

REVIEW ARTICLE

Nitrogen application and tillage system effects on cotton yield and GHG emission

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**Abstract** Cotton is planted worldwide as a “cash crop” providing us fiber, edible oil, and animal feed as well. In this review, we presented a contemporary synthesis of the existing data regarding the importance of nitrogen application and tillage system on cotton growth and greenhouse gas (GHG) emission. Cotton growth and development are greatly influenced by nitrogen (N); therefore, proper N application is important in this context. Tillage system also influences cottonseed yield. Conservation tillage shows more promising results as compared to the conventional tillage in the context of cotton growth and GHG emission. Moreover, the research and knowledge gap relating to nitrogen application, tillage and cotton growth and yield, and GHG emission was also highlighted in order to guide the further studies in the future. Although limited data were available regarding N application, tillage and their interactive effects on cotton performance, and

GHG emission, we also tried to highlight some key factors which influence them significantly.

**Keywords** Cotton · Greenhouse gases · Nitrogen management · Tillage · Sustainable agriculture

**Introduction**

Cotton is a tropical crop and plays a considerable role in the economic development worldwide. Cotton is an important source of fiber, oil, and animal feed (Dai and Dong 2014). In China, 5.9 million ha of cropland is cultivated with cotton, corresponding to approximately 4 % of the total cultivating area, and on the other hand, the ongoing economic development has resulted in a sharp rise of inorganic N fertilizer consumption between 1980 and 2007 from 9.3 to 23.0 million t N (China Statistical Year book, 2008). The global 20 years’ average (1993/94 to 2013/14) annual planted area is 33 million ha of cotton (source: Bremen Cotton Exchange 2014) producing about 26 million t of lint each year. Different crop husbandry practices such as fertilization especially nitrogen (N) and tillage system greatly influence the cotton yield (Howard et al. 2001). N is an important macronutrient that influences cotton growth significantly (Mokhele et al. 2012). Over and/or under N application from optimum rate resulted in reduced cotton growth and yield (Constable and Rochester 1988; Lokhande and Reddy 2015). Different management practices such as application rate, application methods, N fertilizer types, and their respective use efficiencies also influence cotton production (Larson et al. 2001). Cotton maturity is of big concern while considering N application (Dai and Dong 2014). Excess application of N causes delayed maturity (Pettigrew et al. 1996). Cotton requires high N demand (50–412 kg N ha<sup>-1</sup>), which can develop suitable conditions for the

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emission of greenhouse gases (GHGs) associated with high denitrification process (Scheer et al. 2008a; Zhang et al. 2008). Indeed, significant emissions of these GHGs have been observed from cotton fields across the globe (Scheer et al. 2008b). Moreover, greenhouse gas emissions from the cotton fields due to N fertilization and tillage practices were also discussed. Previously, available reports have revealed variable effects of tillage on cotton yield. Some researchers have reported better cotton growth and higher lint yield under conservation tillage as compared with conventional tillage (Daniel et al. 1999; Nyakatawa et al. 2000). However, some studies have observed no significant yield difference between these different tillage systems (Ishaq et al. 2001; Pettigrew and Jones 2001; Schwab et al. 2002). Triplett et al. (1996) have argued that the exact benefits of conservation tillage in cotton can only be observed after several years of conservation tillage practices. The present review attempts to highlight the role of N fertilization and conservation tillage on growth and yield of cotton and on GHG emission.

## C a d e d e a e

### a ca

Nitrogen (N) is an important macroelement that plays a crucial role in growth and physiology of plants (Marschner 2001). Nonetheless, N stress in the form of N deficiency or excess greatly influences the cotton growth and yield by disrupting the several growth-promoting processes in cotton (Gerik et al. 1998; Lokhande and Reddy 2015). Jaynes et al. (2001) observed stunted growth of cotton with decreased leaf area, number of fruiting branches, and lint yield under N deficiency as compared to control with optimum N application. Availability of optimum N governs physiological growth and activity of cotton, while N limitation during the early growth stages resulted in reduced leaf expansion associated with decreased cell division and cell expansion (Chapin 1980; Tang et al. 2012).

Nitrogen deficiency also induces the competition for the translocation of N within plant. Lokhande and Reddy (2015) substantiated that during the reproductive growth of cotton, growing bolls have priority for plant assimilates, and as a result, the vegetative growth of cotton was suppressed. Nitrogen deficiency also reduced the fruiting pattern and boll formation in cotton. Gerik et al. (1998) observed the altered fruiting pattern and reduced boll size, boll weight, and number of bolls per plant per unit time with limited N supply as compared to N optimal condition.

