Nitrogen use efficiency and optimization of nitrogen fertilizer application for stable yields and high quality of cereals grown in conservation agriculture

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Summary

In most agroecosystems, nitrogen (N) is the most important nutrient limiting plant growth. One management strategy that affects N cycling and N use efficiency (NUE) is conservation agriculture (CA), an agricultural system based on minimum tillage, crop residue retention and crop rotation. Available results on the optimization of NUE in CA are inconsistent and studies that cover all three components of CA are scarce. Presently, CA is promoted in the Yaqui Valley in Northern Mexico, Mexico´s major wheat-producing area which represents one of the world´s largest wheat growing systems under irrigation, similar to the Indian and Pakistani Punjab and the Nile Valley in Egypt. From 1968 to 1995, fertilizer application rates for the cultivation of irrigated durum wheat (*Triticum durum* L.) at 6 t ha^{-1} increased from 80 to 250 kg ha^{-1}, demonstrating the high intensification potential in this region.

This thesis summarizes the current knowledge of N management in CA and provides insights in the effects of tillage practice, residue management and crop rotation on grain quality and N cycling. I identified N fertilizer application strategies that improve N use efficiency and reduce N immobilization in CA with the ultimate goal to stabilize cereal yields, maintain grain quality, minimize N losses into the environment and reduce farmers' input costs. Soil physical and chemical properties in CA were measured and compared with those in conventional systems and permanent beds with residue burning focusing on their relationship to plant N uptake and N cycling in the soil and how they are affected by tillage and N fertilizer timing, method and doses. For N fertilizer management, we analyzed how placement, time and amount of N fertilizer influenced numerous yield and quality parameters of durum and bread wheat, but we could not find a general recipe for a N fertilizer strategy in CA systems. Overall, grain quality parameters like grain protein concentration decreased with zero-tillage and increasing amount of residues left on the field compared to conventional systems. Additionally, CA had lower NUE than with conventional ploughing, which seems largely due to N fertilizer immobilization through crop residues.

In the second part, the dissertation provides an overview of applied methodologies to measure NUE and its components. We evaluated the methodology of ion exchange resin cartridges under irrigated, intensive agricultural cropping systems on vertisols to measure nitrate leaching losses. The typical cracks in vertisols, and the preferential flow that results from those, caused high spatial variability in the leaching data. Nevertheless, the data indicated that around 20% of the applied mineral fertilizer was leached and thus not taken up by the plant. These leached nutrients first reach the drainage channels of the entire valley and ultimately end up in the Sea of Cortez.

A throughout analysis of N inputs and outputs was conducted to calculate a N balance in three different tillage-straw systems. As fertilizer inputs are high, N balance resulted to be positive in all treatments indicating the risk for soil N to get leached or lost in gaseous form during or in subsequent cropping seasons and during heavy rain fall in summer. Nitrogen in roots was determined to account for its effect on the indigenous soil N supply for subsequently grown crops. Complex processes and turnover of N from organic to mineral forms and *vice versa* were found in soils that were significantly affected by tillage-straw treatment. Volatilization and denitrification losses were determined with a portable dynamic closed chamber system attached to a photoacoustic multi-gas field monitor. Gaseous losses were higher compared with model estimations. Contrary to the common belief, we did not find any negative effect of residue burning on soil nutrient status, yield or N uptake.

A labeled fertilizer experiment with urea ^{15}N was implemented in micro-plots to measure N fertilizer recovery and the effects of residual fertilizer N in the soil from summer maize on the following winter crop wheat. Obtained N fertilizer recovery rates for maize grain were with an average of 11% very low for all treatments ,but after wheat harvest total recovered ^{15}N (^{15}N in maize and wheat straw and grain, residual soil N after wheat harvest) was over 50% in treatments with residue burning which exceeds the worldwide efficiency of 33%. However, more than 20% of labeled ^{15}N was found in the 0-90cm soil profile in permanent beds after wheat harvest which highlights the need of long-term studies and continuous monitoring of soil nutrient status to avoid over-application of mineral fertilizer.

Interactions between components of CA and their effects on crop yield, grain quality, soil and fertilizer parameters are complex and will likely require site-specific management options. Awareness is lacking about the importance to protect the marine ecosystem in the Sea of Cortez where most of the highly nutrient loaded drainage water from the fields eventually ends up. This ecosystem provides employment for thousands of fishermen and a source of income for touristic activities. Its contamination with mineral N fertilizer though inefficient N fertilizer management under irrigated conditions may lead in the long term to a drastic reduction in fish populations and declining biodiversity.

Zusammenfassung

In den meisten Agrarökosystemen ist Stickstoff der wichtigste, aber auch meist limitierende Pflanzennährstoff. Eine Bewirtschaftungsform, die die Stickstoffdynamik im Boden und die Stickstoffeffizienz eines Anbausystems beeinflusst, ist die konservierende Bodenbearbeitung. Hierbei handelt es sich um ein landwirtschaftliches System basierend auf den drei Komponenten der minimalen Bodenbearbeitung, dem Hinterlassen von Ernterückständen auf der Bodenoberfläche und einer ökonomisch sinnvollen Fruchtfolge. Die bisherigen Erkenntnisse zur Optimierung der Stickstoffeffizienz und Düngerausbringung in konservierender Bodenbearbeitung sind inkonsistent und die Vereinigung aller drei Komponenten in bisher durchgeführten Studien ist selten. Derzeit wird die konservierende Bodenbearbeitung im Yaqui Tal in Nordmexiko durch Nichtregierungsorganisationen und dem mexikanischen Agrarministerium gefördert. Das Yaqui Tal ist das größte, bewässerte Hartweizenanbaugebiet des Landes. Es herrschen dort klimatisch und anbautechnisch ähnliche Bedingungen wie im indischen und pakistanischen Punjab und dem Niltal in Ägypten. Von 1968 bis 1995 stieg die Ausbringung von Düngemitteln von 80 auf 250 kg N ha^{-1} für den Anbau von bewässerten Hartweizen (*Triticum durum* L.) und erzielt heutzutage durchschnittliche Erträge von 6 t ha^{-1}. Hier zeigt sich das hohe Intensivierungspotential dieser Region.

Diese Dissertation fasst den aktuellen Erkenntnisstand über den Nährstoff Stickstoff in konservierender Bodenbearbeitung zusammen und gibt einen Einblick über die Wirkungsprinzipien der minimalen Bodenbearbeitung, Fruchtfolge und Ernterückständen bzw. Strohmulch auf Bodenqualität, Erträge, Kornqualität und den Stickstoffkreislauf. Es werden verschiedenere Düngerstrategien zur Verbesserung der Stickstoffeffizienz und zur Reduzierung der Immobilisierung von Stickstoff in konservierender Bodenbearbeitung untersucht, mit dem Ziel Erträge und Kornqualität zu stabilisieren, Umweltbelastungen durch kontaminierenden Mineraldünger zu minimieren und die Ausgaben für die Landwirte besonders durch Kraftstoffeinsparungen zu reduzieren. Physikalische und chemische Eigenschaften des Bodens in Systemen der konservierenden Bodenbearbeitung wurden gemessen und mit denen in herkömmlichen Pfluganbausystemen verglichen. Zudem wurde eine weitere Behandlung mit einbezogen: das Verbrennen von Ernterückständen, einer immer noch gängigen Praxis im Yaqui Tal. Bezüglich des Düngermanagements haben wir untersucht, wie sich Platzierung, Zeitpunkt und Höhe der Düngung auf den Ertrag und zahlreiche Qualitätsparameter von Hart- und Brotweizen in den verschiedene Bodenbearbeitungssystemen auswirken. Jedoch konnte keine allgemeingültige Empfehlung für die optimale Düngung in konservierender Bodenbearbeitung gegeben werden. Insgesamt sank die Getreidequalität mit minimaler Bodenbearbeitung und zunehmender Menge von Ernterückstände auf dem Feld im Vergleich zu herkömmlichen Pflugsystemen. Das führte zu einer niedrigeren Stickstoffeffizienz was weitgehend auf die Immobilisierung des Düngers durch Ernterückstände und den anfangs erhöhten Einsatz von Düngemittelmengen zurückzuführen.

Im zweiten Teil der Dissertation wird ein Überblick über die angewandten Methoden zur Messung von Stickstoffeffizienz und ihren Komponenten gegeben. Harzkartuschen wurden verwendet, um die Nitratauswaschung in bewässerten, intensiven Anbausystemen von Mais und Weizen in einem Vertisol zu messen. Die natürlich gebildeten Risse in den Vertisolen führten zu präferentiellen Flüssen von Bewässerungswasser innerhalb des Bodengefüges, was wiederum zu einer hohen räumliche Variabilität in den Auswaschungsergebnissen führte. Die Resultate zeigten, dass rund 20% des eingesetzten mineralischen Düngers ausgewaschen wurden. Dieses mit Nährstoffen beladene Sickerwasser gelangt zunächst in die Entwässerungskanäle im gesamten Yaqui Tal und letztendlich im Golf von Kalifornien.

Eine Aufgliederung der gesamten Stickstoffeingänge- und Ausgänge wurde für den Weizenzyklus 2013/14 durchgeführt, um eine vollständige Stickstoffbilanz in drei verschiedenen Bodenbearbeitungssystemen zu erhalten. Düngermengen in Höhe von 278 kg N ha^{-1} führten zu einer positiven Stickstoffbilanz und hohem Restbodenstickstoff in allen Behandlungen, jedoch erhöhten sich damit auch die möglichen Stickstoffverluste durch Auswaschung und Emissionen. Der gebundene Stickstoff in den Weizenwurzeln wurde ermittelt, um seine möglichen Wirkungen als späteren Stickstoffbeitrag nach Mineralisierungsprozessen für danach angebaute Kulturen zu quantifizieren. Komplexe Prozesse und Umsätze des Stickstoffs, die stark von der Bodenbearbeitung und der Bewahrung der Ernterückstände auf der

Bodenoberfläche abhängig sind, wurden von den organischen zur mineralischen Stickstoffformen und umgekehrt festgestellt. Ammoniakverflüchtigung und Denitrifizierungsverluste wurden mit einem tragbaren dynamischen geschlossenen Kammersystems gemessen, das aus einem photoakustischen Multigasmonitor und einer mit Polytetrafluorethylen beschichteten Kammer bestand. Die gemessenen Gasemissionen waren höher als die vorher im Modell geschätzten Werte. Entgegen der weit verbreiteten Annahme haben wir keine negativen Auswirkungen durch die Verbrennung von Ernterückstände auf die Nährstoffversorgung des Bodens, den Ertrag oder die Stickstoffaufnahme durch die Pflanze feststellen können.

Das Düngerexperiment mit ^{15}N markiertem Harnstoff wurde in Mikroparzellen durchgeführt, um die Mineraldüngereffizienz auf den Sommermaisanbau und den darauffolgenden Winterweizen zu quantifizieren. Die Düngereffizienz für Maiserträge war sehr gering in allen Behandlungen und betrug durchschnittlich nur 11%. Nach der Weizenernte betrug die totale Düngereffizienz über 50% in der Behandlung mit Verbrennung aller Ernterückstände, wenn man die komplette Wiederfindungsrate in Betracht zieht (^{15}N in Mais- und Weizenstroh- und Korn, der Boden N Gehalt nach der Weizenernte). Das liegt weit über der weltweit geschätzten Stickstoffeffizienz von 33%. Jedoch wurden nach der Weizenernte noch mehr als 20 % des markierten Stickstoffs im 0-90 cm Bodenprofil wiedergefunden, was die Notwendigkeit für Langzeitstudien und die kontinuierliche Überwachung des Bodens unterstreicht, um Überdüngung zu vermeiden.

Die Wechselwirkungen zwischen den Komponenten der konservierenden Bodenbearbeitung und deren Auswirkungen auf die Ernteerträge, Kornqualität, Bodeneigenschaften und Stickstoffdynamik sind komplex und standortspezifisch. Es herrscht mangelndes Bewusstsein über die Wichtigkeit des Schutzes der marinen Ökosysteme im Golf von Kalifornien, worin letztendlich die meisten der hoch belasteten Abwässer aus allen Bereichen der Landwirtschaft enden. Dieses Ökosystem schafft Arbeitsplätze für Tausende Fischer und ist auch für den Tourismus von größter Bedeutung. Die Kontaminierung mit Mineraldünger durch dessen ineffiziente Ausbringung unter bewässerten Anbaubedingungen können dazu führen, dass die Fischbestände und die biologische Vielfalt drastisch reduziert werden.

Chapter 1

1 General introduction

Parts of this chapter have been published in CABI Reviews.

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1 General introduction

Due to the dramatic increase in world population and changes in consumer demands towards more meat-based diets, global cereal yields have to double by 2050 to satisfy global crop demand (Tilman et al., 2011). Despite the availability of improved crop varieties with increased yield potential, the necessary rise in production levels is generally not reached in farmers' fields because of poor crop management by inefficient nitrogen (N) fertilizer use and wasteful use of natural resources, especially irrigation water. The lack of inputs and shortage of appropriate seeding implements intensifies the concern (Reynolds and Tuberosa, 2008). Reflecting increases in the cost of petrol products, N fertilizer prices have climbed more than 2.5-fold over the past decade from 200 US$ per tonne (t) of urea to 554 US$ (Hirel et al., 2007; Agricultural Prices, 2013). Over the past 50 years, N fertilizer application has increased 20-fold and amounted to 110 Mio t in 2013 (IFA, 2015). Its worldwide application is projected to increase to 119 Mio t by 2018 (FAO, 2015). For high-input environments, an efficient of mineral fertilizer is crucial to prevent excessive N fertilization that may cause NO_3-N leaching, ending in the eutrophication of water bodies and the destruction of aquatic ecosystems (Matson et al., 1998; Mitsch et al., 2001). Overapplication of N fertilizer may also increase environmentally harmful NOx/N_2O emissions and ammonia (NH_3) volatilization. Additionally, and maybe more important for the farmer is that production costs need to be reduced by more efficient fertilizer application, since N fertilizer is one of the most expensive inputs for farmers. Worldwide, N use efficiency (NUE) averages only 33% in cereals (Raun and Johnson, 1999) indicating the potential to increase NUE by improved management and varietal selection. Grain quality, an often neglected production parameter, is mainly determined by grain N concentration which is required to be high for specific end-use properties, thereby increasing farmers' profits (Cassman et al., 2002). To meet farmers' expectations concerning grain yield and necessary quality traits, nutrient and N fertilization management have to be optimized.

Conservation agriculture (CA) has been proposed as a set of management principles to sustainably improve agricultural productivity by improving water use efficiency, reducing soil erosion and conserving resources such as farmers' time, labour and fossil fuels. It is based on three key components: (1) minimal soil movement, (2) partial retention of residues as a soil cover, and (3) economically viable crop rotations, which together should to lead to reductions in management costs and increased profitability and sustainability of the cereal production system (Hobbs et al., 2008). Conservation agriculture can be conducted on the flat or on permanent raised beds where residues are retained and distributed on top of the beds and beds are reshaped when needed (Govaerts et al., 2005). Retention of straw residues and minimum or zero tillage of the soil combined with direct planting was found to change physical, chemical and biological soil quality components compared with conventional practices involving tillage (Verhulst et al., 2010) and thus affects N cycling in the soil which will be explained in detail in the following paragraph. Therefore, it is likely that N fertilization has to be adjusted in CA-based cropping systems compared to conventional production systems where ploughing ensures the homogenization of soil particles to a certain depth .

1.1 Effects of changes in soil properties and processes in CA systems on the N cycle

Tillage controls the placement of crop residues and the compaction and collocation of soil aggregates. With conventional tillage, straw residues are incorporated into the soil, whereas crop residues in a CA system remain at the soil surface which influences the chemical, physical and biological attributes of soil health (Fig. 1, Turmel et al., 2015). Usually, C and N mineralization are accelerated and stabilized by the incorporation of plant residues through tillage activity by making SOM within the macroaggregates more available to microorganisms (Lichter et al., 2008; Verachtert et al., 2009; Dendooven et al., 2012). But if residues stay on top of the soil, microbial breakdown is decelerated. Crop residues with low N concentrations and a C/N ratio over 30 cause temporary net N immobilization after which microbial growth is limited (Franzluebbers et al., 1995; Schoenau and Campbell, 1996; Burgess et al., 2002; Angas et al., 2006; Verachtert et al., 2009). In the first years of conversion from conventional practice to CA, occurring short-term N immobilization can be compensated for by increased application of N fertilizer and N losses can be reduced by a better synchronization of N application and plant uptake needs

(Dawson et al., 2008). For barley, Angas et al. (2006) found that CA systems did not require additional N fertilizer applications because tillage had no effect on NUE. The same was true for maize where no differences in N dynamics between tillage systems were found, even no immobilization occurred (Burgess et al., 2002). If mineral N fertilizer is applied during the peak plant N demand, immobilization and losses from the soil-plant system can be minimized and hence NUE can be increased (Torbert et al., 2001; Verachtert et al., 2009; Verhulst et al., 2009). However, research studies regarding N mineralization and N availability in production systems with zero tillage and residue retention are not decisive (Verhulst et al., 2010) and will be further investigated in this dissertation.

Soils under CA were reported to have higher total N, but lower mineral N than conventionally tilled soils (Verachtert et al., 2009; Verhulst et al, 2009; Wu et al, 2009) depending on the sampling depth (Dalal et al, 1998; Gal et al., 2007) as well as the amount of residue which are retained on the field (Govaerts et al., 2007). Salinas-Garcia et al. (1997) reported that N dynamics were significantly more affected by tillage than by N fertilizer application. They pointed out that N dynamics within the growing season depend on the long-term substrate availability from crop residues. In a laboratory experiment, Verachtert et al. (2009) observed that soil NH_4 concentrations did not change with different tillage, residue or fertilizer management and the same was true for NO_2. Soil temperature and soil moisture often differs in conventional and zero-till systems due to residue retention on top of the soil, which than influences soil microbial activity and changed N mineralization and immobilization, N plant uptake and leaching losses (Burgess et al, 2002; Govaerts et al., 2007). Follett (2001) stated these biological processes are crucial for the conservation of soil N derived from N fertilizer to minimize N losses. In the long term, CA increases SOM and hence soil microbial biomass (Dalal et al., 1998; Balota et al., 2004). Soil microbial biomass acts as source and sink of soil nutrient availability (Salinas-Garcia et al., 1997).

Global N losses by volatilization were averaged to be 18% for developing countries (Bouwman et al.; 2002), but other authors reported volatile NH_3 losses to be more than 50% of applied urea in systems with residue retention (Terman, 1979; Hargrove, 1988). This is mostly due to insufficient fertilizer incorporation and inadequate fertilizer machinery in CA systems (Aulakh et al., 1984; Angas et al., 2006). Generally, leaf and stem residues have a minimal buffering capacity or cation exchange capacity (CEC) and can absorb only small amounts from the urea fertilizer released ammonium (NH_4). Crop residues on the soil surface decompose more slowly due to greater fluctuations of surface temperature and moisture, hereby causing reduction and inhibition of biological activity on the soil surface, but increasing the amounts of the enzyme urease (Schoenau and Campbell, 1996). Therefore, urease activity is stimulated and the applied urea fertilizer is hydrolysed in the soil to CO_2 and NH_4, and the latter can occur as gaseous NH_3 and is lost when not incorporated properly into the soil (Palma et al., 1998; Gioacchini et al., 2002). Volatilization losses are favored by high air temperatures, high soil pH and initially moist soil followed by drying.

Crop residue retention and tillage affect processes which exercise reverse effects on denitrification. CA on the one hand often increases the soil water and SOM content compared with conventional tillage which favors N_2O emissions. High soil moisture content increases the number of saturated pores and the anaerobic fraction in the soil and hereby induces denitrification (Christensen et al., 2006). On the other hand, decreased soil temperatures and a better soil structure and thus improved aeration and less anaerobic sites may reduce N_2O emissions (Hao et al., 2001; Liu et al., 2005). Denitrification rates depend on the soil type: naturally heavy and poorly drained soil increase the risk of N losses. Six et al. (2002, 2004) found an increase of annual N_2O fluxes after conversion from conventionally tilled soils to zero tillage in temperate regions. The emissions were, however, strongly time-dependent and decreased with years after conversion from conventional till to zero tillage. Twenty years after conversion, soils in humid climates with zero tillage and residue retention emitted less N_2O than conventionally tilled soils, but in dry climates emissions were similar for the two tillage systems (Six et al., 2004). Halvorson et al. (2008) measured N_2O emissions in an irrigated cropping system with different tillage and N fertilizer management and diverse crop rotations. N fertilization and rotation had a greater effect on N_2O emissions than tillage. Emissions were highest in the zero tillage maize-bean (*Vicia faba* L.) rotation with the highest N application rate (246 kg N ha^{-1}). In addition, higher emissions were found in continuous maize under CT compared with continuous maize under zero tillage. Mineral N fertilizer represent the largest anthropogenic N source to the environment. A model in Northern Mexico showed that an increase from 110 to 250 kg N ha^{-1} resulted in an 11% decrease, a 10% increase, and a 157% increase in N_2, N_2O, and NO emissions, respectively (Christensen et al., 2006).

Several studies made clear that soils with zero tillage or permanent raised beds combined with residue retention have larger and more water-stable aggregates compared with soils with residue removal or tillage activity (Fuentes et al., 2009; Hobbs and Govaerts, 2010; Verhulst et al., 2011c). Improved aggregate stability prevents soil surface sealing and compaction. As a result, infiltration rates are generally higher on CA soils compared with tilled soils with or without residue removal (Thierfelder et al., 2010; Verhulst et al., 2011a). This might increase N leaching losses. Furthermore, leaching losses in CA systems could increase due to an increased number of earthworm biopores depending on the soil type and tillage operations (Baumhardt and Lascano, 1996; Chan, 2001). On the other hand, slower nitrification in zero tillage during fallow periods could reduce the potential for NO_3 leaching (Power and Peterson, 1998). Meek et al. (1995) analyzed NO_3-N leaching in a furrow-irrigated maize-wheat rotation with up to 3.3 m deep soil borers and found 21 kg ha^{-1} higher soil NO_3-N below the root zone for conventional tillage than for zero-tillage.

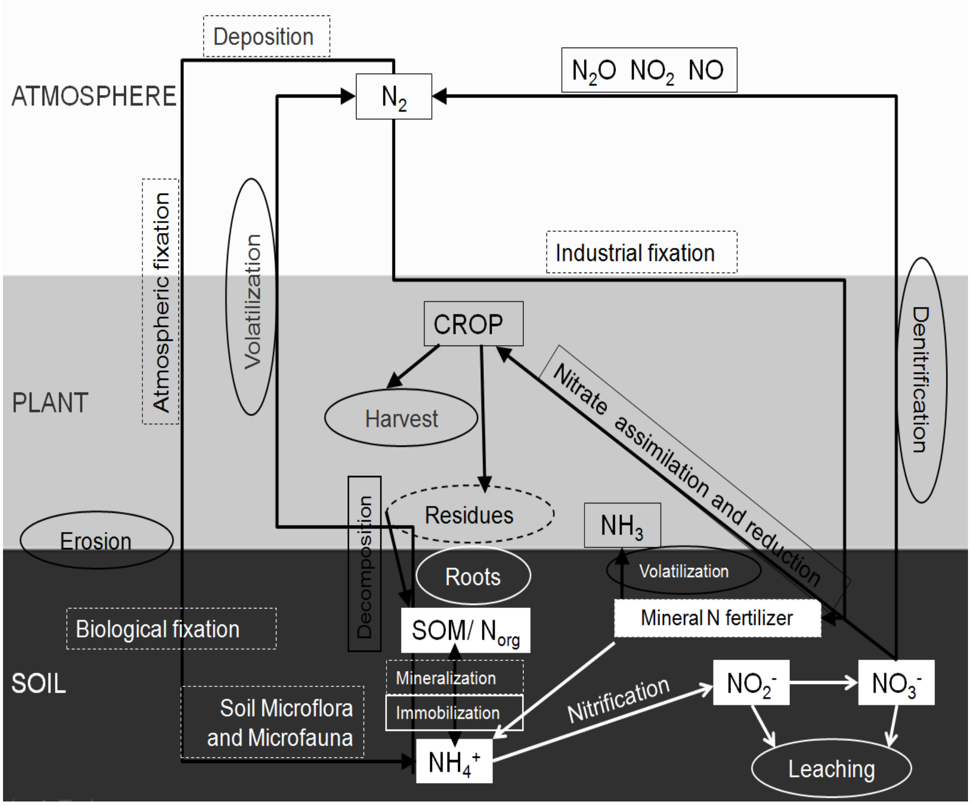

Figure 1 N cycle in conservation agriculture systems (square with continuous line: N component; square with dotted line: N input; oval: N loss; Grahmann et al., 2013).

1.2 Nitrogen use efficiency in CA

NUE is a function of soil texture, climate conditions, interactions between soil and bacterial processes and the nature of organic and inorganic N sources and many formulas exist to describe its tendencies and cropping system efficiencies (Hirel et al., 2007). Agronomic efficiency (AE) depends on management practices and is the product of nutrient recovery from mineral or organic fertilizer and the efficiency with which the plant utilizes each additional unit of nutrient (Dobermann, 2007). It ranges from 10 to 30 kg yield increase per kg of nutrient applied (Dobermann, 2005). Nitrogen fertilizer recovery (NFR) is the balance between crop N uptake and N immobilization caused by microbial soil processes and retention of crop residues with high C/N ratio. NFR accounts for a 0.30 to 0.50 kg increase in N uptake per kg N applied and is mainly determined from ^{15}N labeled fertilizer experiments (Mahli et al., 2004; Dobermann, 2007).

An extensive literature review on NUE and N fertilizer management showed that most studies were conducted under conventional tillage and very little information is available about N management in CA systems. Many articles focus on only zero tillage (Rice and Smith, 1984; Power et al., 1986; Christensen et al., 1994), only rotation (Halvorson et al., 2004) or residue management (Rahimizadeh et al., 2010; Schoenau and Campbell, 1996) while modern CA systems contain the above mentioned three components which were only considered in very few studies (Salinas-Garcia et al., 1997; Limon-Ortega et al., 2000; Al-Kaisi et al., 2005). Based on the little available data, CA seems to have lower NUE rates than conventional systems, which is largely due to N fertilizer immobilization through crop residues and increasing fertilizer rates with CA. An adjustment of N fertilizer management in CA needs to be done to improve NUE management. Possible options can be the adaption of amount, type, timing, and placement of N fertilizer (Hodges, 2010).

In CA, fertilizer efficiency and behaviour are affected by the carry-over effect that describes the time-related, delayed effects of N fertilizer in the following cropping seasons. This is especially the case when fertilizer is applied in combination with straw residues since fertilizer can get immobilized and is released in the following years (Lopez-Bellido et al., 2006). Immobilization of N generated by residues left on top of the field is a problem in CA systems and reported to be one of the principal causes for reduced NUE under CA (Verachtert et al., 209; Burgess et al., 2002). For wheat, Lopez- Bellido and Lopez-Bellido (2001) found a NUE of 15.2 and 16.4 kg kg^{-1} for CA and conventional tillage, respectively. Huggins and Pan (1993) reported similar results and found a NUE for zero tillage with residue retention of 24.7 and 19.2 kg h^{-1} for 0 and 168 kg N fertilizer, respectively. Conventional tillage had NUE values of 32.2 and 24.2 kg ha^{-1} for 0 kg N and 168 kg N fertilizer, respectively. NUE decreases with increasing N fertilizer applications and NUE is generally largest with low levels of applied N (Lopez-Bellido and Lopez-Bellido, 2001; Halvorson at el., 2004). In a long-term experiment, Limon-Ortega et al. (2000) observed the highest NUE in permanent beds with stubble retention or with all straw burned (28.2 and 29.1 kg grain kg^{-1}, respectively) compared with CT. To understand the changes in the N cycle under CA systems after the new soil-plant equilibrium has been established, long-term studies are important.

1.3 Research area

The different trials were established at CIMMYT's experiment station CENEB (Campo Experimental Norman E. Borlaug), near Ciudad Obregón, Sonora, Mexico (lat. 27.33°N, long. 109.09°W, 38 m a.s.l.). The site has an arid climate, with an annual average rainfall of 300 mm over 20 years and an annual reference evapotranspiration of approximately 1800 mm. Between 1986 and 2012, annual rainfall ranged from 90 to 590 mm reflecting the high level of rainfall variability at the site. Rainfall is summer dominant and only 20% of the average annual rainfall occurs during the wheat-growing season (November-May; Verhulst et al., 2011b). The soil is a Hyposodic Vertisol (Calcaric, Chromic) according to the World Reference Base soil classification system (IUSS Working Group, 2007) and a fine, smectitic Chromic Haplotorrert in the USDA Soil Taxonomy system (Soil Survey Staff, 2010). All horizons in the soil profile up to 2 m are low in organic matter (<1%) and slightly alkaline (pH 8).

The Yaqui Valley (Fig. 2) is agro-climatically representative of areas where 40% of the wheat is produced in the developing world (Indian, Pakistani Punjab, Nile Valley. This area is characterized by grain yields >6 t ha^{-1} and high fertilizer inputs which average for wheat 275 kg N ha^{-1}. This intensity explains the necessity to find more efficient N fertilizer strategies. Cropping systems have changed in the Yaqui Valley over the last decades. During the last 25 years more than 95% of the farmers changed from flood irrigation on the flat to planting on raised beds with furrow irrigation. Another drastic change was that farmers changed their residue management from burning them to incorporating the residues. Finally, in the last 20 years researchers tried to increase the sustainability of the beds by making them permanent through avoiding tillage (only reshaping of beds) and retaining residues on the surface.

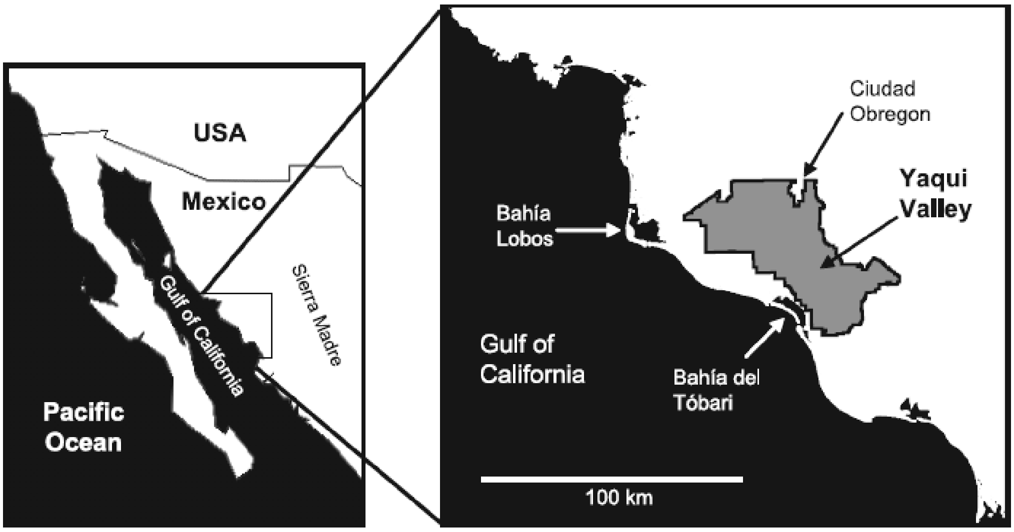

Figure 2 Yaqui Valley, Sonora, Mexico (Ahrens et al. 2008) .

1.4 Research objectives, hypotheses and thesis outline

The overall objective of this dissertation was to investigate basic processes of nitrogen dynamics and nitrogen use efficiency (NUE) in high-input, irrigated CA wheat-based systems. Current practices of N fertilizer management in the Yaqui Valley under CA were assessed to identify research gaps that need to be addressed to optimize N management.

The objectives were diversified as followed:

(1) Quantification of the effect of tillage practice, residue management and crop rotation on nitrate leaching, N immobilization, N mineralization, ammonia volatilization, residual soil N and plant uptake of N fertilizer in an furrow-irrigated agroecosystem.

(2) Evaluation of the effect of timing and dose of N application (basal, split, application at 1st node for durum wheat) on NUE and grain quality in conventional and CA systems.

(3) Determination of the effect of mode and timing of N application (broadcast, banded with disc in the furrow or top of the bed for bread wheat) on grain quality and NUE in conventional and CA systems.

(4) Translation of the results from (1) to (3) into recommendations for farmers of alternative management practices that will reduce both N leaching losses and trace gas emissions, while remaining grain quality and yields.

The above mentioned research objectives were based on the following hypotheses:

(1) Since tillage practice, crop residue management and crop rotation affect soil properties and microbial community structure, they also alter N cycling.

(2) It is feasible and recommendable to remove part of the crop residue for other uses such as animal fodder or fuel without having yield disadvantages but to maintain wheat quality.

(3) Fertilizer management has to be adapted to conservation agriculture systems as NUE is lower compared to conventional systems.

(4) Fertilizer practice in the Yaqui Valley is unsustainable due to over fertilization and inadequate management and is causing environmental problems.

The thesis is structured as followed: After this introduction, chapter 2 focuses on the effect of timing and dose of N fertilizer application on durum wheat yield and quality parameters comparing five different tillage-straw systems for two cropping cycles. Chapter 3 continues with the topic of N fertilizer management on bread wheat quality and yield parameters comparing placement and timing of mineral N fertilizer in two different tillage systems over four cropping cycles. In chapter 4, nitrate leaching measured by resin cartridges is determined in three different tillage-straw systems and two crops. Chapter 5 contains a detailed N balance of measured and estimated N inputs and outputs in three different tillage straw systems measured for one cropping cycle by means of the difference method. More information about additional methodologies that were applied during the project period are critically reviewed and presented in chapter 6 where I also present final conclusions and recommendations .

1.5 References

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Chapter 2

2 Durum wheat (*Triticum durum* L.) quality and yield as affected by tillage-straw management and nitrogen fertilization practice under furrow-irrigated conditions

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2 Durum wheat (*Triticum durum* L.) quality and yield as affected by tillage-straw management and nitrogen fertilization practice under furrow-irrigated conditions

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Keywords:

Conservation agriculture, durum wheat, grain quality, permanent raised beds, grain protein, principal component analysis

2.1 Abstract

Little is documented about the effect of different tillage and residue management practices on durum wheat (*Triticum durum* L.) quality. This study aims at examining the effect of tillage-residue management systems on wheat yield and quality in two cropping cycles, 19 years after establishment of tillage-residue management systems in 1992. Wheat grain samples were collected in an experiment with a durum wheat-maize (*Zea mays* L.) rotation and furrow-irrigation, conducted in the arid Yaqui Valley of north-western Mexico. Main plots had five tillage-crop residue management treatments: conventionally tilled raised beds (CTB) with straw incorporated and permanent raised beds (PB) with straw burned, removed, partly retained or fully retained. Split plots had seven nitrogen (N) fertilizer treatments with different rate (0, 150 or 300 kg N ha^{-1}) and timing of application (basal, 1st node and split between both). Highest yields were obtained with PB-straw partly retained and 300 kg N ha^{-1}

split application in 2010/11 (7.48 t ha^{-1}) and with PB-straw removed and 300 kg N ha^{-1} applied at 1st node in 2011/12 (8.26 t ha^{-1}). Permanent beds with full residue retention had high yellow berry (YB, opaque and starchy endosperm) incidence, even with 300 kg N ha^{-1}; 19.5% in 2010/11 and 9.4% in 2011/12 of the grain kernels were affected by YB. Four groups of tillage-straw systems with different characteristics in relation to the durum wheat quality and yield were distinguished with a principal component analysis: PB-partly retained with high yields and acceptable quality, PB-straw retained with low quality and acceptable yields, CTB with intermediate quality results and lower yields and PB-straw burned with high quality and low yields. Results indicate a significant effect of timing of N application on durum wheat grain quality in PB. For both cycles and both N rates, the application of mineral N resulted in higher grain quality when all N was applied near 1st node. Grain quality was highest in PB-straw burned, but this practice had the lowest yields. For PB-straw fully retained, 1st node application of N fertilizer is recommended to minimize N immobilization. To obtain stable yields and desirable quality, alternative tillage practices such as PB with full or partial residue retention require adjusted, site-specific N management. Further research is required to identify fertilization strategies in tillage systems with full or partial residue retention that include fertilizer applications after first node to improve grain quality.

2.2 Introduction

Durum wheat (*Triticum durum* L.*)* represents 6-8% of the total worldwide wheat production and its major use is the manufacturing of pasta, couscous and traditional dishes, such as burgul (Troccoli et al., 2000). Pasta producers require consistent semolina quality to maximize dough uniformity. Core quality traits for durum wheat are kernel vitreousness with less than 15% yellow berry (YB, an N deficiency indicator resulting in starchy, low endosperm protein), allowing high semolina yields during milling and grain protein concentrations (GPC) of at least 12.5% to achieve good pasta cooking tolerance, and high yellow pigment concentration, which confers the desirable bright yellow colour consumers look for in pasta products.

During the last two decades, worldwide N fertilizer prices have strongly increased and land use for biofuel production, urbanization and industrial expansion is reducing available cropping area in many countries (Harvey and Pilgrim, 2011). An efficient use of mineral fertilizers is essential for cost effective farming and to prevent excessive N fertilization in high-input environments, and its environmental consequences such as NO_x/N_2O emissions and NO_3-N leaching (Matson et al., 1998; Beman et al., 2005). To meet the expectations of farmers, industry, and society concerning grain yield, quality traits and N use efficiency (NUE), appropriate crop management technologies have to be developed.

The Yaqui Valley in Northern Mexico is Mexico's major wheat-producing area, particularly durum wheat (Matson et al., 1998). Farmers' practice is based on high input levels, obtaining average durum yields of 6 t ha^{-1} and higher. Nitrogen use efficiency estimations average 31% (Ortiz-Monasterio and Raun, 2007), indicating a high potential to improve NUE and N fertilizer use by improved management practices. Currently in the Yaqui Valley timing of fertilizer application is similar for bread and durum wheat, but bread wheat is known to have greater N requirements in terms of N fertilizer dose due to higher grain and total N uptake (Geleto et al., 1995). Farmers usually do not receive premium prices for high GPC, but get a lower price when the percentage of durum wheat kernels affected by YB exceeds 15-20%. Farmers in the Yaqui Valley typically plant on tilled beds with irrigation applied in the furrows and incorporation of crop residues (Aquino, 1998). Conservation agriculture (CA) has been proposed in this area as a set of management practices that may allow a more sustainable agricultural production and reduced production costs, thereby increasing profitability. The CA system is based on three principles: (1) minimal soil movement, (2) the retention of rational amounts of residue cover, and (3) economically viable crop rotations (Hobbs et al., 2008). In irrigated systems, the first CA principle can be applied by converting the conventionally tilled beds into permanent beds, which are only reshaped when necessary and residues are retained at the soil surface.

Residue retention with zero tillage (or permanent beds) contributes to retention of soil moisture, improves soil organic matter content and affects mineralization and immobilization processes of inorganic N in the soil compared to conventional systems

(Rice and Smith, 1984; Torbert et al., 2001). Nitrogen immobilization due to slow decomposition of crop residues can result in a lack of synchrony between N application and crop N demands, and consequently a reduction in NUE and GPC in CA compared to systems involving conventional tillage (Grahmann et al., 2013). This makes it necessary to adjust nutrient management in CA compared to conventional production systems. There are few reports about the effect of CA on durum wheat quality compared to conventional tillage practices and results are inconsistent. Some studies have shown higher GPC in conventional durum (Pisante and Basso, 2000; De Vita et al., 2007) and bread wheat (Lopez-Bellido et al., 2001) production as compared to CA, whereas others showed a positive effect of CA on grain quality, especially in locations or years with limited rainfall for both durum (Pisante and Basso, 2000) and bread wheat (Melaj et al., 2003) while Maiorano et al. (2004) observed only minor differences between tillage practices. Interactions between CA components and their effects on crop yield, grain quality, soil and fertilizer parameters are complex and often site-specific.

An important aspect of N fertilizer management is the timing of N application. Common approaches to improve NUE and grain quality are split- and late season-application of mineral N fertilizer, mainly as a top-dressing (Wuest and Cassman, 1992; Sowers et al., 1994; Lopez-Bellido et al., 2001; Garrido-Lestache et al., 2004) or by sub-surface N application (Rice and Smith, 1984; Grant et al., 2001). About 14 days before anthesis of bread wheat when the first spikelet of the head is becoming visible, the number of wheat kernels is determined by the plant´s internal N status which can be enhanced by an additional N application before heading (Zadok 50) to improve N uptake and grain quality (Dutta et a., 1970; Ayoub et al., 1994). Also foliar applied N fertilizer at or after anthesis has been reported to be highly efficient at increasing grain protein and hence bread-baking quality in conventional systems (Gooding and Davies, 1992; Woolfolk et al., 2002; Bly et al., 2003). N fertilizer applications at crop anthesis compared to N application before planting improved N fertilizer recovery and grain protein levels in bread wheat without decreasing soil N uptake (Wuest and Cassman,1992; Dawson et al., 2008).

