Chapter 15
Cotton-Based Cropping Systems and Their Impacts on Production

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Abstract Cotton farming symbolizes single largest use of arable land for fiber production on earth, and cotton-based cropping systems are practiced under diverse agro-climatic environments in more than 100 countries. World cotton production has escalated in recent past and has undergone numerous technological transformations and socioeconomic interventions in quest of productivity and sustainability. Cotton-based cropping systems range from low-input rainfed systems in Australia and Africa to highly mechanized intensive farming systems in the United States, Brazil, and China. In India and Pakistan, multiplicity of cotton varieties, weather extremes, uncertainty of climatic optima, spurious seeds, non-remunerative markets, and low quality plus adulterated chemicals or pesticides are key problems leading to low yields besides net profits in otherwise high productivity cotton-based cropping systems. Resource conserving, eco-efficient, climate smart, and economically viable cropping systems that rotate/intercrop cotton with cereals, oilseeds, and legumes are required. Relay or intercropping and crop rotations will lead to the ecological intensification of cotton-based cropping systems. An ideal cotton-based cropping system should aim at higher yields and net profits per unit area, bring stability into the production system, ensure optimal utilization of the available resources, be able to meet domestic requirements of farmer, and avoid ecological uncertainty in the form of shifts in insect pests or weed populations or evolution of pesticide resistance in the long run. Another area requiring significant improvement is integrating current curative pest management options with other cultural methods to avoid insecticide/herbicide resistance development in an era of transgenics. The transgenics have their own pros and cons, and due deliberations in the best interest of agro-ecosystem

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sustainability and small landholders be made with involvement of all stakeholders. Biotech seed industry should plan safe mechanisms for herbicide-tolerant crop development to evade resistance development or gene introgression in weeds. Productivity and profitability of cotton-based cropping systems needs to be explored with greater ecological orientation under conventional and organic management systems. This chapter documents the productivity and resource use efficiency of cotton-based cropping systems based on existing agronomic and experimental evidences. Crop growth and development, productivity, quality, resource use efficiencies, and profitability of various systems have been discussed at the plant, field, and system levels.

Keywords Climate smart cotton production · Insect pests · Lint yield and quality · Productivity and profitability · Resource use efficiency · Sustainable cropping systems

Abbreviations

g ha^{-1}	Gram per hectare
K	Potassium
kg ha^{-1}	Kilogram per hectare
t ha^{-1}	Tons per hectare
ATER	Area time equivalent ratio
LER	Land equivalent ratio
LUE	Light use efficiency
N	Nitrogen
NUE	Nitrogen use efficiency
P	Phosphorus
PAR	Photosynthetically active radiation
Zn	Zinc

15.1 Introduction

The cotton plant includes 40 species in genus *Gossypium* that is native to tropical plus subtropical areas (Lee and Fang 2015). Cotton cultivation is an integral component of crop production since centuries, and more than hundred countries produce cotton. Worldwide it is grown on an area of 35 M ha primarily in longitudinal band between 37°N and 32°S with a total production of 26 M tons of lint (ICAC 2015). Besides production, its trade involves more than 150 countries which either export or import cotton (Ahmad et al. 2014, 2017, 2018; Abbas and Ahmad 2018; Ahmad and Raza 2014; Ali et al. 2011, 2013a, b, 2014a, b). At farm level, it provides source of income to more than 100 million farm families. About 2/3 of the world's cotton is produced in four countries (China, the USA, India, Pakistan) (Khan

Table 15.1 Country-wise area and production of seed cotton in the world during year 2017

Sr. No.	Country	Area (000 ha)	Production (000 tons)
1	India	12200.00	18530.00
2	China	3625.39	17148.46
3	USA	4492.22	12000.00
4	Pakistan	2699.00	5700.30
5	Brazil	927.99	3842.87
6	Uzbekistan	1201.18	2900.18
7	Turkey	501.48	2450.00
8	Australia	518.59	2150.96
9	Mexico	211.92	1009.10
10	Burkina Faso	844.90	844.34
11	Greece	262.62	792.00
12	Argentina	253.31	616.16
13	Mali	630.81	591.64
14	Turkmenistan	531.67	483.19
15	Syria	119.77	441.44

Source: FAO (http://www.fao.org/faostat/en/)

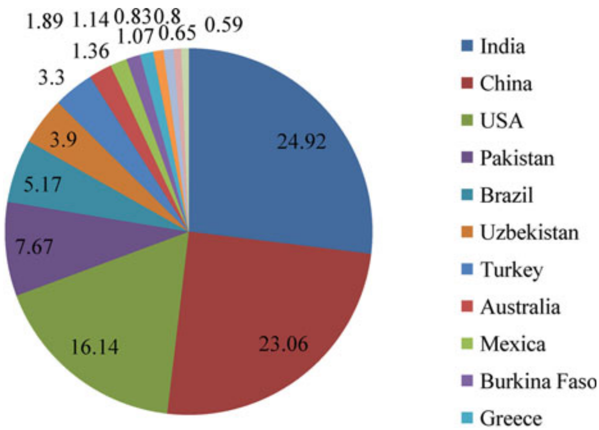

Fig. 15.1 Distribution of cotton production worldwide (2017)

et al. 2004; Usman et al. 2009; Amin et al. 2017, 2018; Rahman et al. 2018; Tariq et al. 2017, 2018). India and China are largest producers having share of 25 and 23%, respectively (Table 15.1; Fig. 15.1), followed by the USA (16%), Pakistan (7.67%), and Brazil (5.17%). China, India, and Pakistan consume approximately 2/3 of the world's cotton having shares of 35, 15, and 10%, respectively. About 1/3 of worldwide cotton production is being traded internationally. The USA is the largest cotton exporter having a share of 41%, and then China is the largest importer having a share of 19% in global imports.

India is the only country where all four cultivated cotton species are being sown. Area wise, India ranks first globally (about 20%), but with regard to production, it is ranked second, after China (Gopalakrishnan et al. 2007). Three cotton-growing zones include northern *G. hirsutum* and *G. arboreum* zone (Punjab, Haryana, and Rajasthan), central *G. hirsutum*, *G. arboreum*, and *G. herbaceum* zone (Gujrat, Madhya Pradesh, and Maharashtra), and composite southern *G. hirsutum*, *G. arboreum*, *G. herbaceum*, and *G. barbadense* zone (Tamil Nadu, Andhra Pradesh, Karnataka) (Blaise 2017).