Cotton fiber is the ultimate purpose of farmers in cotton cultivation. Cotton fiber is elongated and thickened single cell of seed epidermis, which achieves its maximum length in the early period of anthesis (15–20 days after anthesis) followed by cellulose deposition on secondary wall, giving rise to strength and maturity (Davidonis et al. 2004). N limitation

during fiber development stage resulted in reduced fiber strength and quality. It has been reported that N deficiency decreased the fiber length and strength (Read et al. 2006) while increased the micronaire value (Reddy et al. 2004). A positive relationship was also found between fiber strength and N fertility (Fritschi et al. 2003).

The major portion of N is important for physiological growth of cotton, as leaf N is the major component of chloroplast. N deficiency resulted in reduced chlorophyll production with concomitant decline in photosynthetic activity and carbon assimilation in cotton (Zhao et al. 2003). It has been reported that cotton leaves accumulate about 44 g kg<sup>-1</sup> of N (Reddy et al. 2004) under well-fertilized conditions. The strong relationship between leaf N and photosynthesis in cotton has been widely recognized and reported. N deficiency decreases leaf area and chlorophyll content, which lowers net photosynthesis rate (Radin and Boyer 1982). In another study, Reddy et al. (1996) reported a strong positive correlation among photosynthetic rate, stomatal conductance, and leaf N. They further substantiated that under limited N, Rubisco enzyme activity was reduced. Some other researchers also reported the strong association between leaf N content and photosynthesis in cotton (Shiraiwa and Sinclair 1993) with N deficiency adversely affecting lint yield through reductions in stem elongation, leaf expansion (Lu et al. 2001), photosynthetic and metabolic activities (Ciompi et al. 1996), and biomass production (Fritschi et al. 2003).

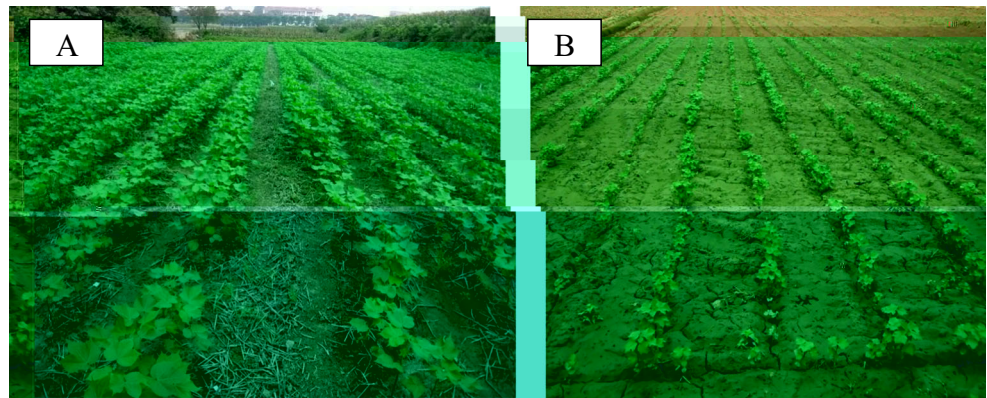
Cotton plants under deficient-N conditions produced significantly lower biomass 23 % per plant as compared to cotton that received sufficient amount of N (Lokhande and Reddy 2015). The reduction in biomass due to the insufficient N supply has been related to the reduction in leaf area (Fernández et al. 1996) and CO<sub>2</sub> assimilation rate (Reddy et al. 1997) that in turn restrict the reproductive growth of cotton.

Excess N application induced prolonged vegetative growth and delayed reproductive growth (Marschner 2001). Ayissa and Kebede (2011) observed delayed squaring, flower initiation, and boll opening of cotton plant significantly under higher N fertilization (92 kg ha<sup>-1</sup>) than the unfertilized plot while intermediate application (68 kg ha<sup>-1</sup>). The earliness attained in initial boll setting by the intermediate N rate, irrespective of cotton variety, could be due to optimum nitrogen demand of the crop for the heavy nutrient sinks of cotton bolls to be opened. At the same time, higher rate of nitrogen prolonged vegetative growth and delayed opening period of bolls.