This study was conducted in a long-term experiment started in 1992. A study of soil quality in the same experiment distinguished three groups with different characteristics in relation to the soil environment: PB-straw burned, CTB-straw incorporated, and PB-straw not burned (Verhulst et al., 2011a). The PB-straw burned had the lowest soil quality with high electrical conductivity, Na concentration and penetration resistance and low soil resilience and aggregation. The CTB-straw incorporated was distinguished from the PB practices by the soil physical variables, especially the low direct infiltration and aggregate stability (Verhulst et al., 2011a). The long-term use of PB-straw retained improved soil aggregation and stability and increased C and N from the soil microbial biomass over time (Limon-Ortega et al., 2006). Long-term yields (1999-2009) with basal N application were the highest for PB-straw retained and PB-straw removed (7.30 t ha^{-1} and 7.24 t ha^{-1}, respectively) and the lowest for PB-straw burned (6.65 t ha^{-1}) (Verhulst et al., 2011b).

In view of the existing knowledge gaps in this field, the objective of this study was to evaluate the effects of tillage-straw management and timing and rates of N fertilizer application on durum wheat yield and grain quality in a furrow-irrigated system under arid conditions, in plots that have been used during 19 years for CA research. It was hypothesized that durum wheat quality would decrease with increasing residue load due to immobilization processes in permanent beds. Split application of N was expected to improve grain quality in all tillage systems compared to basal N application.

2.3 Materials and Methods

2.3.1 Characterization of the experimental site

The long-term trial was established at CIMMYT’s experiment station CENEB (Campo Experimental Norman E. Borlaug), near Ciudad Obregón, Sonora, Mexico (lat. 27.33°N, long. 109.09°W, 38 m a.s.l.). The site has an arid climate, with an annual average rainfall of 300 mm over 20 years and an annual reference evapotranspiration of approximately 1800 mm. Between 1986 and 2012, annual rainfall ranged from 90 to 590 mm reflecting the high level of rainfall variability at the site. Rainfall is summer dominant and only 20% of the average annual rainfall occurs during the wheat-growing season (November-May; Verhulst et al., 2011b). The mean annual temperature for the included growing periods (winter cycles 2010/11 and 2011/12) was 24 °C and mean monthly temperatures ranged from 5.0 °C in February 2011 to 39.5 °C in September 2011. Frost events were recorded from 3 to 5 February 2011. Freezing temperatures went down to -3.2°C, averaged -1.0 °C and were recorded for these three days in the early morning hours for around 3 h daily. Total annual rainfall amounted to 169, 271 and 264 mm for 2010, 2011 and 2012, respectively (Fig. 1). The climatic data were obtained from a standard weather station at the experimental site. The soil is a Hyposodic Vertisol (Calcaric, Chromic) according to the World Reference Base soil classification system (IUSS Working Group, 2007) and a fine, smectitic Chromic Haplotorrert in the USDA Soil Taxonomy system (Soil Survey Staff, 2010). All horizons in the soil profile up to 2 m are low in organic matter (<1%) and slightly alkaline (pH 8).

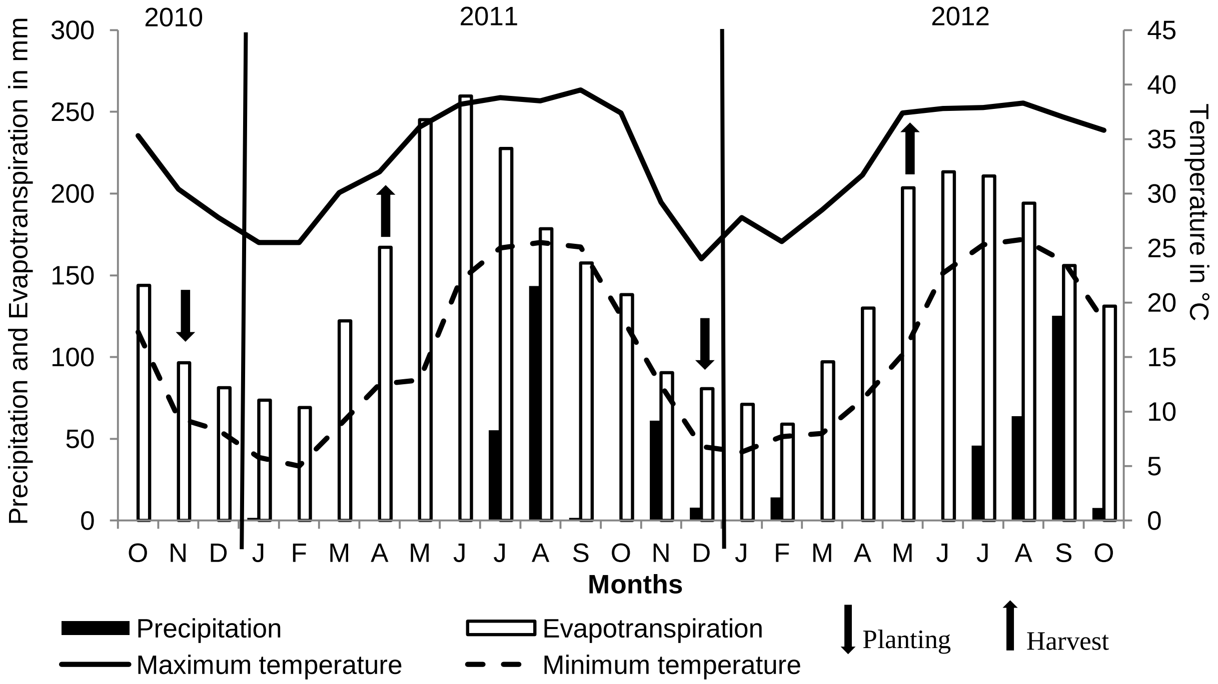

Figure 1 Climate for the study period in Ciudad Obregón, Mexico. Arrows indicate planting and harvest of the durum wheat (Data provided by the National Water Commission ("Comisión Nacional del Agua"), Mexico DF, Mexico).

2.3.2 Description of the long-term trial

The long-term experiment with its tillage-straw treatments was set-up in 1992 and consists of a randomized complete block design with a split plot treatment arrangement and three replicates per treatment. N fertilizer treatments were adjusted in the 2000/2001 cycle and stayed unchanged from then on. Data presented here for the same treatments were collected in the two subsequent cropping cycles 2010/11 and 2011/12. The cropping system is an annual rotation of maize in the summer and durum wheat as the winter crop with furrow irrigation. One pre-planting irrigation of approximately 120 mm was followed by four auxiliary irrigations of 80-100 mm around the 1st node stage and thereafter every 18-21 days. The whole experiment is irrigated at the same time, allowing runoff from the plots to ensure homogeneous water distribution and total infiltrated irrigation water per season and crop is approximately 500 mm. In the 2010/11 cycle, irrigations took place on November 12, January 10, February 7, March 1 and March 22. In the 2011/12 cycle, the experiment was irrigated on November 11, January 25, February 20, March 12 and March 30. Durum wheat ("Patronato Oro", a commercially used cultivar in the Yaqui Valley) was sown on November 29, 2010 in permanent beds and one day later in conventional beds for the cropping cycle 2010/11 and for the following cropping cycle on December 14 for permanent beds and December 15 for the conventional ones. All plots were planted with a multi-use/multi-crop machine developed and built by CIMMYT. Wheat sowing density was 120 kg ha^{-1} and plant stand density at emergence ranged from 109 plants m^{-2} in CTB with 150 kg N ha^{-1} basal application to 221 plants m^{-2} in PB-straw retained with 150 kg N ha^{-1} at first node in 2010. In 2011, plant density ranged from 146 plants m^{-2} in PB-partly retained with 300 kg N ha^{-1} basal application to 229 plants m^{-2} in PB-straw burned and 150 kg N ha^{-1} split application. The experiment was harvested on April 29, 2011 and May 7, 2012. Crops were seeded on 0.75 m raised-beds with wheat in two rows seeded 24 cm apart. Traffic was confined to the furrows and narrow tractor tires were used for all operations. Main treatments consisted of tillage-straw management systems as follows:

CTB-straw incorporated: Conventionally tilled raised-beds (CTB; tilled after each crop with a disk harrow to 20 cm after which new beds were formed), wheat and maize residues were incorporated by tillage; PB-straw burned: Permanent raised-beds (PB; zero tillage with repeated reuse of existing beds, which were reformed in the furrows without disturbance of the tops of the beds as needed), residues of both wheat and maize are burned; PB-straw removed: PB; residues of wheat and maize are removed by baling, leaving about 30% of the total residue in the field; PB-straw partly retained: PB; maize residues are removed by baling and wheat straw is retained on the soil surface; PB-straw retained: PB; maize and wheat residues are kept on the soil surface.

Split plots measure 6 m × 13 m and comprise seven N fertilizer treatments differing in dose and timing of application. Nitrogen treatments included a 0 kg N ha^{-1} control plot, and 150 and 300 kg N ha^{-1} treatments whereby N was applied at different times in the cropping cycle. N fertilizer was applied as urea in the furrow and incorporated through irrigation. Timing of N application was (i) all fertilizer applied before the pre-planting irrigation (basal), (ii) all fertilizer applied near 1st node (before the first auxiliary irrigation), or (iii) split application with 1/3 N basal and 2/3 at 1st node. Each cycle, wheat received 45 kg P_2O_5 ha^{-1} banded in the furrow and incorporated through cultivation when reshaping beds. Chemical soil characteristics can be found in Table 1. The soil was analyzed for total C and N as described by Verhulst et al. (2011a) and soil samples were taken in the top 20 cm on the 1st of August 2011 (Jiménez-Bueno et al., 2014). Irrigation water has low nutrient concentrations (<0.1 ppm ammonia, <3.0 ppm nitrate). Weeds were controlled by tillage in CTB before and at planting. In PB glyphosate (Faena®, 2 l ha^{-1}) was applied one or two days after planting. Aphids were controlled as needed by the insecticide Mural Max®, containing 19.60% Imidacloprid and 8.40% Betacyfluthrin (250 ml ha^{-1}).

Table 1 Chemical soil propierties as affected by tillage, residue management and N fertilizer application (Jiménez-Bueno et al., 2016).

Tillage-straw management	N fertilization	total N	total C
	kg^{-1} ha	$g\ kg^{-1}$ soil	
CTB-straw incorporated	0	0.48	10.1
CTB-straw incorporated	300 Basal	0.54	10.9
PB-straw burned	0	0.47	9.6
PB-straw burned	300 Basal	0.56	10.2
PB-straw removed	0	0.44	8.9
PB-straw removed	300 Basal	0.62	9.9
PB-straw partly retained	0	0.47	8.9
PB-straw partly retained	300 Basal	0.60	9.1
PB-straw retained	0	0.50	12.9
PB-straw retained	300 Basal	0.60	13.3

2.3.3 Grain quality analysis and yield determination

Wheat yield was measured according to Pask et al. (2012). The central area of the plot (two center beds of 13 m plot length) was combine-harvested and grain weight and moisture content determined. Grain yield (in t ha^{-1}) was calculated and expressed at 12% moisture content. Thousand kernel weight was determined by counting a subsample of 200 grains and determining dry weight. Test weight is defined as wheat per unit volume and expressed in kilograms per hectoliter (kg hl^{-1}; Halverson and Zeleny, 1988). The grains were poured through a cone in a 250 ml vessel and converted to the test weight of a hectoliter.

Grain protein concentration was determined by near-infrared reflectance (AACC method 39-10, 2000) with the Foss NIR Systems Feed and Forage 6500 instrument (Foss, Hillerød, Denmark), expressed at 12.5% moisture. Flour protein and moisture were analyzed by using the Perten Instruments DA 7200 Protein Concentration Analyser (Perten Instruments, Hägersten, Sweden) expressed at 14.0% moisture. For the percentage of yellow berry, a 25 g grain subsample was examined for non-vitreous, glassy kernels in the endosperm and calculated as percentage grams of discolored kernels divided by 25 and then multiplied by 100. The Sodium Dodecyl Sulphate-Sedimentation test (SDS-S in ml) of Axford et al. (1978), as modified by Peña et al. (1990) was used for the estimation of gluten strength (Peña, 2002). Yellowness was measured with the reflectance colorimeter method as expressed by the “Minolta *b*-value” (AACC method 14-22, 2000), using a Konica-Minolta Chroma Meter CR-410. The mixograph mixing peak time value was determined according to the AACC method 54-40A.

2.3.4 Statistical analysis

The statistical analysis was conducted with SAS PROC MIXED (SAS Institute, 1994). Analyses were conducted within the cropping cycle. Three class factors were distinguished: block (repetition), tillage-straw system and N fertilization level. Significance of the three factors was determined by analysis of variance (ANOVA) assuming random block effects with a split-plot treatment design. Main treatments consisted of tillage–straw management systems and split-plot treatments comprised seven N fertilizer treatments differing in dose and timing of N application. Differences between tillage-straw systems were based on differences of least square means using the MIXED procedure. Significance of correlations were determined at $P < 0.05$.

Principal component analysis (PCA) was performed with R prcomp (version 2.15.2, www.cran.r-project.org) to construct a lower-dimension summary of the quality parameters. With PCA, the correlated quality parameters are described in terms of a new set of uncorrelated variables (principle components), each of which is a linear combination of the original variables. The PCA analysis was interpreted graphically by constructing a bi-plot of the first two PCs (Everitt, 2005).

2.4 Results

2.4.1 Effects of tillage-straw management, N fertilization and its interaction on yield and quality parameters

Nitrogen fertilization, including dose and timing of N application, had a highly significant effect on all yield and quality parameters (Table 2). In both cropping cycles, grain and flour protein, incidence of YB, sedimentation and the Minolta *b*-value were significantly affected by tillage-straw management, but thousand kernel weight was not. The interaction effect of tillage-straw management and N fertilization was significant for all parameters, except for yield in 2010/11 and thousand kernel weight in 2011/12. Tillage-straw management and N fertilization significantly affected grain yield in 2010/11, but there was no significant interaction between both factors, whereas in 2011/12 the effect of tillage-straw management was not significant, but the interaction was.

Table 2 F-probabilities (significance values) of effects of tillage-straw management (TIL-STR), N fertilization (N) and their interaction on yield and grain quality parameters for cropping cycle 2010/11 and 2011/12.

Parameter	Cycle	TIL-STR	N	TIL-STR × N
Yield	2010/11	0.0023	<0.0001	0.1105
	2011/12	0.1336	<0.0001	0.0005
Test weight	2010/11	0.0056	<0.0001	0.0066
	2011/12	0.0001	<0.0001	0.0016
Thousand kernel weight	2010/11	0.2893	<0.0001	0.0197
	2011/12	0.1695	<0.0001	0.2904
Yellow berry	2010/11	<0.0001	<0.0001	0.0276
	2011/12	0.0002	<0.0001	<0.0001
Grain protein concentration	2010/11	<0.0001	<0.0001	0.0216
	2011/12	<0.0001	<0.0001	<0.0001
Flour protein concentration	2010/11	<0.0001	<0.0001	<0.0001
	2011/12	<0.0001	<0.0001	<0.0001
SDS-sedimentation volume	2010/11	<0.0001	<0.0001	<0.0001
	2011/12	0.0004	<0.0001	<0.0001
Minolta b-value	2010/11	0.0032	<0.0001	0.0001
	2011/12	0.0058	<0.0001	0.0419
Mixing peak time	2010/11	0.0046	<0.0001	<0.0001
	2011/12	0.1091	<0.0001	<0.0001

Yield was not significantly different for CTB-straw incorporated and PB-straw retained with 150 kg N ha^{-1} (6.61t ha^{-1} and 6.76 t ha^{-1}, respectively), but with 300 kg N ha^{-1} CTB-straw incorporated had significantly lower yields than PB-straw retained (7.54 t ha^{-1} and 8.07 t ha^{-1}, respectively). In 2010/11, CTB-straw incorporated had significantly lower yields with 150 and 300 kg N ha^{-1} than PB where straw was partly retained or removed. In 2011/12, the difference was only significant comparing CTB-straw incorporated and PB-straw removed. In 2010/11, the highest durum wheat yield (7.48 t ha^{-1}) was reached with PB-straw partly retained and split application of 300 kg N ha^{-1} (Fig. 3). In 2011/12, the highest yield (8.26 t ha^{-1}) was obtained with PB-straw removed and 300 kg N ha^{-1} applied at first node. Wheat yield results were consistent between the two studied cycles. With the exception of the 150 kg N ha^{-1} basal treatments with PB-straw partly or fully retained, yields in 2010/11 varied from 84% to 96% of the 2011/12 yields and were consistently higher in the latter cropping cycle.

The lowest yields were found in treatments without N fertilizer application, PB-straw burned in 2010/11 (1.60 t ha^{-1}) and CTB-straw incorporated in 2011/12 (2.49 t ha^{-1}). Compared with CTB-straw incorporated, PB without residue burning had significantly higher yields except in 2011/12 for the 150 kg N ha^{-1} treatments. Here, yield was 0.3 t ha^{-1} higher for PB-straw burned than for the other treatments. Burning of residues on PB resulted in yield reductions of 0.47 t ha^{-1} and 0.75 t ha^{-1} for 150 kg N ha^{-1} and 300 kg N ha^{-1}, respectively, in 2010/11 compared to the highest yielding treatment, PB-straw partly retained. In 2011/12, no significant yield differences between PB-straw burned and the other tillage-straw systems were observed for 150 kg N ha^{-1}, but for 300 kg N ha^{-1}, the difference between PB-straw burned and the PB treatments without burning averaged 0.68 t ha^{-1} and was statistically significant. Yields increased with increasing N dose (2.33 t ha^{-1}, 6.31 t ha^{-1} and 6.95 t ha^{-1} for 0, 150 and 300 kg N ha^{-1}, respectively, in 2010/11; 2.93 t ha^{-1}, 6.77 t ha^{-1} and 7.86 t ha^{-1}, in 2011/12) and the effect of N dose was larger than that of tillage-straw management (Table 2, Fig. 2 and 3).

Grain protein concentration (GPC) averaged 12.2% over all treatments in 2010/11 and 10.9% in 2011/12. The GPC increased with increasing N fertilization, averaging 9.9%, 11.8% and 13.3% for 0, 150 and 300 kg N ha^{-1}, respectively, in 2010/11 and 8.5%, 10.2% and 12.4%, in 2011/12. For 150 kg N ha^{-1}, PB-straw retained had the lowest GPC (10.2% in 2010/11 and 8.7% in 2011/12) and PB-straw burned the highest one (13.3% in 2010/11 and 12.0% in 2011/12). For 300 kg N ha^{-1}, PB-straw retained had significantly lower GPC that all other tillage-straw systems (11.6 in 2010/11 and 10.8% in 2011/12). Basal application of 300 kg N ha^{-1} resulted in a GPC similar to applying 150 kg N ha^{-1} at 1st node (11.6% and 11.5%, respectively). In 2011/12, N application at 1st node resulted in an approximately 1% higher GPC than split or basal application, with both 150 kg N ha^{-1} (9.7%, 8.8% and 8.7%, respectively) and 300 kg N ha^{-1} (12.0%, 11.2% and 10.8%, respectively) which was significant for 300 kg N ha^{-1} . For PB-straw retained, the 0 kg N ha^{-1} control had GCP similar to some of the 150 kg N ha^{-1} treatments: with split application in 2010/11 (9.9% and 10.2%, respectively) and with split and basal application in 2011/12 (8.1% for 0 kg N ha^{-1} and 8.7% for both 150 kg N ha^{-1} treatments). Conventional beds had similar or slightly lower GPC than PB-straw fully or partly removed, but significantly higher GPC than PB-straw retained when averaging the different timings for each rate.

In both cycles, GPC was significantly affected by tillage-straw management × N treatment interaction (Table 2). The interaction effect was due to ordinal rather than crossover interaction (Fig. 2). Tillage-straw treatment has a larger effect on yield and GPC under one particular N treatment than under another treatment and this effect was larger with 150 kg N ha^{-1} than with 300 kg N ha^{-1}. In 2010/11, the difference between 1st node and split application of 150 kg N ha^{-1} was larger with PB-straw partly and fully retained and PB-straw burned than with PB-straw removed and CTB-straw incorporated. In 2011/12, the difference in GPC between 1st node application and basal and split application was more pronounced in PB-straw not burned than in PB-straw burned and CTB-straw incorporated.

Test weight was significantly affected by tillage-straw system in both cycles and was highest in PB-straw burned in 2010/11 and highest in CTB-straw incorporated in 2011/12 (83.6 and 83.8 kg hl^{-1}, respectively, and averaged over all N rates) and lowest in both cycles in PB-straw partly retained (82.9 and 82.4 kg hl^{-1}, respectively) (data not shown).

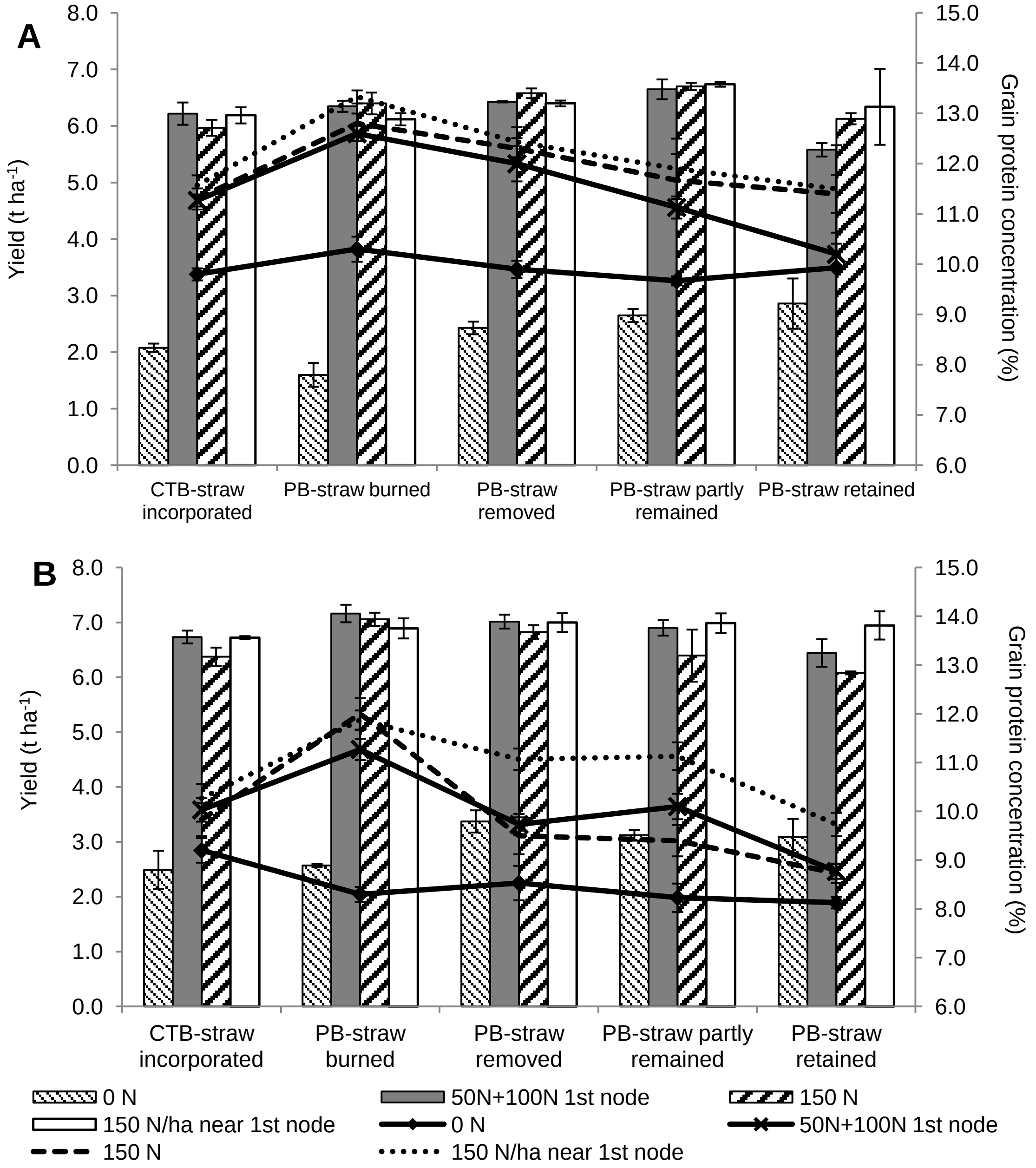

Figure 2 Durum wheat yields (kg ha^{-1}, bars) and grain protein concentration (%, lines) for 150 kg N ha^{-1} (A) in 2010/11 and (B) in 2011/12 for different tillage-straw systems and timing of N application. Bars indicate standard error.

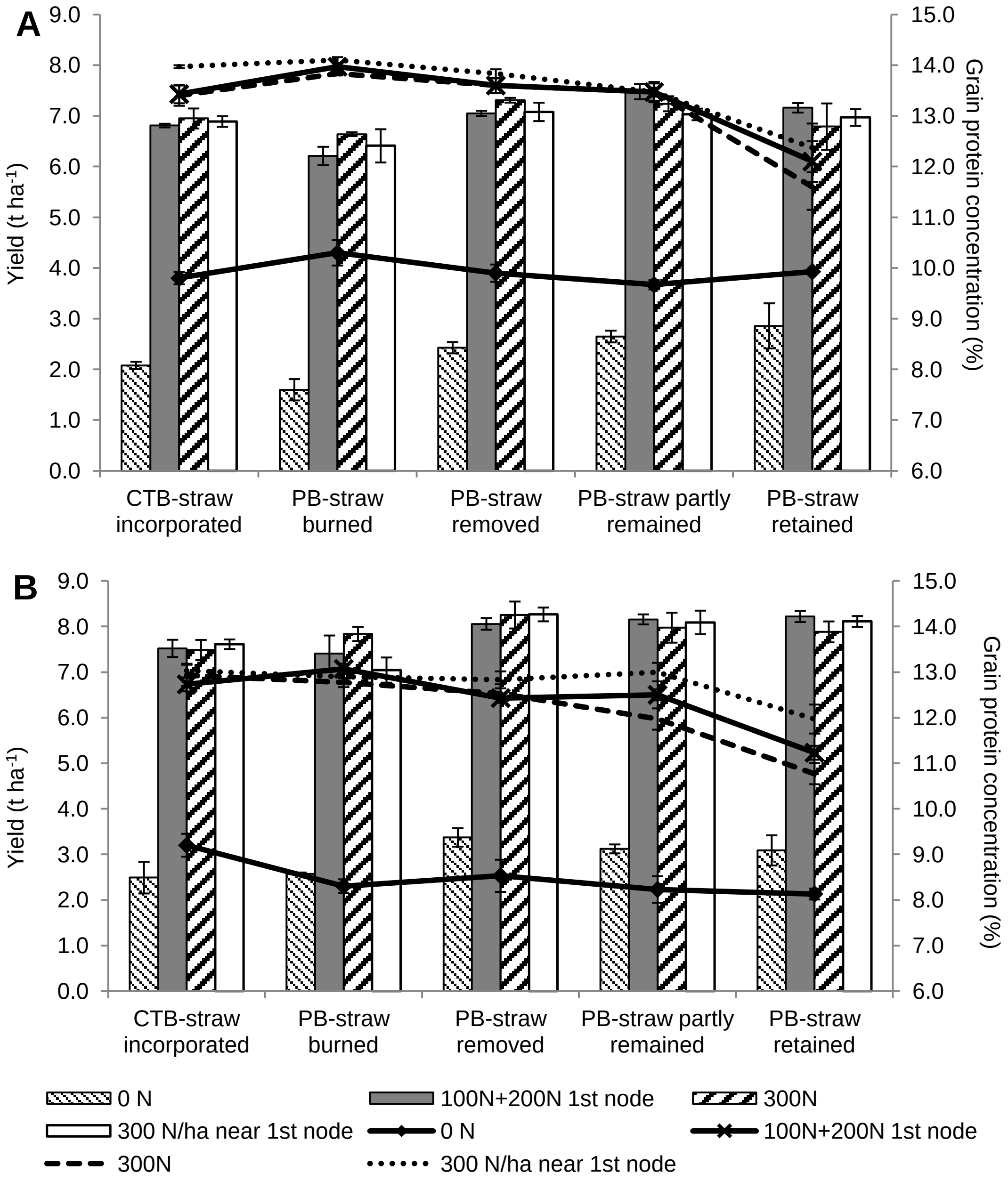

Figure 3 Durum wheat yields (kg ha^{-1}, bars) and grain protein concentration (%, lines) for 300 kg N ha^{-1} (A) in 2010/11 and (B) in 2011/12 for different tillage-straw systems and timing of N application. Bars indicate standard error.

2.4.2 Yellow berry as affected by tillage–straw management and N fertilization

With increasing GPC at higher N dose, the percentage of grains affected by YB decreased (Fig. 4). Plots without N application had high N deficiency and YB, with 83.5% non-vitreous, starchy kernels in 2010/11 and 48.2% in 2011/12. With 150 kg N ha^{-1}, PB-straw retained had the highest YB values for all N application timings (on average 42.2% for both cycles), while PB-straw burned had the lowest YB values (on average 3.7% for both cycles). With 300 kg N ha^{-1}, PB-straw retained was the only tillage-straw system with significant YB incidence (Fig. 4). Averaged over basal, split and 1st node application, this tillage-straw system had YB of 19.5% in 2010/11 and 9.4% in 2011/12 compared to an average value of 0.2% and 1.8% for the other tillage-straw systems in 2010/11 and 2011/12, respectively. In both cycles the threshold value of 15% YB for market requirements in the Yaqui Valley was exceeded in treatments with PB-straw retained for all N timings with 150 kg N ha^{-1} and for basal application with 300 kg N ha^{-1}. For both cycles, a significant interaction of tillage-straw management and N fertilization was found. In 2011/12 PB-straw burned had higher YB than the other tillage-straw treatments with 0 kg N ha^{-1}, but lower YB than the other tillage-straw treatments with all 150 kg N ha^{-1} treatments (Fig. 4).

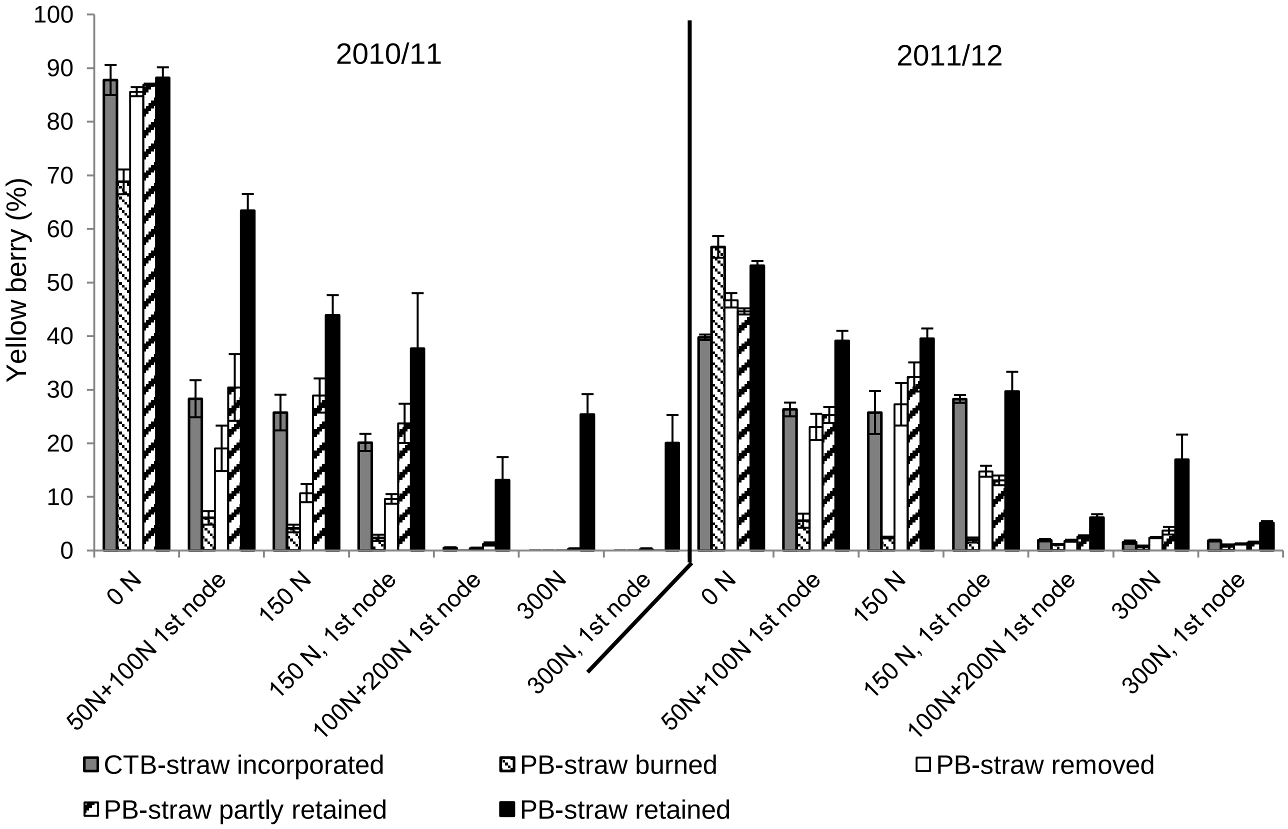

Figure 4 Effects of tillage-straw management and N fertilization on yellow berry (%) in 2010/11 and 2011/12. *N fertilization* 0N: control without N fertilization; 50N+100N 1st node: split application of 50 kg N ha^{-1} pre-plant and 100 kg N ha^{-1} at 1st node; 150N: 150 kg N ha^{-1} pre-plant; 150N, 1st node: 150 kg N ha^{-1} near 1st node; 100N+ 200N 1st node: split application

of 100 kg N ha^{-1} pre-plant and 200 kg N ha^{-1} at 1st node; 300N: 300 kg N ha^{-1} pre-plant; 300N, 1st node: 300 kg N ha^{-1} near 1st node. Bars indicate standard error.

2.4.3 Correlations between yield and quality parameters

All quality parameters were highly correlated (Table 3), whereby quality and yield parameters were negatively correlated with YB, except for thousand kernel weight. Flour protein concentration and sedimentation showed a high positive correlation (Pearson´s r = 0.74). Thousand kernel weight was not highly correlated to most of the quality parameters, except for a negative correlation with colour, GPC, and sedimentation. Yield and GPC were positively correlated (Pearson´s r = 0.60).

Table 3 Correlation coefficients between quality and yield parameters for durum wheat in 2010/11 and 2011/12.

	YLD	TW	TKW	YB	GPC	FPC	SDS	COL	PT
YLD	1.00								
TW	0.47	1.00							
TKW	-0.05	-0.03	1.00						
YB	-0.82	-0.49	0.16	1.00					
GPC	0.60	0.43	-0.53	-0.77	1.00				
FPC	0.72	0.40	-0.17	-0.90	0.84	1.00			
SDS	0.42	0.29	-0.52	-0.68	0.80	0.74	1.00		
COL	0.60	0.43	-0.66	-0.66	0.86	0.64	0.71	1.00	
PT	0.44	0.28	-0.12	-0.47	0.31	0.32	0.28	0.38	1.00

Quality and yield parameters YLD: yield; TW: test weight; TKW: thousand kernel weight; YB: yellow berry; GPC: grain protein concentration; FPC: flour protein concentration; SDS: Sodium Dodecyl Sulphate-sedimentation volume; COL: Minolta b-value; PT: mixing peak time.

2.4.4 Principal component analysis

A principal component analysis showed significant grouping of the different tillage-straw treatments regarding quality and yield parameters. For the 150 kg N ha^{-1} treatments in 2010/11, the two first principle components accounted together for 69% of the variance (Fig. 4a). The PB-straw retained plots were separated from the other plots by high YB percentage and low GPC. The PB-straw partly retained plots are grouped and separated by low thousand kernel weight and high yields. For PB-straw burned, high grain quality is paired with low yields.

For the 150 kg N ha^{-1} treatments in 2011/12, the first principal component explained 56% and the second 15% of the variance (Fig. 4b). As in the previous cycle, PB-straw retained plots were separated from the other by high YB. The PB-straw burned had high values for most quality parameters, separating these plots from the other tillage-straw treatments. The CTB-straw incorporated plots were grouped with intermediate quality results, lower yields and high thousand kernel weight.

For the 300 kg N ha^{-1} treatments, the formation of groups was less marked than for 150 kg N ha^{-1} and less variance was explained by the first two principle components in both cycles (Fig. 4c,d). For both cycles, PB-straw retained plots were again separated from the other plots by high YB incidence. For 2010/11, PB-straw burned plots were separated by high test weight and low yield and the two first principal components accounted for 58.1% of the variance in the original variables. For 2011/12, PB-straw partly retained plots were separated by high loadings on the second principal component, related to high mixing peak time and yield and low test weight.

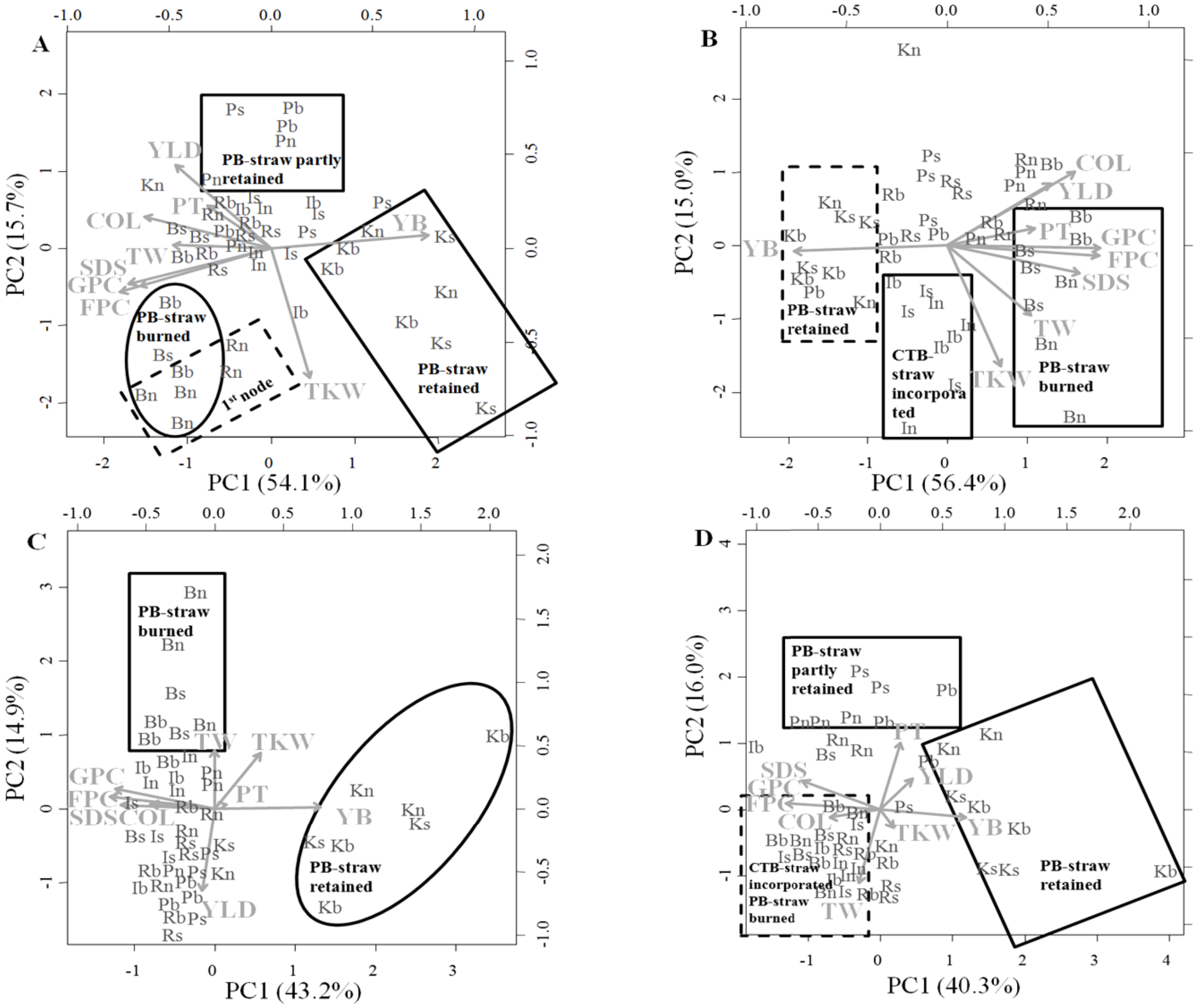

Figure 5 Bi-plots of the first two components of the principle component analysis for quality and yield parameters for (A) 150 kg N ha^{-1} and (C) 300 kg N ha^{-1} in 2010/11 and (B) 150 kg N ha^{-1} and (D) 300 kg N ha^{-1} in 2011/2012. *Tillage-straw system*- I: CTB-straw incorporated, B: PB-straw burned, R: PB-straw removed, P: PB-straw partly retained, K: PB-straw retained; *Timing of N fertilization*- b: basal, s: split, n: 1st node; *Quality and yield parameters*- YLD: yield, TW: test weight, TKW: thousand kernel weight, GPC: grain protein concentration, FPC: flour protein concentration, YB: yellow berry, SDS-S: Sodium Dodecyl Sulphate-sedimentation volume, PT: mixing peak time. Groupings with solid lines, tendencies with dashed lines. Numbers in brackets indicate first and second principal components.

