronomic technology and material equipment. Material equipment includes cotton varieties, agricultural machinery, fertilizers and plant growth regulators. The integration of agronomic techniques and mechanization occurs throughout the entire cotton production process, including land preparation and pre-sowing irrigation, the management of previous crop stubbles and recycling residual plastic film before tillage, tillage, cultivation, field management and even cotton harvesting and many other aspects of mechanization, resulting in the minimization of manual operations and inputs (Yu et al., 2015). Cotton mechanization involves the complex integration of several disciplines, including genetics and breeding, agronomic cultivation, mechanical design, information control and intelligent equipment. In recent years, the Production and Construction Corps has performed in-depth research to improve mechanization (Dai and Dong, 2014). They developed 66 cm + 10 cm and 72 cm + 4 cm width narrow row-spacing configurations that are appropriate for mechanical harvesting (Mao et al., 2014a). Cotton seed processing technology and equipment were also developed. A cultivation mode of dwarfing, close planting, early-topping, film-mulching and ultra-narrow row precision seeding was proposed and widely applied. Based on the idea of modular design, they developed a mechanical hole sowing device to solve seed technical issues relating to seed breakages and seeds clogging the machine, and achieved precision seeding through developing an ultra-narrow row and mechanical under-mulching drip irrigation precision seeder. This seeder not only reduces seed loss, but also simplifies the steps of planting and thinning. Furthermore, they also developed combined land preparation machinery supported by high-powered tractors to perform wide-film laying, precision sowing and seed emergence. Through the implementation of foreign advanced drip irrigation technology, they successfully developed Chinese style low-cost drip irrigation water-saving technology and equipment (Tian et al., 2016). A novel sprayer was developed and solved the issue of poor pesticide application in the high-density cultivation mode and broke the bottleneck of defoliant uniform spraying technology. On this basis, they successfully constructed a fully mechanized cotton production technology system with a core of under-mulching drip irrigation, precision sowing, wide-film mulching and water and fertilizer integration (Tian et al., 2016). A high degree of agronomy and material equipment integration was achieved, and the contradiction between

high yield and simplification was addressed, further promoting continued high yields and efficiency in the region (Bai et al., 2017).

6. Challenges facing northwest cotton production

While cotton production in the northwest inland region has been greatly successful owing to its unique cultivation techniques, it still faces many challenges. Particular difficulties include improving cotton yields, declining fiber quality, substantial increases in the cost of planting cotton, as well as the white pollution caused by plastic film mulching (Mao et al., 2014a).

6.1. The rapid increase in yields is associated with a loss of fiber quality

Unique cotton cultivation techniques implemented since the 1990s have increased the average cotton yield in the region by 70.8% compared to the previous decade, reaching a record high of 2057 kg hm⁻² in 2012 (Fig. 1). Achieving such a high average lint yield in more than two million hectares of land is remarkable. However, of greater concern is the significant decrease in cotton quality.

Our analysis of cotton quality decline provided the following explanations: firstly, a long-term focus on yield ignores fiber quality in the selection of cotton varieties, as well as in cotton cultivation and management. Secondly, while mechanically harvested cotton practices have developed rapidly in the region, the cotton varieties, cultivation management techniques and cotton processing technologies were ill suited, resulting in the gradual decrease in fiber quality, particularly fiber length, with an average annual decline of 0.4% (Fig. 2). Thirdly, the heterogeneous fiber content is high. Mechanical harvesting technologies have aggravated the residual film pollution. In order to meet the textile requirements, heterogeneous fiber content should be controlled at ≤0.1–0.3 g/t. However, according to recent research conducted in the northwest inland, heterogeneous fibers accounted for 1.0 g/t (Bai et al., 2017). Fourthly, the consistency of the cotton fiber quality is poor. The cotton varieties grown nationwide differ and are often agriculturally mixed, in that the cultivation of dozens of varieties in a single region is very common. In fact, some northwest inland areas grow in excess of 100 cotton varieties, and each county (city) grows more than 10–20 cotton varieties (Mao et al., 2014a,b). Different varieties with varying fiber qualities are combined, resulting in a mixed quality product, and has brought great difficulty to textile enterprises. Fifthly, China's cotton fiber quality supply and demand structures are