The three core cotton-growing zones in China are Yangtze River basin, Yellow River basin, and northwestern inland (Dai and Dong 2014). These zones include 13 provinces, autonomous regions, and direct-controlled municipalities: Tianjin, Hebei, Shanxi, Jiangsu, Anhui, Jiangxi, Henan, Shandong, Hubei, Hunan, Shaanxi, Gansu, and Xinjiang. In 2007, these three zones represented 99.85% of total cotton-growing parts in China (Yang and Cui 2010).

In the USA, the Cotton Belt includes 17 states in 4 geographical regions, viz., the Southeast (22% of the total; Alabama, Arkansas, Georgia, Florida), mid-South (34% of the total; Arkansas, Louisiana, Mississippi, Missouri besides Tennessee), Southwest (35% of the total; Texas, Kansas plus Oklahoma), and the West (9% of the total; Arizona, California and New Mexico) with 70% of the production concentrated in the mid-South, Southwest regions (ITC 2011). Cotton production is highly mechanized and capital-intensive precision agriculture.

In Brazil, cotton production occurs primarily in states of Mato Grosso, MatoGrosso do Sul besides Goi as of the Centre-West region. Balanced fertilizer use and favorable weather conditions have remarkably increased the cotton productivity during last one and half decade transforming Brazil from a net importer to an exporter. Subsequently, moving to Centre-West, its production has become most efficient, and growers are now amid most technologically advanced in world (Graham 2009).

Pakistan is world's fourth largest raw cotton producer, with almost 8.0% share in worldwide cotton productivity (Fig. 15.1). Cotton is mostly cultivated in Punjab and Sindh province which contribute about 79% of the total cotton production of Pakistan (Anonymous 2018). Pakistan's cotton belt extends above 1200 km beside River Indus from latitudes of 27°N–33°N besides altitudes from 27 m to 153 m. Soils vary from sandy to clay loam with clay dominant towards south (Gillham et al. 1995). In Punjab, it is mainly cultivated in Bahawalpur, Rahim Yar Khan, Bahawalnagar, Multan, Vehari, Khanewal, Dera Ghazi Khan, Muzafar Garh, Rajanpur, besides Lodhran (Salma et al. 2012), while, in Sindh, it is grown in Nawabshah, Ghotki, Sanghar, and Nosheroferoz districts (Khushk et al. 1990).

Ranking sixth regarding global cotton production, the Uzbek cotton is grown in periphery of Aydar Lake and also to some extent in Tashkent along Syr Darya and along Amu Darya in border areas with Turkmenistan.

Around 50% of Turkish cotton produces are in southeastern Anatolia, having semi-arid climate. Summers are very hot along with mean temperatures higher than 30 °C in July and August. Mean temperature in January is between 2 and 5 °C. Annual rainfall varies amid 350 and 800 mm. Other major production areas are the Aegean and Cukurova regions (Karademir 2006).

Australia is the world's largest exporters of raw cotton with over 90% of domestic produce exported to China, Indonesia, and Thailand. Cotton production in Australia is located in New South Wales (NSW) besides Queensland, particularly in Murray-Darling river basin (ITC 2011). Major production zone in NSW stretches south from Macintyre River on Queensland border and covers Gwydir, Namoi, and Macquarie valleys. In NSW, cotton is also grown along Barwon besides Darling Rivers in west and Lachlan and Murrumbidgee Rivers in south and spreading into new areas like Forbes. In Queensland, cotton is grown mostly in south in Darling Downs, St George, Dirranbandi, and Macintyre Valley regions and also near Emerald, Theodore, and Biloela in Central Queensland (Farrell 2017). In Africa, Burkina Faso and Mali are the important cotton-producing countries.

15.2 Cotton-Based Cropping Systems

Cotton production is carried out in five continents under diverse agro-climatic conditions with contrasting productivity levels and production constraints. Developing eco-efficient cropping systems that are productive and sustainable is a key to food/agricultural security (Mao et al. 2015). Often rotation, relay or intercropping of major crops with minor/special crops is exploited to bring diversity and increase productivity in agro-ecosystems. In cotton-based cropping systems, intercropping has been reported to cause a yield reduction to the tune of 8–31% than sole stand of cotton. Nevertheless, total productivity and net returns greater in intercropping compared to sole cropping (Mohammad et al. 1991) and cotton-based intercropping system reported to more revenue up to 30–40% (Saeed et al. 1999). Various cotton-based cropping systems are discussed in the following sections. Moreover, issues and possible strategies to address these are given in Table 15.2.

15.2.1 Wheat-Cotton Relay Cropping Systems

China is a major country regarding cotton production and 200 million Chinese farmers are engaged in cotton production. Major cotton production in China is focused in three distinct areas, namely, Yellow River Valley, Yangtze River Valley, and northwestern regions, representing 47, 26 and 21% of the total area under cotton, respectively (Zhang 2007). Nevertheless, average farm size is quite less corresponding to 0.10–0.13 ha per person. The highest lint yield of 1393 kg ha^{-1} is harvested in Gansu and Xinjiang provinces of northwestern region. Lint yield is low in Yellow River Valley (810 kg ha^{-1}) compared to Yangtze River Valley (947 kg ha^{-1}). In the northwestern provinces of China, cotton is sown as monocrop at higher densities. Contrarily, in other two regions, cotton is either intercropped with wheat (Yellow River Valley) or double cropped with winter wheat or rapeseed (Yangtze River Valley). Intercropping of cotton in wheat ensures production of cash as well as food crop simultaneously. Area under cotton-wheat intercropping systems in three provinces (Hebei, Henan, and Shandong) was 0.12 million ha in 1980 that

Table 15.2 Issues of various cotton-based cropping systems and possible strategies