Different studies indicated that under different N source and application methods, optimum N rate varies and showed different responses under different N rate (Table 1). Nitrogen use efficiency in cotton can also be influenced by the efficiency of N application methods. Different methods have been studied to supply N in cotton such as broadcasting (Boquet

and Breitenbeck 2000), split application (McConnell et al. 1993), and deep banding (Elberhar and Tupper 1988); nonetheless, the efficiency of each method varies with experimental conditions. Moreover, it was observed that split N application method significantly improved N fertilizer recovery (Sower et al. 1994). Cotton biomass and yield are also affected by the N split ratio assuming that the N rate is fixed. Yang et al. (2011) reported that the split ratio of 0 % at preplant, 40 % at first bloom, and 60 % at peak bloom harvested the highest biomass and yield when N was applied at 225 kg ha<sup>-1</sup>. But cotton biomass accumulated the fastest from first bloom to peak bloom for each of the N split application ratios (Wang et al. 2010; Yang et al. 2011). Guo et al. (2010) found that the treatment of N application splitting into 40 % at preplant, 15 % at squaring stage, 23 % at first bloom, and 22 % at peakm,

**F . 1** Comparative cotton growth under conservation tillage (a) vs conventional tillage (b) (picture courtesy; Adnan Noor Shah, Huazhong Agricultural University, China)

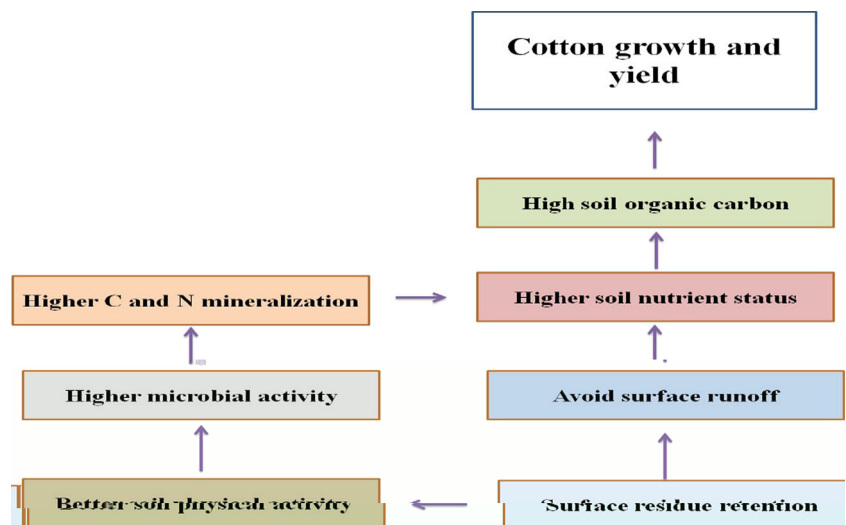


systems for sustainable cotton production. Nonetheless, integrated weed management options can be used while adopting conservation tillage for cotton.

Mulching and residue retention on soil surface due to conservation tillage is another crucial factor that can influence plant growth and yield (Yang et al. 2013). Cotton is a tropical summer crop, and water availability during cotton germination is one of the biggest obstacles in maintaining optimum plant population of cotton per unit area (Ayissaa and Kebede 2011). Nyakatawa and Reddy (2000) substantiated that surface residue retention under conservation tillage resulted in increased soil moisture contents, thus increasing the cottonseed germination, root growth, and lint yield compared with conventional tillage. Nonetheless, poor root penetration and difficulties in obtaining adequate stands and weed control have been observed to reduce cotton yields in no tillage (Schertz and Kemper 1994; Triplett et al. 1996). Veiga et al. (2008) reported that the stubble incorporation under conservation tillage improved the soil microbial activity, with concomitant increase in infiltration rate, fast drainage, aggregate stability, hydraulic conductivity, and redox potential. Soil losses due to erosion under conventional tillage occur due to the loosening and pulverizing effects of heavy tillage, while conservation