When analysing the 150 kg N ha^{-1} and 300 kg N ha^{-1} data together (results not shown), the treatments CTB-straw incorporated and PB-straw partly or fully retained were separated for both cycles. An overall strong correlation between grain and flour protein concentration, sedimentation value, flour colour and yield was observed. Treatments were grouped by the amount of N fertilizer, but some of the 150 kg N ha^{-1} plots with 1st node N application had yields and quality characteristics similar to 300 kg N ha^{-1} on PB-straw retained.. PB with partial or full residue retention resulted in comparable yields and even higher quality when 150 kg ha^{-1} N was applied at 1st node than when 300 kg N ha^{-1} was applied pre-planting. For the 2011/12 cycle, a third group, PB-straw burned, was distinguished, with a tendency for high mixograph values and test weight. The separation between both N rates was clearer than for 2010/11.

Analysing the treatments without any fertilizer application, for both cycles the plots with PB-straw burned were grouped with low yields (data not shown). However, for 2010/11 these plots had low YB, whereas for 2011/12 they had high YB incidence. CTB-straw incorporated showed high mixograph values and thousand kernel weight 2010/11, high test weight in 2011/12 and low yields in both cycles.

2.5 Discussion

2.5.1 Effects of tillage-straw management

Yields in 0 kg N ha^{-1} treatments were lower than the 150 and 300 kg N ha^{-1}. Within 0 N treatments, PB without residue burning obtained higher yields than CTB-straw incorporated or PB-straw burned indicating that the potential mineralized N from crop residues can compensate partially for the zero N rate, sustaining wheat grain yields over time (Campbell et al., 1993). The yield results for the two studied cycles are consistent with long-term results obtained from 1999-2009 in the same experiment (Verhulst et al., 2011b). Retaining all or only part of the residue on PB resulted in similar yields. This supports the hypothesis that it is feasible and recommendable to remove part of the crop residue for other uses such as animal fodder or fuel without yield disadvantages under these irrigated conditions with a double cropping system resulting in a high residue load and higher root contribution than in low-input rainfed conditions. Overall the yield differences were relatively small, as expected for irrigated conditions.

In the PCA graphs of yield and grain quality, three groups of tillage-straw systems were distinguished. A study of soil quality in the same experiment distinguished the same three groups with different characteristics in relation to the soil environment: PB-straw burned, CTB-straw incorporated, and PB-straw not burned (Verhulst et al., 2011a). The PB-straw burned had the lowest soil quality with high electrical conductivity, Na concentration and penetration resistance and low soil resilience and aggregation. But for the same experiment, Verhulst et al. (2009) analyzed durum wheat development with an optical NDVI sensor and found that plant performance in PB-straw burned was significantly lower compared to other tillage treatments. The initial plant growth was fast, but senescence was also faster than for the other treatments. The remobilization and translocation of plant N from senescent leaf and root material to the spike and finally to the grain seems to be accelerated in PB-straw burned (Masclaux-Daubresse et al., 2010). The lower grains per m², and related to that the higher thousand kernel weight, with PB-straw burned indicate some moisture stress around flowering. This could explain the lower yields in this practice resulting in an increased GPC due to concentration effects. Additionally, some moisture stress during the grain-filling phase due to reduced soil quality (Verhulst et al., 2011a) could have increased GPC because high temperatures and water stress during the grain-filling phase are known to favour GPC and hinder the conversion of sucrose into starch (Rao et al., 1993).

For both cropping cycles, GPC was lower and YB higher for PB-straw retained than for CTB-straw incorporated which coincides with various studies for both durum (Pisante and Basso, 2000; De Vita et al, 2007) and bread wheat (Lyon et al., 1998; Lopez-Bellido et al., 2001; Lopez-Bellido and Lopez-Bellidio, 2001) mainly explained by a higher N use efficiency and greater N uptake in conventional systems with straw incorporation. Grain quality was below industry standards in PB-straw retained, even with a high N fertilizer dose of 300 kg N ha^{-1}. This indicates a problem with N distribution during the grain filling phase and decreased N availability in this tillage-straw system. The N immobilization by high residue loads decreased N availability and could have led to a reduced post-anthesis N assimilation and thus high YB incidence and low protein in treatments with straw retention. This is also confirmed by the correlation results between yield and GPC. Over all tillage-straw treatments, yield and GPC were positively correlated (r=0.60 with Pearson and 0.49 with Spearman) which is inconsistent with the often mentioned dilution effect, demonstrating an adequate N supply of the plants and efficient translocation to the developing grain during the grain filling phase. Even when separating the three N levels, no negative correlation was observed for 0, 150 or 300 kg N ha^{-1} (r=0.33, 0.0003 and 0.22, respectively). Yellow berry incidence also varies genetically which might contribute to the absence of this dilution effect. Only in PB-straw retained treatments, a negative correlation between yield and GPC was found. This points to a potential for an additional N application between heading and anthesis to compensate reduced N availability in this tillage-residue treatment.

The high residue load may cause reduced net N mineralization and rapid immobilization of soil mineral N in these systems due to the high C/N ratio of the wheat and maize residues, especially since the N in this experiment was applied on top of the residue as urea, a common farmer practice in the area. The urea was applied only in the furrow and on the same day as the irrigation, which reduced possible volatilization losses to a minimum but this was apparently insufficient to prevent immobilization when high residue loads were present. Several approaches might help overcome this problem. Disking the urea into the soil minimizes contact between fertilizer and residue and could reduce N immobilization while at the same time reducing the potential for volatilization and thus increase fertilizer recovery and grain N uptake (Rice and Smith, 1984; Schoenau and Campbell, 1996).

Literature points to the use of more finely divided or macerated residues to promote faster residue decomposition as a potential solution (Angers et al. 1997; Silgram and Shepard, 1999; Burguess et al. 2002). Reducing irrigation such as omitting the 4th auxiliary irrigation to induce some light moisture stress at the stage of late grain filling could be used as a management tool to increase GPC if farmers would get paid for grain quality. However, water is getting scarce in the Yaqui Valley and farmers might get forced in future to reduce their irrigation events, which automatically can result in higher GPC.

It was observed that removing part of the residues on PB in this experiment increased grain quality, while maintaining yields and soil quality to similar levels compared to full residue retention. The PB-straw removed or partly retained had lower YB incidence and higher GPC than the PB-straw retained. On the other hand, increased immobilization of applied N fertilizer by crop residues may reduce losses of mineral fertilizers (Ladha et al., 2005), especially in high-input conditions such as in

Northern Mexico. Options to adjust N management to tillage-straw system will be further discussed in the following section.

Three nights with frost occurred at the beginning of February 2011, during the heading stage (65-67 days after planting, about two weeks before flowering). The wheat crop was slightly damaged (some frost burn occurred at the end of the leaves), but no visible spike damage by frost was found. Yield was on average 0.60 t ha^{-1} lower in 2010/11 than in 2011/12, which could be the result of frost damage. The frost effect on quality development depends on the wheat maturity stage and the duration and severity of the frost event (Labuschagne et al., 2009). The differences in yield and GPC from cycle to cycle could be due to the high yield results obtained in 2011/12 and do not necessarily arise from frost damage. These higher yields in 2011/2 led to lower GPC, presumably due to a dilution effect linked to higher starch accumulation in the grain, and the opposite happened in 2010/11, when GPC was higher, but overall yields lower.

2.5.2 N fertilizer management in different tillage-straw systems

Without any fertilizer application, PB-straw retained and PB-straw partly retained had significantly higher yields than PB-straw burned or CTB-straw incorporated treatments (Fig. 2, Fig. 3). Hence, conservation agriculture with full residue retention could be a suitable, economically reasonable practice for small-scale farmers who cannot afford chemical inputs to obtain higher and stable yields which may be an important factor determining adoption by smallholder farmers in systems with competition for crop residues.

For both cycles split or basal application of 150 kg N ha^{-1} resulted in similar grain quality, whereas 1st node application significantly improved quality compared to basal and split application. For 300 kg N ha^{-1} almost no effects of N timing were noted, likely due to the high amount of N fertilizer. The N deficiency indicator YB incidence was unaffected by N timing for 300 kg N ha^{-1} (Table 4). As reported by Gauer et al. (1992) and Wuest and Cassman (1992), N requirements for biomass and yield production have to be satisfied before additional N application increases grain N.

Nitrogen requirements of wheat in growing kernels are typically satisfied by the mobilization and utilization of N assimilated before anthesis and stored temporarily in leaves, culms, and chaff (pre-anthesis N) and by the utilization of N assimilated during grain filling (post-anthesis N; Masoni et al., 2007).

For the high 300 kg N ha^{-1} dose, yield was unaffected by timing of N fertilization and only GPC showed significant differences between basal and 1st node application. For 150 kg N ha^{-1}, yield demands might not be fulfilled thus hampering N assimilation into grain protein. In 2011/2, differences between N timings for the respective rate were more pronounced than in 2010/11. The differences between 1st node application and split and basal application for GPC, FPC and SDS-S were highly significant in 2011/12 and less pronounced in 2010/11 with significant differences only between split and 1st node, but not for basal application (Table 4).

Table 4 Differences of least square means between N management practices for 150 and 300 kg N ha^{-1} and overall p-values for N-management at 150 and 300 kg N ha^{-1}(analyzed separately) for each cropping cycle (2010/11 and 2011/12).

		YLD	TW	TKW	YB	GPC	FPC	SDS	COL	PT
2010/11 150 kg N ha^{-1}	split vs basal	0.58	0.38	0.43	0.13	0.06	0.11	0.20	0.29	**0.0037**
	split vs 1st node	0.37	0.25	0.20	0.02	**0.0052**	**0.0002**	**0.0097**	**0.03**	**<0.0001**
	basal vs 1st node	0.72	0.05	0.05	0.37	0.27	**0.01**	0.14	0.20	**0.0086**
	p-value	0.66	0.14	0.13	0.06	**0.02**	**0.001**	**0.03**	0.08	**<0.0001**
2011/12 150 kg N ha^{-1}	split vs basal	**0.0069**	0.56	0.51	0.48	0.60	0.65	1.00	0.57	0.05
	split vs 1st node	0.57	0.47	0.38	**0.01**	**<0.0001**	**<0.0001**	**0.0004**	**0.03**	0.07
	basal vs 1st node	**0.0018**	0.88	0.13	**0.002**	**<0.0001**	**0.0002**	**0.0004**	0.09	0.89
	p-value	**0.0039**	0.74	0.31	**0.005**	**<0.0001**	**<0.0001**	**0.0003**	0.07	0.10
2010/11 300 kg N ha^{-1}	split vs basal	0.99	0.41	0.95	0.23	0.37	0.19	0.25	0.24	0.54
	split vs 1st node	0.34	0.07	**0.0099**	0.55	0.12	0.35	**0.04**	0.65	0.34
	basal vs 1st node	0.35	0.30	**0.01**	0.54	**0.02**	0.69	0.32	0.46	0.73
	p-value	0.55	0.19	**0.01**	0.48	0.06	0.39	0.11	0.49	0.62
2011/12 300 kg N ha^{-1}	split vs basal	0.91	0.84	0.19	0.10	0.12	0.31	0.81	0.71	1.00
	split vs 1st node	0.72	0.17	0.90	0.66	**0.0089**	0.08	0.06	0.42	0.19
	basal vs 1st node	0.64	0.24	0.16	**0.04**	**0.0002**	**0.0084**	0.10	0.65	0.19
	p-value	0.88	0.33	0.28	0.09	**0.0007**	**0.03**	0.13	0.71	0.32

Quality and yield parameters YLD: yield; TW: test weight; TKW: thousand kernel weight; YB: yellow berry; GPC: grain protein concentration; FPC: flour protein concentration; SDS: Sodium Dodecyl Sulphate-sedimentation volume; COL: Minolta b-value; PT: mixing peak time.

For the same experiment, Verhulst et al. (2009) compared plant performance with an NDVI sensor for split and basal application of 150 and 300 kg ha^{-1} of N fertilizer in the five tillage treatments and found no significant advantage of split application. When straw was (partly) retained, performance was even lower with 300 kg ha^{-1} split application compared to basal fertilization (Verhulst et al., 2009). Under conventional conditions, Garrido-Lestache et al. (2005) reported that timing and splitting of N fertilizer had no clear impact on durum grain yield nor on quality parameters such as gluten index or GPC. However, in another study by Garrido-Lestache (2004), bread grain yield and GPC were improved by split application (half or one-third of the N fertilizer was applied at stem elongation) compared to basal N fertilization at sowing or tillering. The effect of N splitting depends heavily on the number of fertilizer applications and their timing and quantities, on weather conditions, the amount of available soil mineral N, and without doubt on the cropping system (Arregui and Quemado, 2008).

There is a need to better understand the low quality of durum wheat in PB-straw retained treatments. In addition to the options discussed in the previous section, the adjustment of the timing of N application shows some potential to increase GPC and quality in treatments with high residue load. In both cycles, the application of 150 or 300 kg N ha^{-1} at 1st node resulted in an up to 1% higher GPC than a split or basal application of the same amount of N fertilizer. However, once the amount of required N for biomass production and adequate yields has been applied, additional fertilization e.g. as a top dressing at ear emergence even later in the season could lead to an increase in GPC and improved grain quality (Lopez-Bellido et al., 2001). For both cycles and both N rates, the application of mineral N resulted in highest GPC for PB-straw retained treatments when all N was applied near the 1st node stadium. The average year differences in GPC result from the dilution effect as in 2010/11 lower yields were accompanied by overall higher protein concentrations. Whereas some moisture stress during late grain-filling can help increase GPC, irrigation can contribute to an efficient uptake of late season N application between heading and anthesis (Wuest and Cassman, 1992; Ottman et al., 2000). Crop residues can increase soil moisture content and thus contribute to improving N fertilizer distribution in the soil and N uptake by the plants, unless residues immobilize applied fertilizer N. In the study of Gauer et al. (1992) improved soil moisture by residue retention positively affected protein concentration and grain use efficiency of the applied fertilizer.

The application of mineral N fertilizer at the right time, in the right amount and the right place will not only increase and improve yield and yield components, but may also improve crop health and reduces pest incidence which should be considered in tandem with IPM management strategies (Ladha et al. 2005).

2.6 Conclusions

Even with a high N fertilizer rate of 300 kg N ha^{-1}, no acceptable durum wheat quality (high yellow berry incidence and low grain protein concentrations) was obtained in permanent beds with full straw retention. It is likely that the high amounts of residues left on the field might explain the temporarily N immobilization and reduced N efficiency, because the fertilizer was surface-applied. Therefore, 1st node application of N fertilizer is recommended to minimize N immobilization in permanent beds with full residue retention. Application of N at 1st node in permanent beds with residues removed or partially retained led to acceptable yields and good quality traits, indicating a scope to remove part of the residues which is important for adoption of CA by small-scale farmers in areas where there is pressure on residue for other uses such as fodder. In summary, N fertilizer grain uptake, and consequently durum wheat quality, could be increased by applying N during the periods of highest N plant demand and by delaying the early or pre-plant N application which highlights the importance of a suitable source-timing and placement combination in CA systems. Late-season applied N fertilizer and splitting of N fertilizer applications should be evaluated as a tool under irrigated conditions to improve grain protein concentration and reduce yellow berry when residues are kept. Further research is needed to define the most efficient mode of N application in permanent beds with full or partial residue retention that reduces N fertilizer immobilization leading to increased grain quality in this production system.

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Chapter 3

3 Nitrogen fertilizer placement and timing affects bread wheat (*Triticum aestivum*) quality and yield in an irrigated bed planting system

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3 Nitrogen fertilizer placement and timing affects bread wheat (*Triticum aestivum)* quality and yield in an irrigated bed planting system

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N application method; Nitrogen use efficiency; Grain protein concentration; Tillage; Yaqui Valley

3.1 Abstract

Searching for sustainable cropping systems has often focused on the optimization of system sustainability, yield or ideally both. It is important to also include wheat quality characteristics like grain protein concentration (GPC) and bread-making quality (loaf volume). The effect of placement and timing of nitrogen (N) fertilizer on performance and quality of the bread wheat cultivar Navojoa, was tested in two tillage systems under furrow irrigation: conventionally tilled beds (CTB; new beds formed after disc ploughing and residue incorporation) and permanent beds (PB; only furrows reshaped and residues retained on the surface). N fertilizer (120 kg N ha^{-1} as urea) was broadcast, applied in furrows or disk-banded on top of beds. The timing treatments were all fertilizer applied before planting or split between pre-planting and first node. Permanent beds had the highest yield and grain quality with split bed and furrow application. Averaged over four years, N use efficiency and GPC were significantly higher in CTB (24.5 kg kg^{-1} and 10.1%, respectively) than in PB (22.2 kg kg^{-1} and 9.9%, respectively) indicating the necessity in PB for optimal N management to obtain stable yields and acceptable grain quality. A reduced number of cold hours and solar radiation negatively affected grain yield. Broadcast fertilizer application reduced grain quality and N use efficiency. N fertilizer management in furrow-irrigated wheat cropping systems should combine splitting the N dose and disking it on the bed pre-planting and in the furrow later in the season, depending on the crop needs at the application time.

3.2 Introduction

Bread wheat (*Triticum aestivum* L.) accounts for 95% of worldwide wheat production (USDA, 2015). Wheat as a value crop is embedded in an end user value chain and requires a transformation process to produce flour (UNCTAD, 2013). The main quality parameters for bread wheat classification are its grain protein concentration (GPC), flour yield (% extraction), falling number, dough quality, and baking performance (loaf volume) (Gooding and Davies 1997). Grain protein concentration varies from 6 to 19%, depending on genotype and environmental conditions, which include climate and N fertilization (Amir and Sinclair 1991, Kong et al. 2013, Ray et al. 2015). Grain protein concentration is used to grade bread wheat into different end use categories like the manufacturing of leavened breads (>13%, Peña 2002), soft wheat products like cookies and cakes (8-10%; Faridi et al. 1994), traditional flat breads, like Arab *baladi* (12-14%) or Indian *chapati* (11-13%) and alcoholic beverages such as wheat beer (13%, Arendt and Zannini, 2013). The common presence of a negative correlation between grain yield and GPC, mainly caused by the dilution of protein by more carbohydrates, is challenging for breeders and farmers (Garrido-Lestache et al., 2004) and therefore GPC is often neglected in breeding and agronomic studies with grain yield as top priority. Fortunately, wheat quality does not depend only on GPC but on protein quality and other grain components, which properly combined lead to desirable end-use quality. Therefore, both yield and several grain quality parameters were considered important in the present study and evaluated over four cropping cycles in two different tillage environments.

The Yaqui Valley in northern Mexico represents the largest wheat mega environment under irrigation and is agro-climatically representative of areas where 40% of wheat is produced in the developing world, such as the Indian and Pakistani Punjab and the Nile Valley in Egypt (Ortiz-Monasterio et al. 2010). Local wheat yields have consistently increased from 1951 to 2005 (Matson et al. 1998) and actually exceed 6 t ha^{-1} with an average N application rate for wheat of 275 kg N ha^{-1} (Naylor et al. 2001). However, annual yield fluctuations have become larger and more frequent, mainly due to climatic events (Ortiz et al. 2008).

Conservation agriculture (CA) is a set of management practices that may allow more sustainable agricultural production and reduced production costs by (1) minimal soil movement, (2) the retention of rational amounts of residue cover, and (3) economically viable crop rotations (Hobbs et al. 2008). In the Yaqui Valley, a furrow-irrigated system, minimal soil movement is practiced by converting the conventionally tilled beds into permanent beds that are only reshaped when necessary with the residues retained on the soil surface. The impact of surface residue retention on N cycling and availability is unclear (Verhulst et al. 2010). Incorporated residues decompose faster, thereby releasing N, whereas CA systems temporarily increase N immobilization due to slower residue decomposition, which is affected by soil moisture and surface soil temperature (Malhi and O´Sullivan 1990; Schomberg et al. 1994; Franzluebbers et al. 1995). The slower decomposition of residue in CA can increase soil organic N content during the cropping cycle by releasing N more gradually, affecting N uptake and grain N accumulation (Silgram and Sheperd 1999; Balota et al. 2004; Govaerts et al. 2006).

Literature on the effect of tillage management on bread wheat quality under furrow irrigation is scarce. Under rainfed conditions, Lopez-Bellido et al. (2001) reported higher yield, GPC and dough quality for hard red spring wheat in conventional tillage than CA. Huggins and Pan (1993) obtained higher soil N, GPC and overall nitrogen use efficiency (NUE) for rainfed spring wheat in conventional tillage than no-tillage systems. Grahmann et al. (2014) found unacceptable grain quality and high yellow berry incidence in permanent beds with full residue retention and high fertilizer dose for irrigated durum wheat (*Triticum durum* L.) in the Yaqui Valley.

Split- and late season-applications of mineral N fertilizer are common approaches to improve NUE and wheat grain quality (Wuest and Cassman 1992; Lopez-Bellido et al. 2001; Garrido-Lestache et al. 2004; Velasco et al. 2012; Grahmann et al. 2014). In CA systems, placement of N fertilizer is more important than timing of fertilizer application to reduce N fertilizer losses resulting from immobilization and volatilization (Malhi et al. 2001; Ladha et al. 2005; Grahmann et al. 2013). When fertilizer is placed deeper, nutrients are available for a longer period of time during the cropping cycle (Ma et al. 2009). Sub-surface placement of N fertilizer resulted in increased NUE, N fertilizer recovery, yield and GPC in no-till wheat compared to surface broadcast application (Rao and Dao 1992; Malhi et al. 1996; Rao and Dao 1996). Knowledge on the most effective timing and placement of N fertilizer application in irrigated CA systems is limited and is therefore addressed in the present study.

The objective was to evaluate the effects of N fertilizer management, including placement and timing of N fertilizer, on bread wheat yield and grain quality in a furrow-irrigated system under arid conditions in two tillage systems. Disked in application of N was expected to improve grain quality in both tillage systems compared to broadcast N application and split application was expected to increase grain quality compared to basal application. In view of the existing knowledge gaps in this field, we conducted this study with a substantial dataset of yield and quality parameters collected over four years to identify recommendations for optimal N fertilizer strategies in different tillage systems.

3.3 Materials and methods

3.3.1 Climate and soil conditions

The trial was conducted at the CENEB (Campo Experimental Norman E. Borlaug) experimental station, near Ciudad Obregón, Sonora in northwestern Mexico (lat. 27.33°N, long. 109.09°W, 38 m a.s.l.). The site has a hot, arid climate, with an average annual precipitation of 320 mm (Ahrens et al. 2010). Meteorological data were obtained from a weather station located approximately 2 km from the experimental site (Fig. 1). The experiment began in 2005 and data are reported for four cropping cycles (2012-2015). Total rainfall increased over the four cropping cycles and heavy rainfall events were recorded within one month prior to planting on several days in 2011/12 (41.5 mm), 2013/14 (15.6 mm) and 2014/15 (36.4 mm; Table 1). Temperatures below zero were only recorded on 12 to 15 and 17 January 2013 and 12 to 14 February 2013 (2012/13 cropping cycle). Recorded cold hours (when temperature during one hour is less than or equal to 10°C), which are related to wheat productivity (Valencia et al. 2009), were reduced by approximately half in the last two cycles than the first two cycles of the study, while average temperatures increased. Solar radiation as the sum of the period 20 days before and ten days after anthesis decreased over the cropping cycles (Table 1).

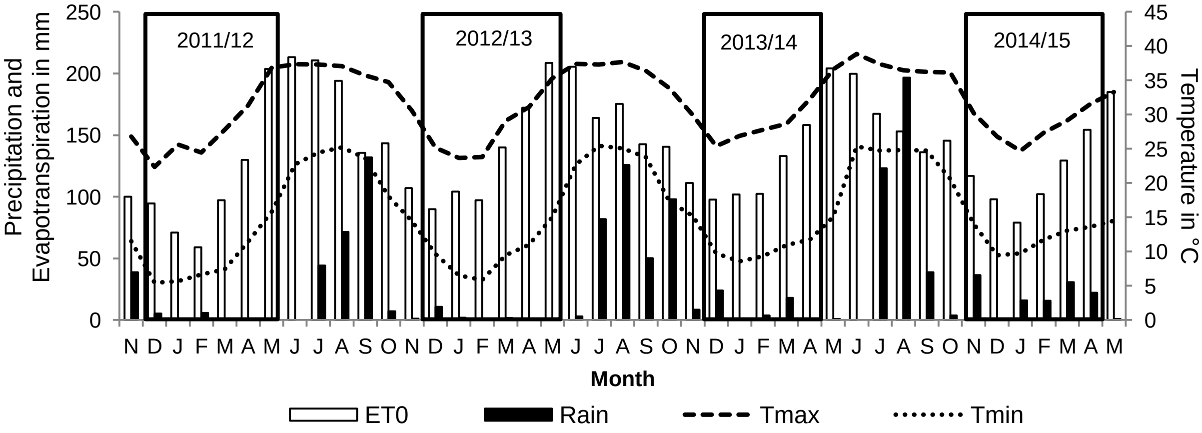


Figure 1 Precipitation and evapotranspiration and minimum and maximum temperatures over four cropping cycles in the experimental station near Ciudad Obregón, Sonora, NW-Mexico. Black dotted line: monthly averaged daily minimum temperatures, black dashed line: monthly averaged daily maximum temperatures, white bar: evapotranspiration (ET0), black bar: precipitation (Rain), black square: cropping cycle

Table 1 Field activities and climatic conditions for cropping cycles at the CIMMYT experimental station near Ciudad Obregón, Sonora, NW-Mexico.

Cropping cycle	Planting date	Harvest date	Cold hours[a]	Solar radiation[b] (Mj m²)	Average tempert ure [c] (°C)	Minimum temperature[c] (°C)	Maximum temperature[c] (°C)	Precipitation[a] (mm)
2011/12	15-Dec-11	4-May-12	475	714	18.4	8.7	28.1	6.4
2012/13	11-Dec-12	7-May-13	593	655	17.5	8.5	26.6	14.4
2013/14	11-Dec-13	29-Apr-14	271	609	19.1	10.1	28.2	39.3
2014/15	24-Nov-14	20-Apr-15	210	398	20.1	12.0	28.3	84.7

[a] Sum for the entire cropping period
[b] Sum for the critical period 20 days before and 10 days after anthesis
[c] Average for the entire cropping period

The experimental soil was a Hyposodic Vertisol (Calcaric, Chromic) according to the World Reference Base (Verhulst et al. 2009; IUSS Working Group 2007) and a fine, smectitic Chromic Haplotorrert in Soil Taxonomy (Soil Survey Staff, 2010). It is low in organic matter (< 1%) and slightly alkaline (pH around 8). Detailed chemical and physical soil properties can be found in Table 2.

Table 2 Chemical and physical soil properties for a soil profile in CIMMYT's experimental station in the Yaqui Valley near Ciudad Obregon, Sonora, Mexico (after Verhulst et al., 2009).

Depth	OM	Total N	pH	P-$_{\text{Olson}}$	CEC	Particle size fraction			BD
						Sand	Silt	Clay	
cm	%	%		ppm	meq/100g	%	%	%	g/cm³
0-15	1.2	0.04	8.9	17	33.9	32	18	50	1.27
15-40	0.9	0.06	8.9	6	30.5	34	18	48	1.20
40-70	0.7	0.03	8.4	3	32.4	32	16	52	1.38
70-120	0.3	0.01	5.9	3	18.7	24	16	60	1.37

OM: Organic matter content, Total N: Total nitrogen content, CEC: Cation Exchange Capacity, BD: Bulk density

3.3.2 Experimental design

A raised bed planting system was used with crops planted on top of the beds and irrigation applied in the furrows. Plot size was 22.5 m^2 and each plot consisted of four 7.5 m long and 0.75 m wide beds. The trial had a wheat-maize rotation with wheat as a winter crop planted in November to December and maize as a summer crop planted in June. Wheat was sown at a rate of 120 kg ha^{-1} in two rows with 24 cm between the rows. Traffic was confined to the furrows and narrow tractor tires were used for all operations. The trial was set up as a split plot design, with tillage as the main blocks. Tillage treatments were permanent raised beds (PB) and conventionally tilled beds (CTB). The CTB were tilled after each crop with a disk harrow to 20 cm then new beds were formed. The PB were not tilled with continual reuse of existing beds, which were reformed in the furrows without soil disturbance on top of the bed before planting. Within each tillage environment, ten N management treatments were tested with three repetitions (Table 3). The basal N application was completed before the pre-planting irrigation. The N application at first node was completed immediately prior to the first auxiliary irrigation. Nitrogen was either applied once (pre-planting) or split between pre-planting and first node. The methods of application included broadcasting the fertilizer, furrow application (in 2011/12 and 2012/13 applied manually at the surface a couple of hours before irrigation, and in 2013/14 and 2014/15 disked in with a machine) or disking it in the center of the beds.

All other management operations were conducted according to standard practice. Phosphorus was disked in the center of the beds at 22 kg P ha^{-1} prior to sowing of the bread wheat cultivar Navojoa M2007. This commercially used cultivar was chosen because of its high yield potential and resistance against leaf rust (*Puccinia triticina)* at the beginning of the study (Figueroa-López et al., 2009). Plots were irrigated with 120 mm prior to seeding (wet seeding) and four auxiliary irrigations of 80-100 mm each were applied. Pesticides and herbicides were applied when needed.

Table 3 N management treatments used in the cropping cycles (2011/2012 to 2014/2015). All treatments were applied in three repetitions in each environment (permanent beds and conventionally tilled beds). Furrow application of N changed from manual application in 2011/12 and 2012/13 to disked in with a machine in 2013/14 and 2014/15.

No.	Basal N Rate (Urea)	First Node Stage N Rate (Urea)	Abbreviation
1	0 kg N ha^{-1}	0 kg N ha^{-1}	0 N
2	120 kg N ha^{-1} – Broadcast	0 kg N ha^{-1}	120 N Broadcast (Bc)
3	120 kg N ha^{-1}– Furrow-applied	0 kg N ha^{-1}	120 N Furrow (Fu)
4	120 kg N ha^{-1}– Disked in center of bed	0 kg N ha^{-1}	120 N Bed (Be)
5	40 kg N ha^{-1}– Broadcast	80 kg N ha^{-1}– Broadcast	40-80 N Broadcast (BcS)
6	40 kg N ha^{-1}– Furrow-applied	80 kg N ha^{-1}– Furrow-applied	40-80 N Furrow (FuS)
7	40 kg N ha^{-1}– Disked in center of bed	80 kg N ha^{-1}– Disked in center of bed	40-80 N Bed (BeS1)
8	40 kg N ha^{-1}– Disked in center of bed	80 kg N ha^{-1}– Furrow-applied	40 N Bed-80 N Furrow (BeFu1)
9	80 kg N ha^{-1}– Disked in center of bed	40 kg N ha^{-1}– Disked in center of bed	80-40 N Bed (BeS2)
10	80 kg N ha^{-1}– Disked in center of bed	40 kg N ha^{-1}– Furrow-applied	80 N Bed-40 N Furrow (BeFu2)

3.3.3 Data collection

Wheat yield was measured according to Pask et al. (2012). The central area of the plot (two center beds 13 m long) was combine-harvested and grain weight and moisture content measured. Grain yield was expressed at 12% moisture content. Thousand kernel weight (TKW) was measured by counting a subsample of 200 grains and measuring the dry weight. Test weight is defined as wheat per unit volume and expressed in kilograms per hectoliter (kg hL^{-1}; Halverson and Zeleny 1988). The grains were poured through a cone in a 1 L vessel and converted to the test weight of a hectoliter. Harvest index was calculated by dividing the dry grain weight from 50 stems by the dry weight of 50 stems and used to calculate biomass. Grain protein concentration and grain hardness were determined using near-infrared reflectance (AACC method 39-10, 2000) with the Foss NIR Systems Feed and Forage 6500 instrument (Foss, Hillerød, Denmark), expressed at 12.5% moisture. Nitrogen use efficiency (agronomic efficiency; NUE) and grain nitrogen use efficiency (GNUE) were calculated according to Gauer et al. (1992).

$$\text{NUE}\left[\frac{\text{kg yield increase}}{\text{kg of nutrient applied}}\right]=\frac{\text{Crop yield}_{\text{fertilized plot}}\text{-Crop yield}_{\text{unfertilized plot}}}{\text{N fertilizer rate}}$$

$$\text{GNUE [\%]}=\frac{\text{Grain N uptake}_{\text{fertilized plot}}\text{-Grain N uptake}_{\text{unfertilized plot}}}{\text{N fertilizer rate}}*100$$

$$\text{Grain N uptake}=\text{Grain yield}\times\text{Grain N concentration}$$

Wheat grain subsamples (total flour milled kernels in g) were conditioned with distilled water one day prior to milling with a desirable moisture content of 12.5% (moisture for milling in %). Milling was done using the experimental mill “Quadrumat Sr.” (C.W. Brabender Instruments Company, Duisburg, Germany). Flour yield was calculated as:

$$\text{Flour yield (\%)}=\frac{\text{(100-flour moisture)}\times\text{total flour milled kernels}}{\text{100-moisture for milling}}\times 100$$

Flour protein and moisture were measured using the Perten Instruments DA 7200 Protein Concentration Analyser (Perten Instruments, Hägersten, Sweden) expressed at 14.0% moisture. Loaf volume is an indicator of the dough’s capacity to retain gas during the fermentation process of bread-making and was measured by rapeseed displacement (Shogren and Finney, 1984).

3.3.4 Statistical analysis

Data were analyzed using SAS 9 software (SAS Institute, 2002). Data were blocked by tillage environment and split by N fertilization treatment. First, data were analyzed with a mixed model for significant effects of tillage and cropping cycle and interactions between tillage × N treatments and tillage × cropping cycle. All variables were significantly affected by cropping cycle due to high climatic variability and therefore data were analyzed separately for each cropping cycle. Then, PROC Mixed was applied for data sets separated by cropping cycle and tillage environment. Kenward Rogers adjustment was used to get better estimates of F probability and standard errors of fixed effects for small sample sizes. All data presented are means for the three replicates. Residuals were normally distributed and differences between means were analyzed using ANOVA. Multiple comparisons were made using the least significant difference test at P<0.05 to determine significant effects. Unless stated otherwise, average values and F-probabilities are presented without including the 0 kg N ha^{-1} control treatments.

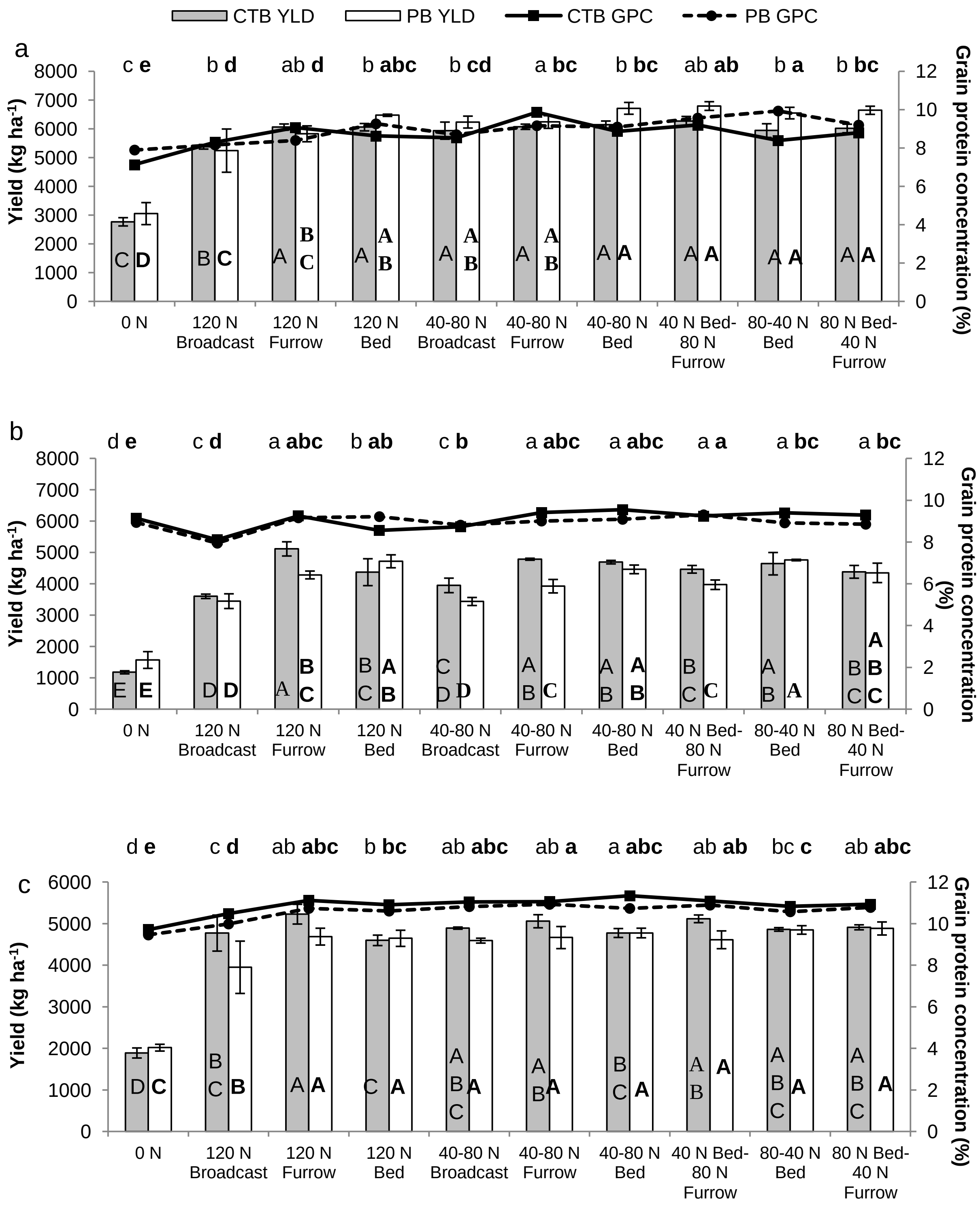
Principal component analysis (PCA) was performed with R prcomp (www.cran.r-project.org) to construct a lower-dimension summary of the quality parameters. With PCA, the correlated quality parameters are described in terms of a new set of uncorrelated variables (principle components), each of which is a linear combination of the original variables. The PCA analysis was interpreted graphically by constructing a biplot (Everitt 2005).