Cotton-based cropping systems	Issues	Strategy	References
Intercropping	Greater N requirements of Bt cotton than other cotton cultivars	Intercropping with groundnut	Rochester et al. (2001); Ghosh et al. (2008)
	Nutrient management	Cotton intercrop with leguminous crops	Singh et al. (2009)
		Integrated nutrient management	Singh et al. (2013); Singh and Ahlawat (2014)
	Weed infestation	Cotton intercrop with sesbania/green gram along with bioinoculants such as *Azospirillium* and *Pseudomonas* not only suppresses the weed dry biomass but also increases seed cotton yield	Sivakumar (2004); Vaiyapuri et al. (2010); Marimuthu and Subbian (2013)
	Aphid attack	Cotton-cowpea intercropping increases the population of natural enemies/predators of aphid	Fernandes et al. (2018)
		Cotton-fennel intercropping increases the population of predators	Ramalho et al. (2012); Fernandes et al. (2015)
		Cotton intercropping or field boundary with alfalfa increases the population of predators	Lin et al. (2003); Zhang et al. (2004)
	Insect pest management	Cotton-basil intercropping significantly reduces overall pest population and results in about 50% reduction in pink bollworm infestation	Schader et al. (2005)
Wheat-cotton relay cropping system	Late sowing of wheat	Relay cropping with zero till	Singh et al. (2016)
	Time conflict between Bt cotton sowing and wheat harvest	Adjusting sowing time of Bt cotton by transplanting one and half month old cotton nursery	Shah et al. (2017)
	Low yield	Relay cropping of wheat increases the productivity of wheat-cotton system	Buttar et al. (2017); Singh et al. (2016); Sajjad et al. (2018)
	Nutrient management	Integrated nutrient management (inorganic+ FYM+ bioinoculants)	Ramprakash and Prasad (2000); Das et al. (2004)
	Insect pest management	Wheat-cotton relay intercropping controlling cotton aphid	Parajulee et al. (1997); Li (2001)

(continued)

Table 15.2 (continued)

Cotton-based cropping systems	Issues	Strategy	References
Wheat-cotton double cropping system	Soil potassium deficiency	Incorporation of wheat straw	Sui et al. (2015); Yu et al. (2016)
	Soil nutrient management	Crop residue management	Liebman and Gallandt (2002); Takahashi et al. (2003); Wang et al. (2007); Rafique et al. (2012); Northup and Rao (2015); Suriyagoda et al. (2014)
		Inclusion of legumes in crop rotation	Rocheser and Peoples (2005)
	Low yield	Wheat-cotton double cropping system improves the productivity per land area	Dai and Dong (2014); Feng et al. (2017)
	Nematode management	Crop rotation (cotton-peanut, maize, grain sorghum), deep tillage to bury the nematode and weed seeds, nematicide application at appropriate rates	Mueller et al. (2012)
Rainfed cotton system	Nutrient management	Integrated nutrient management (inorganic + organic sources)	Mannikar (1993); Katyal et al. (1997); Venugopalan and Pundarikakshudu (1999)
	Water management under limited supply	Skip-row planting/row width and orientation	Milroy et al. (2004); Bange et al. (2005)
	Low yield	Intercropping with oilseeds and legumes improves cotton yield and net returns from cropping system	Reddy et al. (1985); Sarkar et al. (1995); Aladakatti et al. (2011)

increased to about 1.2 million ha in 1988 and witnessed an increase of 1.6 million ha in 1990 and has remain stabilized since then (Zhang and Li 1997; Zhang 2007). A relay strip intercropping approach is being followed for wheat and cotton, in which at the onset of spring, cotton is intersown in wheat strips that were planted in fall. The whole field is occupied by cotton after the wheat harvest in early summer. Once cotton is harvested in fall, two crops have successfully completed their life cycle in 1 year on a single piece of land. There is overlapping of seedling phase of cotton with maturation phase of wheat from April to June in this system (Zhang et al. 2007, 2008a, b). However, cotton harvest is early enough to permit timely sowing of wheat. Various variations based on a number of alternating rows of wheat and cotton are in practice, i.e., 3:1. 3:2, 4:1, and 6:2. The 3:1 pattern means 3 rows of wheat and

1 of cotton in an alternating fashion. Although crop production per unit of land area is significantly increased compared to the monocrops, relay intercropping can have some tradeoffs manifested as shading effect of wheat on young cotton seedlings and competition for resources. These limitations might hinder cotton growth and development hampering lint yield and quality.

Wheat yield in intercropping stretched from 4.6–5.2 t ha^{-1} and was 70–79% of the yield recorded for monoculture of wheat (6.55 t ha^{-1}). Upper limit of wheat yield (79%) under intercropping was realized for 3:1 system followed by 6:2 (73%), 4:2 (70%), and 3:2 (70%) systems, respectively. Likewise, cotton lint yield averaged over 3 years under relay intercropping with wheat range from 0.59 to 0.74 t ha^{-1}. These yield levels corresponded to 54–69% of the cotton grown in monoculture, and 3:2 and 4:2 systems produced 69 and 68% of cotton lint yield realized in monoculture. Lowest (1.28) LER was observed for 6:2 system as compared to 1.39 recorded for the remaining three systems. Moreover, estimated growth rate of cotton observed for 3:2 (8.4 g m^{-2} d^{-1}) and 4:2 (7.7 g m^{-2} d^{-1}) systems was not significantly different from that (8.9 g m^{-2} d^{-1}) observed for monoculture (Zhang et al. 2007). A developmental delay in cotton growth compared to its monoculture was also noticed. Adding further, Zhang et al. (2008a) proposed that such developmental delay in cotton under intercropping was 10–15 calendar days which corresponded to 4.7 physiological days and 115 growing degree days (thermal time calculated from sowing to first square). This delay resulted in reduced fruiting branches, nodes, and fruits. Fruit formation was also delayed resulting in less number of fruit with low average fruit age having negative implications for sink capacity of cotton plant and its harvest index and lint yield. Such findings were attributed to the competitive effects of wheat on the young cotton seedlings and suboptimal thermal climate that prevails in wheat-cotton relay intercrops. Such effects were quite pronounced in 3:1 system than other systems.