avoids such losses, as soil aggregates bind together due to high concentration of organic matter in soil which ultimately increases the cotton yield (Hutchinson et al. 1995). Soil hydraulic conductivity under conservation tillage is pertained to be more due to increased fauna activity resulting in large macropores, while soil under conventional system exhibited less macropores and hydraulic conductivity (Ferrerias et al. 2000). Saturated hydraulic conductivity is found to be high in tilled soils due to the loosening of soil at the beginning of season, while at the end of the season, all particles were settled down and resulted in reduction of hydraulic conductivity (Shaver et al. 2002). Crop residue retention can improve soil nutrient status. For instance, the replacement effects of potassium fertilizer by various wheat straw incorporation rates can at least partly, even totally, replace chemical potash according to soil available K concentration in actual cotton production (Sui et al. 2015). In mulch tillage, stubbles on the soil surface limit raindrop action and hard crust formation (Gilley 1995). In addition, residues slow down surface runoff and increase infiltration rate. Bezborodov et al. (2010) noted that cotton yields were up to 800 kg ha<sup>-1</sup> higher and crop water productivity (lint + seed) up to 0.47 kg m<sup>-3</sup> greater in the mulching treatments than the farmers' managed fields with

**F . 2** Summary of the effects of conservation tillage and related factors on cotton growth and yield



conventional practices in the same region. In another study, mulching increased seed cotton yield by 36.1 % as compared to no-mulch or conventional tillage system (Dong et al. 2005). Yoo et al. (1988) found that reduced tillage with winter wheat as cover crop was the most effective in reducing the surface runoff, sediment, and nutrient losses while maintaining comparable cotton yield. They also observed that runoff and sediment concentrations from conventional tillage system were high during the “critical period” (from planting to the last cultivation of the conventional tillage system), while some other researchers (Mueller et al. 1984) have shown the opposite. Differences in runoff volumes among tillage systems have been attributed to the varying effects of tillage on surface conditions and residue cover (Lindstrom and Onstad 1984). Andraski et al. (1985) reported that the tillage practices affect the runoff volumes and peak flows of surface runoff. Besides the amount of residue retention in soil, soil texture also influences nutrient uptake; for example, K uptake by seed cotton and cotton plant increased by 201.65 and 226.7 % than that of control, respectively, while on Dafeng sandy loam, potassium uptake by seed cotton and cotton plant was increased by 47.2 and 37.1 % in response to wheat straw incorporation, respectively.

Sustainability of the farming system can be improved by combining winter cover crops with conservation tillage. Cotton yield is often improved by planting winter cover crops in conservation tillage systems (Hutchinson et al. 1995; Sainju et al. 2006) because cover crops provide additional residues that act as mulch in conservation tillage, thereby improving soil moisture and germination of cotton seedlings (Boquet et al. 2004). Soil carbon (C) mineralization is governed by soil organic matter (SOM) and is important for improving soil fertility. Zero tillage retains sufficient amount of organic residue over soil surface pertained to be efficient in replenishing SOM pool, while conventional tillage decreases SOM because of less incorporation of crop residues in soil (Balesdent et al. 2000). Continuous soil stirring led to oxidation of organic matter; contrarily no tillage sequestered 67 to 512 kg C ha<sup>-1</sup> per year than conventional tillage (McConkey et al. 2003). Sainju et al. (2006) attributed the higher cotton growth and lint yield under conservation tillage to better soil physical, chemical, and biological properties as compared with conventional tillage. Besides C sequestration, conservation tillage also increases the availability of nutrient in soil. Van Den Bossche et al. (2009) substantiated that no tillage reduced the N losses by increasing N mineralization and enhanced the N use efficiency than conventional tillage (Van Den Bossche et al. 2009). Placement and accumulation of plant residues on soil surface increase the soil organic carbon contents with concomitant increase in microbial activity (Amato and Ladd 1992). The enhanced microbial activity increases N mineralization, pertaining to more in upper soil surface, which consequently increased the crop production (Schimal et al. 2004). Placement and accumulation of plant residues on soil surface increase the soil organic carbon contents with concomitant