3.4 Results

3.4.1 Yield and N use efficiency

The effect of tillage practice on grain yield was not significant in any of the cropping cycles (Table 4). Variability in yield among the cropping cycles was relatively high, with an average yield for fertilized treatments of 6.15, 4.30, 4.77 and 3.36 t ha^{-1} in 2011/12, 2012/13, 2013/14 and 2014/15, respectively. Yield showed high yearly variability, decreasing from 2011/12 to 2012/13 by 30.5%, then increased from 2012/13 to 2013/14 by 11% and finally decreased again 29.5% from 2013/14 to 2014/15. N treatment significantly affected wheat grain yield in PB in all four cropping cycles, but did not significantly affect yield in CTB in 2013/14 (P=0.138) or 2014/15 (P=0.352). From 2012/13 to 2014/15 the broadcast application of fertilizer (basal or split) resulted in significantly lower yields than bed or furrow application in PB (Fig. 2). In 2011/12 and 2012/13, significantly lowest yields in CTB were also obtained with 120 N Broadcast and 40-80 N Broadcast (Fig. 2ab). In the first two cropping cycles, bed application resulted in significantly higher yields than furrow application on PB, whereas on CTB both methods had similar yields. In the last two cropping cycles, no clear difference between bed and furrow application on PB was found, and in 2014/15 the 120 N Furrow even had the highest yield on PB (Fig. 2d). Nitrogen use efficiency showed trends similar to wheat yield and was affected by tillage environment in 2012/13 (P=0.017) but not in the remaining cropping cycles. Averaged over four cropping cycles, NUE was greater in CTB than PB (24.5 and 22.2

kg kg^{-1}, respectively; P=0.0002). Nitrogen treatment did not significantly affect NUE in CTB in 2013/14 (P=0.138) or 2014/15 (P=0.353), but did significantly affect NUE in PB in all cropping cycles. An interaction between tillage environment and N treatment for yield and NUE was recorded in 2012/13 (P=0.024).



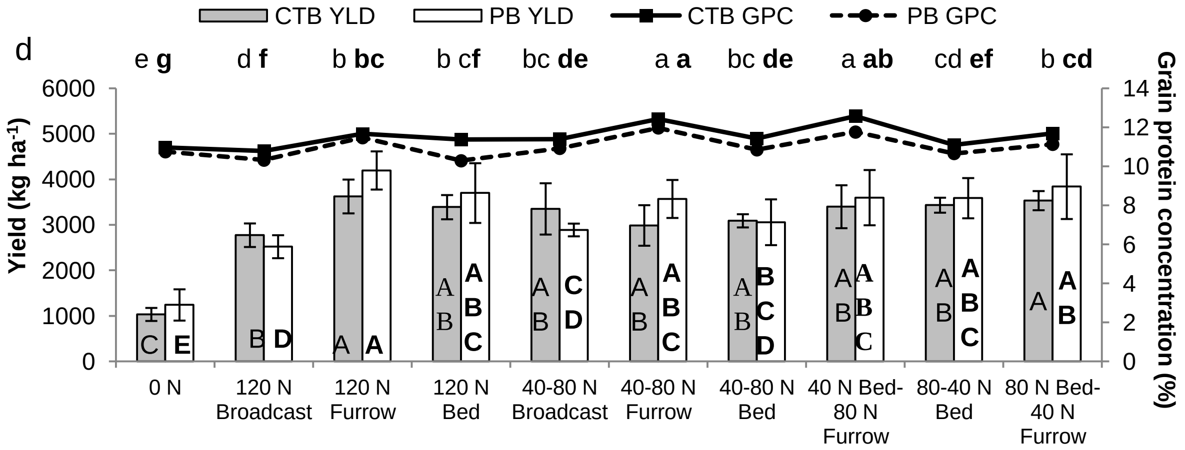


Figure 2 Average yield (YLD; kg ha^{-1}) and grain protein concentration (GPC; %) for cropping cycle 2011/12 (a), 2012/13 (b), 2013/14 (c) and 2014/15 (d) for two tillage-straw systems (CTB- conventionally tilled beds with straw incorporation; PB- permanent beds with residue retention) in the experimental station near Ciudad Obregón, Sonora, NW-Mexico. Yield is presented in bars, grain protein concentration in lines. Fertilizer treatment abbreviations as in Table 3. Error bars are the standard deviation of the average yield per repetition. Means with the same letter are not significantly different by least significant difference test at P<0.05. Capital letters are used for yield and lower-case letters for grain protein concentration; plain letters show CTB, bold letters show PB.

3.4.2 Grain quality and grain N use efficiency

Considering the four-year average, thousand kernel weight (TKW) was affected by tillage (P<0.0001) and N fertilizer treatment (P=0.01). The TKW was higher for CTB than PB (41.6 and 40.5 g, respectively). Separated into cropping cycles, there was no significant effect of tillage on TKW in 2011/12 (P=0.662) and 2014/15 (P=0.260). In 2011/12, N fertilizer treatment did not affect TKW (P=0.121, Table 4). Thousand kernel weight was higher in the first cropping cycle than the subsequent cycles (43.0, 40.1, 40.0 and 40.4 g, respectively). Thousand kernel weight was highest for CTB with a single broadcast or bed application and for PB with 120 N Broadcast.

Test weight was significantly affected by tillage in all cropping cycles except 2014/15 (P=0.42). In three out of four cropping cycles, test weight was higher in CTB than PB. N management also significantly affected test weight for all seasons except 2012/13 (P=0.271). Test weight decreased over the four cropping cycles and was 83.0, 81.8, 81.0 and 79.3 kg hL^{-1}, respectively. Under both environments the highest test weights were obtained with 40 N Bed-80 N Furrow or 80 N Bed-40 N Furrow. Grain hardness and flour protein concentration were significantly affected by tillage or N fertilizer treatment over four cropping cycles, but flour yield was not (Table 4).

Table 4 F-Probabilities (significance values) of tillage environment (TIL), nitrogen fertilization (N) and their interaction (TIL×N) on yield (YLD), biomass (BM), thousand kernel weight (TKW), test weight (TW), grain protein concentration (GPC), grain hardness (GHRD), flour yield (FYLD), flour protein concentration (FPR), loaf volume (LVOL) and nitrogen use efficiency (NUE) recorded for four cropping seasons (* P<0.001; ** P<0.0001).

Cycle		YLD	BM	TKW	TW	GPC	GHRD	FYLD	FPR	LVOL	NUE
2011/12	TIL	0.173	0.121	0.662	**	0.224	*	0.001	1	**	0.858
	N	*	0.002	0.121	*	0.002	**	0.552	**	**	*
	TIL×N	0.379	0.266	0.133	0.299	0.012	0.330	0.044	0.009	0.064	0.379
2012/13	TIL	0.079	*	0.021	0.006	0.343	0.013	0.590	**	**	0.017
	N	**	**	0.017	0.271	**	0.133	**	**	**	**
	TIL×N	0.024	0.007	0.057	0.766	0.01	0.268	0.006	0.011	0.001	0.024
2013/14	TIL	0.126	0.085	**	0.029	0.058	0.044	0.015	0.087	0.302	0.067
	N	0.042	0.119	0.016	0.001	**	*	0.013	**	**	0.042
	TIL×N	0.195	0.274	0.173	0.673	0.580	0.026	*	0.004	0.094	0.196
2014/15	TIL	0.665	0.764	0.260	0.420	0.015	0.175	0.827	0.014	0.213	0.872
	N	0.006	0.002	0.030	0.054	**	0.024	0.616	**	**	0.005
	TIL×N	0.524	0.818	0.616	0.312	0.17	0.099	0.319	0.234	0.246	0.524

Grain protein concentration increased from 2011/12 to 2014/15 and was 8.9%, 9.0%, 10.8% and 11.3%, respectively. In the first two cropping cycles, tillage treatment did not significantly affect GPC (Table 4). In the last two cropping cycles, GPC for CTB was significantly higher than PB (11.3 % and 10.9%, respectively) (Fig. 2cd). The effect of N management on GPC was significant for all tillage environments and cropping cycles and an interaction between tillage practice and N treatment was found in the first two cropping cycles. Basal broadcast application resulted in significantly lower GPC than the other fertilized treatments in all tillage environments and cropping cycles, except 2014/15 in PB where 120 N Bed obtained similar GPC to 120 N Broadcast (Fig. 2). Control treatments without N fertilizer had higher GPC than 120 N Broadcast in 2012/13 (9.0% and 8.0%, respectively) and in 2014/15 (10.9% and 10.6%, respectively). For CTB, the highest GPCs were recorded for 40-80 N Furrow, 40 N Bed-80 N Furrow and 40-80 N Bed. For PB, the highest GPCs were recorded in the first two cycles for 40 N Bed-80 N Furrow and 80-40 N Bed and in the last two cycles for 40-80 N Furrow.

Baking performance expressed by loaf volume was affected by tillage in two out of four cropping cycles (not in 2013/14 P=0.302 or 2014/15 P=0.213) and by N fertilizer treatment in all four cropping cycles (P<0.0001). An interaction between tillage practice and N treatment was only observed in 2012/13. In CTB, highest loaf volume was achieved with 40-80 N Furrow and 40 N Bed-80 N Furrow. In PB, treatments with bed splitting achieved highest loaf volume (40 N Bed-80 N Furrow, 40-80 N Bed, 80-40 N Bed).

Tillage environment had a significant effect on GNUE in 2012/13 (P=0.039) and 2013/14 (P=0.038), with GNUE 10% and 8% higher for CTB than PB, respectively (Table 4). Grain NUE for PB was highest in 2011/12 (48.5%), and was 44.4% in 2013/14, 36.4% in 2014/15 and 33.8% in 2012/13. In CTB, GNUE was 48.7%, 43.4%, 52.1% and 39.2% from 2011/12 to 2014/15, respectively. The lowest GNUE for all cropping cycles and both tillage environments was recorded with 120 N Broadcast (24% in PB and 34% in CTB). For PB, treatments with highest GNUE were 80-40 N Bed in 2011/12 (59.8%), 120 N Bed in 2012/13 (43.2%), 80 N Bed-40 N Furrow in 2013/14 (49.1%) and 120 N Furrow in 2014/15 (51.2%). Highest GNUE values in CTB were recorded with 120 N Furrow (52%) or 40-80 N Furrow (50%) or 40 N Bed-80 N Furrow (48.7%).

3.4.3 Correlations and principle component analysis for yield and quality parameters

Thousand kernel weight only weakly correlated with other yield and quality parameters and test weight highly correlated with biomass (Pearson's r = 0.82). Test weight moderately correlated with TKW (Pearson´s r = 0.50). In both tillage environments the correlation between yield and GPC was negative (Pearson's r = -0.31 in PB and Pearson's r = -0.55 in CTB, data not shown). This negative correlation disappeared when cropping cycles were analyzed separately and there was a positive weak to moderate relationship (Pearson's r = 0.53, 0.39, 0.65 and 0.16 for 2011/12, 2012/13, 2013/14 and 2014/15, respectively). Loaf volume was highly related to flour protein for all four cropping cycles (Pearson's r = 0.87) (Table 5).

Table 5 Correlation coefficients (Pearson's r) between yield parameters for bread wheat, averaging two tillage environments and four cropping cycles, in the experimental station near Ciudad Obregón, Sonora, NW-Mexico.

r	TW	TKW	GHRD	FYLD	GPC	FPRO	LVOL	BM	YLD	NUE
TW	1									
TKW	0.50**	1								
GHRD	-0.08	0.03	1							
FYLD	-0.23*	0.38**	0.19*	1						
GPC	-0.73**	-0.26**	-0.24**	0.27*	1					
FPRO	-0.76**	-0.28**	-0.26**	0.26*	0.97**	1				
LVOL	-0.64**	-0.42**	-0.34**	-0.09	0.84**	0.87**	1			
BM	0.82**	0.39**	-0.11**	-0.08	-0.50**	-0.55**	-0.46*	1		
YLD	0.80**	0.43**	-0.17**	-0.05	-0.42*	-0.47**	-0.39	0.97**	1	
NUE	0.62**	0.27**	-0.29**	-0.07	-0.25**	-0.27**	-0.19*	0.85**	0.82**	1

BM: biomass, FPRO: flour protein concentration, FYLD: flour yield extraction, GHRD: grain hardness; GPC: grain protein concentration, LVOL: loaf volume; NUE: agronomic nitrogen use efficiency, TKW: thousand kernel weight, TW: test weight, YLD: grain yield (* $P<0.001$; ** $P<0.0001$)

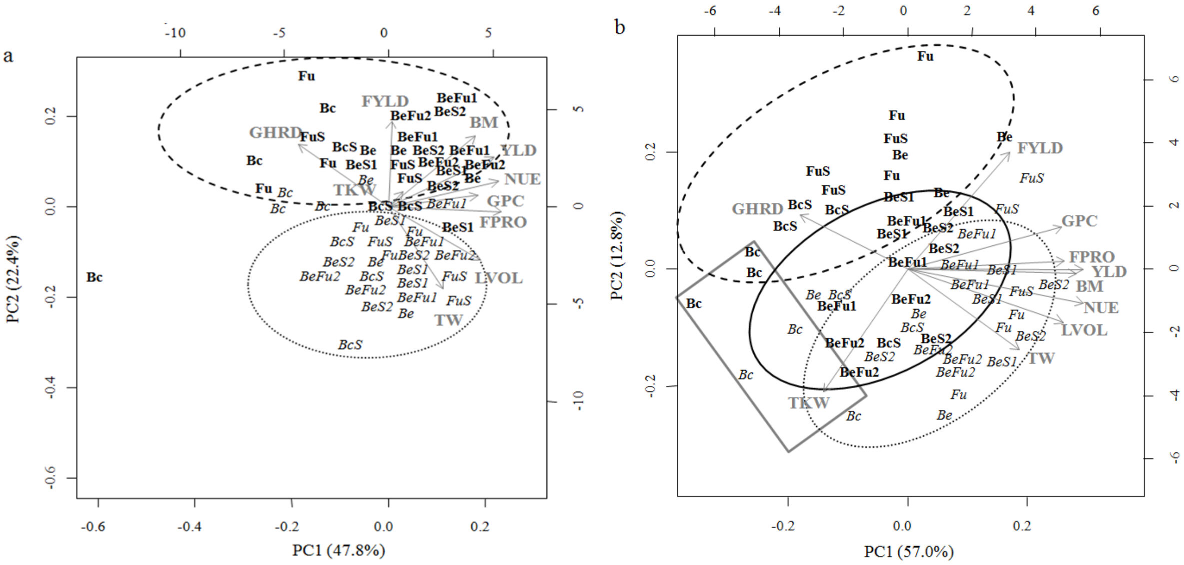
Principal component analysis revealed a visible grouping of treatments in terms of quality parameters and environments in 2011/12, 2012/13 and 2013/14 and to a lesser extent in 2014/15. The 0 kg N ha^{-1} control treatments were excluded from the analysis so as to not obscure treatment tendencies. In 2011/12, the first principal component explained 47.8% and the second 22.4% of the variance (Fig. 3a). Tillage environments (PB: dashed circle, CTB: dotted circle) were clearly grouped and there were positive trends toward yield and biomass for PB and toward test weight for CTB. The bed-furrow split application treatments (BeFu1, BeFu2) tended to have higher yields, flour protein and loaf volume in both environments.

In 2012/13 (Fig. 3b), grouping of tillage environments was less clear and N treatments were mixed, however, there were clear yield and quality advantages for CTB. The first two principle components explained 69.8% of total variance. Broadcast treatments for both environments were separated towards low yield and quality (grey box). Split bed and split furrow treatments for PB had yield and quality characteristics similar to those of treatments on CTB (black circle). Plots with broadcast application

(Bc and BcS) were all in the left quadrants of the biplot, with low yield, GPC and NUE.

Clear grouping of tillage environments and positive trends towards yield, biomass and most quality parameters for CTB were evident in 2013/14 (Fig. 3c). The first principal component explained 46.5% and the second 19.7% of the variance. The N fertilizer treatments with furrow application tended to result in higher yields, NUE and GPC for CTB (grey box) than PB. Plots with 120 N Broadcast on PB were separated from the other plots by low grain yield and quality.

For the 2014/15 cropping cycle (Fig. 3d), no clear separation of tillage environments was found and the first two principal components accounted for 64.3% of the variance in the original variables. A strong correlation between grain and flour protein concentration, biomass, yield and NUE was observed. All plots with broadcast application (Bc and BcS) were found in the left quadrants of the biplot, with the exception of one plot with 40-80 N Broadcast on CTB.



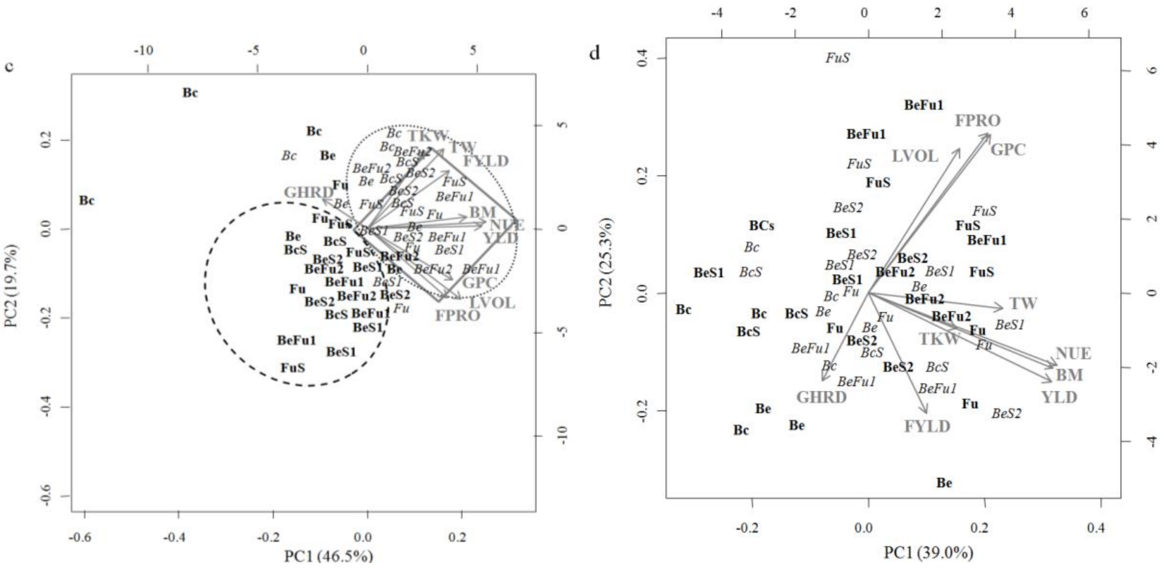


Figure 3 Bi-plot of the first two components of the principle component analysis for quality and yield parameters for nine treatments and for cropping cycle 2011/12 (a), 2012/13 (b), 2013/14 (c) and 2014/15 (d) in the experimental station near Ciudad Obregón, Sonora, NW-Mexico. Tillage-straw system Italic: CTB-straw incorporated, bold: permanent beds; N fertilization- N treatment abbreviations according to Table 3; Quality and yield parameters- BM: biomass, FPRO: flour protein concentration, FYLD: flour yield extraction, GHRD: grain hardness; GPC: grain protein concentration, LVOL: loaf volume; NUE: agronomic nitrogen use efficiency, TKW: thousand kernel weight, TW: test weight, YLD: grain yield

3.5 Discussion

Grain yields were not significantly affected by tillage system in any of the years and this is consistent with a meta-analysis finding showing yield advantages of CA compared to conventional tillage under rainfed conditions in dry climates but generally not when in the absence of moisture stress (Pittelkow et al. 2014). This also coincides with findings from previous studies at the same site (Verhulst et al. 2011; Grahmann et al. 2014). The highest average yield in the first cropping cycle (2011/12) may originate from residual N from past N applications of 180 kg N ha^{-1}. This experiment was first conducted for five cropping cycles (2005/2006-2009/2010) with an N dose of 180 kg N ha^{-1} and no significant effect of application method or timing was found with this application rate (data not reported). Therefore, the N dose was reduced from 180 kg N ha^{-1} to 120 kg N ha^{-1} from 2010/11 onwards, while timing of N treatments and mode of application remained unchanged. The low yield in 2014/15 was probably due to a combination of low number of cold hours and solar radiation near anthesis, and the high average minimum temperature (Table 1); all factors that have been reported to negatively affect wheat yields (Ferris et al. 1998; Lobell et al. 2005; Valencia et al. 2009). Additionally, due to the climatic conditions, there was increased aphid (*Metopolophium dirhodum)* incidence in the experiment.

The 120 N Broadcast treatment increased yield but not GPC, compared with the 0 N control, in two out of four cropping cycles, indicating that the fertilizer was used for biomass production, but translocation of mineral N into the grain and conversion to protein by protein biosynthesis was diminished (Masclaux-Daubresse et al. 2010). This was confirmed by the relatively low overall GNUE in PB (24%) and CTB (34%) for 120 N broadcast treatments**.** The main pathways for loss of broadcast applied urea in irrigated systems are surface runoff, volatilization of NH_3 and leaching of mineral N. Urea is also subject to immobilization which does not count as direct fertilizer loss, but N fertilizer is not available for the corresponding cropping cycle. Immobilization of N fertilizer is increased by surface residue retention (Rice and Smith 1984) and leads to reduced plant N uptake and grain N accumulation. Disking the urea into the soil minimizes contact between fertilizer and crop residues and reduces N immobilization (Rice and Smith 1984; Rao and Dao, 1996; Schoenau and Campbell 1996). Our results show a clear advantage of furrow and bed application over broadcast application to increase wheat yield and quality in both CTB and PB with irrigation. Adjusting fertilizer placement is particularly important in the Yaqui Valley where still most of the farmers apply their fertilizers by broadcast or as ammonia gas in irrigation water (Matson et al. 2005; Fig. 2).

Campbell et al. (1993) suggested that the response to the N fertilizer treatments decreased over the years because the available mineral N increased under no-till management over years with adequate fertilization. However, in CTB, N fertilizer management only had a significant effect on yield in the first two cropping cycles and the effect of N management was smaller compared to PB (Table 6). In 2013/14 and 2014/15, the timing and placement of N did not affect yield and GNUE in CTB. It is likely that in tilled systems the effect of N management is smaller due to regular soil ploughing that incorporates crop residues and ensures homogenous soil and residual fertilizer N distribution in the first 30 cm of the soil profile. On the other hand, in PB soil movement is absent and residues are retained at the surface where they can come in contact with surface-applied fertilizer. Additionally, in Vertisols cracks are preserved in PB which makes preferential fertilizer flow more likely to occur resulting in more heterogeneous soil mineral N availability, nutrient shortage and hence reduced N plant uptake (Bandyopadhyay et al. 2003; Greve et al. 2010). This makes precise and optimal N management essential in CA to achieve stable yields and acceptable grain quality.

Table 6 Overall p-values for N-management of permanent beds (PB) and conventionally tilled beds (CTB) (analyzed separately) for four cropping cycles (2011/12-2014/15) and selected parameters.

Year	2011/12		2012/13		2013/14		2014/15	
Treatment	PB	CTB	PB	CTB	PB	CTB	PB	CTB
YLD	0.006	0.026	<	0.0008	0.049	0.138	0.019	0.352
GPC	0.001	0.051	<	<	0.0002	0.033	<	<
GNUE	0.0001	0.006	<	0.0001	0.002	0.049	0.003	0.147

(YLD: yield, GPC: grain protein concentration, GNUE: grain nitrogen use efficiency)

For PB, split application had positive effects on most of the yield and quality parameters particularly with the pre-plant application on the bed and the one at first node in the furrow. This was also confirmed for durum wheat at the same study site, however, application of all fertilizer (150 kg N ha^{-1}) before planting in the furrow significantly decreased quality and had similar GPC to 0 kg N ha^{-1} control plots (Grahmann et al. 2014). Farmers need to weigh the benefit of split application against the cost of an additional field operation. Velasco et al. (2012) found in four out of six experiments for bread wheat that yield, aboveground biomass and GPC were greater for split N application (applied at tillering (Zadok 24) and flag leaf stage (Zadok 39)) than for full N application at tillering. Several studies have found that N fertilizer applications at crop anthesis, rather than before planting, improved NUE and GPC in bread wheat without decreasing soil N uptake (Wuest and Cassman 1992; Dawson et al. 2008). This should be investigated further.

The tillage environment significantly affected GPC, which was lowest for PB in three out of four cropping cycles due to higher NUE and greater N uptake in conventional systems with straw incorporation. This coincides with findings from Huggins and Pan (1993), Strong et al. (1996), Lyon et al. (1998), Lopez-Bellido et al. (1998) and Lopez-Bellido et al (2001). Blackshaw et al. (2000) did not find any significant effect of tillage on GPC. In 2011/12, average grain yields were highest and average GPC was lowest compared to the other three cropping cycles. This was partly explained by the dilution effect and reflected in the negative correlation between yield and GPC (Table 5). High variability of GPC between years was due to a considerable year-on-year effect as detected by Lopez-Bellido et al. (2001).

Other grain quality parameters showed similar tendencies and were higher under CTB. Test weight was higher in CTB during three cropping cycles, contrary to findings of Lopez-Bellido et al. (2001) who did not find any significant effect of tillage on test weight. However, Lopez-Bellido et al. (1998) found a significantly higher test weight with no-tillage. Coinciding with Maali and Agenbag (2006), loaf volume was higher in CTB than PB. Loaf volume of bread wheat has been reported to be principally affected by environment (Nel et al. 2000), but in the present study it mainly depended on N fertilization and less on tillage practice. The high flour protein and loaf volume correlation coincided with findings from Panozzo and Eagles (2000; Table 5). This high correlation implies that the achievement of high end-use quality for bread wheat depends on the achieved GPC, since the other quality parameters like flour protein and loaf volume are influenced by the latter.

3.6 Conclusions

Consideration of bread wheat quality when evaluating cropping systems is increasingly important due to improving wheat value chains. Results for the different tillage and N fertilizer placement and timing treatments were not consistent for all examined parameters of yield and quality for bread wheat and varied among cropping cycles. In both tillage systems, an increase in minimum temperatures and decrease in solar radiation led to significant yield reductions. A pre-planting broadcast application of 120 kg N ha^{-1} resulted in the lowest wheat yields and quality in both tillage systems. The most efficient placement of N fertilization for PB was a split bed application in combination with furrow application near first node. In CTB, best results were obtained with furrow application (single pre-plant or split). Tillage did not significantly affect yield, but PB with surface residue retention did negatively affect GPC and other quality parameters compared to CTB. This shows the need to differentiate between tillage systems and to identify the optimal method of fertilizer application to improve bread wheat quality in PB. We recommend switching from broadcast application of urea to a combination of disked in bed and furrow application which ideally should be split into at least two applications in cropping systems with conservation agriculture. In future studies, soil samples need to be taken to determine mineral soil N and evaluate the N efficiency for the whole cropping system. Additionally we suggest experiments be undertaken with later timing and a third application of N.

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Chapter 4

4 Ion exchange resins to estimate nitrate leaching from a furrow irrigated wheat-maize cropping system under different tillage-straw systems

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4 Ion exchange resins to estimate nitrate leaching from a furrow irrigated wheat-maize cropping system under different tillage-straw systems

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Keywords:

Nitrate leaching; Permanent raised beds; Ion exchange resins; Fertilizer; Residual N

4.1 Abstract

Nitrate (NO_3-N) leaching from agricultural soils can lead to substantial losses of fertilizer nitrogen (N) and cause considerable contamination of aquatic ecosystems and groundwater. This study aimed at estimating NO_3-N leaching losses for three tillage-straw management systems in the intensely cropped Yaqui Valley, Northern Mexico using ion exchange resins. To this end data were collected in 2013/2014 from a tillage experiment established in 2005 as a randomized complete block design with two replications and three subplots on a Hyposodic Vertisol. Tillage-straw treatments were conventionally tilled beds with incorporated crop residue (CTB-straw incorporated), permanent beds with crop residue retained at the surface (PB-straw retained) and permanent beds with residue burning (PB-straw burned). Ion exchange resins were installed at 90 cm depth in a consecutive crop rotation of wheat (*Triticum durum* L.) and maize (*Zea mays* L.) for 6 and 5 months, respectively (from first pre-plant fertilization to harvest). Leaching losses were higher with maize than with wheat cultivation (68.2and 53.5 kg ha^{-1} $season^{-1}$ NO_3-N, respectively; P=0.25). Tillage-straw treatment did not significantly affect NO_3-N leaching in wheat, but in maize. NO_3-N leaching for wheat was 51.1 kg ha^{-1} $season^{-1}$ NO_3-N in CTB-straw incorporated, 60.8 kg ha^{-1} $season^{-1}$ NO_3-N in PB-straw retained and only 46 kg ha^{-1} $season^{-1}$ NO_3-N in PB-straw burned . For maize, overall leaching losses were highest for PB-straw retained (81.9 kg ha^{-1} $season^{-1}$ NO_3-N), followed by 75.6 kg ha^{-1} $season^{-1}$ NO_3-N for CTB-straw incorporated and 47.7 kg ha^{-1} $season^{-1}$ NO_3-N for PB-straw burned. Soil NO_3-N concentrations were significantly affected by sampling date and depth. PB-straw burned had highest residual soil NO_3-N after crop harvest. Ion exchange resins-based NO_3-fluxes displayed high spatial variability, therefore a large number of repetitions were necessary. As 19% of N applied to wheat and 34% of N applied to maize was lost through leaching, farming practices that could lower the risk of nitrate contamination during cropping should be promoted. Additional multi-annual studies are necessary to assess the effects of reduced irrigation, climatic variation and different fertilizer application on nutrient leaching in different tillage-straw systems in Northwestern Mexico.

4.2 Introduction

Nitrogen fertilizer prices have risen more than 2.5-fold over the past decade due to cost increases of petrol products and transportation and an overall increasing global demand (Hirel et al., 2007; Huang 2009; Agricultural Prices 2013). Over the past 50 years, N fertilizer application has increased 20-fold and was 110 Mio t in 2013 (IFA, 2015). Its application is projected to increase to 180 Mio t by 2030 (FAO, 2011). NO_3-

N can move easily with water beyond the root zone into surface and ground waters and due to sub-optimal soil, irrigation and fertilizer management, globally large amounts of N are lost through NO_3-N leaching (Cassman et al., 2002). An efficient and non-polluting approach to mineral fertilizer use is essential to prevent excessive N losses, particularly for irrigated, high-input agro-environments, such as our study area, from where eutrophication of water bodies and the destruction of water ecosystems have been reported (Matson et al., 1998; Mitsch et al., 2001; Beman et al., 2005). As high nitrate and nitrite in drinking water resulting from the transport of leachates in lakes, rivers and ground water may pose a risk to human and animal health, a concentration limit of 10 mg NO_3-N L^{-1} has been proposed (Townsend et al., 2003; Cecena and Vega, 2011).

In the 2013/14 wheat season in the Yaqui Valley, wheat was seeded on almost 200,000 ha and grain wheat yields averaged 6.2 t ha^{-1} (SAGARPA and SIAP, 2014). This included fertilizer application rates averaging 297 kg N ha^{-1} (Lares-Orozco et al., 2016) which in addition to enhanced leaching risks also represented farmers´ highest component of direct production costs (Matson et al., 1998). Generally, 75% of mineral fertilizer is applied broadcast approximately 20 days before planting as urea or through injection of anhydrous ammonium. The remainder is applied near the first node stage of plant development (Ortiz-Monasterio and Raun, 2007). Although locally only a small percentage of total N inputs is reportedly transported via surface water to the coast of Sonora (<4%; Ahrens et al., 2008), phytoplankton net production and macroalgae growth are altered and this leads to bottom water hypoxia which negatively affects the fishery industry (Piñón-Gimate et al., 2009).

In the Yaqui Valley it is common practice to grow winter wheat and summer maize on raised beds with furrow irrigation, incorporating residues through tillage after harvest. Summer maize is planted on around 6,000 ha in the Yaqui Valley and yields 5-5.5 t ha^{-1}. In recent times, permanent beds, a conservation agriculture (CA) management practice under irrigated conditions, have been promoted to increase sustainability by reducing tillage to a minimum, only reshaping beds as needed, and retaining and distributing crop residues on the surface (Hobbs et al., 2008). Soils with minimum soil movement or permanent raised beds combined with residue retention were reported to have larger and more water-stable aggregates than soils with residue removal or conventionally tilled soils (Limon-Ortega et al.,2006; Lichter et al., 2008). Improved aggregate stability prevents soil surface sealing. Additionally, CA systems were reported to have an increased number of earthworm biopores (Baumhardt and Lascano, 1996). As a result, water infiltration rates are generally higher on soils with minimum soil movement and residue retention than conventionally tilled soils with or without residue removal (Verhulst et al., 2011a; Verhulst et al., 2011b). Higher infiltration rates increase the risk of increasing N leaching losses in CA systems (Boddy and Baker 1990; Singh and Malhi 2006). In contrast, various studies have found higher NO_3^- leaching under conventional tillage due to increased N mineralization (Angle et al., 1993; Randall and Iragavarapu, 1995; Jackson et al., 2003). Slower nitrification in zero-tillage during fallow periods could reduce the potential for NO_3^- leaching (Power and Peterson, 1998).

Most approaches to measure leaching losses in conventional agriculture are based on point measurements such as by lysimeters (Wegehenkel et al., 2008; Goss and Ehlers, 2009) or suction plates (Siemens and Kaupenjohann, 2004; Kasteel et al., 2007). These methods allow a dynamic and time-specific soil-water-solution sampling, but they disturb the soil structure during installation and therefore do not allow representative measurements in systems with zero-tillage and residue retention. The use of ion exchange resin cartridges allows to determine cumulative leaching losses at the plot-scale if proper care is taken to maintain the original soil structure and cartridges are properly screened for consistency of adsorption results (Bischoff, 2009; Predotova et al., 2011; Siegfried et al., 2012). Several authors have confirmed the reliability of ion exchange resins in cumulative nutrient-leaching studies (Lehmann et al., 2001; Lang and Kaupenjohann, 2004; Bischoff, 2007) where resins stay in the soil for the entire vegetative period and thus provide an accumulated value of nutrients passing through the soil profile (Skogley and Dobermann, 1996; Bischoff, 2007). Typically after harvest, resin cartridges are removed from the soil and the adsorbed ions are extracted and analyzed in the laboratory (Schnabel, 1983; Skogley et al., 1996).

Previous studies in the Yaqui Valley have measured gaseous N emissions from soils (Matson et al., 1998; Panek et al., 2000) and streams (Harrison and Matson, 2003; Harrison et al., 2005), but studies on leaching losses are limited and only based on lysimeter and suction cup measurements or modeling approaches (Riley et al., 2001). The objective of this research therefore was (1) the evaluation of resin cartridges to estimate total leaching losses of nitrate ions over the cropping cycle and (2) the quantification of N losses by nitrate leaching in different tillage management systems and for two different crops under irrigation in the intensively cropped Yaqui Valley of northwest Mexico.

4.3 Materials and methods

4.3.1 Study site

The long-term cropping systems trial is located at CENEB (Campo Experimental Norman E. Borlaug), near Ciudad Obregón, Sonora, Mexico (27.33°N, 109.09°W, 38 m a.s.l.). The site has an arid climate, with a 20 year average annual rainfall of 304 mm and an annual reference evapotranspiration of approximately 1,800 mm. Between 1993 and 2014, total precipitation ranged from 160 to 570 mm. Rainfall is summer dominant and only 20% occurs during the wheat-growing season (November-May; Verhulst et al., 2011b). During the 2013/14 growing cycle mean temperature was 19.7°C for wheat and 29.7°C for maize. Monthly average temperatures ranged from 8.5°C minimum temperature in January 2014 to 38.9°C maximum temperature in June 2014. Total rainfall was 55 mm for wheat and 363 mm for maize (Fig. 1).

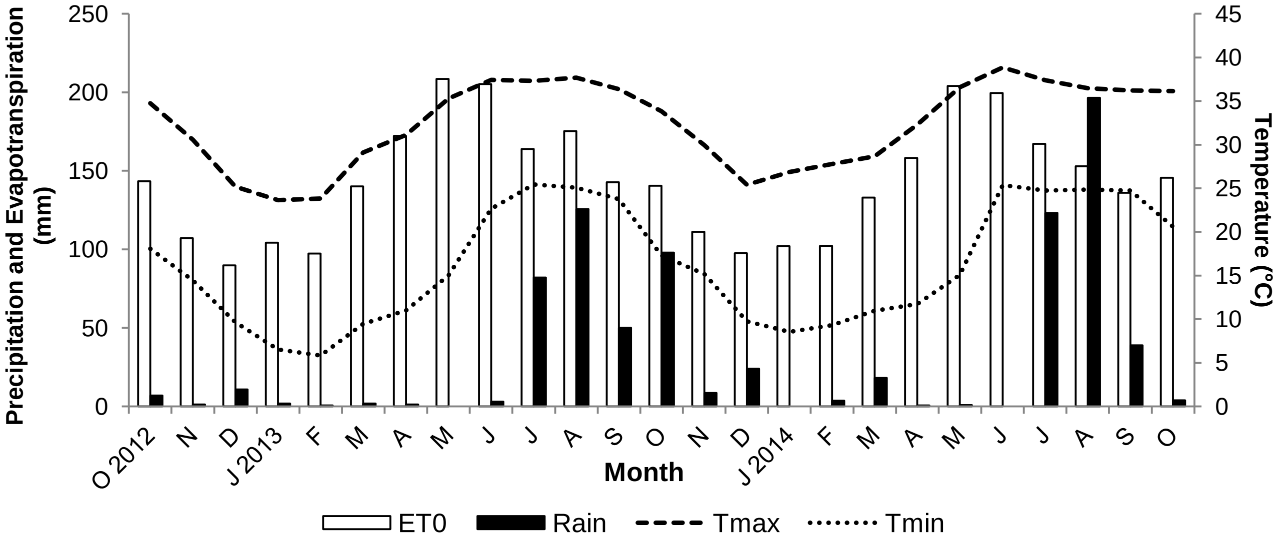

Figure 1 Climate for the study period in Ciudad Obregón, NW-Mexico. Data provided by CONAGUA (2007), Mexico DF, Mexico. ET0 = Evapotranspiration, Tmax = Maximum temperature, Tmin = Minimum temperature

The soil at the experimental site was classified as a Hyposodic Vertisol (Calcaric, Chromic) according to the World Reference Base soil classification system (IUSS Working Group, 2007) or a fine, smectitic Chromic Haplotorrert according to the USDA Soil Taxonomy system (Soil Survey Staff, 2010). Throughout the upper 2 m depth soil organic matter is <1.2% with pH >8. At 0-70 cm depth, the particle size fraction contains 33% sand, 17% silt and 50% clay. At 70-120 cm depth, sand decreases to 24%, 16% silt and clay increases to 60% (Verhulst et al., 2009).

4.3.2 Long term experiment

The long-term trial was established in 2005 and consists of 17 treatments, which differ in tillage-straw system and rotation. In this study only three treatments were used, (1) CTB-straw incorporated: conventionally tilled raised-beds (CTB; tilled after each crop with a disk harrow to 20 cm after which new beds were formed), wheat and maize residues were incorporated by tillage; (2) PB-straw burned: permanent raised-beds (PB; zero-tillage with repeated reuse of existing beds, which were reformed in the furrows without disturbance of the tops of the beds), residues of both wheat and maize are burned; (3) PB-straw retained: PB, maize and wheat residues are kept on the soil surface. The experimental design is a randomized complete block with two repetitions. Each plot consists of eight beds (80 cm wide), 6.4 m wide and 130 m long (832 m^2) and is divided into 3 subplots, with an area of 277.3 m^2 each.

Wheat and maize are irrigated and managed in annual succession. The durum wheat cultivar "Movas C-2009", which is commercially used in the Yaqui Valley, was sown on 13 December 2013 at a seeding rate of 120 kg ha^{-1}. Wheat was fertilized with 103 kg N ha^{-1} and 22.7 kg P ha^{-1}, disked in the center of the beds before planting (19 November 2013) and received a second fertilization of 175 kg N ha^{-1} disked in the furrow before the first auxiliary irrigation (27 January 2014). Wheat flowered on 2 March 2014 and was harvested on 30 April 2014. The commercial, heat tolerant maize variety "H431" was planted on 17 June 2014 and received 103 kg N ha^{-1} and 22.7 kg P ha^{-1}, disked in the beds before planting (29 May 2014) and a second application of 100 kg N ha^{-1} was disked in the furrow before the first auxiliary irrigation (15 July 2014). Maize was harvested on 15 October 2014. Nitrogen was applied in both crops as urea and P in form of Monoammonium Phosphate (MAP, 11-52-0). At each irrigation time the experiment was watered for two days, starting at day one with block one and day two with block two. Total irrigation water per season and crop was approximately 500 mm. For wheat, treatments were irrigated on 20/21 November, 29/30 January, 24/25 February, 21/22 March and 3/4 April and for maize on 2/3 June, 25/26 June, 16/29 July (heavy rainfall on 16 July delayed irrigation of the second block), 2/3 September and 18 September. Irrigation water was analyzed for nutrient concentrations following standard procedures and had low nutrient concentrations. Total N input by irrigation water amounted 9.2 kg ha^{-1} (0.3 kg NH_3-N ha^{-1}, 0.1 kg NO_2-N ha^{-1}, 0.8 kg NO_3-N ha^{-1} and 8.0 kg dissolved organic nitrogen (DON) ha^{-1}) per crop. Total P input was 1.8 kg ha^{-1} and K amounted 17.2 kg ha^{-1} per season and crop. Weeds were controlled by tillage in CTB before planting. In PB, glyphosate (N-(Phosphonomethyl)-glycin) was applied one or two days after planting. Pests were controlled chemically as needed.