Zhang et al. (2008b) quantified the light interception and its utilization efficiency by cotton and wheat grown as monocultures or intercrops (3:1. 3:2, 4:1, and 6:2) under varying row width besides rows strip^{-1}. These authors concluded that LUE of wheat plus cotton remained unaffected by intercropping systems and intercrops intercepted more light than monocultures of cotton. The wheat strips in intercropping harnessed 20% more light per unit strip area than sole stand of wheat. Three years average revealed that wheat under aforementioned intercropping systems intercepted 83, 71, 73, and 75% as much light as intercepted by pure stand of wheat (471 MJ m^{-2} PAR). The corresponding values for cotton were 73, 93, 86, and 67%, respectively, as against 3 year's average 471 MJ m^{-2} PAR intercepted by sole crop. The increased productivity of intercrops relative to monoculture was attributed to greater accumulation of intercepted light per unit land area suggesting complementary light interception over time and space. The water productivity of wheat (0.95–1.28 kg m^{-3}) and cotton (0.11–0.22 kg m^{-3}) under these relay intercropping systems was 27 and 40% less as compared to the monocultures of these crops, respectively (Zhang 2007). The total N uptake by wheat did not vary between mono and relay intercropping systems. The N-yield per unit area for wheat and cotton ranged from 203–288 kg ha^{-1} and 110–127 kg ha^{-1} and was greater in monoculture than intercrops. Cotton N uptake was diminished through intercropping phase which recovered later on. Intercrops utilized more N per unit production as revealed by relative N yield total (1.4–1.7) and relative yield total (1.3–1.4) values. Yearly N surplus under intercropping (400 kg ha^{-1}) far exceeded the N surplus under monoculture of wheat (220 kg ha^{-1}) besides cotton (140 kg ha^{-1}) suggesting a potential environmental risk necessitating the need of demand-based rate besides N timing application under such intercropping systems (Zhang et al. 2008c).

In India and Pakistan, about 80–90% of area under cotton is devoted to cotton-wheat rotation corresponding to 1.40 and 2.62 million ha, respectively (Mayee et al. 2008, 2009). Wheat sowing is often delayed past its optimum planting time due to late picking of cotton and time spent in land preparation (Singh et al. 2016; Shah et al. 2016, 2017). To resolve time conflict in this system, relay sowing of wheat seems a promising option that ensures timely planting of wheat with concurrent increase in wheat productivity and overall system profitability (Sajjad et al. 2018). Relay cropping of wheat allowed one bonus picking compared to conventional tillage wheat, and this improved cotton yield by 12%. Likewise, sowing of wheat was advanced by 31 days which also enhanced wheat yield up to 19% over conventional practice. The relay sowing of wheat in cotton using strip rotor or zero-till double-disc openers was better for wheat emergence besides final productivity than zero-till tine openers. The practice of relay cropping was also advantageous economically and net benefits were increased to the tune of 311 to 425 US$ ha^{-1} (Singh et al. 2016). With recent introduction of Bt-cotton hybrids in this rotation (usually grown at a wider row spacing of 90–120 cm), possibility exists of successfully growing a short period intercrop such as groundnut (Singh et al. 2009). This notion was tested by Singh and Ahlawat (2014) who appraised the two-tiered intercropping of cotton besides peanut when 50% of the recommended N dose for wheat was substituted through farm yard manure. Wheat grain yields were 5% more numerous under this management scenario than grown solely after cotton. Soil physicochemical properties were also positively influenced under cotton + groundnut-wheat rotation. In Pakistan, wheat is usually harvested in late April, while optimal time of planting of Bt cotton is first fortnight of March (Shah et al. 2016, 2017). Cotton planting on a fallow land in March resulted in greater cotton yields compared with planting in April after wheat (Shah et al. 2017). Productivity of Bt cotton is constrained by 30–35-day time conflict which can be overcome by transplanting of one and half month old cotton nursery transplants. This study concluded that yield of wheat sown on beds was significantly higher than wheat sown on a flat bed or ridges. Moreover, bed-transplanted cotton had highest yield at both locations, i.e., Vehari and Multan. Upper limits of net benefits, benefit-cost ratio and marginal rate of return were realized when 45-day-old cotton seedlings were transplanted on beds after bed sown wheat.

Under relay cropping of wheat in cotton, Zohry - (2005) reported seed cotton yield similar to its sole planting under Egyptian environments. Wheat yield was 80% of the sole planting under this system. Moreover, irrigation given to wheat (harvested in April) was also used by cotton (sown in March) (Zohry and Ouda 2015). The timing of the last two irrigations given to the wheat crop affected the LER and ATER in this system (Sultan et al. 2012a). Sultan et al. (2012b) studied the response of sole and relay intercropping of cotton and wheat to sowing date and row width. These authors found better performance of both sole and intercropped cotton in terms of fruiting branches, bolls, boll weight and seed cotton yield at wider ridge width of 100 cm compared to 80 and 90 cm. However, seed and lint yield of sole crop was highest in case of 15 March sowing, while intercrops had highest yield when sown on 1 April.

15.2.2 Cotton-Wheat Double Cropping System

Cotton-wheat double cropping in sequence integrates potential higher yield and income using mechanization (Dai and Dong 2014). Du et al. (2015) suggested that cotton productivity under double cropping systems is limited by lower interception of PAR rather than radiation use efficiency. Interception of PAR by cotton cultivars (Siza 30 and CCRI 50) was significantly less compared to their monoculture when these were sown under wheat/intercropped cotton, wheat/transplanted cotton, and wheat/direct-seeded cotton systems. Nitrogen uptake, besides use efficiency, was quantified by Du et al. (2016) under aforementioned cropping systems. These authors reported that decline in N accumulation rate and shortening of period during which faster accumulation of N occurred were conducive to lower N uptake by cotton under wheat-cotton system compared to cotton monoculture. The N uptake was less for both cultivars than their monocultures, although early-maturing cultivar CCRI 50 had high NUE than mid-late maturing Siza 30. A perusal crop N balance revealed significant N surpluses for preceding wheat in wheat-cotton rotations than cotton monoculture. The study by Hussain et al. (2014) involving omission plot technique in Bt cotton-wheat system revealed that omitting N, P, and K reduced cotton yield up to 28, 6.5, and 14.5% during the first year of study with N being the most limiting factor. The corresponding reduction during the second year of study amounted to 26.5, 15.5, and 12.4%, respectively. The greater yield reduction due to P omission during the second year of study led to the conclusion that P supply is depleted at a faster rate than K in cotton-wheat rotation. To overcome such issues, Rochester et al. (2001) had advocated the use of legumes to improve N fertility besides soil properties in cotton-based systems. Recently, Feng et al. (2017) appraised the effects of sowing patterns (monoculture cotton, cotton intercropped in wheat, cotton transplanted after wheat, besides cotton direct-seeded after wheat) on growth and yield plus economic benefits in wheat-cotton cropping system. Regardless of the cropping systems and fields, cotton yields were lower in double cropping relative to monoculture. However, such decrements were quite small for cotton sown in field with high fertility status. Yield differences among cropping patterns were attributed to difference in number of bolls besides weight. Yield variation between two fields with contrasting soil fertility was due to differences in boll numbers. Over the 2-year study period, net revenue varied from 11 to 35% in low fertility field and 32 to 74% in high fertility field compared to cotton monoculture. Luo et al. (2018) proposed that N application rate can be reduced to the tune of 20–30% without sacrificing yield as N applied at 264 kg ha^{-1} via fertigation in high density crop stand of cotton (19.5 plants m^{-2}) was effective in improving agronomic NUE and N recovery efficiency as compared to higher N application rates (319 and 375 kg ha^{-1}) under conventional application method or low plant density (12.0 plants m^{-2}). Abid et al. (2013) founded that single application of 7.5 kg Zn $ha^{-1}$was adequate for two cycles of cotton-wheat system, while Zn total uptake by wheat (134.9–289.6 g ha^{-1}) was more superior compared to cotton (92.3–192.5 g ha^{-1}). Two-year constant application of 5.0–7.5 kg Zn ha^{-1} did not depress yields under the rotation.