increase in microbial activity (Qiu et al. 2014). The enhanced microbial activity increases N mineralization, pertaining to more in upper soil surface which consequently increased the crop production (Paul 2014). Studies suggest that conversion of conventional till (CT) to no till (NT) can sequester atmospheric CO<sub>2</sub> by 0.1 % ha<sup>-1</sup> at the 0–5-cm soil depth every year, a total of 10 t in 25–30 years (Lal and Kimble 1997). Sequestration of C in the soil by adopting no tillage can also conserve N, because soil organic carbon (SOC) and total N levels are highly related (Sainju et al. 2002). However, SOC and STN levels below the 7.5-cm depth can be higher in tilled areas, depending on the soil texture, due to residue incorporation at greater depths (Clapp et al. 2000). Bayet et al. (2006) found that compared to conventionally tilled soil, the C stocks in no-till sandy clay loam Oxisol increased by 2.4 Mg ha<sup>-1</sup> (C sequestration rate = 0.30 Mg ha<sup>-1</sup> year<sup>-1</sup>) and in the clayey Oxisol by 3.0 Mg ha<sup>-1</sup> (C sequestration rate = 0.60 Mg ha<sup>-1</sup> year<sup>-1</sup>). The mean rate of C sequestration in the no-till Brazilian tropical soils was estimated to be 0.35 Mg ha<sup>-1</sup> year<sup>-1</sup>, similar to the 0.34 Mg ha<sup>-1</sup> year<sup>-1</sup> reported for soils from temperate regions but lower than the 0.48 Mg ha<sup>-1</sup> year<sup>-1</sup> estimated for southern Brazilian subtropical soils. Feng et al. (2003) reported that the no-till treatment increased SOC and total nitrogen contents in the surface layer by 130 and 70 %, respectively, thus significantly increased cotton yield. Moreover, zero tillage along with adequate amount of crop residues minimizes N leaching (Sainju et al. 2006). N accumulation in the soil under conservation tillage by cotton may be partially masked by soil potential N mineralization (Sweeney and Moyer 2004). Karlen et al. (2001) showed that tillage system has a direct impact on N transport and its destination by altering soil physical properties peculiarly mineralization of organic contents, macropores, and available water. Cotton lint yield and N uptake were as good as or better in no till than in strip till and chisel till (Sainju et al. 2006). Conclusively, lower production cost and greater environmental benefits of reduced soil erosion and N leaching and increased C sequestration in conservation tillage make conservation tillage more promising for cotton production as compared to conventional tillage (Smart and Bradford 1999; Paxton et al. 2001). Feng et al. (2003) explained that how conservation tillage practices improve soil quality and sustainability in a cotton cropping system and suggested that during the growing season, changes in the microbial community may be primarily determined by soil conditions responding to cotton growth and environmental variables such as moisture and temperature; during fallow or prior to cotton establishment, community changes associated with tillage practices become more pronounced.

## Ge e se a e e

In the current scenario of agriculture and climate change, sequestration of C in the soil is necessary to increase soil C pool

for C trading and for mitigating greenhouse gas emissions. This can be accomplished by the adoption of novel soil and crop management practices for a long term, which will not only increase soil C but also improve the soil quality and increase economic crop production. Likewise, N sequestration is another environmental issue and is needed to be investigated to reduce the rate and cost of N fertilization, N leaching, and N<sub>2</sub>O emission. Conservation tillage is reported as an effective approach in mitigating emanation of greenhouse gases and sequestration of C and N in soil. Furthermore, N fertilization triggers the release of greenhouse gases from arable crop fields. This section consists of two subsections science pertaining to greenhouse gas emission (1) under conservation vs conventional tillage system and (2) under different N management practices. More possible effects of these greenhouse gases on cotton production and further than can reduce greenhouse gas emissions were also discussed.

### Greenhouse gas emission

The release of greenhouse gases can also be affected by the type of N fertilizer application method, timing of application, placement of N, and N rate (Fig. 3). Availability of N and its losses are greatly influenced by its placement in soil and timing of N application. Venterea et al. (2005) found a significant interaction of tillage and N placement method on greenhouse gas emission and observed that N<sub>2</sub>O release was higher under no tillage as compared with conventional tillage when N was applied at post emergence by broadcasting, nonetheless an opposite effect was noted when N was either injected or broadcasted at pre-planting. N is volatile in nature, thus its contact with oxygen could result in release of N as N<sub>2</sub>O in air but this is not in case conventional tillage. Breitenbeck and Bremner (1986) noted that soil injection of anhydrous NH<sub>3</sub> at the depth of 30 cm caused 107 % higher N<sub>2</sub>O release as compared with the soil injection at 10 cm. They also found that the effect of depth of application of anhydrous NH<sub>3</sub> on emission of N<sub>2</sub>O was less when this fertilizer was applied at a rate of 225 kg N ha<sup>-1</sup>. While it is suspected that anhydrous NH<sub>3</sub> may

possibly inhibit nitrifying bacteria and allow the accumulation of nitrite in soil. Venterea and Stanenas (2008) observed no increase in denitrification with substantially no release of N<sub>2</sub>O at the depth of 30 cm under aerobic conditions. Placement of N on soil surface or at more depth resulted in higher N loss either by volatilization or by the release of N<sub>2</sub>O under irrigated conditions. Research comparing the surface-applied urea to urea placed in a band below and to the side of the seed-row showed that N<sub>2</sub>O emissions were higher under broadcasting compared with band placement (Hultgreen and Leduc 2003). Conclusively, placement of N at proper depth is of significant importance in the increasing N use efficiency in cotton, thus more research is required to study this aspect under different tillage systems and different agro ecological zones.