4.3.3 Resin cartridges and their installation in the soil profile

Leaching losses were estimated using PVC cartridges as described in Bischoff (2007) and Lang and Kaupenjohann (2004). The PVC cartridges had a diameter and height of 0.1 m and contained a mixture of commercial cation and anion exchange resins and fine silica sand. The mixture was prepared and the cartridges installed according to the guidelines of TerrAquat Consultancy (Stuttgart, Germany; www.terraquat.com). Before use, resins were washed with 1 M NaCl and silica sand was washed with 0.1 M HCl followed by thorough rinsing with deionized water. In each treatment and block, two measuring sites, located in the first and the third subplot, were chosen for the installation of the cartridges. These were installed between 6 and 14 November 2013 for wheat and removed between 21 and 28 May 2014. Cartridges for the maize cycle were installed during the removal of wheat cartridges and collected from 28 to 30 October 2014.

For installation in each plot a 1 m^3 pit was dug in the outer beds of the first and third subplot, perpendicular to each other. Cartridges were placed below an undisturbed part of the plot by digging horizontal access tunnels of about 0.15 m height and 0.40 m depth at 0.9 m profile depth, under the main rooting zone of cereals. Five tunnels were dug per pit (tunnel number) and two cartridges were installed behind each other (cartridge location). For each tillage-straw treatment and crop, 40 cartridges were installed. After installation, the horizontal tunnels were tightly refilled and the pits were closed to allow field traffic. After removal, each resin cartridge was divided into four layers (0-4, 4-6, 6-8 and 8-10 cm) to allow assessment of a nutrient-concentration profile for each cartridge (Bischoff et al., 1999). Each layer was weighed, labeled and stored in a cooling chamber at 5°C until extraction. Subsequently, from each layer of resin–sand mixture, a 5 g ± 0.5 g sample was taken for the estimation of dry weight (65°C, 48h).

4.3.4 Ion extraction and analysis

Two extraction agents (0.5 M H_2SO_4 and 1 M KCl) and a number of extractions were tested in the year previous to the present field study to increase analytical efficiency in the laboratory. For this study samples came from a field experiment conducted in 2012/13 comparing two tillage treatments (CTB and PB-straw retained) and installation depths (90 and 120 cm depth). From each treatment and depth, samples with highest NO_3^- concentration were taken for extraction studies. From each layer, 15 g of resin mixture and 60 mL of 0.5 M H_2SO_4 or 1 M KCl were added to exchange the ions that were adsorbed to the resins. They were stirred at 180 rpm for two hours at 25°C. The solution was filtered through #40 Whatman paper and the filtrate was recovered in a plastic tube (aliquot 1). The material retained on the filter paper was washed again with 60 mL of 0.5 M H_2SO_4 or 1 M KCl and stirred again for two hours at 180 rpm. The second extraction was filtered again on the same paper and stored in another plastic tube (aliquot 2). This procedure was repeated up to six times to establish the optimal number of extractions. In the end, depending on the number of extractions that were tested, all aliquots of one resin sample were mixed together and a subsample of 50 mL was taken for further analysis. To verify the analysis, standard solutions and their dilutions of NO_3-N (1,000 ppm) and NH_4-N (1,000 ppm) were used as controls. Spiked control samples contained 5, 10 and 20 ppm NO_3-N (3 mL) and NH_4-N (1.2 mL), all of them extracted six times with 0.5 M H_2SO_4 or 1 M KCl. Six samples of the washed silica sand and three samples of the pure anion- and cation-exchange resins were extracted similarly and used as blanks. Extractions were diluted with deionized water (1:14) and then analyzed NO_3-N (μmol) with the continuous flow autoanalyzer SKALAR+ (Skalar Analytical B.V., Breda, The Netherlands). Samples were analyzed for calcium (Ca) and magnesium (Mg) by atomic absorption spectroscopy (Perkin Elmer 3100, Perkin Elmer Inc., Waltham, MA, USA) whereby calibration curves were diluted with lanthanum chloride at 1:10 and 1:100 (Willis, 1961).

After laboratory testing, we extracted all samples from the field trial as follows: 15 g of each resin sample were weighted and 60 mL 0.5 M H_2SO_4 were added and stirred at 180 rpm for one hour at 25°C. This was done twice with the sample resin sample, thereafter both aliquots from each extraction were mixed and a subsample of 1 mL was taken and diluted with 14 mL of deionized water, stored at 4°C and analyzed as described above.

4.3.5 Soil sampling and analysis

Soil samples were taken for each crop four times. For wheat, they were collected one day before fertilization (20 November 2013), five days after planting (18 December

2013), two weeks after the second fertilization (10 February 2014) and after harvest (20 May 2014). For sampling two composite cores were taken randomly near each pit on top of the bed and in the furrow at five different depths (0-15, 15-30, 30-45, 45-60 and 60-90 cm). For wheat, soil samples were analyzed for total N concentration (Kjeldahl) and inorganic N (NO_3-N and NH_4-N by 1 M KCl extraction). For maize, soils were sampled two weeks after the first fertilization (18 June 2014), two days before the second fertilization (14 July 2014), four weeks after the second fertilization (11 August 2014) and after harvest (20 October 2014). Samples taken during the maize cycle were analyzed for total N (DELTA C mass spectrometer, Finnigan MAT GmbH, Bremen, Germany) and NO_3-N and NH_4-N concentration (Skalar San+ Skalar Analytical BV, Breda, The Netherlands). The soil moisture profile of the experimental site was monitored at 10 min intervals using automatic sensors (WatchDog 1400 Irrigation Station 4-Watermark, Spectrum Technologies, Aurora, IL, USA). Six loggers were installed in three treatments (two per treatment) and each was connected to three soil moisture sensors placed at 30, 60 and 90 cm depth.

4.3.6 Data analysis

Each cartridge was examined for an existence of a "zero-layer" with minimum or no NO_3-N accumulation in the third layer. All cartridges containing substantial NO_3-N concentrations in the 6-8 cm layer were deleted from the dataset to exclude possible contamination from the bottom layer. The amount of leached NO_3-N from ion exchange resins was calculated from the concentrations measured in the extracts from the first and second resin layer (0-4 cm, 4-6 cm), multiplied by the dry weight of each layer, and summed up for both layers. Cumulative leaching losses were calculated based on the cartridge surface area of 78.5 cm^2 and presented as kg NO_3-N ha^{-1} $season^{-1}$. Residuals of datasets were analyzed for normal distribution with the Shapiro-Wilk test. Outlier values were not deleted from the dataset to show the natural variation of the soil system. Data were analyzed with the R software package (version 2.15.2 (2012; www.cran.r-project.org) with factors being replication (or block) and treatment assuming fixed block effects. Differences ($P<0.05$) between treatments were based on least squares means with an adjusted Tukey test for multiple comparisons if data were normally distributed. For data with residuals that were not normally distributed, the Kruskal-Wallis test was used to analyze treatment differences.

4.4 Results and discussion

4.4.1 Ion exchange resins - laboratory tests

Two consecutive resin extractions with H_2SO_4 yielded recovery rates of more than 90% of NO_3-N for the added samples which was similar to data reported by Siegfried et al. for six extractions with a 1 M or 0.5 M NaCl solution (2012; Fig. 2). For Mg, 90-98%, and for Ca, 94-99% of the added ions were extracted with four extractions, regardless of the extraction reagent (data not shown). With only one extraction, H_2SO_4 extraction yielded 77% higher concentrations of NO_3-N for 15 of 17 comparative samples than KCl extraction. It was noted that approximately 5 mL of the extraction solution from the previous extraction did not properly pass through the filter and remained mixed with the resin-sand sample. This entailed a high residual concentration of NO_3-N from the previous step. Based on these results, all resin and control samples in the field study were extracted twice with 0.5 M H_2SO_4 to allow quick, cost-efficient and accurate analysis of the large number of samples.

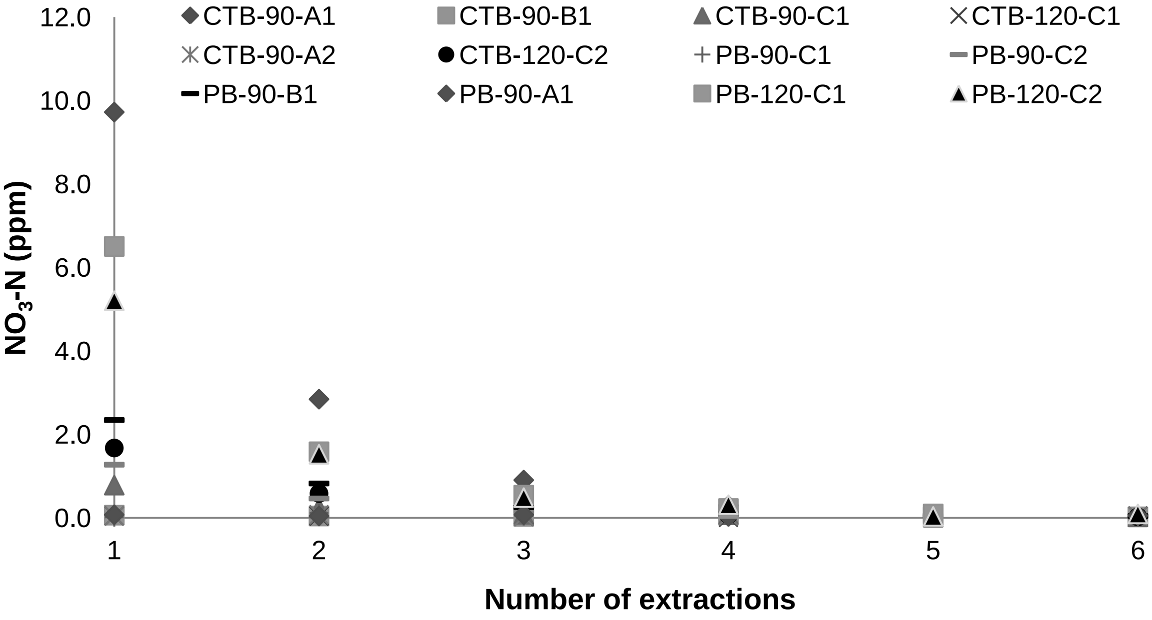

Figure 2 Desorption characteristics of NO_3-N (ppm) by 0.5 M H_2SO_4 with 12 different resin samples (CTB = conventionally tilled beds, PB = permanent beds with residue retention; 90 = 90 cm installation depth, 120 = 120 cm installation depth; A = resin layer 0-5 cm, B = resin layer 5-7 cm, C = resin layer 7-10cm; 1 = repetition 1, 2 = repetition 2) that were extracted up to six times.

4.4.2 Nitrate leaching in different crops and tillage-straw systems

For both crops, NO_3-N was highest at both ends of the cartridges, that is in the first and fourth layer. The anion-concentration gradient across layers showed that in 74.2% and 58.3% of the cartridges in wheat and maize respectively, the third layer had only minimal or no anion concentrations (Fig. 3). The remaining 31 and 50 cartridges for wheat and maize were deleted from the dataset as a non- existing zero-layer indicates a mixture between leaching and water logging effects and will thus lead to erroneous data. In the first two layers of the cartridges representing leaching losses we found 61.7% and 76.5% of the total NO_3-N for wheat and maize, respectively (Fig.3). NO_3-N concentrations in the bottom resin layers for all treatments and crops indicating the effects of temporary water logging in the Vertisol averaged 27.1 and 14.7 kg season^{-1} NO_3-N for wheat and maize, respectively. The data indicate that in our study soil water was moving predominantly downwards yielding thus reliable leaching estimates (Predotova et al., 2011). Likely differences in soil texture and particle size of original clay and artificial sand may have contributed to the upwards flux phenomenon (Bischoff, 2007).

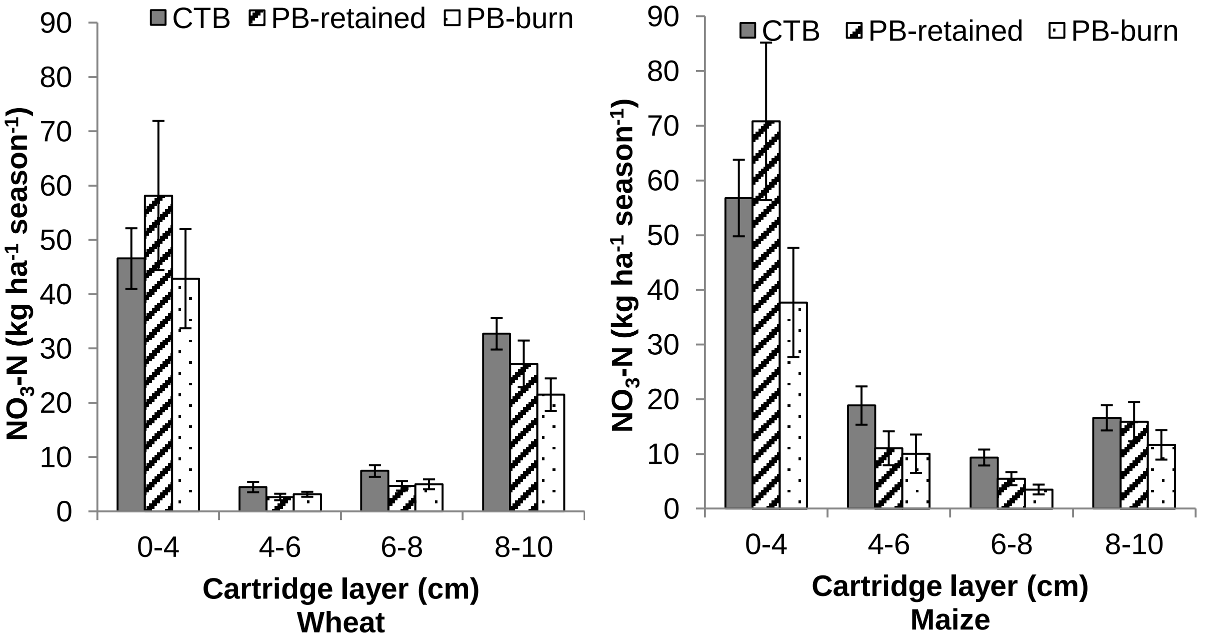

Figure 3 Cumulative NO_3-N concentrations (kg ha^{-1} season^{-1}) in the four layers of the cartridges filled with an ion-exchange resin–sand mixture from the top (0-4) to the bottom (8-10) in three tillage-straw systems during the wheat (n=89, 6 months) and maize cropping season (n=70, 5 months) of a tillage-straw experiment on a Vertisol in NW Mexico in 2013/14. Error bars show ± one standard deviation of the mean NO_3-N concentration per repetition. CTB = conventionally tilled beds, PB-retained = permanent beds with residue retention and PB-burn = permanent beds with residue burning.

The data show that tillage-straw treatments did not significantly affect resin-derived NO_3-N leaching in wheat (p=0.18) which might be due to the fact that tillage activity in CTB took place in the upper 20 cm, but leaching also heavily depends on the soil structure in deeper soil horizons where tillage activity has no influence on soil fabric. On the other hand, leaching losses in maize were significantly affected by tillage-straw treatment (p=0.04). Total NO_3-N leaching losses averaged over three tillage-straw systems were 53.5 kg ha^{-1} season^{-1} NO_3-N for wheat and 68.2 kg ha^{-1} season^{-1} NO_3-N for maize, representing 19% and 34% of the applied N fertilizer, respectively (Fig. 3). NO_3-N leaching losses were similar (p=0.246) for both crops, which contradicts the results of Fang et al. (2006) from the North China Plain who reported significantly higher amounts of NO_3-N leached below 100 cm during the maize cycle than the wheat cycle reflecting the effects of summer rainfall in maize. In our study, numerical leaching was probably higher in maize due to additional water that entered the field during extreme rainfall events in summer, hence increasing infiltration and possible leaching. Also the root system of maize is shallower compared with wheat and reaches less profound. As indicated in former studies, the main active rooting zone is at 80 and 60 cm for wheat and maize, respectively, a zones where most of the nutrients are taken up (Yang et al., 2010; Chen and Weil, 2011). Goenster et al. (2014) reported similar leaching losses under irrigated conditions in home gardens of the Nuba Mountains, Sudan, as did Siegfried et al. (2011) for organic vegetable production in northern Oman. Riley et al. (2001) undertook lysimeter studies in farmers' fields in the Yaqui Valley and found that 23% of the applied N was leached over the wheat season.

For both crops and tillage-straw systems NO_3-N leaching losses were highest in PB-straw retained. Leaching losses were similar for both crops in PB-straw burned, but 21.1 and 24.5 kg ha^{-1} season^{-1} NO_3-N higher for maize in PB-straw retained and CTB, respectively. Meek et al. (1995) analyzed NO_3-N leaching in a furrow-irrigated maize-wheat rotation and found 21 kg ha^{-1} higher soil NO_3-N below the root zone at 1.35-3.3 m depth for conventional tillage than for zero-tillage. In our study, leaching losses in wheat totaled 51.1 kgNO_3-N ha^{-1} for CTB-straw incorporated 46 kg NO_3-N ha^{-1} for PB-straw burned and 60.8 kg NO_3-N ha^{-1} PB-straw retained per season^{-1} (Fig. 3). Qin et al. (2004) reported that wheat root length density under zero-tillage was increased near the soil surface, but decreased from 10 to 30 cm compared with conventional tillage which could have increased NO_3-N leaching due to reduced plant N uptake. Leaching losses under maize were 75.6 kg NO_3-N ha^{-1} for CTB-straw incorporated, 47.7 kg NO_3-N ha^{-1} for PB-straw burned and 81.9 kg NO_3-N ha^{-1} for PB-straw retained per season^{-1} (Fig. 3). These values were much higher than found by Portela et al. (2006) who reported only 7.5 kg N ha^{-1} for maize grown under zero-tillage in deep, well drained Mollisols in Argentina. However, Huang et al. (2015) found that soil NO_3-N concentrations at 1.2 m depth during maize cropping with urea application were lower under conventional tillage than under zero-tillage in all five years of the study reaching up to 51.5 kg NO_3-N ha^{-1}. Again, differences in root length or weight density for maize between tillage-straw treatments could have affected leaching under irrigated conditions but literature on this is scarce.

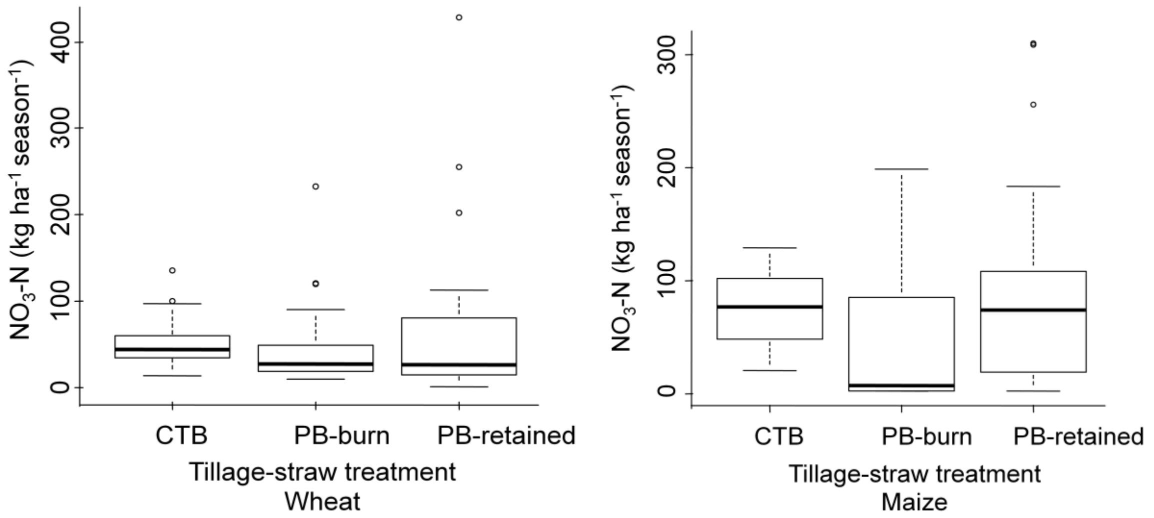

Figure 4 Cumulative leaching losses of NO_3-N (kg ha^{-1} season^{-1}) for three tillage-straw systems (CTB = conventionally tilled beds; PB-burn = permanent beds with residue burning; PB-retained = permanent beds with residue retention) during wheat (6 month) and maize (5 month) cultivation in NW Mexico. The minimum and maximum values are indicated by a thin horizontal line, the median is indicated by thick horizontal line and lower and upper margins of the box show the 25th and 75th percentiles. Outlier indicted by an open circle.

Under PB-straw retained, NO_3-N leaching varied widely and outliers reached 435 kg ha^{-1} season^{-1} NO_3-N for wheat and 311 kg ha^{-1} season^{-1} NO_3-N for maize (Fig. 4). Straw residues clustered in patches in the furrow likely caused by flowing irrigation water which lead to irregular irrigation flow and water infiltration. In a study conducted by Kienle (2008), the area of soil cracks in PB-straw retained was significantly higher compared with CTB and PB-straw burned 133 days after planting (0.0116 m², 0.0069 m² and 0.0062 m², respectively), which favored preferential flow of irrigation water in this treatment. The median was lowest for PB-straw retained and PB-straw burned in wheat and for PB-straw burned in maize (Fig. 4). Values in CTB-straw incorporated plots were for both crops likely more consistent as indicated by smallest boxes because the soil was more homogenous due to ploughing, which also broke up cracking planes close to the surface. On the heavy Vertisols of our study area, N losses totaled up to 82 kg ha^{-1} season^{-1} NO_3-N for maize in PB-straw retained. This indicates the need for improved management strategies to reduce NO_3^- leaching, for example by adjustment of irrigation water application, improved fertilizer management and a more efficient fertilizer application technology (Quemada et al., 2013).

4.4.3 Soil nitrate concentrations in different tillage-straw systems

Soil NO_3-N concentrations changed significantly over the four sampling dates in the wheat cropping season and were low before planting and after wheat harvest but high after each fertilizer application (Fig. 5). NO_3-N was significantly affected by the tillage-straw system, sampling depth and fertilizer location (disked-in on top of the bed pre-planting or into the furrow at first node). One day before the first urea application of 103 kg N ha^{-1}, NO_3-N concentrations were similar in all three tillage-straw systems and highest in the deepest sampling layer (Fig. 5a). Five days after planting and 29 days after the first fertilizer application into the bed, NO_3-N concentration increased compared with the initial NO_3-N concentration and was highest in the upper sampling depths (0-15, 15-30 cm) and lower in the furrow than the bed. This was likely due to fertilizer placement in the latter (Fig. 5b). This difference was greater in PB than in CTB-straw incorporated. The tillage-straw system did not affect NO_3-N concentrations at the upper sampling depth, but NO_3-N concentration was significantly higher at all other depths in PB-straw burned treatments.

Two weeks after the second fertilization, NO_3-N concentrations increased significantly in all treatments for the upper sampling depths in the furrow (Fig. 5c). This was likely due to the second fertilizer application of 175 kg N ha^{-1} being placed into the furrow. PB-straw burned had significantly higher soil NO_3-N concentrations than the other two treatments, with similar concentrations in bed and furrow. Tillage-straw system affected NO_3-N concentration at the 60-90 cm sampling depth, but not in the others. Water infiltration, and hence downwards NO_3-N transport, were strongly affected by tillage-straw system and the amount of existing soil micro-and macropores, and soil cracks which were frequently found in the studied Vertisol (Hobbs et al., 2008; Verhulst et al., 2009). Under conventional tillage, soils have a more homogenous structure due to regular ploughing which avoids NO_3-N accumulation and soil stratification over time at a certain spot and also mixes soil from the bed and furrow.

After wheat harvest, soil NO_3-N concentrations decreased in all treatments and were highest at the lowest depth (Fig. 5d). The effect of tillage-straw system was not significant (P=0.06), but furrow samples had significantly higher concentrations at 15-30 cm than soil samples taken from the bed. After harvest, 24, 13 and 28 kg NO_3-N ha^{-1} remained at 60-90 cm in CTB-straw incorporated, PB-straw retained and PB-straw burned, respectively, and was not leached. No significant yield differences were found for wheat in the three different tillage systems (P=0.107).

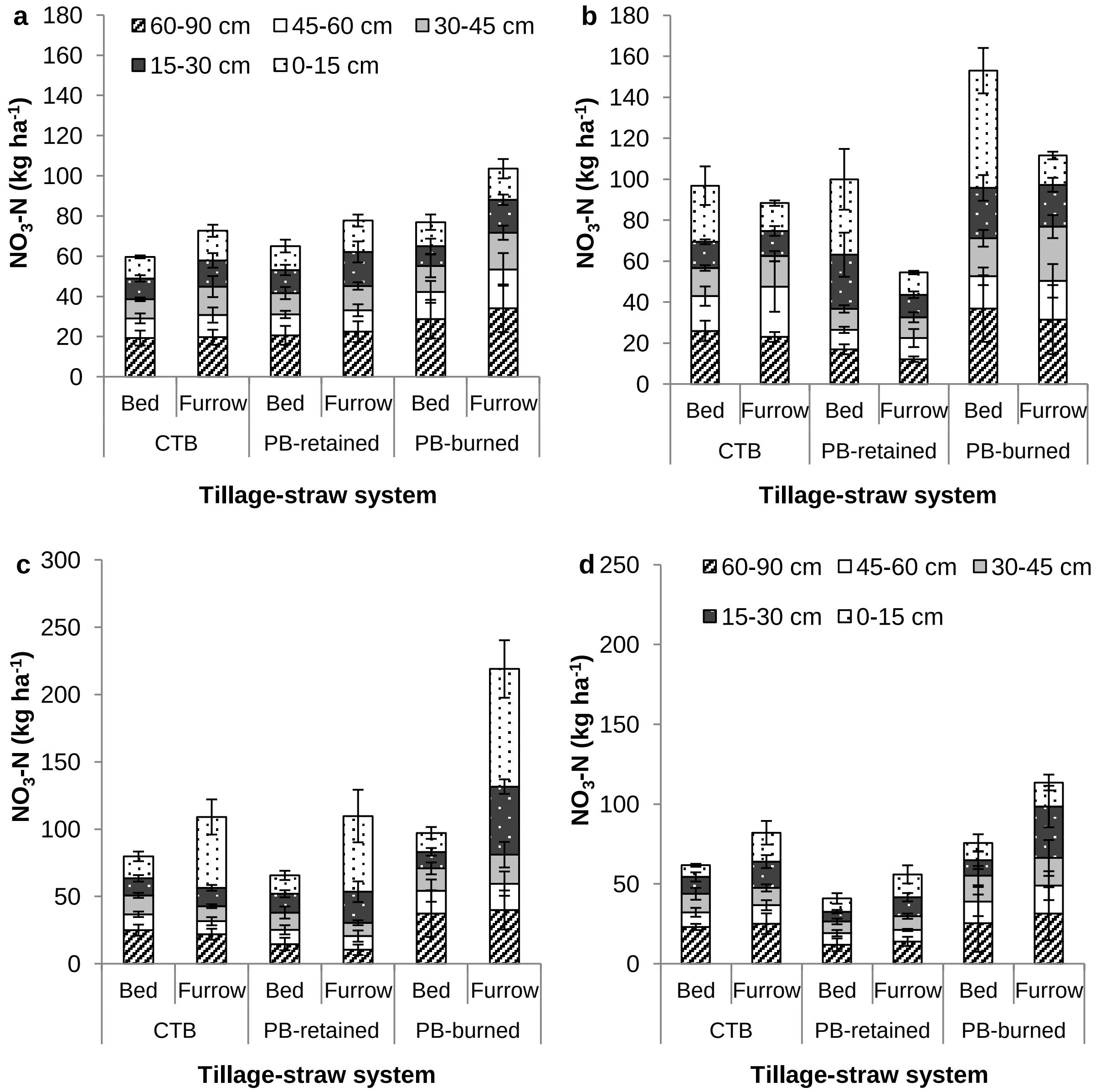

Figure 5 Soil NO_3-N (in kg ha^{-1}) during wheat cropping season at five depths a: 19 November 2013 (one day before the first fertilization), b: 18 December 2013 (five days after planting), c: 10 February 2014 (two weeks after the second fertilization), d: 20 May 2014 (three weeks after harvest) in a tillage experiment on a Vertisol in Ciudad Obregon, NW

Mexico. Error bars show +/- one standard deviation of the mean (CTB = conventionally tilled beds; PB-burned = permanent beds with residue burning; PB-retained = permanent beds with residue retention).

For maize, one week after the first fertilization into the bed, NO_3-N concentrations were highest at the first 15 cm sampling depth. Tillage-straw system affected NO_3-N concentrations in the lower soil layers from 30 to 60 cm (Fig. 6a). Four weeks later and two days before the second fertilization into the furrow, overall NO_3-N concentrations in the soil decreased and were significantly affected by tillage-straw system at 15-90 cm depth (Fig. 6b). PB-straw retained had the lowest NO_3-N concentrations across depth and dates, but highest numeric leaching losses. Leaching of mineral N in this treatment probably occurred between the first and second fertilization when soil NO_3-N concentrations decreased significantly. It may not have increased further during the following sampling events and after the second fertilization, indicating possible immobilization of mineral N fertilizer by residues (Murphy et al., 2016). Four weeks after the second fertilizer application, soil NO_3-N was significantly higher in CTB-straw incorporated and PB-straw burned treatments in the furrow, likely due to fertilizer application into the furrow (Fig. 6c). Nitrate concentrations in beds of CTB and PB-burned treatments decreased by more than half four weeks after the second fertilization compared with samples taken two days before the second fertilization, but concentration in PB-straw beds remained similar after 27 days. Leaching of mineral soil and fertilizer N in CTB-straw incorporated and PB-straw burned occurred probably between the second fertilization and maize harvest because of heavy rainfall events on 16 July (64 mm), 8 August (53 mm), 11 August (31 mm), 17 August (71 mm) and 22 August (28 mm) as concentrations in the furrow decreased significantly. Five days after maize harvest, soil NO_3-N concentrations decreased in all treatments and were highest in PB-straw burned, followed by CTB and lowest in PB-straw retained (74.0, 50.5 and 14.0 kg NO_3-N ha^{-1}, respectively; Fig. 6d) which is similar to our results for wheat. However, PB-straw burned had the lowest leaching losses, reinforcing that point measurements through regular soil sampling for soil NO_3-N are not sufficient to quantify the amount of fertilizer being leached over the season (Biggar and Nielsen, 1976; Zotarelli et al., 2007). In contrast to other studies (Follett et al., 2005; Halvorson et al., 2006), PB-straw burned and PB-straw retained had higher maize yields (6.51 t ha^{-1} each) than CTB-straw incorporated (4.90 t ha^{-1}).

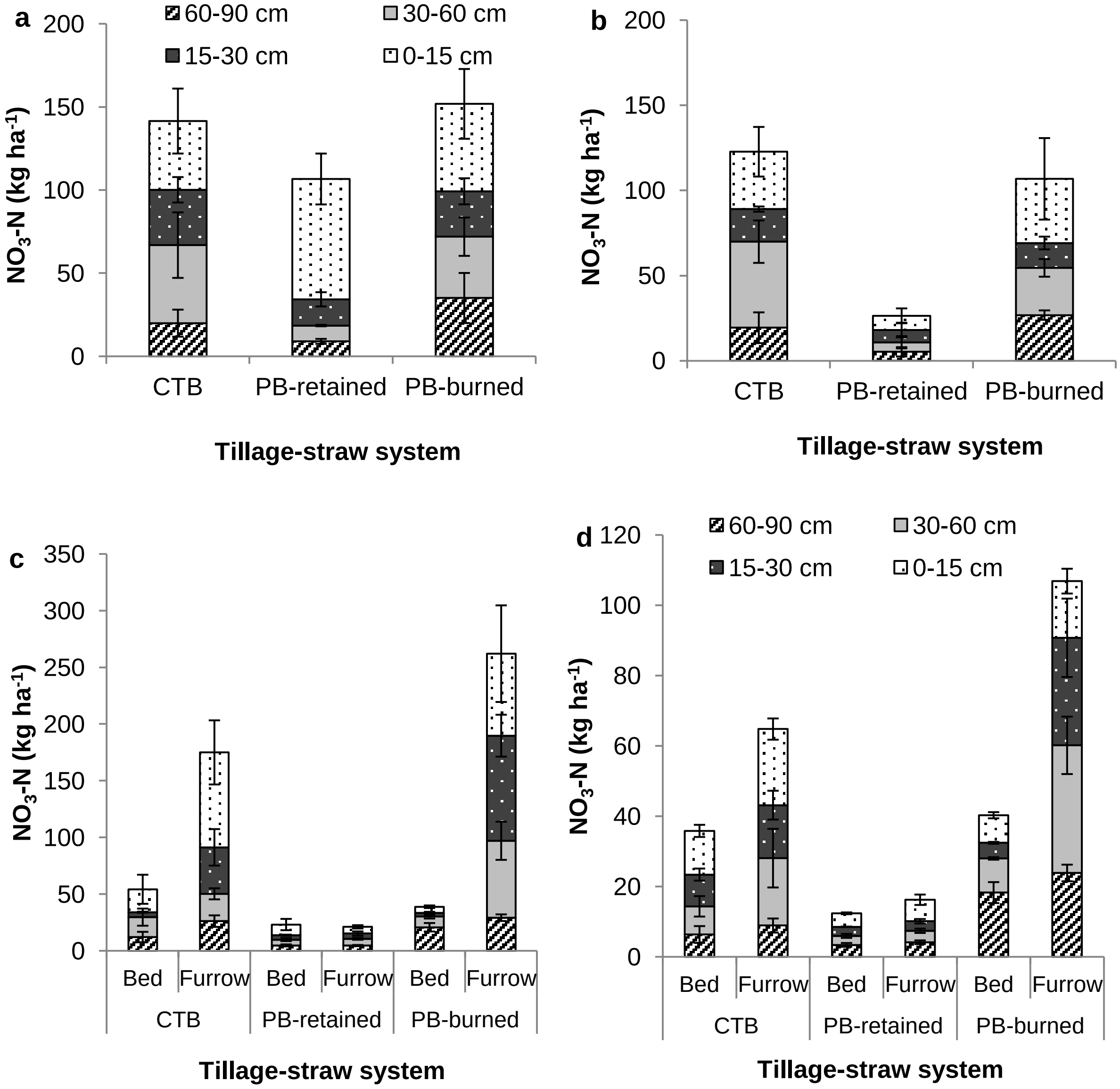

Figure 6 Soil NO_3-N (kg ha^{-1}) during maize cropping season at four depths a: 18 June 2014 (only bed, two weeks after the first fertilization), b: 14 July 2014 (only bed, two days before the second fertilization), c: 11 August 2014 (four weeks after second fertilization), d: 20 October 2014 (five days after harvest) in a tillage experiment on a Vertisol in Ciudad Obregon, NW Mexico. Error bars show +/- one standard deviation of the mean (CTB = conventionally tilled beds; PB-burned = permanent beds with residue burning; PB-retained = permanent beds with residue retention).

4.4.4 Spatial variability, soil moisture and reliability of ion exchange resins

Physical and chemical soil properties of Vertisols of the Yaqui Valley are known to vary greatly over short distances (Lobell et al., 2002; Lobell et al., 2005). Spatial variability of resin-based NO_3-N leaching losses was higher in PB-straw retained and PB-straw burned than in CTB (Fig. 7). In CTB-straw incorporated, deep ploughing at 20 cm depth likely contributed to regularly homogenize the soil, brake up cracking planes and eliminate macropores. Kienle (2008) found locally deep cracks up to 30 cm depth in Vertisols with high amounts of montmorillonite which are known to cause preferential flow of highly nutrient loaded irrigation water which may then appear as data outliers (Fig. 4; Favre et al., 1997; Greve et al., 2010). High spatial variability was clearly visible in pit one of PB-straw burned during the maize cycle when seven out of ten installed cartridges did not contain NO_3-N, but in the previous wheat cycle, NO_3-N leachings varied between 10 and 44 kg ha^{-1} $season^{-1}$ NO_3-N for the same pit. Clay has been reported to block downwards NO_3^- movement, causing NO_3 accumulation (Zhang et al., 2005) and the heavy clay layer in the present soil may have been responsible for high spatial variability of residual N storage at deeper horizons (Figs. 5 and 6). The inhomogeneous distribution of residual soil N was mirrored by significant treatment differences in NO_3-N concentrations for the second and third soil sampling, which in both crops occurred after fertilizer application.

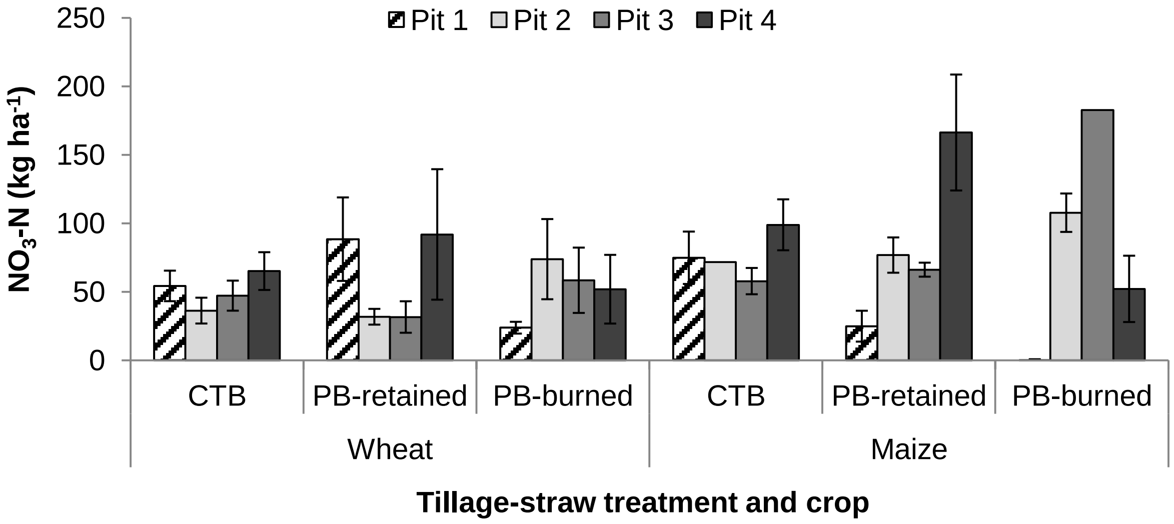

Figure 7 Distribution of NO_3-N leaching losses in (kg ha^{-1}) divided by pit numbers (one to four, subplot-dependent), tillage-straw systems (CTB = conventionally tilled beds with residue incorporation; PB-retained = permanent beds with residue retention, PB-burned = permanent beds with residue burning) and rotation (wheat, maize) on a Vertisol in NW Mexico. Error

bars show +/- one standard deviation of the mean (Bars without standard deviation had only one cartridge left in the pit).

In principle the use of resin cartridges for leaching estimates worked well as confirmed by permanently installed moisture sensors that indicated humid soil conditions during the entire period of resin cartridge measurements (data not shown). Soil tension never exceeded the critical value of field capacity (-42 kPa in clay soil). During the maize cropping season, PB-straw retained and PB-straw burned reached a soil tension above field capacity leading to much drier subsoil than in wheat. As time intervals were short, the resin-sand mixture probably stayed sufficiently moist to absorb ions from soil water (Qian and Schoenau, 2002).

Ion exchange resins allowed reliable leaching estimates which were in the range of previously published values (Mitchell et al., 2001; Mack et al., 2005; Aparicio et al., 2008). Riley et al. (2001) reported minor leaching losses of 6 to15 kg N ha^{-1} and 0.21 to 5.2 kg N ha^{-1} during the 1995-96 and 1997-98 wheat cycle, respectively, in farmers' fields in the Yaqui Valley using NLOSS model estimations. However, direct leaching measurements are certainly preferred over estimations and modeling approaches (Salo and Turtola, 2006). Liu et al. (2003) measured soil NO_3-N concentrations at a depth of 100-300 cm in a clay loam soil and found leaching losses of 89.5 and 71 kg ha^{-1} for wheat and maize, respectively, averaged over two cropping cycles with 240 kg ha^{-1} N fertilizer input.