The K deficiency has been acknowledged as a major factor limiting cotton yield (Mullins and Burmester 2010; Yu et al. 2016). A substantial amount of wheat residues (estimate at 6 hundred million tons per annum) are produced in this cropping system. Out of these, only 16% of wheat straw is recycled, while 23% is burned causing wastage of resources and environmental pollution (Zeng et al. 2007; Cao et al. 2008). To cope with K demand of cotton, inorganic salts of K (rich in chlorides or sulfates) are used which have potential to cause soil degradation through crust formation, acidification, and groundwater contamination (Pernes-Debuyser and Tessier 2004; Paradelo et al. 2013; Udeigwe et al. 2015). Wheat straw incorporation has been suggested as an alternative of inorganic K sources (Sui et al. 2015) which significantly improved the availability of macronutrients NPK and also enhanced fraction of water-soluble organic carbon. Residue recycling in cotton-wheat system resulted in 2–7% higher yields of cotton, and 2–10% improvements in wheat yields in 5-year crop residue management study undertaken at two alkaline calcareous aridisols soils of Pakistan. The balance nutrient management and integrated nutrient management systems were found superior to farmer fertilizer use, and all apparent N balances were positive with substantial improvements in nitrate-N and organic matter (Rafique et al. 2012). Under the influence of wheat straw incorporation at 4.5 and 9.0 t ha^{-1} in cotton-wheat double cropping systems of Nanjing and Defang, China, the K concentration of cotton and seed cotton yield was similar to that achieved with inorganic K application at 150 kg ha^{-1} of K_2O (Yu et al. 2016). These authors postulated that wheat straw incorporation at 9.0 t ha^{-1} can substitute inorganic K application at 150 kg ha^{-1} of K in cotton-wheat double cropping systems within less than 3 years.

Application of saline-sodic water for cotton-wheat rotation decreased cotton yield by 21% compared with good-quality canal water over a 7-year study period. Reduction in wheat yield was not observed during the course of study. Farm yard manure and gypsum application improved seed cotton yield, and reduction under these amendments was only 10 and 9% compared to good-quality water (Buttar et al. 2017). Besides agronomic limitations, the wheat-cotton relay intercropping system is also constrained by demand for manual labor and a steady decline has been observed in the use of this system (Feike et al. 2012).

15.2.3 Rainfed Cotton Systems

Modern cotton cultivars like their wild ancestors possess the ability to adapt and survive periods of extremely dry weather and intermittent water supply that occurs under rainfed conditions (Hearn 1990). In Australia, rainfed cotton production has expanded and accounts for 17% acreage of the total cotton area in Australia (Dowling 2002; Bange et al. 2005). The rainfed cotton production system uses "skip-row orientation" in order to maximize the use of limited water supply, reduce the production risk, improve lint quality, and lower the input costs (Milroy et al. 2004; Bange et al. 2005). Gwathmey et al. (2008) suggested that cotton growers interested in skip-row sowing should consider rows spacing of 76 cm or less to minimize weed problems besides productivity loss since skip-row cotton matured later than solid sowing, but the effect was diminished using narrower rows. Moreover, weed growth in narrowly spaced skipped rows was less compared to wider skip-row spacing of 102 cm. In India, the central cotton zone comprising of states of Gujarat, Madhya Pradesh, and Maharashtra is primarily rainfed accounting for 68% of the cotton area. Maharashtra alone occupies one-third of the country's cotton area; however, only less than 10% of the area is irrigated (Blaise 2017). Cotton is grown on an area of 7.10 M ha on vertisols in this rainfed region. Opening of furrows of alternative rows during the month of August facilitates in situ rainwater conservation. Historically cotton was rotated with grain sorghum in the central India, but low prices of sorghum favored continuous cropping of cotton in rainfed area. The rainfed cotton productivity (230 kg ha^{-1}) is lower than India's average cotton productivity of 478 kg lint ha^{-1} (Singh et al. 2012). A system of high density plantation of straight cotton varieties with 25% more NPK is becoming popular in the wake of early canopy closure and limits evaporation losses with additional benefits of optimizing bolls $plant^{-1}$besides boll weight. Response of Bt cotton hybrids to K application in vertisols low in exchangeable K has been reported (Blaise 2012). Such responses were not observed in the past with old cotton varieties (Mannikar 1993). In Benin (Africa), cotton cultivation is also rainfed and compact and early genotypes could be used in crossbreeding to produce varieties adapted to these environments (Sekloka et al. 2018). In the USA, low input rainfed cotton production systems exist in Texas contrary to intensive cotton farming in California and Arizona (James and Choudhary 2010).

15.2.4 Systems Involving Intercropping of Cotton with Other Crops

Agroforestry as an opportunity cropping for cotton was recently evaluated in China by Wang et al. (2016). The authors tested different densities of cotton, viz., 13.5, 18.0, and 22.5 plants m^{-2} sown within 6 m path between jujube plantations. Leaf area and dry matter accumulation by cotton was reduced in rows adjacent to the jujube trees, and biomass allocation to the cotton fruiting parts was also restricted. Shading effect was two rows deep in case of 6-year-old stand of jujube, while it was extended to three rows deep in a 7-year-old jujube stand. These authors inferred that shading effect on cotton yield can be compensated by having more number of bolls per unit land area by increasing cotton density.