N<sub>2</sub>O release also depends on the type of chemical fertilizer use; e.g., Tenuata and Beauchamp (2003) compared release of N<sub>2</sub>O from different N fertilizer sources under field and laboratory conditions and observed a decreasing trend of N<sub>2</sub>O production from urea, ammonium sulfate and calcium sulfate. They further recorded that moisture contents also interferes with the release of N<sub>2</sub>O under aerobic conditions for instance release of N<sub>2</sub>O was higher when N was supplied from urea than with other fertilizer with only fewer differences at high moisture contents. The authors concluded that this observation warrants more research since ammonium phosphate is commonly used and because of the possible implication of P status impacting N<sub>2</sub>O emissions from N fertilizers. Harrison and Webb (2001) stated that it is difficult to say with any certainty if a strategy based on urea or ammonium nitrate would result in the smaller N<sub>2</sub>O emissions. Contrarily, More recent comparisons among urea, NH<sub>4</sub>-based and NO<sub>3</sub>-based N source have shown higher emissions of N<sub>2</sub>O from urea (Tenuta and Beauchamp 2003), and higher N<sub>2</sub>O emissions from NH<sub>4</sub>-based N fertilizers compared to NO<sub>3</sub>-based fertilizers (Velthoff et al. 2003; Tenuta and Beauchamp 2003). This higher emission with NH<sub>4</sub>-based fertilizers may be related to potential NO<sub>2</sub> accumulation or N<sub>2</sub>O production during nitrification (Venterea and Stanenas 2008). Bouwman et al. (2002) reviewed numerous studies and



reported N<sub>2</sub>O emissions appear to be lower for NO<sub>3</sub>-based fertilizers compared to NH<sub>4</sub>-based fertilizers and organic or synthetic-organic sources. Yet, one might expect a potentially higher N loss with an abundance of NO<sub>3</sub>-N in soil systems from NO<sub>3</sub>-based fertilizers compared to other N fertilizers, since NO<sub>3</sub> and NO<sub>2</sub> are essential for denitrification (Coyne 2008; Alexander 1977). However, anhydrous NH<sub>3</sub> has exhibited higher N<sub>2</sub>O emissions in several studies comparing it with other N sources (Breitenbeck and Bremner 1986; Venterea et al. 2005). Different studies reported emission and flux of different GHGs in cotton under different nutrient regimes (Table 2).

**Intensive tillage facilitates the microbial decomposition of organic matter at higher rates as compared with minimum tillage which produces CO<sub>2</sub> (Reicosky et al. 1997). Different researchers suggested that the reduction in tillage intensity could be beneficial in reducing CO<sub>2</sub> emission from soil and could be helpful in the sequestration of C in soil (Potter et al. 1998; Reicosky et al. 1997). Conservation tillage involves the placement of stubbles on soil surface to avoid soil erosion and addition of organic matter and for moisture conservation (Farooq et al. 2011). This technique can mitigate emission of N<sub>2</sub>O gas by affecting directly NO<sub>3</sub> availability or by modifying indirectly the soil microclimate and cycling of C and N. In many regions, soil C storage increased and potential of global warming decreased by appropriate conservation tillage (Lal 2003). There is a conflict among different researchers regarding the extent of the release of greenhouse gases under different tillage systems, and there is no clear positive or negative relation of the mitigation of greenhouse gases and tillage system. It appears that, in some regions, the benefits of minimum tillage include an increase in stored SOM, both organic C and N, to a greater degree than any potential increase in N<sub>2</sub>O emissions, so that the net global warming potential (GWP) decreases. In other studies, the GWP was slightly increased by switching from conventional tillage to conservation or no**

till (Gregorich et al. 2001; Lal 2003). Malhi et al. (2006) observed that in the region of Alberta Parkland, no tillage considerably reduced the emission of greenhouse gases. In a Canadian prairie region, Malhi et al. (2006) noted the higher N losses in the form of N<sub>2</sub>O under conventionally tilled plots as compared to no-tilled plots. Halvorson et al. (2002) noted the reduced N<sub>2</sub>O emissions under no till compared to conventional till, when averaged across years and four N rates. Hulugalle (2000) observed higher C sequestration under different cotton-based cropping systems under conservation tillage as compared with conventional tillage. Although it is well evident that the conservation tillage reduced the emanation of greenhouses gases, nonetheless, little information has been reported so far pertaining to the release of greenhouse gases in cotton fields and their effects on cotton growth and productivity.