Resin cartridges had a high spatial variability which has also been reported in other studies (Skogley and Dobermann, 1996; Mack et al., 2005), making it necessary to install additional field replications and/or increase the number of years or cropping cycles. Weihermueller et al. (2007) detailed the possible underestimation of leached N because ion exchange resins cannot capture soluble organic N forms.

4.5 Conclusions

No significant effects on resin-measured N leaching was found for wheat, but for maize maybe due to different rooting pattern. Nitrate leaching was numerically higher in maize compared with wheat (68.2 and 53.5 kg ha^{-1} season^{-1} NO_3-N, respectively). After crop harvest soil residual NO_3-N at 60 to 90 cm depth ranged from 13 to 28 kg

NO_3-N ha^{-1} in wheat and from 4 to 21 kg NO_3-N ha^{-1} in maize, and was largest in PB-straw burned. High residual soil N in deeper soil horizons does not necessarily lead to a higher risk of NO_3^- leaching. Leached nitrate concentrations varied among tillage-straw treatments and reached up to 435 kg ha^{-1} $season^{-1}$ NO_3-N during the wheat cycle in PB-straw retained. This high spatial variability likely mirrors the importance of preferential flow (cracks) on the Vertisols of our study site and the importance of know-how for installation of cartridges. However, our data allow consistent estimations of overall leaching losses of mineral N in a furrow irrigated wheat-maize rotation and proved the functionality and applicability of the resin-based leaching methodology under field conditions. Two extractions with 0.5 M H_2SO_4 were apparently sufficient to obtain reliable extraction results. As 19% of N applied to wheat and34% of N applied to maize was lost, farming practices that could lower the risk of nitrate contamination during cropping should be promoted. Such practices may comprise yield-adjusted fertilizer rates, splitting of N application at times of greatest crop requirements and the use of nitrification inhibitors. Assuming that around one fifth to one third of intensive fertilizer doses are leached into the Yaqui Valley groundwater, contamination through nitrate leaching remains a major challenge and threatens the marine ecosystems in the Sea of Cortez.

4.6 References

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Chapter 5

5 Nitrogen balance and short-term N dynamics in different tillage-straw systems in the Yaqui Valley, Mexico

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5 Nitrogen balance and short-term N dynamics in different tillage-straw systems in the Yaqui Valley, Mexico

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Keywords:

Conservation agriculture, Nitrate leaching, Nitrogen dynamics, Total soil N, Permanent raised beds

5.1 Abstract

Nitrogen (N) surpluses from agriculture can cause major environmental harm including pollution of surface water, groundwater and air. Nitrogen balances are a complex but useful tool to estimate the depletion of nutrients and optimization of nutrient use and to measure system externalities. However, detailed information on N budgets for furrow irrigated systems under conservation agriculture is scarce and often incomplete. Data from a long-term experiment were collected in 2013/14 on a Vertisol in northwestern Mexico to examine the impact of three tillage-straw management practices (CTB: conventionally tilled beds, PB-straw retained: permanent raised beds with residue retention, PB-straw burned: permanent raised beds with residue burning) on N dynamics in soil fractions and N balance. Tillage and sampling date had significant effects on soil NO_3-N, NH_4-N and total N concentrations. Soil NO_3-N in the 0-90 cm profile was highest in PB-straw burned at all sampling events and ranged from 77 kg ha^{-1} in the bed before pre-plant fertilization up to 269 kg ha^{-1} in the furrow after the second fertilization. Annual N balance was +156 kg N ha^{-1} in CTB, +181 kg N ha^{-1} in PB-straw retained and +173 kg N ha^{-1} in PB-straw burned. Residual soil N was significantly affected by tillage-straw management and amounted to 283 kg N ha^{-1} for CTB, 205 kg N ha^{-1} for PB-straw retained and 283 kg N ha^{-1} for PB-straw burned in the entire soil profile. Soil NO_3-N moved out of the effective wheat root zone, as indicated by the high residual NO_3-N concentrations in 30-90 cm depth, which is an important pathway of N leaching. Findings suggest that N input is quite to high in all tillage-straw treatments leading to considerable losses and mineral residual N pool.

5.2 Introduction

The Yaqui Valley in Northern Mexico is the country’s major wheat-producing area (Matson et al., 1998) and represents one of the largest wheat growing systems under irrigation, similar to the Indian and Pakistani Punjab and the Nile Valley in Egypt where 40% of the wheat is produced in the developing world (Ortiz-Monasterio et al., 2010). From 1968 to 1995, fertilizer application rates for the cultivation of irrigated durum wheat (*Triticum durum* L.) at 6 t ha^{-1} increased from 80 to 250 kg ha^{-1}, demonstrating the high intensification potential in this region (Matson et al., 2005). Nitrogen use efficiency (NUE) estimations for the Yaqui Valley average 31% (Ortiz-Monasterio and Raun, 2007) and reflect the high potential to enhance NUE and N fertilizer use by improved management practices. Conservation agriculture (CA) in combination with a permanent bed planting system was introduced in the late 1990´s in the Yaqui Valley as a set of management principles to improve water use efficiency, reduce soil erosion and conserve resources such as farmers’ time, labor and fossil fuels. It is based on three key components: (1) minimal soil movement, (2) partial retention of residues as a soil cover, and (3) economically viable crop diversification, which together reduce management costs and increase profitability and sustainability of the cereal production system (Hobbs et al., 2008). Permanent raised beds (PB) imply residue retention on top of the beds, which are reshaped when needed (Govaerts et al., 2005). Earlier studies show that under local conditions CA affects physical, chemical and biological soil quality compared with conventional practices involving tillage. It thus changes N cycling and N dynamics in the soil (Verhulst et al, 2010). As the burning of straw residues is still a common, although legally forbidden practice in the Valley, this treatment was included to further support its negative effect on yields and soil characteristics. Sayre et al. (2005) reported that five years after the initiation of a long-term experiment, yield started to decrease in PB-straw burned with an average yield loss of 0.5-1.3 t ha^{-1} compared with the highest yielding treatments (PB-straw retained and PB-straw removed). Verhulst et al. (2009) analyzed wheat development with an optical sensor in the same long-term experiment and found that plant performance in treatments where residues are burned was significantly lower than in other tillage treatments, even if the initial plant growth was still acceptable due to N fertilization.

The carry-over effect that describes the time-related, delayed effects of N fertilizer in the following cropping seasons plays an important role for NUE in CA. This is especially the case when fertilizer is applied with retained crop residues since this can increase temporary immobilization which is reported to be one of the primary causes for low NUE under CA (Rice and Smith, 1984; Schoenau and Campbell, 1996; Burgess et al., 2002; Lopez-Bellido et al., 2006; Verachtert et al., 2009). Soil temperature and soil moisture, which often differ in conventional and CA systems due to residue retention on top of the soil, influence soil microbial activity and hence contribute to changes in mineralization and decomposition patterns, N plant uptake and leaching losses (Baker et al., 1996; Burgess et al, 2002; Govaerts et al., 2007; Grahmann et al., 2016, under revision). Soils under CA were reported to have lower mineral N, but higher total N than conventionally tilled soils (Verachtert et al., 2009; Verhulst et al., 2009; Wu et al., 2009). Total N content in soils under CA compared with conventional tillage depends on the sampling depth (Dalal et al., 1998; Gal et al., 2007) as well as the amount of residue retained on the field (Govaerts et al., 2007). Nitrogen dynamics within the growing season depend on the availability of crop residues. High temperature and irrigated conditions accelerate the turnover of soil organic matter and short-term N changes and also increase the risk of higher N losses. CA systems have been reported to have higher N losses due to volatilization of NH_3-N (Terman, 1979; Aulakh et al., 1984; Hargrove, 1988; Palma et al., 1998; Angas et al., 2006) and favor N_2O emissions due to higher soil moisture. On the other hand, CA decreased soil temperatures and led to better soil structure which improved aeration, with less anaerobic sites resulting in a reduction of N_2O emissions (Hao et al., 2001; Liu et al., 2005). Changes in N dynamics cannot be evaluated immediately after the adoption of conservation tillage, as chemical and biological soil properties need to establish a new equilibrium that counterbalances between N release and N immobilization (Yeates et al. 1999).

Given the existing knowledge gaps in the N availability of CA systems, the aim of this study was to evaluate the effects of tillage-straw practice on short-term soil N dynamics and N fertilizer use efficiency in a wheat cropping cycle. Analysis of soil, straw, grain and roots was used to better understand the different modes of action of N fertilizer in the three investigated tillage systems to explain possible pathways for N losses.

5.3 Materials and methods

5.3.1 Research site and experimental setup

The study was carried out at the experimental station CENEB (Campo Experimental Norman E. Borlaug), near Ciudad Obregón, Sonora, Mexico (27.33°N, 109.09°W, 38 m a.s.l.). The site has an arid climate, with a 20 year annual average rainfall of 300 mm and an annual reference evapotranspiration of about 1800 mm. Between 1986 and 2012, annual rainfall fluctuated from 90 to 590 mm reflecting the high level of rainfall variability at the site. Rainfall is summer dominant and only 20% of the average annual rainfall occurs during the wheat-growing season (November-May; Verhulst et al., 2011b). The mean annual temperature for the 2013/14 growing period was 20.5 °C and mean monthly temperatures ranged from 2.3 °C in January 2014 to 40.9 °C in May 2014. Total annual rainfall was 153 mm and rain events in the wheat cropping cycle were recorded for Dec 5 (7.1mm), Dec 12 (16 mm) and Mar 9 (15.2 mm; Table 1.). The soil is a Hyposodic Vertisol (Calcaric, Chromic) according to the World Reference Base soil classification system (IUSS Working Group, 2007) or a fine, smectitic Chromic Haplotorrert in the USDA Soil Taxonomy system (Soil Survey Staff, 2010). All horizons in the soil profile to 2 m are slightly alkaline (pH 8).

Table 1 Average climatic conditions at Ciudad Obregón, Mexico for the winter period of October 2013 to May 2014 (Max Temp: maximum temperature in °C, Min Temp: minimum temperature in °C, Mean Temp: mean temperature in °C, Precip: precipitation in mm, Evapo: evapotranspiration in mm).

Month	Max Temp	Min Temp	Mean Temp	Precip	Evapo
Oct	33.8	17.3	24.8	97.8	140.6
Nov	29.9	15.2	21.8	8.4	111.1
Dec	25.4	9.7	16.7	23.9	97.6
Jan	26.9	8.5	16.6	0.0	102.0
Feb	27.8	9.3	17.4	3.6	102.3
Mar	28.7	11.0	19.0	17.8	133.1
Apr	32.3	11.7	21.6	0.5	158.3
May	36.6	15.1	25.8	0.8	204.1

The long-term trial was established in 2005 and consists of a total of 17 treatments, which differ in tillage practice, rotation, and residue management, however, in the current study only three of these were included. The trial has a randomized complete block design with two repetitions and three subplots per repetition. Each plot consists of eight beds (80 cm wide), 6.4 m wide and 130 m long (832 m^2). Each plot is divided into three subplots, each having an area of 277.3 m^2. All considered treatments in the cropping cycle 2013/2014 have a wheat-maize rotation. Main treatments consisted of tillage-straw management systems as follows: CTB-straw incorporated: conventionally tilled raised-beds (CTB; tilled after each crop with a disk harrow to 20 cm after which new beds were formed), wheat and maize residues were incorporated by tillage; PB-straw burned: permanent raised-beds (PB; zero tillage with repeated reuse of existing beds, which were reformed in the furrows as needed without disturbance of the tops of the beds), residues of both wheat and maize are burned; PB-straw retained: PB, maize and wheat residues are kept on the soil surface.

The durum wheat cultivar "Movas C2009", a commercially used cultivar in the Yaqui Valley, was sown on 13 December 2013 at a seeding rate of 120 kg ha^{-1}. Wheat flowered on 2 March 2014 and was harvested on 30 April 2014. One pre-planting irrigation of 120 mm was followed by four auxiliary irrigations of 80-100 mm on 20 November, 29 January, 24 February, 21 March and 4 April. The entire experiment was irrigated at the same time, allowing runoff from the plots to ensure homogeneous water distribution. Total infiltrated irrigation water per season and crop was approximately 500 mm. Weeds were controlled by tillage in CTB before planting and by glyphosate (Faena$^{®\ at}$ 2 L ha^{-1}) applied one day after planting in PB. Pests and diseases were controlled with common on-station measures.

5.3.2 Nitrogen input

Wheat was fertilized with 103 kg N ha^{-1} and 22.7 kg P ha^{-1} basal on the beds before planting (19 November 2013) and received a second fertilization of 175 kg N ha^{-1} before the first auxiliary irrigation in the furrow (27 January 2014). N was applied as urea and P in form of MAP 11-52-0, Monoammonium Phosphate.

Soil samples were taken in six increments before first fertilization (0-N state) on 19/11/2013 (0-15, 15-30, 30-45, 45-60, 60-90 and 90-120 cm) and in five increments right after planting (18/12/2013), right after the second fertilization (10/2/2014) and after harvest (20/5/2014; 0-15, 15-30, 30-45, 45-60 and 60-90 cm). One composite soil sample consisted of two soil samples, divided into bed and furrow. Soil samples were analyzed for total N concentration (Bremner, 1965a), available soil phosphorus (Olson et al., 1954), inorganic N (NO_3-N and NH_4-N by KCl extraction after Bremner, 1965b), organic matter (Walkley and Black, 1934) and exchangeable potassium. Available N for plant uptake included the initial 30 cm of mineral soil N (NO_3-N and NH_4-N) before planting and potentially mineralized N (PMN). We assumed that 95% or total N was organic N and that mineralization rate during the 164 days wheat cycle was 2% (Pierzynsiki et al., 2005). Straw and grain samples were taken after harvest and analyzed together with root samples for total N by Kjeldahl digestion (Bremner, 1965a). Straw residue samples consisted of a mixed sample of furrow and bed residues, assuming that 50% of total N from wheat residues was incorporated from microbial biomass during decomposition (Parton et al., 1993; Stewart et al., 2015).

Root samples were taken 10 days after flowering (four points per subplot) using a Giddings soil borer to a depth of 60 cm at three increments (0-15, 15-30 and 30-60 cm). Samples were stored at 8 °C until processing. Each soil/root sample was soaked for a day. Afterwards, samples were sieved with four reduced mesh sizes and roots retained on in the lowest sieve were collected using tweezers. Samples were dried for 2 days at 75 °C. After drying, dry weight was noted and dried root samples milled in a ball mill (MM 400, Retsch GmbH & Co. KG, Haan, Germany). Milled samples were analyzed for total Kjeldahl N (Bremner, 1965a). Nitrogen input by roots and their deposited nutrients was calculated by multiplying root mass in t ha^{-1} by root N content. Based on literature, 65% of root N was assumed to be plant available by mineralization and rhizodeposition during cropping cycle (Janzen, 1990; Rroco and Mengel, 2000; Muñez-Romero et al., 2013)

Volumetric soil moisture was measured three times a week, at morning and noon at 6cm depth, in bed and furrow using a ThetaProbe ML2x FD-Sonde and Infield7 handheld meter (UMS GmbH Munich, Germany). Soil temperature was measured on the same days, times and depth as volumetric soil moisture using a conventional food thermometer. Amounts of irrigation water inflow and outflow (surface runoff) were measured using a V-notch weir (personal communication Nele Verhulst, 2016; data not shown). Irrigation water and runoff surface water was analyzed for nutrient concentrations following standard procedures. During the growing cycle N input through irrigation water amounted to 0.3 kg ha^{-1} NH_3-N, 0.1 kg ha^{-1} NO_2-N, 0.8 kg ha^{-1} NO_3-N and 8 kg ha^{-1} DON. Nitrogen input by deposition was estimated according to Holland et al. (2005).

5.3.3 Nitrogen output

Wheat yield was determined according to Pask et al. (2012). The central area of the plot (two center beds of 15 m) was combine-harvested and grain weight and moisture content were measured. Grain yield (in t ha^{-1}) was calculated, expressed at 12% moisture content and was divided by grain N content to obtain N output by harvested grain. Leaching of mineral N was determined using ion exchange resin cartridges.

Details regarding installation, extraction and analysis can be found in Grahmann et al. (2016, under revision).

Gaseous losses in form of soil emissions of NH_3 and N_2O were measured by a portable dynamic closed chamber system consisting of a photoacoustic multi-gas field monitor (INNOVA 1312-5, Lumasense Technologies Inc., Balerup, Denmark) and a PTFE coated PVC chamber (0.30 m diameter; 0.11 m high). Both units were connected by two 2 m long inflow and outflow PTFE tubes (Predotova et al. 2010). Between November and May, gaseous emissions were assessed in each treatment bi-weekly over three consecutive days, each day another repetition. In each treatment, 5 measuring points, two in the furrow and three on top of the bed, were selected. To assess the effects of diurnal soil temperature and soil moisture changes on gaseous emissions, all measurements were taken during the coolest (6–8 a.m.) and hottest (1–3 p.m.) time of the day. The multi-gas monitor was manufacturer-calibrated and set to compensate for cross-interferences of gases and water vapor with NH_3 and N_2O. Measured N emissions were calculated according Siegfried et al. (2011).

Surface runoff by outflow water and nutrient concentration of the same were determined as described above. Nitrogen output through effluent irrigation water amounted 0.002 kg ha^{-1} NH_3-N, 0.001 kg ha^{-1} NO_2-N, 0.13 kg ha^{-1} NO_3-N and 0.23 kg ha^{-1} DON per irrigation event. Erosion was marginal and thus not considered as an output (Lobell et al., 2003).

5.3.4 Nitrogen balance

Horizontal nitrogen balance was calculated based on Meisinger et al. (2008) and Diogo et al. (2010). Nitrogen inputs included mineral fertilizer (FN), irrigation water (IRWN), wet and dry depositions, (WDN), straw N (STRN), root N (RN), initial soil N (SN) and potentially mineralizable N (PMN). Outputs included harvested products (HPN), leaching losses (LN), gaseous emissions (GEN) and surface runoff (SRN) from the soil surface through irrigation water. Residual soil N after wheat harvest was evaluated separately and not included in the balance. Net changes in the soil storage (Δ Soil N) of N were calculated as:

$$\Delta \text{ Soil N} = (\text{FN}+\text{IRWN}+\text{WDN}+\text{STRN}+\text{RN}+\text{SN}+\text{PMN}) - (\text{HPN}+\text{LN}+\text{GEN}+\text{SRN})$$

5.3.5 Statistical analysis

All statistical analyses were conducted with the R software package (version 2.15.2 of 2012, www.cran.r-project.org). Residuals of data were analyzed for normal distribution with the Shapiro-Wilk test. Two class factors were distinguished: replica (or block) and treatment assuming fixed block effects. Differences ($P<0.05$) between treatments were based on least squares means with an adjusted Tukey test for multiple comparison if data were normally distributed. For data with non normally distributed residuals, the Kruskal-Wallis test was used to analyze treatment differences. Datasets were collected from a randomized compete block with two repetitions (blocks) and subsamples taken the first and third subplot of each block for yield, straw N, grain N, soil samples and root samples.

5.4 Results

5.4.1 Soil moisture and soil temperature

Soil moisture was significantly affected by tillage-straw management ($P=<0.0001$) at both sampling locations; furrow and bed. Similarly, the effect of sampling date and the interaction between sampling day and tillage were significant. The lowest soil moisture at 6 cm depth in the bed was recorded in CTB (21.7%, averaged over the whole cropping cycle), followed by PB-straw burned (25.3%) and the highest in PB-straw retained (27.6%; Fig. 1). CTB had lower soil moisture and dried out faster than PB-straw retained, with the highest volumetric soil moisture, particularly after planting, when plots were not irrigated for 48 days. Soil moisture significantly increased after each irrigation event. A slight rise in soil moisture was determined after rainfall events with more than 10 mm precipitation. After the first auxiliary irrigation, soil moisture increased to 45%, indicating highly saturated water conditions at field capacity. This changed during the following three auxiliary irrigations, with highest values reaching 37%, 32% and 35%, respectively (Fig. 1).

Soil moisture in the furrow was highest in PB-straw retained (35%), then PB-straw burned (31.1%) and CTB (30%) at 6 cm depth. Due to lasting irrigation events in the furrow, volumetric soil moisture was always higher in the furrow than in the beds. CTB dried quicker after irrigation events and reached minimum soil moisture values of 11.5%, whereas for PB-straw retained minimum values were 20.7% (data not shown).

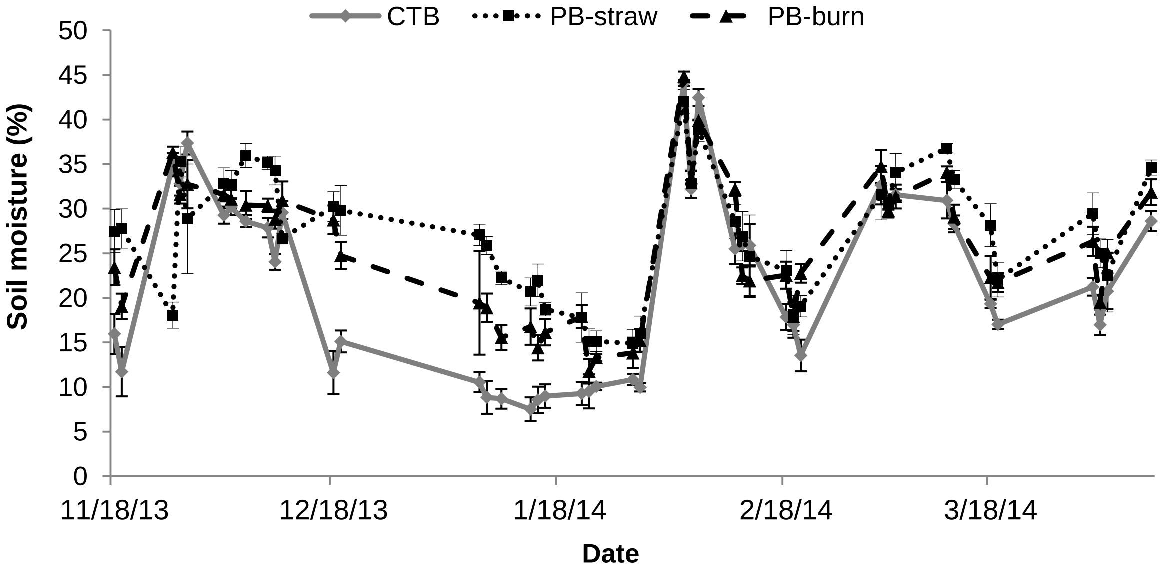

Figure 1 Volumetric soil moisture (%) at 6 cm depth for three different tillage treatments measured in the planting bed at Ciudad Obregón, Sonora, Mexico. Error bars represent one standard error of the mean. Arrows indicate irrigation events, stars indicate rainfall events >10 mm. (CTB: conventionally tilled beds, PB-straw: permanent raised beds with residue retention, PB-burned: permanent raised beds with residue burning).

Soil temperature at 6 cm depth was significantly affected by time (days) after planting (P=<0.0001), location (bed or furrow; P=0.0011) and tillage-straw management (P =0.0015). Soil temperature at 6 cm soil depth increased over the wheat cropping cycle with increasing maximum air temperature (Table 1). Soil temperature was significantly lower in PB-straw retained than in the other two treatments where no differences were observed (Fig. 2). Average soil temperature over the whole wheat cropping cycle in the bed was 19.4 °C for PB-burned, 19.25 °C for CTB and 19.0 °C for PB-straw retained (Fig. 2). In the furrow, soil temperature was 20.0 °C for PB-burned, 19.7 °C for CTB and 19.4 °C for PB-straw retained (data not shown).

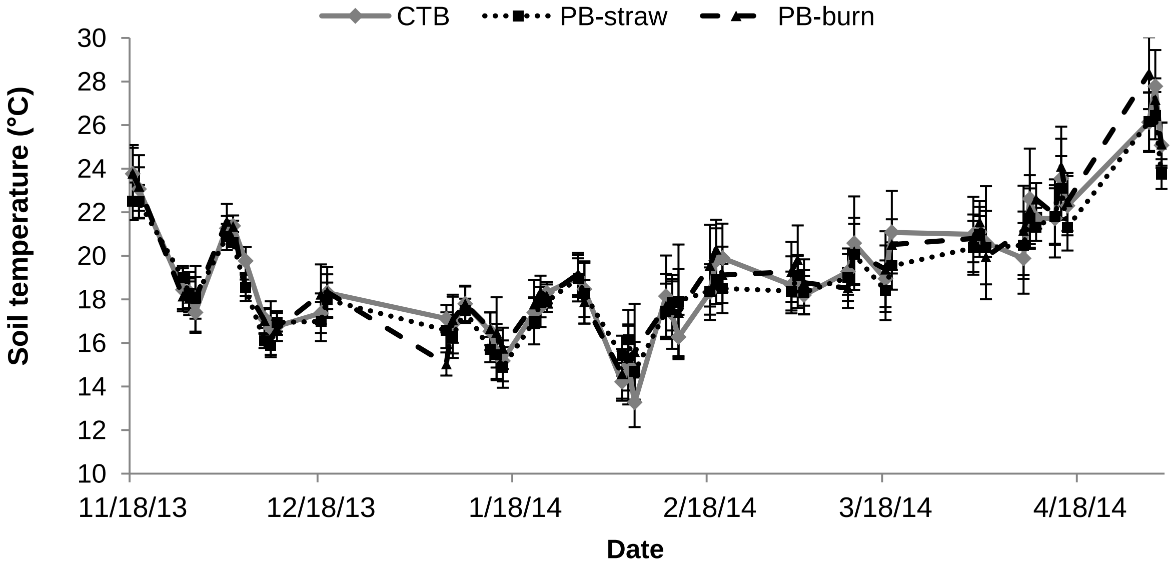

Figure 2 Soil temperature (°C) at 6 cm depth for three different tillage treatments measured in the bed at Ciudad Obregón, Sonora, Mexico. Error bars represent one standard error of the mean. (CTB: conventionally tilled beds, PB-straw: permanent raised beds with residue retention, PB-burned: permanent raised beds with residue burning).

5.4.2 Root biomass and wheat yield

Tillage-straw management did not significantly affect root biomass (mg cm^3), total root N (%) or root mass (kg ha^{-1}), but soil depth significantly influenced all of them and was highest at 0-15 cm sampling depth ($P<0.0001$). Total root N averaged 1.5% over all treatments and depths. Total amount of N in root mass to 60 cm depth was 21.5 kg N ha^{-1} in CTB, 40.1 kg N ha^{-1} in PB-straw and 35.6 kg N ha^{-1} in PB-burn.

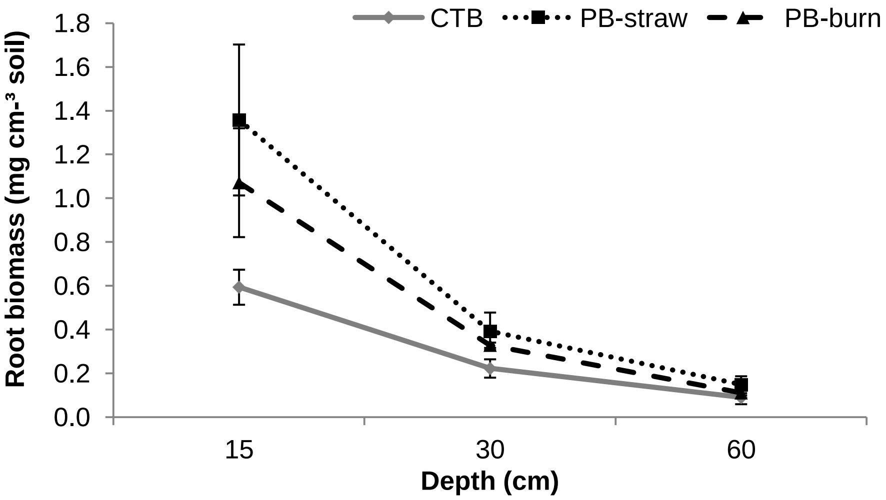

Figure 3 Root biomass at three depths (0-15, 15-30 and 30-60 cm) for three different tillage treatments measured in the bed and furrow at Ciudad Obregón, Sonora, Mexico. Error bars represent one standard error of the mean. (CTB: conventionally tilled beds, PB-straw: permanent raised beds with residue retention, PB-burned: permanent raised beds with residue burning).

Yield was 5916 kg ha^{-1}, 5435 kg ha^{-1} and 5225 kg ha^{-1} in PB-straw retained, CTB and PB-straw burned, respectively. Yield was not significantly affected by tillage-straw management (P=0.13). In the previous cropping cycle 2012/13, wheat yield was higher at 6899 kg ha^{-1} for PB-straw burned, 6588 kg ha^{-1} for PB-straw retained and 6317 kg ha^{-1} for CTB. Total grain N was significantly affected by tillage-straw treatment (P=0.04), being lowest in PB-straw retained (2.1% N) and similar in CTB and PB-straw burned (2.4% N each). Straw N was similar for all tillage-straw treatments (P=0.09) and amounted 0.57% N in PB-straw burned and 0.46% N in PB-straw retained and CTB each.

5.4.3 Soil N dynamics

Significant Pearson's product correlations (R) were found between organic matter and total N in kg ha^{-1} (R=0.65) and NH_4-N and NO_3-N in kg ha^{-1} (R=0.77). Sampling date significantly affected amounts of NH_4-N, NO_3-N and total N in kg ha^{-1}.

Soil total N concentration decreased with increasing depth for all sampling points and locations (Fig. 4). In the first 30 cm, PB-straw retained had highest total N before planting and after second fertilization. Five days after planting, PB-straw burned had highest total N and concentrations decreased drastically in the bed after planting. Total N concentrations were equal in bed and furrow before planting but increased in the bed after first fertilization (Fig. 5). After second fertilization, total N was significantly higher in the furrow and increased slightly in the bed in CTB and PB-straw retained. Total N increased in all treatments five days after planting and slightly decreased 14 days after second fertilization, especially at 60-90 cm depth. Total N was similar in PB-straw retained and PB-straw burned after wheat harvest (Fig.4) and decreased almost to the level recorded before planting in all treatments (Fig. 5). CTB treatments in bed and furrow always had the lowest total N at all depths. In the entire soil profile, total N was only significantly affected by tillage-straw at the last sampling event (P=0.012). When looking at different sampling depths, tillage significantly affected total N concentration at first sampling at 0-30 cm depth, at the second and third sampling at 0-15 cm depth and at the fourth sampling at 15-30 and 45-60 cm depth.

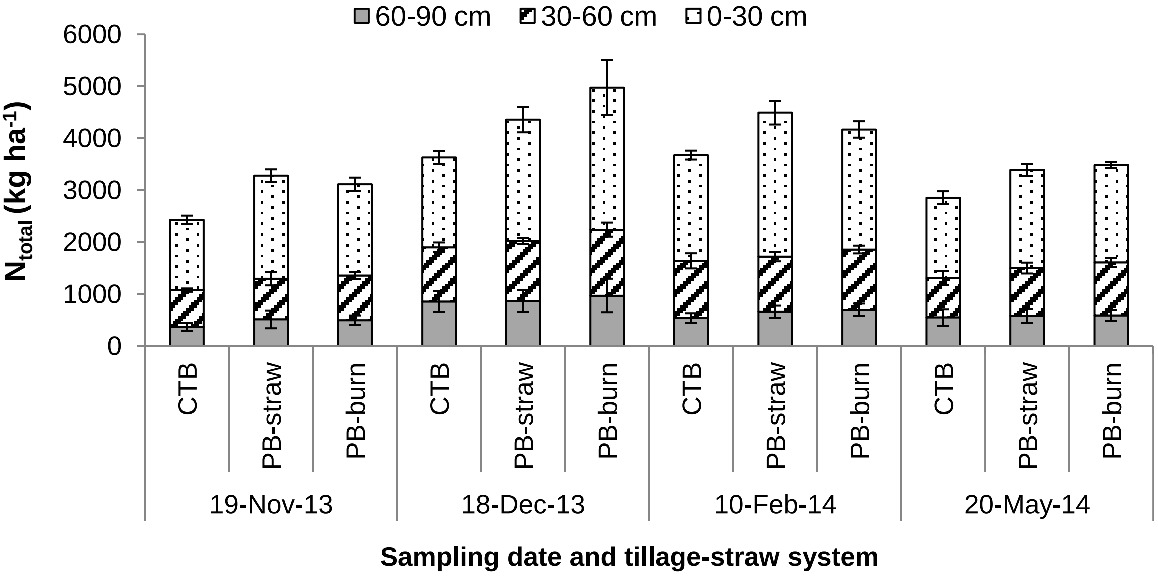

Figure 4 Total N concentration (kg ha^{-1}) in three soil depths for three different tillage systems averaged in bed and furrow measured before first fertilization (19-Nov-13), after planting (18-Dec-13), after second fertilization (10-Feb-14) and after harvest (20-May-14) in a tillage experiment in Ciudad Obregon, Mexico. Error bars represent one standard error of the mean. (CTB: conventionally tilled beds, PB-straw: permanent raised beds with residue retention, PB-burn: permanent raised beds with residue burning).

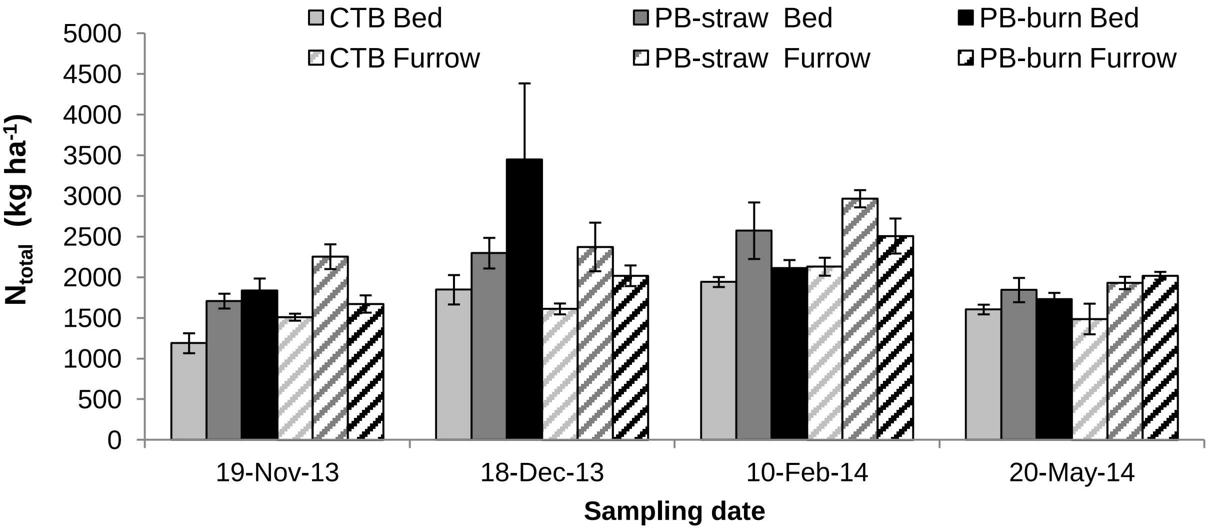

Figure 5 Total N concentration (kg ha^{-1}) in the first 30 cm soil depth for three different tillage systems measured separately in bed and furrow before first fertilization (19-Nov-13), after planting (18-Dec-13), after second fertilization (10-Feb-14) and after harvest (20-May-14) in a tillage experiment at Ciudad Obregon, Mexico. Error bars represent one standard error of the mean. (CTB: conventionally tilled beds, PB-straw: permanent raised beds with residue retention, PB-burn: permanent raised beds with residue burning).

Tillage-straw management did not affect NO_3-N concentrations before planting, but these significantly differed in the following three sampling events and were highest in PB-straw burned (Fig. 6). After planting, tillage-straw treatment had a significant effect on NO_3-N concentrations in 15-90 cm depth and after second fertilization and harvest at 60-90 cm depth. At this depth, possible leaching of NO_3-N occurred after irrigation events. Nitrate concentrations before first fertilization were low at 0-30 cm depth for all sampling locations and treatments (Fig. 7) and stayed below 33 kg NO_3-N ha^{-1}, but were higher in the furrow. After planting, when the first fertilization was applied on top of the bed, NO_3-N concentrations greatly increased for the first 30 cm in the bed up to 120 kg NO_3-N ha^{-1} in PB-straw burned (Fig. 7) and decreased to only 36 kg NO_3-N ha^{-1} after second fertilization. In the same way, when the second fertilizer dose was applied in the furrow, NO_3-N concentrations increased considerably in the first 30 cm of the furrow in PB-straw burned up to 191 kg NO_3-N ha^{-1}. Sampling location affected NO_3-N concentrations before planting, two weeks after second fertilization and after harvest with higher values in the furrow compared with the bed, which was significant in the 0-15 cm horizon.

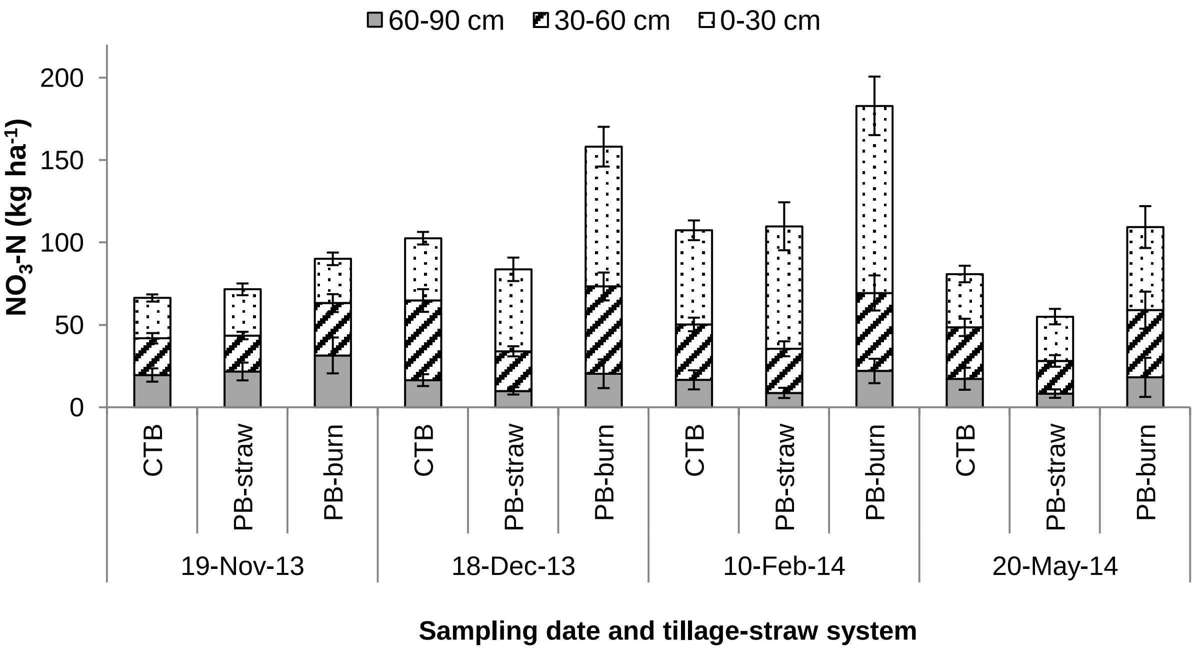

Figure 6 Nitrate-nitrogen (NO_3-N) concentration (kg ha^{-1}) at three soil depths for three different tillage systems averaged in bed and furrow measured before first fertilization (19-Nov-13), after planting (18-Dec-13), after second fertilization (10-Feb-14) and after harvest (20-May-14) in a tillage experiment at Ciudad Obregon, Mexico. Error bars represent one standard error of the mean. (CTB: conventionally tilled beds, PB-straw: permanent raised beds with residue retention, PB-burn: permanent raised beds with residue burning).