In Egypt, Lamlom et al. (2018) studied the combinations of four systems in winter (double cropping systems of Egyptian clover besides cotton, relay intercropping cotton with faba bean, onion or wheat) besides three systems during summer (sole-cotton, intercropping cowpea-or-sesame with cotton). They found highest LER and ATER under Egyptian clover/cotton + cowpea followed by onion + cotton/cotton + cowpea. The later combination recorded maximum monetary benefits and improved fiber quality traits compared to conventional cropping system consisting of Egyptian clover/cotton.

Pigeon pea/cotton intercropping system has been reported as a cash cropping system of black cotton soil of Deccan Plateau, India. Interactive effect of land configuration systems (flat, ridge and furrow and broad bed and furrow) with strip widths (1.5:4.5, 3.0:3.0, 4.5:1.5, and 6:0 m) was nonsignificant for yield of both pigeon pea and cotton crops besides total biomass production. A reduction in strip width was accompanied with decrease in yield of both cotton and pigeon pea. However, greater yield reduction was recorded in case of cotton compared to pigeon pea. Strip combination of 4.5 m pigeon pea and 1.5 m cotton gave highest land equivalent and monetary value equivalent ratios (Potdar et al. 1996). In cotton + black gram intercropping system, cotton is mainly irrigated one time in 15–20 days. Intercrop of black gram is often affected by surplus water and resulted in reduced productivity. In such circumstances, skip furrow method of irrigation is advocated.

15.3 Productivity and Cost-Effectiveness of Cotton-Based Cropping Systems

Studying productivity besides cost-effectiveness of cotton-based cropping systems under conventional and conservation agriculture systems is important (Daujanov et al. 2016). In the first crop cycle (2007–2008), the cotton and wheat yields were lowered by 29 and 27%, respectively, in organic production system compared to conventional system. However, such differences for yield were not observed in the second crop cycle (2009–2010), and yields were similar under all systems. During the first crop cycle, higher gross margins (+29%) were recorded for conventional systems. However, in the second crop cycle, these were higher by 25% in organic system due to lower variation in cost of production (Forster et al. 2014). Across 4 harvest years, gross margins associated with soybean under organic systems were always higher. These authors suggested that soybean production is a viable option for small landholders under cotton-based cropping systems of India. This notion of maximizing the profitability of cotton-based cropping system through legume incorporation has been explored in Australia and India (Williams et al. 2011; Turkhede et al. 2017). Inclusion of vetch in continuous cotton or cotton-wheat system increased gross margins per ha by 23 and 12%, respectively, in Australia. The gross margins increased because of higher yields and reduction in input cost of N since the same was contributed by vetch. The cost of N produced by vetch more than paid for its cost of production. In India, the sowing of cotton on one side of the permanent raised broad bed and intercropped with mung bean resulted in 37 and 10% higher productivity over conventional tilled flat cotton-wheat systems (CT), and permanent raised beds with cotton sown in the center without mung bean. This treatment combination improved system irrigation water productivity by 131%, energy productivity by 54% and net returns by 69% as compared to CT (Choudhary et al. 2016). Conservation agriculture practices in cotton-wheat cropping systems of Indo-Gangetic Plains were evaluated in terms of crop and water productivity and cost-effectiveness (Das et al. 2014). These authors concluded that seed cotton yield under zero-tilled broad bed with residue retention was 24 and 51% more numerous as compared to zero-tilled narrow bed without residue retention and sowing on flat beds after conventional tillage without residue recycling. Higher water productivity (12–48%), productivity of system in terms of wheat-equivalent yield (13–15%), and net returns (13–36%) were also associated with this treatment combination.

Braunack (2013) appraised factors that influence cotton yield besides quality in Australian cotton-based farming systems and how these have changed over time (2004–2011) since the adoption of transgenic cotton Bollgard II® varieties in irrigated and dryland systems. The study revealed that over the study period, the use of N fertilizers was increased, while P use remained steady in the irrigated cotton system. Nevertheless, use of both these nutrients was decreased in dryland cotton. The number of insecticide sprays was decreased in both systems. Lint yield and fiber length showed an increasing trend in irrigated cotton with a decrease observed for fiber strength and micronaire. The yield of dryland cotton was decreased with increase in fiber strength, length, miconaire, and trash level.

Additional income and monetary benefits can be achieved by sowing cotton in wider rows and planting a relay crop in between these rows (Rao 1991). Wheat and barley sown as intercrops in cotton recorded 69 and 23% higher yields, respectively, compared with sole planting of these crops, although cotton yield remains unaffected in relay cropping (Khan and Khaliq 2005). Wheat relayed in cotton recorded yield of 2964 kg ha^{-1} as well as 1750 kg ha^{-1} recorded for wheat that was sown after cotton. Depending upon the sowing time of cotton, relay cropping increased land use efficiency by 81–213% (Hussein 2005). Bio-economic efficiency of cotton in 80 cm rows and 120/40 cm spaced rows besides cowpea and sorghum as intercrops was evaluated in Pakistan (Aasim et al. 2008). Advantage of 32–46% for LER over sole cropping was realized in both planting designs. Sorghum intercropping in cotton resulted in greater reduction in cotton yield than cowpea.

Dhaliwal and Sandhu (2015) evaluated the productivity and economics of seven cotton-based cropping systems (S_1, Bt cotton (*Gossypiumhirsutum*)-wheat (*Triticumaestivum*L.); S_2, American cotton-wheat; S_3, desi cotton (*Gossypiumarboreum*)-wheat; S_4, alternatively Bt cotton and desi cotton-wheat;

S_5, Bt cotton-barley (*Hordeum vulgare*); S_6, Bt cotton-onion (*Allium cepa* L.); and S_7, Bt cotton-transplanted gobhi sarson (*Brassica napus*) in Indian Punjab. Greater rice-equivalent productivity as compared to all-other systems were realized under Bt-cotton-onion (235.5 q ha^{-1}) followed by desi cotton-wheat (123.3 q ha^{-1}) systems. Greater rice-equivalent yield under Bt cotton-onion system was attributed to greater bulb yield besides market price of onion crop only; however, *Kharif* crop under this system failed to produce any difference amid cotton yield from other cotton-based system. In cotton-based cropping systems of Mahrashtra, India, intercropping with pigeon pea and mix cropping with green gram, maize, sesame, and pearl millet resulted in greater net profit than cotton as sole crop (Gahukar 2017).