**The availability and management of N under conservation tillage depend on numerous factors, which ultimately affect the cotton yield. Excess and imbalanced N application under intensive or conventional tillage has been known to cause groundwater contamination through N leaching. Furthermore, overapplication of N increases cost of production by millions of dollars each year (Koch et al. 2004). Howard et al. (2001) stated that the optimum N application is the key for determining a wide range of cotton plant yield variables including plant size, fruiting intensity, boll retention rate, boll size, and total boll number per plant.**

**Nitrogen fertilization rate for optimizing cotton yield can vary with the type of tillage and cover crop. Boquet et al. (2004) reported that the cotton yields were lower in no tillage than in surface tillage without applied N, but with optimum N**

**Tab e 2** Reported GHG emission and their fluxes in different countries in cotton

| Place of study | GHG under study   | GHG emission                                                                                                              | GHG flux                                    | Reference                |
|----------------|-------------------|---------------------------------------------------------------------------------------------------------------------------|---------------------------------------------|--------------------------|
| Pakistan       | N <sub>2</sub> O  | 3.2 kg ha <sup>-1</sup>                                                                                                   | 2.33 g N ha <sup>-1</sup> day <sup>-1</sup> | Mahmood et al. (2008)    |
| China          | N <sub>2</sub> O  | 2.6 kg ha <sup>-1</sup>                                                                                                   | 30 μg N m <sup>-2</sup> h <sup>-1</sup>     | Liu et al. (2010)        |
| China          | NO                | 0.8 kg ha <sup>-1</sup>                                                                                                   | 8.8 μg N m <sup>-2</sup> h <sup>-1</sup>    | Liu et al. (2010)        |
| Uzbekistan     | N <sub>2</sub> O  | 0.9 to 6 kg ha <sup>-1</sup>                                                                                              | 3000 μg N m <sup>-2</sup> h <sup>-1</sup>   | Scheer et al. (2008a, b) |
| Australia      | CO <sub>2</sub> e | 127, 127, and 1634 kg ha <sup>-1</sup> (for solid-plant, double-skip, and irrigated cotton farming systems, respectively) | –                                           | Maraseni et al. (2010)   |

rate, yields were higher in no tillage. They also found that higher N rate was required to optimize cotton yield following wheat (*Triticum aestivum* L.) or no cover crop in no tillage and surface tillage, but no N was required following hairy vetch (*Vicia villosa* Roth) in either tillage practice. This suggests that N fertilization rates to cotton can be reduced by using legume cover crops, such as hairy vetch and red clover (*Trifolium pratense* L.), regardless of tillage practices (Hargrove 1986; Blevins et al. 1990). On the other hand, it is not surprising to observe higher soil inorganic N with increasing N fertilization rates, because crops are unable to take 100 % of the applied N (Bergstrom and Kirchmann 2004; Bundy and Andraski 2005). Probably, crop N uptake and N loss due to leaching and/or volatilization occurred more rapidly with N fertilization than with cover crops where the rate of N mineralization is slower (Sainju and Singh 2001; Bergstrom and Kirchmann 2004). Boquet et al. (2004) reported that cotton lint yield and N uptake increased with increasing N fertilization rates from 0 to 118 kg N ha<sup>-1</sup> with wheat cover crop or native cover but decreased with hairy vetch. The tolerance of cotton lint yield following rye to high N rates was probably related to N immobilization caused by high C/N ratio of rye residue (Dabney et al. 2001). It may also be possible that unidentified factors retard cotton's vegetative growth in wheat residue (Hicks et al. 1989). Nitrogen fertilizer rate also affects the cotton maturity, as in case of late-planted cotton, excess N application could not trigger vegetative growth but increase unnecessary growth of unwanted branches and delayed cotton maturity. In another study, Larson et al. (2001) observed that no-tilled cotton followed by hairy vetch cover required 68 lb acre<sup>-1</sup> less applied N to maximize profits when compared with no cover. This reduction in the N fertilizer requirement for vetch was considerably larger than the N savings estimated for cotton production. Results of Sainju et al. (2005) suggested that conservation tillage with the inclusion of cover crop and reduced rate of N fertilization can sustain cotton lint yield better than conventional tillage with full rate of N fertilization.