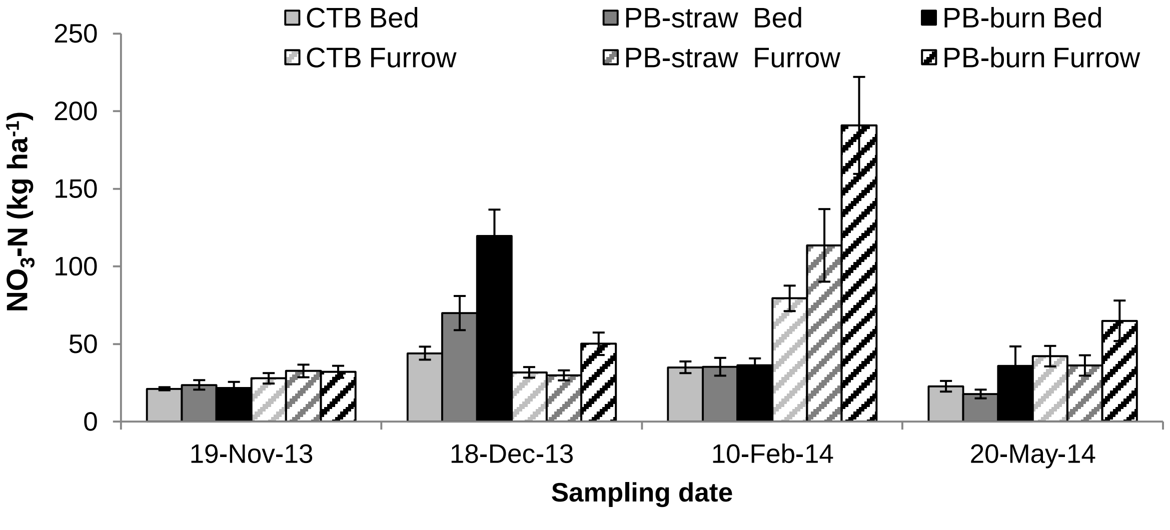

Figure 7 Nitrate-nitrogen (NO_3-N) concentration (kg ha^{-1}) at the first 30 cm soil depth for three different tillage systems measured separately in bed and furrow before first fertilization (19-Nov-13), after planting (18-Dec-13), after second fertilization (10-Feb-14) and after harvest (20-May-14) in a tillage experiment in Ciudad Obregon, Mexico. Error bars represent one standard error of the mean. (CTB: conventionally tilled beds, PB-straw: permanent raised beds with residue retention, PB-burn: permanent raised beds with residue burning).

Ammonium concentrations were significantly affected by tillage-straw treatment before planting (P=0.0001) and five days after planting (P=0.05). NH_4-N concentrations in the entire soil profile were constantly high and between 120 kg NH_4-N ha^{-1} in CTB before planting and 415 kg NH_4-N ha^{-1} in PB-straw burned two weeks after second fertilization (Fig. 8). NH_4-N only increased 14 kg NH_4-N ha^{-1} at 0-30 cm depth 29 days after first urea application (Fig. 9). NH_4-N increased significantly two weeks after second fertilization in all treatments and sampling depths with an average increase of 205 kg NH_4-N ha^{-1} in the furrow from second to third sampling event compared with only 18.5 kg NH_4-N ha^{-1} in the bed (Fig. 8). NH_4-N concentrations changed significantly between bed and furrow after second fertilization and were higher in the furrow than in the bed (P=0.043; Fig. 9).

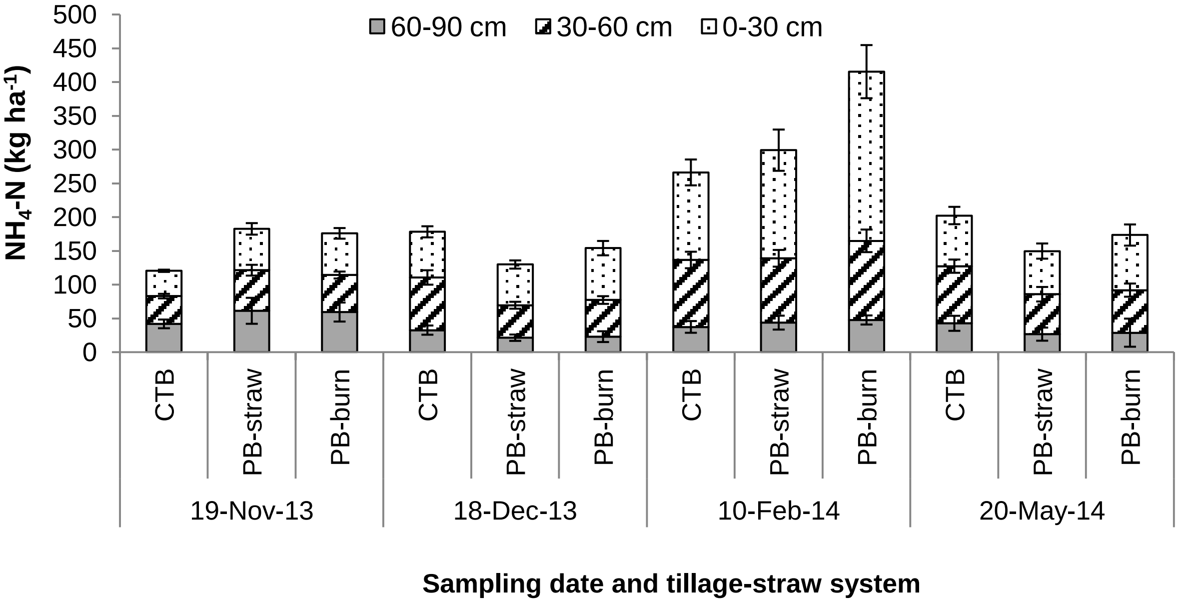

Figure 8 Ammonium-nitrogen (NH_4-N) concentration (kg ha^{-1}) at three soil depths for three different tillage systems averaged in bed and furrow measured before first fertilization (19-Nov-13), after planting (18-Dec-13), after second fertilization (10-Feb-14) and after harvest (20-May-14) in a tillage experiment at Ciudad Obregon, Mexico. Error bars represent one standard error of the mean. (CTB: conventionally tilled beds, PB-straw: permanent raised beds with residue retention, PB-burn: permanent raised beds with residue burning).

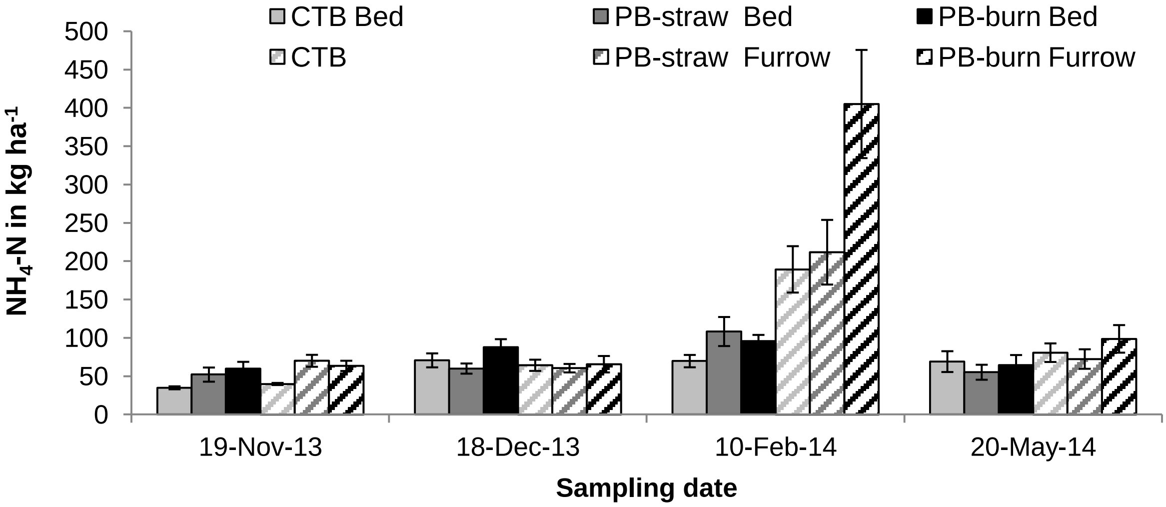

Figure 9 Ammonium-nitrogen (NH_4-N) concentration (kg ha^{-1}) in the first 30 cm soil depth for three different tillage systems measured separately in bed and furrow before first fertilization (19-Nov-13), after planting (18-Dec-13), after second fertilization (10-Feb-14) and after harvest (20-May-14) in a tillage experiment in Ciudad Obregon, Mexico. Error bars represent one standard error of the mean. (CTB: conventionally tilled beds, PB-straw: permanent raised beds with residue retention, PB-burn: permanent raised beds with residue burning).

Residual soil NO_3-N was highest in PB-straw burned, followed by CTB and lowest in PB-straw retained (P=0.0175). Residual soil NH_4-N was similar in all tillage-straw treatments and higher than NO_3-N (Fig. 10). On average only 31% of residual mineral N was NO_3-N and 69% NH_4-N. The total amount of residual mineral N in the entire soil profile was 283, 205 and 283 kg N ha^{-1} for CTB, PB-straw retained and PB-straw burned, respectively. In the case of CTB and PB-straw burned, residual soil N was 5 kg N ha^{-1} higher than mineral fertilizer N which was applied during the wheat cycle.

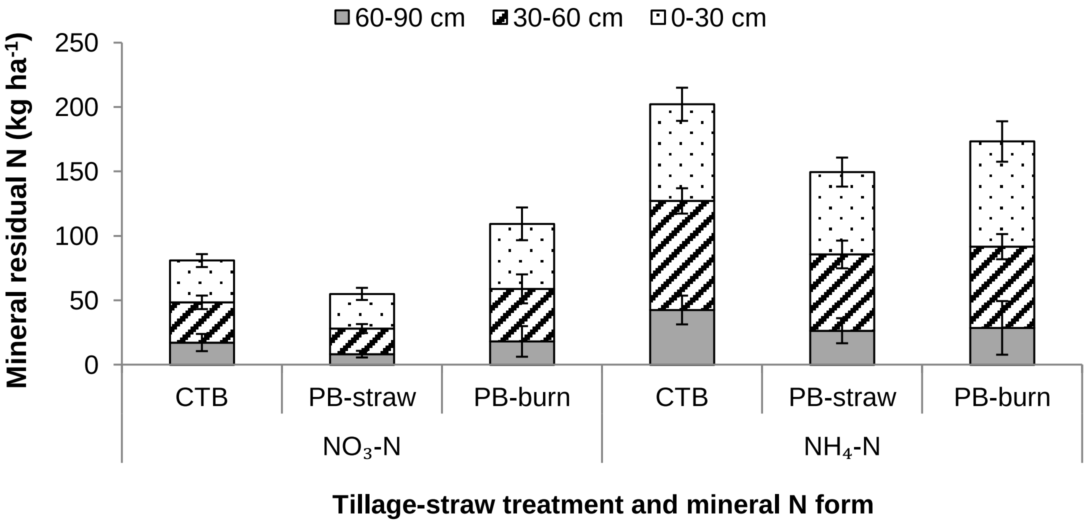

Figure 10 Residual soil mineral N (Nitrate NO_3-N and Ammonium NH_4-N) concentration (kg ha^{-1}) after wheat harvest (20-May-14) at three depths. Error bars represent one standard error of the mean. (CTB: conventionally tilled beds, PB-straw: permanent raised beds with residue retention, PB-burned: permanent raised beds with residue burning).

5.4.4 Nitrogen balance

Nitrogen balance was positive in all treatments (+156, +181 and +173 kg N ha^{-1} in CTB, PB-straw retained and PB-straw burned, respectively). This balance assumed that 65% of root N, 50 % of straw N from previous wheat crop and potentially mineralizable N (2% of total soil N in 0 to 30 cm depth) were made plant-available and taken up by wheat any time during the cycle (Fig. 11). After harvest, concentrations of mineral and organic soil N remained high (Fig. 10). After wheat harvest the reservoir of organic N across the entire soil profile amounted to 2568 kg N ha^{-1} in CTB, 3180 kg N ha^{-1} in PB-straw retained and 3198 kg N ha^{-1} in PB-straw burned.

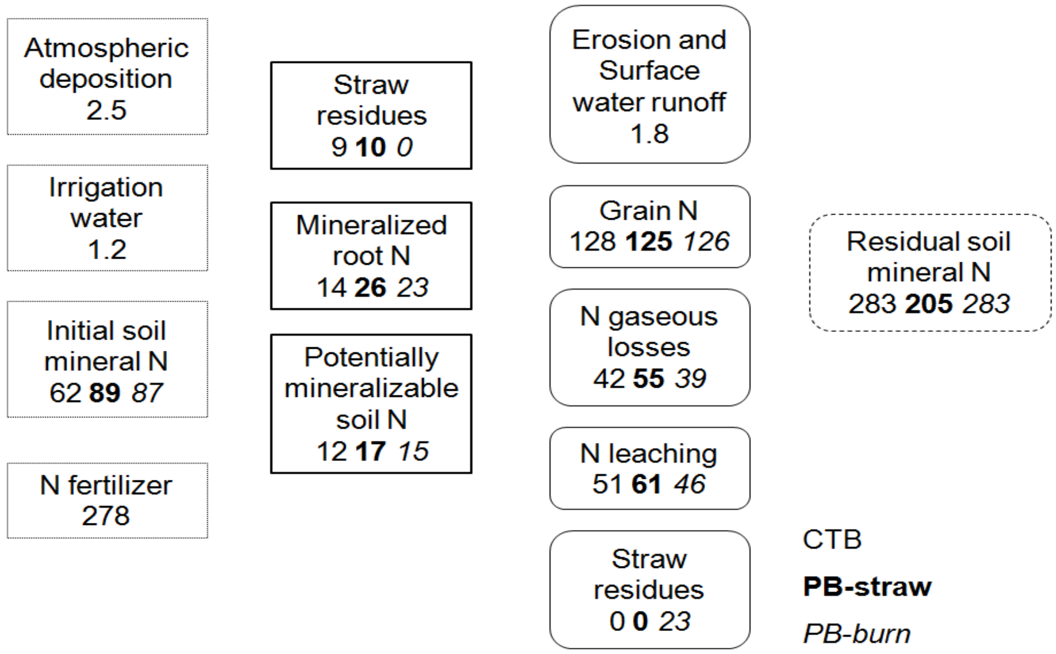

Figure 11 Nitrogen budget for direct (thin line) and indirect N input (bold line), output (oval-shaped) and residual N (dotted line) in three different tillage-straw systems at the field level. Values are expressed in kg N ha^{-1}. (CTB: conventionally tilled beds, PB-straw: permanent raised beds with residue retention, PB-burn: permanent raised beds with residue burning).

Initial soil N was lowest in CTB, as was mineralized root N and potentially mineralizable N. Grain N output was similar for the three tillage-straw treatments. Leaching losses were highest in PB-straw retained (60.8 kg NO_3-N ha^{-1}) and residual N after harvest was lowest for this treatment (Fig. 11). Straw N counted as incorporated input in CTB and as retained input in PB-straw retained, but was an output in PB-straw burned. Gaseous N losses were highest in PB-straw retained (55.2 kg N ha^{-1}) and N losses through denitrification losses were lower than through volatilization (19.6 kg N_2O-N ha^{-1} and 25.8 kg NH_3-N ha^{-1}, respectively). N supply by atmospheric deposition and irrigation water was small. The same was true for N losses by erosion and surface water runoff. Total input fluxes were +378, +424 and +408 kg N ha^{-1} for CTB, PB-straw retained and PB-straw burned, respectively. Total output fluxes were -223, -243 and -236 kg N ha^{-1} for CTB, PB-straw retained and PB-straw burned, respectively.

5.5 Discussion

5.5.1 Abiotic factors and dynamics of nitrogen

Soil temperatures were on average 0.5 °C higher in the furrow than in the bed due to lack of shading from growing wheat plants. The temperature amplitude, indicated by the standard deviation in the early morning hours (6-8 AM) and the afternoon (12-2 PM), was higher in the furrow where soil was not covered with biomass, with differences up to 10 °C (Fig. 2). As also found by Mahli and O´Sullivan (1990), soil temperature was on average lower in PB-straw retained because residues covered the soil and maintained temperature, thereby reducing heating-up of the soil during noon time. This can be advantageous in hot climates where cooler soil temperatures create a favorable environment for root growth and optimum plant growth (Acharya et al., 1998; Turmel et al., 2015). At the end of April highest soil temperatures reached 28.4 °C in PB-straw burned which accelerated microbial activity and N turnover in those treatments. This was evident by significantly higher total N and NO_3-N in these treatments when samples were taken after harvest and air temperature reached 36.6 °C (Fig. 4, Fig. 6, Table 1). As stated by Doran et al. (1998), soil temperature is one of the main factors controlling nutrient release and dynamics and had a great influence on treatment differences in N concentrations of the different fractions in the present study. Soil moisture in the topsoil was, as confirmed in many other studies (Verhulst et al., 2011a, Verhulst et al., 2011c, Turmel et al., 2015), significantly higher in PB-straw retained due to decreased evaporation with residue retention. Under irrigated conditions, water can be stored for a longer period of time which could prolong a proximate irrigation event.

Kätterer et al. (1993) found shallow rooting patterns in wheat caused by irrigation on a clay soil in Sweden which explained the overall small values in wheat root biomass (0.59-1.36 mg cm^3 in the first 15 cm sampling depth) in our experiment. The authors mentioned high turnover rates of roots and did not find any treatment differences due to high variance of the data and few replicates, which was similar in the present study. Wheat root biomass was not significantly different in three tillage-straw systems which was similar in a study conducted in a rainfed Vertisol by Muñoz-Romero et al. (2013). Roots can store N in the plant during its development and wheat is able to redistribute N from the root system to the grains (Andersson et al., 2005). The N content of roots increased from 1.27% N to 1.75% N in 30 cm depth and decreased in 60 cm depth to 1.48% N. The consequent amount of N from the roots in 0 to 60 cm depth was 21.5 kg N ha^{-1} in CTB, 40.1 kg N ha^{-1} in PB-straw retained and 35.6 kg N ha^{-1} in PB-straw burned, suggesting a higher N redistribution from roots to the plant in CTB due to lowest amounts of root N when samples were taken. As only 65% of total root N was estimated to be decayed, on average 21.1 kg N ha^{-1} were made available by rhizodeposition and mineralization in the later stage of plant development during wheat senescence.

Increased N availability due to fertilizer that stimulates decomposition (priming effects; Rao et al., 1992), were observed. Mineralization-immobilization turnover (MIT) between mineral and organic N forms is modified by N availability and can occur simultaneously in the soil (Mary et al., 1996; Meisinger et al., 2008). This was stimulated by fertilizer application events, which was expressed in the increased total N, NH_4-N and NO_3-N in all treatments in the furrow two weeks after second fertilization. In a long-term experiment on a Vertisol in Australia, higher soil total N was found with crop residue retention of wheat compared with burning of crop residues in the first 10 cm due to increased N cycling by increased microbial activity (Dalal et al., 2011). We only observed this in two of four sampling events where PB-straw retained yielded higher total N than PB-straw burned. Zibilske et al. (2002) obtained significantly greater concentrations of soil total N with zero tillage up to 30 cm depth, but stated that total N was uniformly distributed with depth under plow tillage which could not be confirmed in the present study (Fig. 4). Our data concur with studies conducted by Govaerts et al. (2006) and Patiño-Zuniga et al. (2009) who found lower N mineralization and total N content in CTB compared with PB-straw retained in another long-term trial in the Yaqui Valley. In permanent beds, removal of crop residue decreased total N compared with treatments with residue retention (Patiño-Zuniga et al., 2009), which was contradicted in the present study. Against the general assumption that residue burning is decreasing organic N content in the soil and hereby decreases the soil nutrient status, we did not find a negative effect of residue burning on soil N content. This coincided with results from Wuest et al. (2005).

The release of N from residues can only happen when soil mineral N is low or initial N concentration in residue is high enough (Alvarez et al., 2008). Cereal residues with a high C/N ratio can temporally immobilize N during decomposition (Turmel et al., 2015). Buried residues in CTB decompose and decrease their C/N ratio faster than surface residues in PB-straw retained. But PB-straw burned had no incorporated or retained residues left from previous maize or wheat and hence, immobilization of mineral N by straw residues may have been negligible. This explains why we found significantly higher NO_3-N and NH_4-N concentrations after fertilization events in PB-straw burned. Like MIT, urea hydrolysis, nitrification and plant uptake occur at the same time. These processes are intensified by warm soil temperatures and affected mineral N concentrations (Recous et al., 1988). As nitrate is mobile, all available NO_3 at shallow depths was at risk of getting leached into deeper soil horizons after the first pre-plant irrigation. NO_3-N concentrations were higher in the furrow during all sampling events and treatments except five days after planting, when NO_3-N at 0-90 cm depth was 4.6%, 75.1% and 34.5% higher in the bed compared with the furrow in CTB, PB-straw retained and PB-straw burned, respectively. However, to reduce leaching and fertilizer losses, it would be more favorable to have higher NO_3-N concentrations in the bed during the cropping cycle to increase plant N availability for wheat grown on top of the bed (Ding et al., 2015). This is, however, often unpractical as during mechanical fertilizer application young wheat plants may be damaged. Better synchronization between fertilizer placement and plant requirements is necessary as the deposition of fertilizer in the furrow can lead to reduced plant availability of mineral fertilizer. In a laboratory study conducted by Patiño-Zuniga et al. (2009), NO_3-N concentration was only 0.05 mg N kg^{-1} soil day^{-1} under tilled beds compared with 2.38 mg N kg^{-1} soil day^{-1} under no-tilled beds. The authors concluded that permanent beds accumulate NO_3-N over time, which we could only observe in PB-straw burned with high residual NO_3-N reaching almost 110 kg ha^{-1} at 0-90 cm depth, but not in PB-straw retained where NO_3-N halved after harvest (Fig. 6). After the first fertilizer application, NH_4-N concentrations did not significantly change which was due to the fact that soil sampling took place 29 days after first fertilization when NH_4-N had already disappeared by nitrification and NO_3-N increased significantly at the second sampling event (Fig. 7). At the third sampling, fertilizer application had a significant effect on NH_4-N concentrations ($P=0.029$), but not in the remaining sampling dates, coinciding with findings by Govaerts et al. (2006). Total or partial removal, retention, or burning of residues and the application of 0, 150 and 300 kg N ha^{-1} had no significant effect on NH_4-N concentrations seven to 55 days after fertilizer application in their study. Usually, application of urea fertilizer provokes an increase in NH_4-N concentrations before NO_3-N concentrations because urea hydrolysis takes place under moist soil conditions and converts urea fertilizer into CO_2 and NH_4^+ within one day or week. During this time, volatilization losses are favored by high soil pH and temperatures when fertilizer is not incorporated (Jones et al., 2007; Reetz et al., 2015). A lack of O_2, occurring after irrigation events inhibits nitrification and as such concentrations of NH_4^+ increased with water content. This may explain high NH_4-N concentrations at the third sampling, averaging 326.7 kg NH_4-N ha^{-1} at 0-90 cm depth where irrigation took place eleven days before, and therefore the soil was still wet at sampling. Well-aerated soils in wheat favor aerobic N transformations, resulting in nitrification of NH_4-N to NO_3-N (Fan et al., 2007). This was the case for the second sampling event when irrigation and fertilization took place concurrently one month before sampling and the nitrification processes of urea fertilizer were reduced (Figs. 7 and 9). Liu et al. (2003) and Meisinger et al. (2008) reported that soil NH_4-N levels were usually low and changed little over time, except when NH_4-N fertilizers or manure were applied. In our study, NH_4-N concentrations were high and averaged 159.5, 153.9, 326.7 and 175.0 kg NH_4-N ha^{-1} at 0-90 cm depth from the first to the fourth sampling date, respectively. As NH_4-N was nitrified to NO_3-N over time, the same was true for NO_3-N levels.

Yamaguchi (1991) stated that applied mineral N is not used completely by the crop over the growing season and that residual N was estimated to be 20-40% of applied N, but he observed a wide range of data (6-57%) during his literature study. For the present study, residual N averaged over three tillage-straw treatments represented 92.4% of the applied urea, assuming that all residual N came from applied fertilizer N. This enormous surplus of N in the soil is alarming, but maize was planted in summer, 28 days after the last sampling and could have taken up this mineral soil N to prevent it from leaching. Most of the residual N was reported in the upper soil layer (Yamaguchi, 1991) but we obtained high residual N at 30-60 cm sampling depth, being in the same range as mineral N at 0-30 cm depth. Lobell et al. (2004)

estimated an average over-application of more than 35% in irrigated wheat due to uncertainty in N supply and demand, which was well below our data. Liu et al. (2003) found high leaching losses in an irrigated wheat-maize rotation due to very high residual mineral N at 0-100 cm depth ranging between 106 and 430 kg N ha^{-1} for a 240 kg N ha^{-1} fertilizer dose attributed to over-application of urea. Zhao et al. (2006) found elevated residual N levels in 0-90cm depth reaching up to 414 kg N ha^{-1} in wheat and 439 kg N ha^{-1} in maize when 300 kg N ha^{-1} (50% Ammonium bicarbonate at planting and 50% urea at shooting stage) were applied. This highlights the need for precise fertilizer management, particularly in these high-input cropping systems.

Grain protein averaged 13%, which is higher than the tolerance of 12.5% for durum wheat to achieve good pasta cooking quality (Grahmann et al., 2014). As in previous studies (De Vita et al., 2007; Grahmann et al., 2014), grain protein concentration was lowest in PB-straw retained (12%), 13.7% in PB-straw burned and 13.4% in CTB. Permanent beds with residue retention are reported to have problems with N distribution during the grain filling phase and decreased N availability leading to unsatisfactory wheat quality (Pisante and Basso, 2000).

5.5.2 N balance and N losses

A positive N balance at the end of the cropping season indicates possible N losses, especially by leaching that could occur afterwards (Salo and Turtola, 2006; Devkota et al., 2013). Accumulation of N over the cropping cycle averaged 191 kg N ha^{-1}. Nitrogen surplus in the UK in 1995 was on average 115 kg N ha^{-1} and authors found that there is no direct correlation between N surplus and N leaching (Lord et al., 2002). We found leaching losses averaging 53 kg N ha^{-1} (13.2% of total N inputs that is lost in the form of NO_3-N leaching), measured with resin cartridges that were installed at 90cm depth during wheat cycle (Grahmann et al., 2016, under revision). In soils with clayey texture leaching losses under irrigated conditions were reported to reach 82 kg ha^{-1} of NO_3-N below the root zone (>40 to 130 cm; Hernandez-Martinez et al., 2016). However, residual N after wheat harvest shows that mineral N was available in the entire soil profile (Fig. 10), but that plants were not able to incorporate this N into biomass and hence, yield and grain N. Karlen et al. (1998) found that about 50% of the fertilizer N applied at conventional rates was not accounted for by crop removal. This was confirmed in the present study where N uptake by wheat plants account to only 126 kg N ha^{-1} in the grain and 14 kg N ha^{-1} in the straw with a mineral N application of 278 kg ha^{-1} averaged over all treatments. According to the N Index Model that was applied simultaneously to crosscheck measured emission data, volatilization losses were estimated to be 6 kg N ha^{-1} and denitrification losses were 18 kg N ha^{-1}. Model estimations for the Yaqui Valley (Christensen et al., 2006) indicated that around 24 kg N ha^{-1} may have been lost by volatilization and denitrification processes. Work from Saynes et al. (2014), using the N Index Model for Mexico, found average values of 5.3 kg N_2O-N ha^{-1} yr^{-1} which is much lower than average values found in the present study (20 kg N_2O-N kg ha^{-1} $season^{-1}$). Irrigation events provoked denitrification due to high NH_4-N concentrations and anaerobic soil conditions that can last up to one week after irrigation. Volatilization losses were even higher (26 kg NH_3-N kg ha^{-1} $season^{-1}$) and were accompanied by high soil NH_4 concentrations, due to application of urea favoring hydrolysis under moist conditions and high soil pH.

Nitrogen in roots was determined to account for its effect on the indigenous soil N supply for subsequently grown crops (Yamaguchi, 1991). Daigger et al. (1975) found amounts of root N between 15 and 26 kg N ha^{-1} up to 38 cm sampling depth during the different plant development stages. In the present study data ranged from 17, 35 and 31 kg N ha^{-1} up to 30 cm depth for CTB, PB-straw retained and PB-straw burned, respectively. In an incubation experiment conducted by Janzen (1990), 36% of the root-derived N originally present in organic form was mineralized to plant-available N after 76 days and concluded that root N contributed significantly to fertility of soils. For one cropping cycle, N deposition by roots up to 60 cm reached up to 26.1 kg N ha^{-1}, Muños-Romero (2013) found a considerable amount of N derived from rhizodeposition (93 kg ha^{-1}) that was deposited by wheat roots at 0-75 cm depth over two years in a rainfed Vertisol in southern Spain which was equivalent to 41% of total N uptake. In the current study, average N input by decaying roots and rhizodeposition was estimated to be 21 kg ha^{-1} during one wheat cropping cycle, representing 5% of the total N input into the cropping system and 16.7% of total N uptake in the harvested grain (Fig. 3). Root N biomass decay only contributes a small part of rhizodepostion (Muñez-Romero et al., 2013) and some authors consider root N as unavailable soil N pool (Jamieson and Semenov, 2000).

5.6 Conclusions

This study allowed an integral N balance study where different N input, output and pathway factors were measured which have not been considered in other studies. As the data collection was conducted in a long-term experiment, datasets may provide a representative picture of the intensively cultivated Yaqui Valley. They show an average N surplus of 170 kg N ha^{-1}, low N uptake and hence, low fertilizer use efficiency. The presence of high residual soil N at 30-90 cm soil depth after wheat harvest points out the risk of N leaching. Complex processes and turnover of N from organic to mineral forms and *vice versa* were found in soils that were significantly affected by tillage-straw treatment. Tillage-straw management significantly affected N fluxes at the micro-level and led to reduced total N in CTB and lowest mineral N after harvest in PB-straw retained. Contrary to the common belief, we did not find any negative effect on residue burning on soil nutrient status. There is a need to research other N management strategies in irrigated wheat-maize rotation systems that include alternative mineral N fertilizer or changed timing and application.

5.7 References

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Chapter 6

6 Fertilizer use efficiency by ^{15}N fertilizer application in different tillage-straw systems on a Vertisol in Northern Mexico

6. Fertilizer use efficiency by ^{15}N fertilizer application in different tillage-straw systems on a Vertisol in Northern Mexico

6.1 Introduction

Worldwide, agricultural fields are increasing in cropping intensity due to higher production targets and related increasing inputs leading to potentially environmental harmful loads of mineral N fertilizer application. Conservation Agriculture (CA) was proposed as a set of management practices including minimum or zero tillage, retention of crop residue, and economical viable crop rotation. CA under irrigated conditions is implemented by permanent beds (PB) with residue retention, that have the potential to reduce soil degradation and moisture loss, to improve nutrient cycling, to decrease greenhouse gas emissions and to increase farm sustainability (Verhulst et al., 2010; Dendooven et al., 2012). While PB with residue retention have shown clear benefits for cereal yield, soil quality and the environment (Govaerts et al., 2005; Govaerts et al., 2007; Lichter et al., 2008), the overall impacts of CA depend greatly on temperature and irrigation pattern, soil type, management intensity of the agroecosystem, knowledge transfer and available machinery in which CA is adopted (Knowler and Bradshaw, 2007; Wall, 2007; Pittelkow et al., 2015). Adoption of the CA components, either alone or in combination, could increase agricultural sustainability but has received little attention to date in the Yaqui Valley where it is only practiced by a small percentage of farmers (3000 ha in the 2015-2016 wheat cycle, personal communication Jesus Mendoza).

As frequently mentioned, retention of straw residues on the soil surface and reduced or minimum tillage changes soil quality and induces changes in N immobilization and mineralization processes compared with conventional ploughing systems (Turmel et al., 2015). Similar changes in N uptake and N dynamics are the cause of the often reported grain quality problems in cereals cropped under CA (Grahmann et al., 2014). In the Yaqui Valley, burning of residues is prohibited but many farmers still burn their residues by default. The effect of crop residue burning is unclear, as it was reported to reduce yields and soil quality in the long-term (Sayre et al., 2005; Verhulst et al., 2011b), but it obtained higher grain quality (Grahmann et al., 2016a).

Nitrogen is the most limiting and affected nutrient in agricultural systems and is of indispensable significance in intensive, irrigated cropping systems like the Yaqui Valley. But the application of mineral N fertilizer to the fields is often inefficient leading to a NUE of only 31% (Ortiz-Monaterio and Raun, 2007), and low fertilizer recovery rates. Earlier studies have shown high N leaching losses and medium gaseous N losses in this region (Riley et al., 2001; Christensen et al., 2006; Grahmann et al., 2016b). Especially for Vertisols, proper management is needed to reduce anaerobic soil conditions, which provoke volatilization and denitrification (Syers et al., 2001) and to reduce the number of soil cracks caused by shrinking and swelling clay minerals, and hence preferential flow of nutrient loaded irrigation water (Grahmann et al., 2016b).

The application of ^{15}N labeled fertilizer provides a tool to quantify uptake and conversion efficiency of fertilizer N in the soil-plant system (Barraclough, 1995; Portela et al, 2006). Many studies have been conducted to investigate the fate of labeled fertilizers in cereal rotations and soil at the time of harvest (Porter et al., 1996; Fan et al., 2007 Alvarez et al., 2008). However, for high-input, irrigated systems N loss pathways such as volatilization, denitrification or leaching have not been quantified in most of the studies and N fertilizer which is not recovered from crop or soil has been assumed as "unaccounted for" (Gardner and Drinkwater, 2009). The effect of applied fertilizer on a subsequent crop is often neglected as most researchers apply their ^{15}N labeled fertilizer continuously over several cropping cycles.

We used ^{15}N labeled fertilizer in a Hyposodic Vertisol in the Yaqui Valley (heavy clay soil) with a wheat-maize rotation under three different tillage-straw systems to quantify (1) the fate of fertilizer N applied to maize and (2) the relative contribution of residual fertilizer to the following wheat crop under irrigated conditions. In this context, we hypothesize that under the different tillage-straw systems, N recovery from mineral fertilizer is low and the soil is able to retain residual N from fertilizer which will be available for the subsequent crop.

6.2 Materials and methods

6.2.1 Long-term experiment

The study was conducted from June 2014 to May 2015 in a long-term trial that was initiated in 2005. The field experiment used randomized complete block design (6.4 m wide and 130 m long) with two replicates and three subplots (277.3 m^2) and consisted of 17 different treatments whereby in the present study, only three treatments were considered. The three treatments included were: 1) conventionally tilled beds with incorporation of wheat and maize residues (CTB) 2) permanent raised beds with retention of maize and wheat residues (PB-straw) and 3) permanent raised beds with burning of maize and wheat residues (PB-burned).

6.2.2 ^{15}N application

Due to the high cost of ^{15}N labeled fertilizer, two micro-plots (1.9 m x 1.6 m) with a 1.6 m buffer on all sides), were established at the beginning of each plot within the two blocks for ^{15}N fertilizer application. Micro-plots were implemented prior to pre-planting irrigation and fertilization without installing physical boarders. Tillage to 20 cm depth in the CTB micro-plots was done prior to ^{15}N application. The maize variety "H431" was directly seeded into the plots on 17 June 2014 at 8 to 10 seeds per m. Each micro-plot received two applications of ^{15}N labeled urea (CH_4N_2O), enriched at 10.15 atom%, while the surrounding buffer area received no fertilizer inputs during the study period. After the buffer zone, commercial urea was applied in the remaining plot area. The ^{15}N labeled fertilizer was spread evenly in powder form in small rows that were dug about 5 cm deep into the micro-plots, covered with soil and watered with a can. Application occurred before planting on top of the bed on 2 June 2014 (103 kg N ha^{-1}) and into the furrow on 16 July 2014 (100 kg N ha^{-1}) similar to the rates and frequency of fertilizer application in the main field plots. Phosphorus was applied in form of, Monoammonium Phosphate (MAP 11-52-0) at a rate of 52 kg P ha^{-1} at the time of the first N application. When fertilizer was applied to the micro-plots with surface residues (PB-straw), remaining maize and wheat straw was carefully removed from the soil surface and then replaced immediately after fertilization.

After maize, the durum wheat cultivar "Movas C2009", a commercially used cultivar in the Yaqui Valley was planted on 3 December 2014 at a seeding rate of 120 kg ha^{-1}. Wheat was fertilized with commercial urea as split application on 15 November and 12 January 2015. Irrigation events for both crops took place as pre-plant irrigation and four subsequent auxiliary irrigations. Wheat did not receive any ^{15}N application and was sampled for ^{15}N concentrations coming from residual ^{15}N in the soil and decomposed ^{15}N from maize straw.

6.2.3 Field sampling

Soil samples for nutrient and isotopic N analyses were collected at seven occasions from each micro-plot during the maize and wheat cycle. First sampling occurred on 18 June 2014 after first ^{15}N application, followed by sampling on 14 July 2014 two days before the second ^{15}N application, the third sampling took place on 11 August 2014, 26 days after the second ^{15}N fertilization and the last sampling for maize cycle was on 20 October 2014, five days after the maize harvest. Soil sampling continued on 8 December 2014, five days after wheat planting, followed by sampling on 4 February 2015 three weeks after 2nd urea application and was finished on 12 May 2015, five days after wheat harvest. At each sampling date, two soil sub-samples were taken from the furrow and the bed within the micro-plots at four increments (0-15, 15-30, 30-60, 60-90 cm). The soil borer was cleaned with deionized water and dried with paper towel after each micro-plot.

For extraction of mineral N, 9 g of the fresh soil sample were weighted into a plastic cup and 90 ml of a 1 M KCl solution were added and shaken for 1 min by hand. The cups sat for about 24 h and were reshaken the following day for 1 min. One hour after settlement of sediments, each sample was filtered by a separate, new filter (Whatman GF/B) and syringe and a 12 mL subsample was stored in a vial in a freezer at -10°C until further sample analysis. Frozen mineral N extracts were transported to the Plant Nutrition Institute in Göttingen, Germany where they were prepared for micro-diffusion according to Stark and Hart (1995) and subsequent analysis for mineral ^{15}N concentration. For total N, soil samples were air dried for one week and milled by a ceramic mortar and pestle and then fine-sieved. All used tools were cleaned carefully with deionized water after each sample. Bulk density was measured in each plot after the 2014 wheat harvest before the experimental period started using metal cylinders (5 cm diameter and 5 cm length) at six increments (0-15, 15-30, 30-45, 45-60, 60-75, 75-90 cm). As no physical boarders where used on the experimental plots, horizontal N fertilizer movement by surface water runoff was checked by taking soil subsamples at 0.5, 1, 2 4, 8, 16, 32 and 100 m after the end of each micro-plot at 2 depths (0-15, 15-30 cm) in April 2015 after the last wheat irrigation. All samples were proceeded and analyzed for total N and inorganic N.

Maize biomass samples were collected on 14 July and 8 August 2014 and dried at 60°C. All maize plants within each micro-plot were harvested on 15 October 2014 by cutting the stalks at ground level followed by drying at 60°C. Maize plants were separated into straw (leaves, stem, tassel, ears) and cobs and weighted separately. Wheat biomass was sampled on 27 January 2015 and harvested on 5 May 2015. Samples were separated into grain and vegetative biomass, then ground and stored for subsequent nutrient and ^{15}N analyses.