Compared to conventional tillage system and rotation (cotton-wheat-maize), cotton yields were consistently higher over a 3-year study period in Uzbekistan under conservation tillage system and rotation involving soybean as legume (cotton-wheat-soybean) suggesting improvement in soil health and crop productivity (Khaitov and Allanov 2014). Cong et al. (2014) suggested that intercrops have greater belowground productivity and sequester more C and N as compared to sole crops. This notion was supported by the results of their 7-year field study in which soil organic C and N contents and C and N sequestration rates were higher in case of intercrops over sole crops.

15.4 Insect Pests

Lepidoptera insects like *Helicoverpa armigera* (American bollworm), *Earias vittella* (spotted bollworm), *Pectinophora gossypiella* (pink bollworm), *Earias* spp. (spiny bollworm), *Argotis* spp. (cutworms), *Helicoverpa zea* (bollworm), and *Heliothis virescens* (tobacco budworm) are the major pests infesting 88% of the global cotton area (James 2002). Of the total pesticide used worldwide, cotton crop receives over 18% of all insecticides used and substantial amounts of other plant protection chemicals (Deguine et al. 2008). Till the first half of the 1980s, chlorinated hydrocarbons were the major pesticides used to control bollworms in cotton, and later organophosphates and pyrethroids were used for this purpose (Zhao et al. 2011). These insecticide groups were rendered ineffective due to evolution of resistance in bollworms against insecticide molecules owing to their indiscriminate use in ever-rising polluting quantities (Deguine et al. 2008). These insecticides also exerted negative influence on the beneficial insects or natural enemies of bollworms with a concurrent increase in the damage caused by bollworms as well as other secondary pests. Transgenic Bt cotton was developed with an aim to reduce insecticide input and lower down the production costs. Studies document multidimensional benefits for the farmers with the use of Bt cotton such as reduced production costs, high yield and net profits, and biodiversity conservation (Qaim 2003; Pray et al. 2001, 2002; Vitale et al. 2008; Abedullah and Qaim 2015). The advent of Bt cotton is regarded as a major breakthrough that has revolutionized the pest management in a pest-intensive crop like cotton (Alvi et al. 2012). The Bt cotton is now grown on more than 25 M ha in 2 developed (the USA and Australia) and 11 developing (China, India, Pakistan, Argentina, Brazil, Mexico, Colombia, South Africa, Costa Rica, Myanmar, and Burkina Faso) countries (James 2012).

However, acclaimed benefits of Bt cotton are often challenged due to methodological issues and effectiveness of pest control achieved herein due to low or variable level of Bt gene expression and Cry endotoxin protein level in plant tissue (Xu et al. 2008; Shantharam et al. 2008; Jost et al. 2008; Zhao et al. 2011). Theoretically, for effective pest control, whole Bt cotton plant should produce enough toxin that is lethal to arthropod pests especially in period of attack of pest (Naik et al. 2018; Ahmad et al. 2019). Nevertheless, Bt toxin production varies among cotton genotypes (Cheema et al. 2015) and plant parts/tissue (Khan et al. 2018) and has been reported to decline during course of plant growth (Zaman et al. 2015). Unfortunately, the reports of insect resistance to Cry1Ac proteins from different geographical regions of world (Tabashnik et al. 2013; Tabashnik and Carriere 2017; Naik et al. 2018) have challenged the efficacy, prospect, and sustainability of the Bt technology. Additionally, uncertainty about its anticipated ecological impacts such as evolution of resistance in bollworms, negative effect on non-target species/natural enemies of bollworms/predators, soil biota and nutrient dynamics, and increased insurgence of secondary pests might take years or so to manifest (Zhao et al. 2011). Furthermore, Bt cotton is not effective against secondary pests which are otherwise killed by insecticides in conventional cotton. Hence, in the long run, these secondary pests might become the primary pests themselves or will need greater insecticide application, thereby counteracting the benefits of Bt cotton. Displacement of vegetative or boll feeding caterpillars by sucking insects as major pests has been suggested (Deguine et al. 2008). Men et al. (2004a) reported that total pesticide application was similar between Bt and non-Bt cotton due to additional spraying to control secondary insect pests. Likewise, Zhao et al. (2011) concluded that reduction in pesticide use due to adoption of Bt cotton was far less than that reported in literature. Contrarily, Wang et al. (2009) advocated that increased fraction of pesticides for controlling secondary insects was quite small when compared to the overall reduction in pesticide input owing to Bt cotton cultivation. This scenario suggests the need of in-depth studies at plant, field, and agro-ecosystem level while considering the spatiotemporal variations in natural factors regulating pest population, agronomic practices, and socioeconomic factors. In doing so, we would be better able to portray a wider picture of the benefits of Bt cotton and overcome pest-related apprehensions.

Pyke et al. (1987) proposed the concept of "Push-Pull" strategy which consisted of insect diversion via *stimulo-deterrent* techniques. The idea was further advanced and refined by Miller and Cowles (1990). The "Push" includes the use of repellent plants that repel or deter away the pests from the resource (main crop), thereby discouraging the settlement of pests on main crops by masking the host appearance (Cook et al. 2007). The "Pull" on the other hand involves the simultaneous attraction toward the neighboring trap plants with attractive highly apparent stimuli (Cook et al. 2007; Ratnadass et al. 2012). The stimuli may be trophic, visual, or chemical (Gaba et al. 2015). Introduction of a new crop either as push or pull modifies the predator population via creation of new habitat. For Australian cotton production systems, Mensah (1999) recommended the growing of 9–12 wide single median strip of lucerne between two cotton fields 300 m wide. Growing lucerne as a nursery crop around cotton field margins has been reported to act as nursery for ladybird beetles (*Coccinella septempunctata*, *Propylea quatuordecimpunctata*, and *Hypodama variagata*), chrysopids, and other beneficial arthropods. Once lucerne is cut, these beneficial insects move into the cotton and help control cotton aphid-significant pest of cotton in Xinjiang province of China (Lin et al. 2003). Likewise, *Helicoverpa* spp. infestation in cotton was significantly less using field peas and sorghum in Australia and the USA, respectively (Grundy et al. 2004; Tillman and Mullinix Jr. 2004). Another study from India found that neem as a push coupled with pigeon pea or okra as trap crop (pull) was effective against *Helicoverpa* spp. (Duraimurugan and Regupathy 2005).