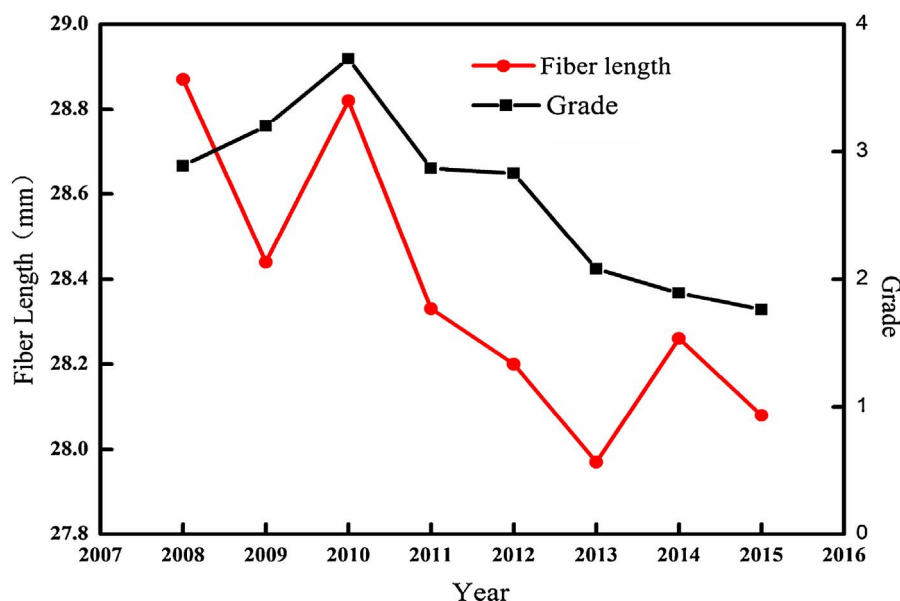


Fig. 2. Variation in cotton fiber length and grade in the northwest inland cotton region from 2008 to 2015.

imbalanced. For instance, the demand proportion for fibers more than 28 mm length and micronaire B1 level is significantly higher than the supply proportion (Table 3). Therefore, the sacrificed fiber quality with rapid increased cotton yield is the major challenge that the region is facing.

6.2. Production cost increased and comparative profits decreased

The unique cultivation techniques in the northwest inland area have undeniably played a significant role in increasing cotton yields. However, economic development and urbanization over the past 10 years has resulted in surplus and cheap labor in cotton production being exhausted and replaced by labor shortages and rising labor costs (Mao et al., 2014a). In addition, excessive fertilizer inputs have resulted in very high material costs. In 2009 the cost of cotton production in the northwest inland region exceeded 3000 US dollars/hectare, while in 2012, total labor costs accounted for more than half of the total cost in the region, up to 50.9% (Mao et al., 2014a). Cotton production costs in this region are much higher than other major cotton producing countries. According to the US Cotton Advisory Committee (ICAC) survey in 2013, compared with northwest inland cotton, cotton planting costs in Brazil were 61.0% lower (central and western cotton-growing area) and 79.0% lower (northeast cotton-growing area); cotton planting costs were 56.9% lower (irrigated cotton-growing areas) and 82.5% lower (non-irrigated cotton-growing areas) in Australia; and US cotton costs were 69.3% lower (Table 4). The increased cotton production costs have led to yearly decreases in income in the region. This has seriously restricted the market competitiveness of cotton and is not conducive to the stability of cotton production in the northwest inland.

6.3. Increasing pollution from mulching film

As plastic film mulching has beneficial effects including temperature and moisture preservation, and weed and pest control, it is widely used in northwest inland cotton production. The plastic film mulch use intensity in the northwest inland increased from 7.0 kg hm⁻² in 1991 to 34.8 kg hm⁻² in 2011 (1 kg plastic film covers an area of 150–250 m²) (Liu et al., 2014). However, due to a lack of effective control of residual film in the soil, waste film in farmland soils has increased annually resulting in intensified farmland pollution. In the northwest inland region, the residual amount of plastic film was 262 kg/hm², 350 kg/hm² and 430 kg/hm² in 10 years, 15 years and 20 years of continuously film mulched cotton fields, respectively, and the residue of agricultural plastic film in the most seriously polluted field was 597 kg/hm² (Sun et al., 2005b). The large amounts of residual film have led to changes in the physical structure of the soil, impeding the transportation of soil moisture and nutrients, overall resulting in decreased soil fertility. Furthermore, water and nutrient use efficiencies

have been hampered, resulting in low emergence rates and stand establishment (Dai and Dong, 2014). Rectifying this white pollution, protecting the ecological environment and promoting the sustainable development of agricultural production is another challenge faced at present.