Inclusion of cover crops in winter acts as additional source of N fertilization in cotton under conservation tillage system. Larson et al. (2001) reported that improved soil quality with winter covers in cotton and conservation tillage may enhance the yield response to N fertilizer. Roberts et al. (1998) estimated a larger reduction in the N fertilization rate required to maximize profit in the presence of legumes as cover crops. Presence of cover crop considerably influences soil inorganic N; however, the amount of inorganic N depends on the conservation tillage and the type of cover crop. Sainju et al. (2006) observed that inorganic N was higher in soil where hairy vetch was used as cover crop as compared to winter rye in no tillage. They further observed that tillage × cover crop interaction was significant for lint yield and N uptake. Sainju and Singh (2001) found hairy vetch as the most efficient cover crop in increasing N in soil, and this was because

of its higher N concentration and lower C/N ratio, rapid decomposition in the soil, and soil N enrichment more than rye. Moreover, hairy vetch releases about half of its N within 2–4 weeks after the residue was incorporated into the soil (Stute and Posner 1995). Other benefit of using cover crops in cotton production is the reduced N losses either by leaching or by volatilization. Different studies have indicated that it is not surprising to observe higher soil inorganic N with increasing N fertilization rates, because crops are unable to take 100 % of the applied N (Bergstrom and Kirchmann 2004; Bundy and Andraski 2005). Probably, crop N uptake and N loss due to leaching and/or volatilization occurred more rapidly with N fertilization than with cover crops where the rate of N mineralization is slower (Sainju and Singh 2001; Bergstrom and Kirchmann 2004).

#### Leaching effect of N fertilizer on GHG emissions

Fertilizer source and tillage interactions can result from differences in soil water content and bulk density and differences in soil nitrite accumulation among N sources and may depend on whether nitrification or denitrification dominates in the crop and soil system (Venterea and Stanenas 2008). Interactions between N sources and tillage systems often occur. Venterea et al. (2005) concluded that emissions of N<sub>2</sub>O with urea were higher under no till and conservation tillage compared to conventional tillage, while no differences among tillage systems were observed with urea. With anhydrous NH<sub>3</sub>, N<sub>2</sub>O emissions were greater with conventional tillage than the other two tillage systems. As reported by Breitenbeck and Bremner (1986), anhydrous NH<sub>3</sub> resulted in higher N<sub>2</sub>O emissions compared to the other two sources and their application methods. However, in a study by Venterea et al. (2005), the fertilizer N source effects were more confounded with placement methods. Higher application of N resulted in accumulation of N as nitrate in soil and reduced the N availability to cotton (Legg and Meisinger 1982). The use of appropriate N rates can help to minimize the soil accumulation of NO<sub>3</sub>-N. Apparently, reducing the amount of applied N cannot be a solution as N application below economic requirement of plant could result in overmining of SOC and long-term decrease in soil productivity. Furthermore, when N application rate exceeds agronomic N threshold level, the rate of N<sub>2</sub>O emission also increases. For instance, Malhi et al. (2006) noted that in a particular cropping study, overdose of N <80 kg ha<sup>-1</sup> resulted in higher release of N<sub>2</sub>O. Likewise, Grant et al. (2006) observed that N rates more than 100 kg ha<sup>-1</sup> resulted in higher N<sub>2</sub>O emission in cornfields. Little information is available regarding the dose-dependent relation of N and N<sub>2</sub>O emission in cotton; therefore, future studies should be directed in this regard.



The exact mechanism of N loss has not been identified in cotton; nonetheless, (Chua et al. (2003) identified denitrification as the major process in N losses from cotton fields under irrigated conditions. Rochester et al. (1996) reported that denitrification can cause N fertilizer loss up to 60 %. In another study, Rochester (2003) used  $^{15}\text{N}$  balance approach and estimated that roughly  $2 \text{ kg N ha}^{-1}$  (1.1 % of the N applied) was lost as  $\text{N}_2\text{O}$  during the cotton-growing season. Skiba and Smith (2000), on other hand, found that soil moisture also played a significant role in the release of  $\text{N}_2\text{O}$  or  $\text{NO}$  by

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