Trap and intercropping have been reported to offset the pest populations by maintaining favorable beneficial insect complexes (Deguine et al. 2008). In cotton grown in Texas, USA, relay intercropped cotton had lower average abundance of aphid than sole stand of cotton crop. Predators appeared earlier in summer and in higher numbers in relay intercropped cotton (Parajulee et al. 1997). In another study, sowing wheat as winter relay crop in cotton caused a significant reduction in the population of cotton aphid and increased the population of predators of cotton pests (Men et al. 2004b). Highest mass of natural enemies besides low populations of cotton aphids were found in cotton relay-intercropped in a wheat variety (Lovrin10) that was susceptible to wheat aphid as compared to aphid-resistant wheat variety (KOK1679). These authors concluded that background of wheat variety (resistance or susceptibility to wheat aphid) could affect natural enemies in cotton and wheat varieties with susceptibility or moderate resistance to wheat aphid might decrease cotton aphid more efficiently by enhancing predators of cotton at seedling stage (Ma et al. 2006).

15.5 Weeds

Cotton owing to its C_3 metabolism competes poorly with weeds especially during early vegetative phase (Bryson et al. 1999; Deguine et al. 2008). Cotton is extremely infested with grasses, sedges, and broadleaf which reduces up to 30% cotton yield (Jabran 2016). Losses as high as 90% have also been reported (Manalil et al. 2017). Major weeds of cotton crop are *Amaranthus* spp. *Convolvulus* spp., *Cyperus rotundus, Cynodon dactylon* (L.) Pers., *Echinochloa* spp., *Dicanthium annulatum* (Forssk.) Stapf., *Ipomoea* spp., *Lolium perenne* L., *Leptochloa chinensis* L. Nees., *Polygonum aviculare* L., *Sporobolus clandestinus* (Biehler) A.S. Hitchc., *T. portulacastrum*, and *Xanthium* spp. (Zhang 2003; Economou et al. 2005; Rajput et al. 2008; Kruger et al. 2009; Hiremath et al. 2013; Manalil et al. 2017). Being a wide-rowed crop, growers control weeds intensively through chemical besides mechanical means.

Torres et al. (2009) described four herbicide-tolerant cottons covering the global cotton market, viz., glyphosate-tolerant Roundup Ready® and Roundup Ready Flex® and bromoxynil-tolerant BXN® varieties and glufosinate ammonium-tolerant LibertyLink®. Research work to develop 2,4-D-tolerant varieties to overcome drift effects and for controlling broadleaf weeds is under way. Overreliance on glyphosate as sole weed control in herbicide-resistant cotton has resulted in 43 resistant weeds across the globe with 16 species stated from Australia alone (Iqbal et al. 2019). The widespread adoption of glyphosate-tolerant cotton in Australia from 2000/2001 growing season till now has caused evolution of numerous glyphosate-resistant weed biotypes (Werth et al. 2012, 2013; Heap and Duke 2018). Weeds like *Amaranthus tuberculatus*, palmer amaranth, annual ragweed, giant ragweed, flea-bane, horseweed (*Conyza canadensis* L.), liverseed grass, windmill grass, annual ryegrass, and Johnson grass have been reported to develop glyphosate resistance (Guest et al. 2014; Sosnoskie and Culpepper 2014; Green 2018).

In an era of herbicide-resistant weeds, due consideration should be given to improve weed management since available evidences have led to the conclusion that weed management system merely relying on herbicides loses its sustainability in the long term (Charles and Taylor 2004; Lamichhane et al. 2017). The weed-suppressive effects of narrow row spacing (Gwathmey et al. 2008; Stephenson and Brecke 2010) in cotton are well documented. Manalil et al. (2017) suggested the use of competitive cotton cultivars with high seedling vigor, manipulation of row spacing, and its orientation with respect to sunlight and high seeding densities as tools that can impart cotton crop a competitive edge over weeds. Furthermore, certain weeds act as host of disease-causing microorganisms and refuge for insect pest; yet many also harbor and sustain population of natural enemies/predators (Showler and Greenberg 2003). In this backdrop, weed management should take into account the phytosanitary context of the whole cropping system (Deguine et al. 2008). Weed density and dry biomass were lowest in cotton intercropped in sesbania in addition to application of *Azospirillum* besides *Pseudomonas*. This system suppressed weed growth by 54.5 and 44% compared to pure-crop-cotton through 2007 and 2008. Higher cotton equivalent productivity of 2052 and 1895 kg ha^{-1} was documented in cotton + onion rotation that was at par with cotton + sesbania rotation with cotton equivalent productivity of 2010 and 1894 kg ha^{-1} in both years (Marimuthu and Subbian 2013).

Cotton unit yield and total output have increased due to intensive farming technologies like increased use of nutrients, advent of Bt cotton varieties, seedling transplanting, double cropping, manipulation of plant architecture, plant training, use of growth regulators, high seeding densities, use of plastic mulch, mechanized picking, etc. However, these have made cotton cultivation labor and input intensive, and endemic ecological effects associated with cotton productivity are increasing in spotlight and are often questioned. Moreover, data regarding sustainability of cotton-based cropping systems are either scanty or not readily available. It is unequivocal that water and soil management, pests and pesticide management, biodiversity and land use patterns, and productivity and profitability of cotton-based cropping systems need to be revisited with greater ecological orientation in pursuit of sustainability. Resource conservation practices like intercropping with legumes, permanently raised beds, zero tillage, drip irrigation, fertigation, residue retention/ recycling, mulching, and green manuring can be opted to bring in the much needed diversity and stability while enhancing the productivity and resource use efficiency of cropping systems. Research efforts and extension recommendations should consider the spatiotemporal variations and cropping system-specific issues and be able to differentiate between various cotton-based cropping systems. Cotton cultivation needs to switch from input-based to cropping system-based growth, and in this paradigm shift, the knowledge generation and its dissemination could play a vital role. The problems faced especially in the backdrop of dwindling natural resource base and climate change are multifarious, and to cope with these challenges, it is imperative to make adjustments and/or fine-tune technology, management practices, and legislation.

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