7. Countermeasures and prospects

The ecological and climatic conditions of the northwest inland region, as mentioned earlier, are somewhat inhibiting to cotton production. Breakthroughs in chemical topping, fertigation, plastic film optimization or alternative technologies, agronomic techniques and mechanization integration, intelligent mechanization and the establishment and promotion of fully mechanized cotton planting and harvesting technology, have been key to easy, simplified, efficient and sustainable cotton production in the region.

7.1. Explore new agronomic techniques to improve yield

The ecological characteristics of the region necessitate that the cultivation strategy requires further modernization. Firstly, light and fertigation should be explored to achieve high yields, quality and economic benefits. More attention should also be paid to the integration of agronomic techniques and mechanization. Secondly, precision seeding should be further improved. Improvements in seed quality, field preparation and sowing will help to achieve full emergence and stand establishment and reasonable base populations. Thirdly, the simple pursuit of high yields should be abandoned and production should rather focus on being benefits-centered and balanced with respect to yield and quality.

The cultivation and management of cotton in the northwestern inland has always been based around heat and water, but there is little potential for the further excavation of heat and water resources, though light has great potential to be tapped (Chen et al., 2014a). Therefore, we should focus on further optimizing LUE population structures, on the one hand, by improving the precision of sowing techniques and fertilization technologies, as well as water and fertilizer integration and chemical pruning technologies. On the other hand, we should develop new fertilizers, plant growth regulators, machinery and other material equipment for sowing, plant protection and topping, controlling population structure and further improving the utilization of light energy to a new level. Additionally, further clarification of the population structure indexes of high-yielding cotton, root development and distribution under the condition of drip irrigation under mulching and fertigation and water/fertilizer use efficiency will provide a theoretical basis to accelerate cotton yields.

7.2. Improve cotton fiber quality

Fiber consistency should be improved. The consistency of fiber quality is affected by the number of varieties in a specific area and field management. Thus on the one hand, the regional distribution of varieties as well as the cultivation of a single variety in a specific area should be implemented for maintaining fiber consistency; on the other hand, the spatial and temporal distribution should be optimized to reduce the fiber quality differences among bolls.

The structure of cotton varieties should be optimized. Currently, the textile industry requires cotton varieties with a fiber length ≥ 30 mm, a fiber breaking strength ≥ 30 cN/tex and A–B grade micronaire value (Mao et al., 2016). Unfortunately, most of the current varieties do not meet the requirements. In order to assure fine quality cotton varieties, we should adjust the validation indicators of varieties and consider fiber quality as an important indicator for official validation. Cotton varieties with a fiber length below 27 mm and fiber breaking strength below 28 cN/tex should be eliminated.

Foreign fiber pollution should be controlled. Foreign fiber pollution

Table 4

Costs of cotton production in the northwest inland of China and major cotton producing countries in 2013.*

Cotton Production Country/ Region	Raw Cotton Production Cost (US \$/ha)	Compared to Northwest inland (%)
Northwest inland	4720.45	–
Brazil, central-western cotton- growing area	1840.25	–61.0
Brazil, northeastern cotton- growing area	989.76	–79.0
Australia, irrigated cotton- growing area	2034.33	–56.9
Australia, non-irrigated cotton-growing areas	824.51	–82.5
United States	1448.85	–69.3

* Source: US Cotton Advisory Committee report for 2013.

has become one of the most important factors that affect the overall quality of cotton products in China. It is essential to control and reduce foreign fiber contamination from harvesting to the processing of cotton. Farmers should be trained and educated on the importance and methods of controlling foreign fiber contamination during harvesting and storage. Wearing cotton hats and using cotton bags instead of plastic bags during harvesting are effective measures to avoid contamination by foreign fibers. Centralized stacking following cotton harvesting should be encouraged and stacks should be kept in a place that cannot be reached by livestock and people. The mechanization of seed cotton handling (loading and unloading) should be implemented, and recontamination should be avoided during transportation and processing. Cotton enterprises should strengthen quality testing, arrange combined hand sampling and testing equipment and strive for the heterogeneous fiber content to reach low levels.