6.2.4 Isotopic analysis and calculations

Solid plant and soil samples were dried at 60°C, milled and weighted into tin capsules. Isotopic analyses were conducted with IRMS (Delta C; Finnigan MAT Inc., Bremen, Germany) coupled with an elemental analyzer (NA1108, Fisons-Instruments SpA, Rodano, Milano, Italy) and an interface (Conflow III, Thermo Electron GmbH , Bremen, Germany; Werner et al., 1999)

The percentage of N derived from fertilizer (Ndff) in plant tissue, dry soil and mineral N from soil KCl extracts water was determined using equation 1. The natural ^{15}N abundance of air (0.3663%) was used as a standard for plant tissue and soil samples (Portela et al., 2006).

$$\%\,Ndff = \frac{\%atom\ 15N\ sample - \%atom\ 15N\ natural\ abundance}{\%\ atom\ 15N\ fertilizer - \%atom\ 15N\ natural\ standard} * 100 \quad \text{(Equation 1)}$$

The percentage of N fertilizer recovery (NFR) in plant tissue and soil was determined with equation 2.

$$\% \, NFR = \frac{\% \, Ndff * total \; N \; (kg \; ha^{-1})}{N \; fertilizer \; dose \; (kg \; ha^{-1})} \quad \text{(Equation 2)}$$

The amount of N derived from N fertilizer that could be recovered in the soil is shown in equation 3.

$$Ndff_{soil} \; (kg \; ha^{-1}) = total \; N \; in \; soil \; layer * (\frac{15N \; atom\% \; excess \; in \; soil}{15N \; atom\% \; excess \; in \; fertilizer}) \quad \text{(Equation 3)}$$

6.3 Results and discussion

After wheat harvest, soil samples were taken to cross-check for lateral and horizontal movement of ^{15}N fertilizer. After a total of 10 irrigations, 2 pre-plant and 8 auxiliary irrigations, ^{15}N labeled urea was transported to the posterior parts of the plots. This is normally avoided by the installation of 10-20 cm deep plastic or metal boarders into the soil, but this idea was overruled given its impracticability under field traffic. As we used unconfined plots, the source of error became higher (Sanchez et al., 1987). These authors claimed that ^{15}N micro-plots with a size of 2 by 2 m are sufficiently large to determine the recovery of fertilizer N for maize crops under most conditions. However, the micro-plots in the present study have a size of only 1.9 m length and 1.6 width, which was sufficient for wheat according to Follett et al. (1991) who suggested a 1.5 by 1.5 m plot size, but likely not for maize. In our plots, maize and wheat were planted on beds and each bed was 0.8 m away from the next crop row which minimized the lateral movement of ^{15}N to left and right adjacent beds, but it did not decrease the possible sideward's movement in the furrow by flowing irrigation water (Fig. 1). Values lower than 1 kg Ndff ha^{-1} were considered marginal which was observed in all treatments after 2 m in 15-30 cm depth. In 0-15 cm depth, marginal amounts of labeled soil N were found in CTB and PB-burn after 8 m, but in PB-straw after 16 m, indicating a possible wide lateral transport of ^{15}N fertilizer in irrigation water (Fig. 1). In the upper soil layer, Ndff was still high in all treatments 1 m after the micro-plot, averaging 5.8 kg ha^{-1} which indicate that parts of the applied N were transported outside the micro-plot which decreased uptake efficiency.

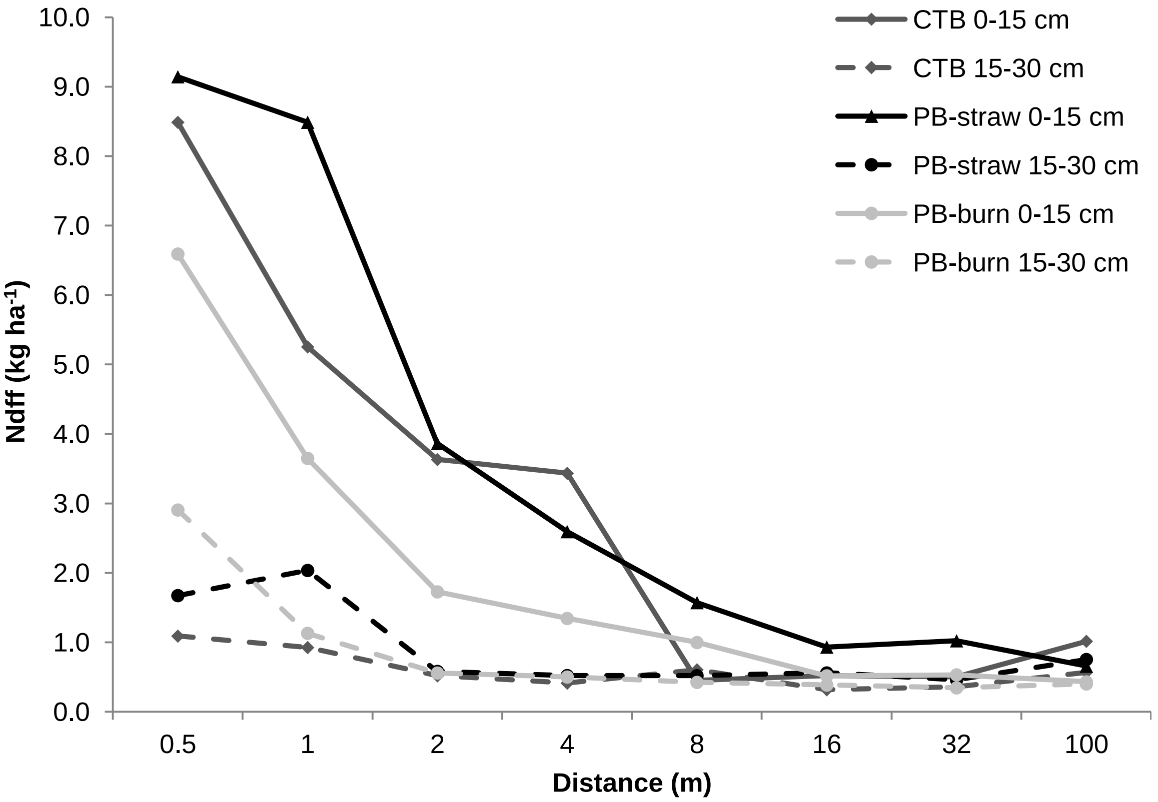

Figure 1 Nitrogen derived from fertilizer (Ndff in kg ha^{-1}) by horizontal movement of ^{15}N fertilizer in 0-15 and 15-30 cm soil depth taken in eight distances (in m) behind the micro-plots (CTB: conventionally tilled beds, PB-burn: PB-straw burned, PB-straw: PB-straw retained) in the Yaqui Valley in NW-Mexico.

Maize straw was colored with natural *Cochinella* right after harvest and could therefore be easily spotted and replaced in the original micro-plot. In CTB, maize straw was collected after harvest and replaced after finishing tillage activities for wheat planting. Maize straw was dug in manually. The same was true for maize straw that was moved by the zero-tillage wheat planters in PB-straw retained. It was placed back by hand to the original micro-plot.

Irrigation management is a major factor influencing the movement of ^{15}N labeled urea through the soil profile. As reported by Onken et al. (1979), furrow irrigation may cause fertilizer movement toward the center of the bed and then downward. This provokes displacement of ^{15}N fertilizer into deeper soil layers and hence reduced plant N uptake. Benjamin et al. (1997) suggested an alternate furrow irrigation which is advantageous for crop production compared with irrigation in every furrow but it can decrease leaching losses of fertilizer.

Table 1 Effect of tillage-straw management on N yield of maize and wheat in the cropping cycle 2014/15 in the Yaqui Valley in NW-Mexico.

	Straw (kg N ha^{-1})		Grain (kg N ha^{-1})	
	Maize	Wheat	Maize	Wheat
CTB	60.4	17.1	72.4	127.0
PB-straw	54.1	17.1	66.3	123.7
PB-burn	95.5	15.9	80.3	119.4

(CTB: conventionally tilled beds, PB-burn: PB-straw burned, PB-straw: PB-straw retained)

In the Yaqui Valle of NW-Mexico, yields of summer maize are always lower compared with those of winter maize due to high temperatures during the growing cycle and the shorter cropping cycle. However, maize yielded 4.6 t ha^{-1} in micro-plots in CTB and PB-straw and 5.0 t ha^{-1} in PB-burn. When looking at the whole plot level outside the micro-plots with commercial urea application, CTB yielded lowest with 4.9 t ha^{-1} and PB-straw and PB-burn obtained 6.5 t ha^{-1}. The yield discrepancy between micro-plots and entire plots was lower for the subsequent wheat cycle. Yield was 5.0, 4.9 and 4.8 t ha^{-1} in CTB, PB-straw and PB-burn, respectively, in the micro-plots and 5.1, 4.6 and 4.8 t ha^{-1} in CTB, PB-straw and PB-burn in the long-term experiment. Straw and grain N yield was highest for PB-burn for maize and similar in all treatments for wheat straw N, but lowest in PB-burn in wheat grain N (Table 1).

Table 2 Effect of tillage-straw management on labeled N fertilizer uptake by maize, wheat and residual soil N after harvest in the cropping cycle 2014/15 in the Yaqui Valley in NW-Mexico.

Ndff	Straw		Grain		Total		Soil 0-90cm	
(kg ha^{-1})	Maize	Wheat	Maize	Wheat	Maize	Wheat	Maize	Wheat
CTB	15.1	0.7	22.3	4.8	37.4	5.5	75.4	22.4
PB-straw	15.2	0.2	21.1	1.5	36.2	1.7	74.1	41.6
PB-burn	26.0	1.0	25.0	7.4	51.0	8.4	79.3	45.6

(CTB: conventionally tilled beds, PB-burn: PB-straw burned, PB-straw: PB-straw retained)

The subsequent wheat crop took up residual ^{15}N from the soil or from the decomposing maize straw material, but it is not possible to say by this approach which was the exact source of ^{15}N found in the wheat plant. Ndff in maize and wheat straw and grain was highest for PB-burn, and total Ndff (grain and straw) was similar for CTB and PB-straw in maize, but lowest in wheat for PB-straw (Table 2). Wheat grain and straw contained lowest Ndff content in PB-straw retained, but straw and grain yield were similar to CTB (Table 1), indicating that N was accumulated to a larger extent from other sources than labeled fertilized that was applied during the maize cycle compared with CTB and PB-burn. Residual soil Ndff after maize harvest was comparable for all treatments in 0-90 cm depth, but after wheat harvest CTB had only about 50% of the residual ^{15}N in the soil compared with PB-straw and PB-burn. In PB-burn, maize straw was burnt after maize harvest which excluded possible decomposition and release of ^{15}N from the organic material. Hence, in this treatment accumulated Ndff in wheat plants was obtained from residual soil N and not from straw residues.

Table 3 Effect of tillage-straw management on fertilizer N recovery in % in the cropping cycle 2014/15 in the Yaqui Valley in NW-Mexico.

	Maize			Wheat			Total
	Grain	Grain Straw	Grain Straw Soil N	Grain	Grain Straw	Grain Straw Soil N	Harvested Products
CTB	11	18.4	55.5	0.4	2.7	13.7	21.1
PB-straw	10.4	17.8	54.4	0.1	0.9	21.4	18.7
PB-burn	12.3	25.1	64.2	0.5	4.1	26.6	29.2

(CTB: conventionally tilled beds, PB-burn: PB-straw burned, PB-straw: PB-straw retained)

Recovery of labeled fertilizer in the harvested maize grain was very low, averaging only 11.2% and the recovery of fertilizer of all harvested products (maize and wheat grain and straw) averaged 23% (Table 3). Fertilizer recovery Ndff is generally low in irrigated systems, which was previously shown by different authors. Kessavalou et al. (1996) found that 54% of ^{15}N ammonium nitrate applied was lost from an irrigated maize cropping system. They attributed 41% to leaching losses and 13% to denitrification and volatilization. Grageda-Cabrera et al. (2011) found a 41% fertilizer N recovery (from %Ndff) for maize grain and straw in an irrigated maize-wheat rotation which received a N dose of 240 kg ha^{-1} in conventional tillage with residue burning, a 59% N recovery in conventional tillage with residue incorporation and only 27% N recovery with zero-tillage. Carefoot and Janzen (1997) found a cumulative N fertilizer recovery for wheat in plant and soil of 64%.

Table 4 Effect of tillage-straw management on Ndff in residual soil N concentrations after maize and wheat harvest in kg ha^{-1} in the cropping cycle 2014/15 in the Yaqui Valley in NW-Mexico.

Maize	CTB		PB-straw		PB-burn	
cm	Bed	Furrow	Bed	Furrow	Bed	Furrow
0-15	37.8	39.8	38.2	50.9	36.2	31.5
15-30	18.9	21.6	11.0	11.3	11.8	39.0
30-60	11.2	12.2	8.9	20.4	10.6	24.0
60-90	6.7	2.7	3.9	3.6	3.0	2.5
Total	74.6	76.2	62.1	86.2	61.5	97.0

Wheat	CTB		PB-straw		PB-burn	
cm	Bed	Furrow	Bed	Furrow	Bed	Furrow
0-15	14.0	11.1	30.4	19.7	33.6	16.3
15-30	3.6	5.3	7.7	8.0	9.6	9.5
30-60	4.4	3.6	7.4	7.6	9.3	7.2
60-90	1.4	1.2	1.5	1.0	2.0	3.8
Total	23.4	21.3	47.0	36.3	54.5	36.8

(CTB: conventionally tilled beds, PB-burn: PB-straw burned, PB-straw: PB-straw retained)

We found an average of 38% Ndff in the soil profile after maize harvest (Table 4). This exceeds findings from Powlson et al. (1992) who reported up to 18% of labeled N in residual soil. The authors discussed the possible pool substitution where plants take up unlabelled N which comes from mineralization of organic N in soil. This unlabeled N can account for 20-50% of the total N content of fertilized crops at harvest which might have been happened in PB-straw during the wheat cycle as we can find similar Ndff content to PB-burn in the soil, but Ndff in grain and straw was much lower. On the other hand, wheat grain yields were not significantly lower compared with CTB indicating that there was plenty N available, but not from a labeled N source from the previous cycle (Table 1). After wheat harvest, Ndff in the soil profile still amounted to 11% in CTB, to 21% in PB-straw and to 22% in PB-burn which is quite high compared with findings from Carefoot and Janzen (1997). They reported after wheat harvest for zero-tillage with residue removal in 0-120 cm soil depth 26.4 and 19.8 kg N ha^{-1} derived from ^{15}N fertilizer in the first and second year of study, respectively. Ndff was similar for bed and furrow in CTB and both crops, but it was higher after maize harvest in the bed for PB-straw and PB-burn which changed after wheat harvest when Ndff was higher in the bed compared with the furrow in both treatments (Table 4). As mentioned by Gardner and Drinkwater (2009),^{15}N recovery only in plants does not reflect the whole picture of ^{15}N pathways, therefore the total recovery of ^{15}N in plant and soil is more appropriate to asses environmental impacts and possible hazards. The amount of fertilizer N after maize harvest which was not allocatable, averaged 85 kg N ha^{-1} (42% of applied fertilizer) over all treatments (Fig. 2). Ladha et al. (2016) found that on average 48% of crop N is not coming from applied fertilizer and soil N which would increase our amount of unaccounted N. The same authors also estimated that non-symbiotic N_2 fixation could contribute up to 24% to total crop N which could be another possible explanation for acceptable grain yields in PB-straw even if Ndff was low.

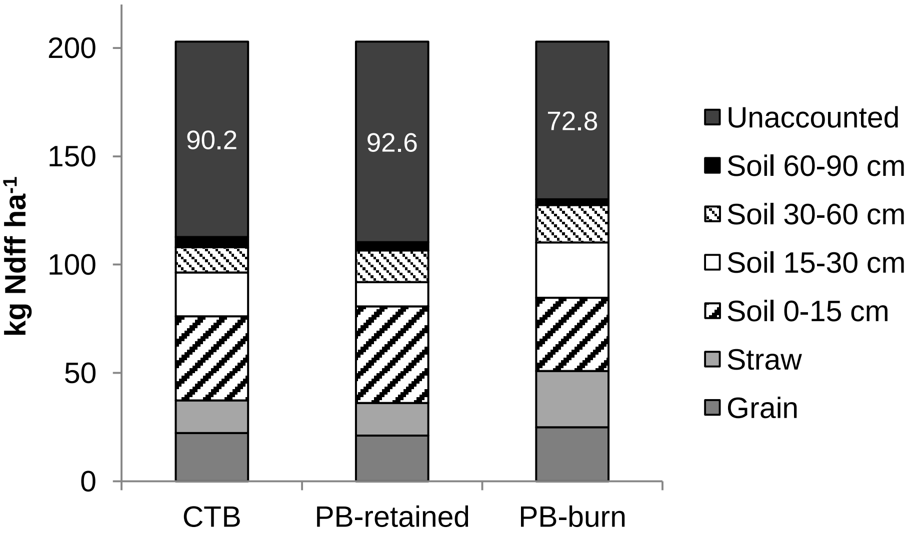

Figure 2 Nitrogen derived from fertilizer (Ndff in kg ha^{-1}) after maize harvest with a N fertilizer dose of 203 kg N ha^{-1} in the cropping cycle 2014/15 in the Yaqui Valley in NW-Mexico. (CTB: conventionally tilled beds, PB-burn: PB-straw burned, PB-straw: PB-straw retained).

Fertilizer use efficiency was highest for PB-burn (52%), followed by 39% in PB-straw and 32% in CTB (Fig. 3). This exceeded the estimations of Ortiz-Monaterio and Raun (2007) who reported a NUE of 31% for the Yaqui Valley. In a meta-analysis including 217 ^{15}N studies, the average amount of unaccounted N was 43 kg N ha^{-1} yr^{-1} with an average N application dose of 114 kg N ha^{-1} yr^{-1}, representing 38% of the total ^{15}N losses (Gardner and Drinkwater, 2009).

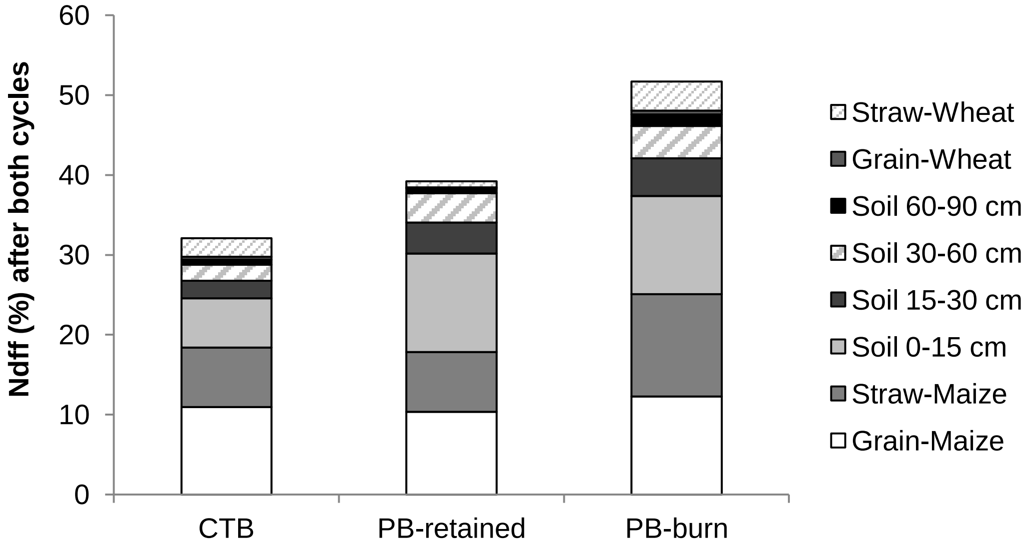

Figure 3 Nitrogen derived from fertilizer (Ndff in %) after wheat harvest with a N fertilizer dose of 203 kg N ha^{-1} applied to the previous maize crop in the cropping cycle 2014/15 in the Yaqui Valley in NW-Mexico. (CTB: conventionally tilled beds, PB-burn: PB-straw burned, PB-straw: PB-straw retained).

6.4 Conclusions

Application of ^{15}N fertilizer revealed possible N losses by surface water runoff. This error source has to be taken into account when calculating fertilizer efficiency on the field level. We found ^{15}N in the first 2 to 4 m behind the micro-plot in the first 15 cm soil depth. Summer maize obtained very low fertilizer efficiencies and was not able to take up large amounts of N for biomass production as yields were very low for all treatments. Residual mineral soil ^{15}N after harvest was high showing that Vertisols could accumulate and store large quantities of mineral N. Highest fertilizer use recovery was found in PB-straw burn which coincided with previous findings from this long-term experiment. NUE in the Yaqui Valley is higher than worldwide estimations if residual soil N after wheat harvest was included into calculations, assuming that it will still be taken up afterwards by subsequent crops. If we only consider ^{15}N accumulation in maize and wheat grain and straw, NUE averaged only 23% which is below the worldwide average. CA is strongly promoted in this area, even if it is apparently not the most efficient cropping system. Before further extension, research should be focus on the improvement of NUE.

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Chapter 7

7 General discussion and conclusions

7 General discussion and conclusions

7.1 Evaluation of the methodology

7.1.1 Experimental set up of the long-term trial

The long term experiment that was used for the studies in chapter 4, 5 and 6.2 consisted of only two repetitions (blocks). Each repetition has three subplots that are to be considered as subsamples. Even with the large size of the subplots (277.3 m²), the experimental error was large and the randomized experimental design could not account for this. The experimental error was reduced because treatments were kept the same for more than ten years, including tillage and fertilization management, which standardized the entire experimental area. As treatments are randomized and plot size is large, an independence among samples is ensured (Petersen, 1994). Subsamples taken from subplots are pseudo-replicates as we did not replicate them in the laboratory but the samples came from different parts of the plot, having a total size of 6.4 m width and 130 m length. Long-term experiments are essential to receive information of sustainable land-use in the long-run and represent an indispensable basis for the calibration and validation of new technologies. Otherwise, long-term experiments are relatively inflexible in their treatments and cannot be used for current and urgent research issues. Especially, in soil science field experiments that run over a long period are necessary to quantify small changes in soil properties over time (Alm, 2007). Often at least 5-7 years are required in CA before reaching stable and higher yields, reduced herbicide applications and improved chemical and physical soil quality (Govaerts et al., 2005). The long term trial in our study is over 10 years old with non-changing treatments assuring a reached plant-soil equilibrium in CA treatments which compensates for the reduced number of repetitions.

The durum wheat variety "Movas" is not the highest yielding variety in the valley, but as it is a long-term trial, a stem rust resistant variety was chosen and kept constant as long as possible in order not to add unnecessary variability to the data. Nevertheless, it cannot be excluded that other, more recent released varieties (e.g. CIRNO C2008, QUETCHEHUECA ORO C2013; Fuentes-Davila et al., 2014) obtain higher yields, better grain quality or higher NUE.

7.1.2 Gaseous losses by INNOVA measurements

Measurements of gaseous emissions were conducted during two wheat and one summer maize cycle. Methodological details can be found in 5.3.3. Unfortunately, various error notifications (pump test failed, microphone test failed, etc.) appeared several times during the measurements. The equipment was repaired after the first measurement cycle but continued with error notifications during subsequent maize and wheat cycle. The number of measuring days had to be reduced and invalid data omitted. Additionally, due to the heavy clay soils with their high water holding capacity, it was not possible to enter the field after irrigation events, but in this timeframe the highest N emissions were expected. We had to wait up to five days to enter the plots to prevent compaction of the beds since the saturated vertisols were very muddy.

Air humidity values were very high in a closed chamber system in the morning hours and after rainfall in summer. But the INNOVA monitor automatically compensates for cross-interference between gases and water vapor interference (Christensen 1990) which was important to obtain reliable emission data on measurement days when no notification error appeared. An accurate and precise functioning of the photo-acoustic multi-gas field monitor device was discussed in previous studies. Rosenstock et al. (2013) tested gas samples of known concentrations by different photo-acoustic field monitors and found overestimations of up to 364% for CH_4, underestimations of up to -16% for N_2O, but only acceptable values ranging from 1% to -4% for CO_2. Padre et al. (2014) compared CO_2, CH_4 and N_2O fluxes measured with a photo-acoustic field monitor or manual gas sampling followed by gas-chromatography and obtained a higher precision with the photo-acoustic field monitor for CO_2 and N_2O in wheat and maize and a lower precision for CH_4 in rice compared to gas-chromatography. Li et al. (2015) examined the photo-acoustic multi-gas monitor in poultry houses for its NH_3 measurements and did not find any significant differences compared with the single-gas photo-acoustic analyzer (Chillgard RT). However, as stated by various authors, the photo-acoustic multi-gas field monitor is an adequate, time and cost-effective method at present for measurements of soil gaseous emissions if properly working (Yamulki and Jarvis, 1999; Pask et al., 2014). Nevertheless, calibration is indispensable before and after field use. The extrapolation of data between measurement days increases the effects of erroneous measurements, which is why the number of measurement days should be always extended to a maximum.

In the following, soil emission results from two subsequent wheat cycles and three different tillage-straw systems will be presented. N emissions led to gaseous N losses of 22.5, 23.7 and 31.2 kg NH_3-N ha^{-1} in PB-burn, CTB and PB-straw, respectively, and 16.5, 18.2 and 24.0 kg N_2O-N ha^{-1} in PB-burn, CTB and PB-straw, respectively, during the wheat cropping cycle 2013/14 (Fig. 1). In the cropping cycle 2014/15, N emissions decreased and were 9.0 kg NH_3-N ha^{-1} in PB-burn, 7.5 kg NH_3-N ha^{-1} in CTB and 13.1 kg NH_3-N ha^{-1} in PB-straw. For N_2O, total amount emissions for the cropping cycle were 17.3 kg N_2O-N ha^{-1} in PB-burn, 12.6 kg N_2O-N ha^{-1} in CTB and 11.5 kg N_2O-N ha^{-1} in PB-straw (Fig. 2). The cumulative N emissions averaged over all tillage-straw systems were 45.4 kg N ha^{-1} in 2013/14 and 23.7 kg N ha^{-1} in 2014/15. This is in the range of N emissions found with the same methodology for homegardens in Sudan (53 kg ha^{-1} a^{-1}, Goenster et al., 2014), for urban gardens irrigated with river water in Niger (50 kg N ha^{-1}, Predotova et al., 2010) and for irrigated vegetable production in Oman with mineral fertilizer (45 kg ha^{-1}, Siegfried et al., 2011). Additionally for the cropping cycle 2013/14, gaseous losses for fertilized plots were estimated using the AGRAMMON model (2009) and the Nitrogen Index model (Delgado et al., 2008) based on the N index for Mexico. The AGRAMMON model included basic production parameters like fertilizer dose for gaseous N losses simulations. According the AGRAMMON model, NH_3 losses in fertilized plots were 42 kg N ha^{-1}, N_20 losses were 6.8 kg N ha^{-1} and NO_x losses were estimated to 1.4 kg N ha^{-1}. The N Index model was fed with soil nutrient, irrigation, crop N uptake and water management information and qualitative factors. The N Index Model resulted in volatilization losses of 6 kg N ha^{-1} and denitrification losses of 18 kg N ha^{-1}, from which N_20 losses were estimated 4.6 kg N ha^{-1}. This was a total of 50.2 kg N ha^{-1} with AGRAMMON, 24 kg N ha^{-1} with the N Index model and 45.4 kg N ha^{-1} directly measured with the photo-acoustic INNOVA device. As the AGRAMMON model is based on simple estimations of N fertilizer type and dose and does not take into account soil, climatic or irrigation data, results from N index model may be more exact. They coincide with gaseous N losses which were directly measured in the cropping cycle 2014/15 (23.7 kg N ha^{-1}).

There was no evidence detected that N emissions increased after N fertilization or after irrigation events. As mentioned before, the field could not be accessed directly after or during irrigation events and it is thus likely that peaks of N emissions were not measured and the presented data are thus likely an underestimation of volatilization and denitrification processes taking place in the highly intensive irrigated cropping systems of our study.

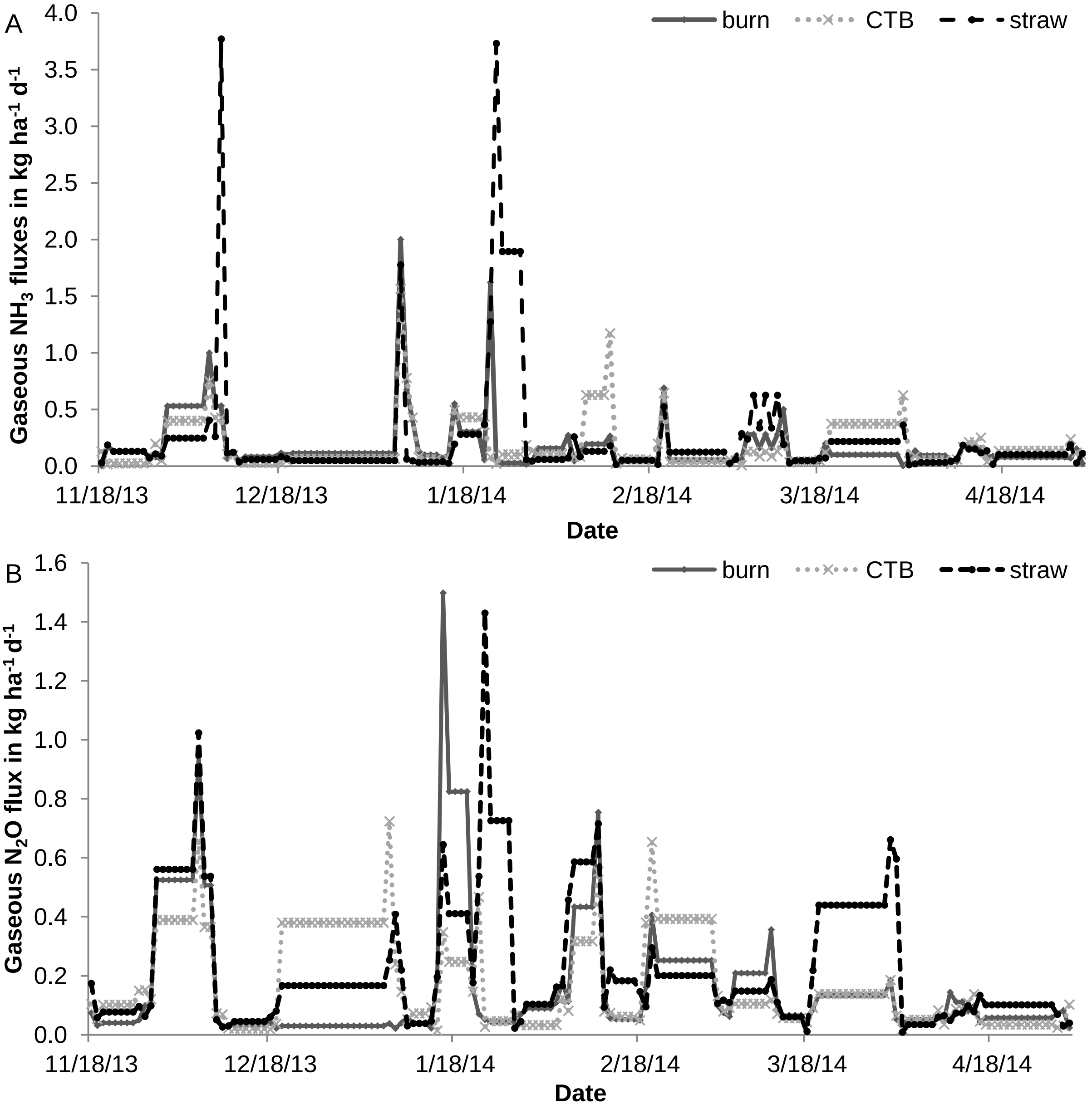

Figure 1 Gaseous emissions for (A) NH_3 and (B) N_2O in kg ha^{-1} d^{-1} from soil in the wheat cropping cycle 2013/14 in three different tillage-straw systems (burn: PB-straw burned, CTB: conventionally tilled beds, straw: PB-straw retained) of the Yaqui Valley in NW-Mexico.

In the cropping cycle 2013/14, a sharp daily increase in NH_3 fluxes was observed on 8 December and 23 January for PB-straw and on 7 January for all treatments. N_2O

fluxes rose severely on 6 December for all treatments, on 16 January in PB-burn and on 23 January in PB-straw. These peaks seemed unrelated to field activities, as the first and second fertilization took place on 19 November and 27 January and irrigation events on 20 November, 29 January and 24 February.

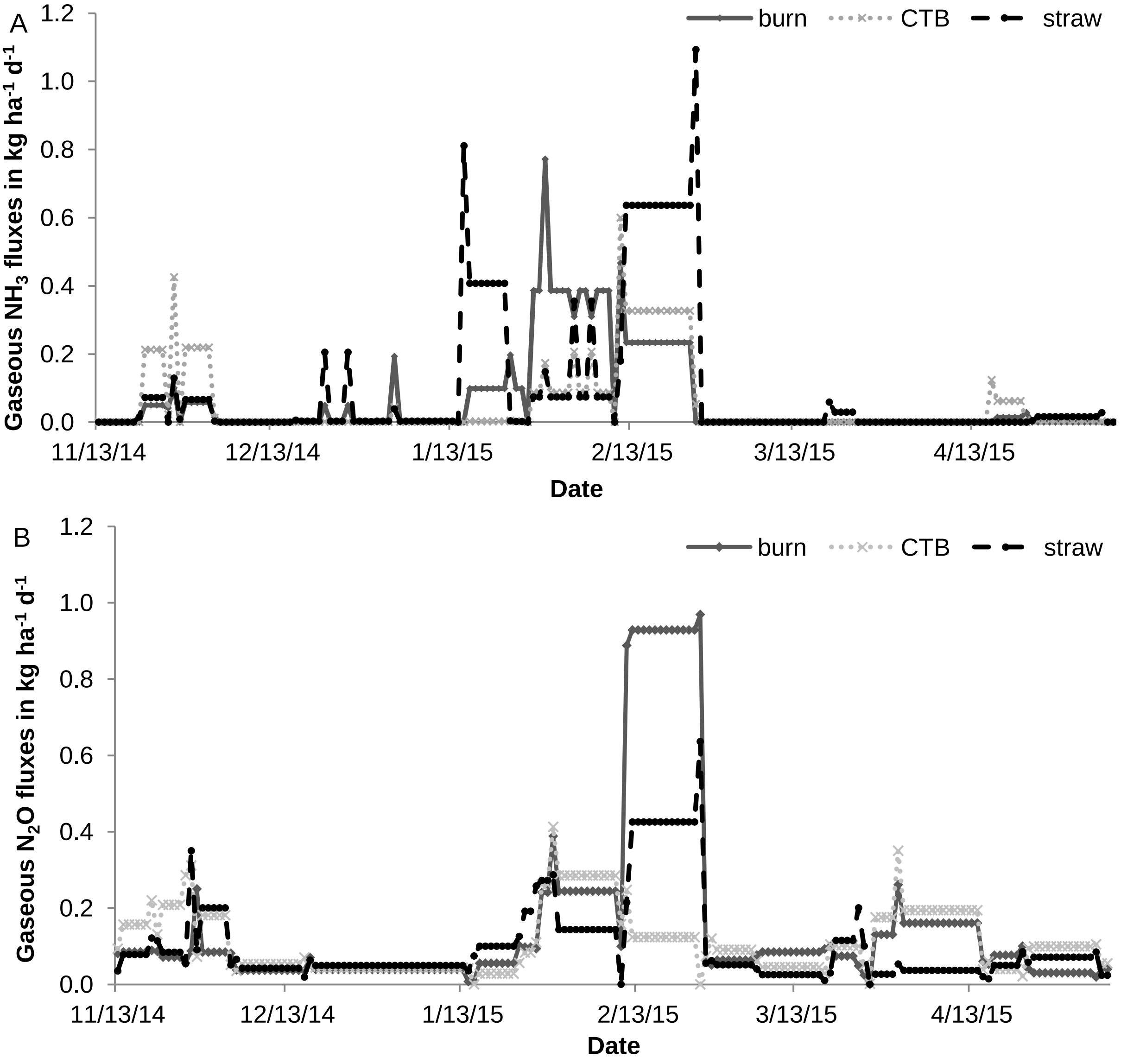

Figure 2 Gaseous emissions for (A) NH_3 and (B) N_2O in kg ha^{-1} d^{-1} from soil in the wheat cropping cycle 2014/15 in three different tillage-straw systems (burn: PB-straw burned, CTB: conventionally tilled beds, straw: PB-straw retained) of the Yaqui Valley in NW-Mexico.

For the cropping cycle 2014/15, N emissions were reduced to almost half compared to the previous cropping cycle. NH_3 fluxes increased visibly on 15 January in PB-straw three days after 2nd fertilization, on 29 January in PB-burn and on 24 February in PB-straw, seven days after second auxiliary irrigation. A sharp increase in N_2O fluxes was only observed on 12 February for PB-burn and 24 February for PB-burn and PB-straw, again seven days after second fertilization. As we did not find an increase in all treatments at a certain measuring day, effects on N emissions by certain field operations such as fertilization or irrigation were not confirmed.

7.2 Conclusions

Three field experiments were conducted to study the effect of nitrogen fertilizer management in wheat and maize on yield, grain quality, efficiency and chemical soil quality parameters under irrigated conditions at CIMMYT´s experimental station during 2013-2015 in Ciudad Obregon, Sonora, Mexico.

One of the largest obstacles to a more widespread use of CA is the increase of N immobilization processes in the soil and more effective N fertilization that is needed to address this problem. The results outlined in this work have shown that it is possible to obtain stable yields similar or above the regional average while using CA, but that mineral fertilizer application is still inefficient and high leading to environmental contamination. Although there is increasing interest regarding the adoption of conservation agriculture systems among farmers and politicians in the Yaqui Valley, significant challenges remain before a widespread adoption can occur.

The conclusions of this dissertation are:

- An extensive literature review showed that research on N fertilizer management in CA is scarce, long-term studies are missing and available results on the optimization of nitrogen use efficiency that include the three components (minimum tillage, residue retention and economical viable crop rotation) are inconsistent.
- The review also showed that CA systems generally have lower NUE rates than conventional systems, which is largely due to N fertilizer immobilization through crop residues leading to higher fertilizer rates.
- Permanent beds with full residue retention and high fertilizer dose resulted in high quality defects (high yellow berry and low grain protein concentration) in durum

wheat. Due to surface application of mineral fertilizer, temporary N immobilization took place and reduced N efficiency. The application of mineral N resulted in higher grain quality when all N was applied near 1st node compared to a pre-plant application.

- For bread wheat, tillage did not significantly affect yield, but permanent beds with surface residue retention negatively affected grain protein concentration and other quality parameters compared with conventional tillage. Nitrogen fertilizer management in furrow-irrigated wheat cropping systems should combine split N application and disking it on the bed pre-planting and in the furrow later in the season to increase yield and quality for bread wheat. A broadcast application resulted in the lowest wheat yields and quality in both tillage systems.
- There were no significant differences in leaching between maize and wheat, but for both crops leaching losses were numerically highest in permanent beds with residue retention. Leaching losses averaged 53 kg N ha^{-1} in wheat and 68 kg N ha^{-1} in maize. In maize, permanent beds with residue burning had significantly lowest leaching losses. High residual soil N was found in both crops in the entire soil profile which points at the risk of N leaching.
- Ion exchange resins were validated for the installation and use in vertisols to measure nitrate leaching and obtained reliable results comparable with previous modeled leaching estimations which made them a good tool for direct field measurements in this area.
- Positive N balances with an average N surplus of 191 kg N ha^{-1} were found for the irrigated, high-input cropping system. We found complex transformation and turnover of soil N from organic to mineral forms and *vice versa* during all sampling events that were affected by the tillage-straw treatment. Tillage-straw management affected N fluxes at the micro-level and led to reduced total N with conventional tillage and lowest mineral N after harvest in permanent beds with residue retention.
- Contrary to previously reported results, we did not find any negative effect of residue burning on crop yields, wheat grain quality, soil nutrient status or fertilizer efficiency.
- ^{15}N fertilizer trials indicated a NUE of only 39% for permanent beds with residue retention under summer maize cultivation with subsequent wheat planting. The

current extension of the CA cropping system in the Yaqui Valley is not sustainable and needs further improvement. Alternative summer crops and fertilizer management should be considered to reduce risks of environmentally harmful contamination and long-term damage.

7.3 Recommendations and future research needs

In all three experiments included in this dissertation, urea was applied as the sole N source. Different types of mineral N fertilizer (ammonium nitrate, urea ammonium nitrate) and the application of slow release fertilizer, nitrification inhibitor products and foliar N fertilizers should be tested alternatively. Also, the use of organic fertilizer like manure, resulting from the intensive meat, milk and egg production in the Yaqui Valley, should be investigated under CA conditions. Organic amendments in addition to straw residues could help to mitigate potential shortages of mineral N fertilizers as they may improve chemical and physical soil quality by increasing organic matter.

For the fertilizer management of wheat as a winter crop under irrigated conditions and under CA, information is scare on the application of fertilizer in later growing stages (e.g. as third application at anthesis) and application of foliar fertilizer to improve grain quality. It is recommended to reduce preplanting application of mineral fertilizers, but to increase the N dose at 1st node fertilization.

Additionally, more diverse crop rotations need to be investigated. In our study, only a wheat-maize rotation was included, but another important summer crop is soybean (*Glycine max* (L.) Merr.). Knowledge about fertilizer management of soybean under irrigated conditions grown under conservation agriculture is scarce. Soybean may have phytosanitary problems due to damage by white fly incidence, but there is a potential for high profitability when white fly incidence is low and soybean prices are high

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Affidavit

I herewith give assurance that I completed this dissertation independently without prohibited assistance of third parties or aids other than those identified in this dissertation. All passages that are drawn from published or unpublished writings, either word-for-word or in paraphrase, have been clearly identified as such. Third parties were not involved in the drafting of the content of this dissertation; most specifically I did not employ the assistance of a dissertation advisor. No part of this thesis has been used in another doctoral or tenure process.

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