7.3. Reduce plastic film pollution

While plastic film mulching has been hailed as a “white revolution,” it has become a source of serious pollution, known as “white pollution” (Liu, 2013). Firstly, fully degradable film might provide a good alternative to replace polyethylene film. Secondly, thickening of the plastic film or the addition of new materials to reduce plastic aging should improve the recovery rate of plastic film and reduce residual film contamination. Thirdly, practices of film removal and collection should be promoted. Once the film has completed its function, it should be removed and collected by hand or machine. This practice can prevent plastic film pollution and protect farmland fertility.

7.4. Reduce costs and improve profits

Production costs can be decreased and profits can be increased through the reduction or simplification of field management, mechanization and intelligent technology. Conventional sowing adopts broadcasting, or multiple seed applications per hole, and thinning after emergence, which requires tremendous amounts of labor and seed costs. Precision seeding can reduce seed usage and reduce sowing labor and costs (Dai et al., 2014). The new technology of sowing can realize synchronized sowing, mulching and drip irrigation laying, which has the advantages of being simple, highly efficient and of low investment. Chemical topping inhibits the growth of stem tops by means of plant growth regulators instead of the manual removal of stem tops. Chemical topping reduces labor costs and improves labor productivity relative to hand topping, and is the inevitable trend of a fully mechanized cotton planting system. At present, chemical topping technology is being used in the northwest inland cotton region (Liu, 2013). Manual topping only removes the top of main stem, while chemical topping inhibits the growth of the top of the main stem, and the growth and development of the lateral branches and leaves are also subject to a certain degree of inhibition. Therefore, it is necessary to further study the mechanisms of cotton chemical capping and its influence on the agronomic traits of cotton in order to master the appropriate spraying time and dosage, thereby speeding up the development of chemical topping specifications. Fertilizers play an important role in the yield and quality of cotton. However, fertilizer use efficiency in China is low, which results in severe environmental pollution and increases material costs (Geng et al., 2015). Further improvements in fertilizer use efficiency are a means of saving costs. The biological characteristics of fertilizer demand and soil nutrient status throughout the cotton growth period should be explored to improve fertilizer use efficiency and reduce physicochemical material costs. In addition, new types of fertilizers such as foliar fertilizers and slow-release fertilizers can also improve efficiency and reduce labor costs (Geng et al., 2015).

Development of mechanization. The mechanization level in northwest inland is the highest among China's three major cotton-growing areas. Despite this, about 210 working days on average are spent per

hectare per annum on cotton farming in the region (Mao et al., 2014a). Thus it is necessary to encourage mechanization, particularly mechanized harvesting, to further reduce costs and improve profits. However, the inconsistencies between agronomic techniques and mechanization, as well as unreasonable field management, have resulted in reduced yield and quality of machine-harvested cotton and restricted the further development of mechanized harvesting. Therefore, research on cotton harvesting machinery needs to be strengthened. Additionally, we should develop appropriate cotton varieties which meet the requirements of maturity and quality standards for machine-harvested cotton.

Application of intelligent technology. The intelligent technology of the northwest inland cotton region is mainly reflected in two aspects of planting and irrigation. In cotton sowing, specialized planting machinery equipped with GPS satellite positioning and automatic navigation systems achieve unmanned automatic operation and can work day and night. Automatic intelligent drip irrigation systems use wireless data acquisition monitoring technology and drip irrigation automation technology corresponding to the location of the cotton fields and the actual water level requirements of users, achieving automatic control of field drip irrigation and fertilization (Sun et al., 2005a). The continued improvement of intelligent sowing and irrigation technology applications requires research and development into intelligent integrated control technology, plant protection technology and mechanical harvesting standardized technology.

8. Conclusion

In summary, the northwest inland cotton region has achieved high yields and efficiency by adopting earliness-stimulating cultivation, exploring heat and light potential for high yields, implementing close planting and dwarfing, integrating irrigation and fertilization and exploring their use for high yields, integrating agronomic techniques and mechanization and exploring simplification of the cotton production process. The natural ecological characteristics of the region necessitate that heat and water potential need to be explored to achieve high yields, and light potential needs to be assessed for quality and economic benefits, while fertigation and the integration of agronomic techniques and mechanization are required for further simplification of the production process. Furthermore, it is necessary to study the biological principles of cotton yields and quality formation and investigate the physiological mechanisms under simplified and mechanized cultivation. We should establish high LUE populations to further improve yields and quality. Chemical topping technology should be further improved and film pollution caused by plastic mulching should be addressed. Intelligent technology should be further developed and established. Improvements to the northwest inland high-yielding and simplified cultivation systems will further promote the sustainable and healthy development of cotton production in the region.

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