Conservation agriculture as a means to mitigate and adapt to climate change, a case study from Mexico[1]

Nele Verhulst[a,b], Bram Govaerts[a*], Ken D. Sayre[a], Kai Sonder[a], Ricardo Romero-Perezgrovas[a,b], Monica Mezzalama[a], Luc Dendooven[c]

[a] International Maize and Wheat Improvement Centre (CIMMYT), Apdo. Postal 6-641, 06600 Mexico, D.F., Mexico,
[b] Katholieke Universiteit Leuven, Department of Earth and Environmental Sciences; Celestijnenlaan 200 E, 3001 Leuven, Belgium,
[c] Cinvestav, Avenida Instituto Politécnico Nacional 2508, C. P. 07360, México D. F., México

* Corresponding author: Tel: +52 5804 2004, E-mail: b.govaerts@cgair.org

Introduction

Conservation agriculture (CA) has been proposed as an adapted set of management principles that assures a more sustainable agricultural production. It combines the following basic principles: (1) reduction in tillage, (2) retention of adequate levels of crop residues and soil surface cover, (3) use of crop rotations. These CA principles are applicable to a wide range of crop production systems. However, the application of CA will be different in different situations. Specific and compatible management components (pest and weed control tactics, nutrient management strategies, rotation crops, appropriately-scaled implements, etc.) will need to be identified through adaptive research with active farmer involvement.

In this chapter, climate change predictions for Mexico will be discussed. Then the potential of CA as a means to mitigate and adapt to climate change will be examined for two contrasting agro-ecological environments, using research results of long-term trials. Finally, the economic potential of CA for climate change mitigation and adaption will be examined and an extension strategy will be outlined.

Materials and methods

Long-term trials that compare tillage and residue management strategies were set up in contrasting conditions, i.e. rainfed conditions in the semi-arid highlands of Mexico and irrigated conditions in arid north-western Mexico. The rainfed experiment was initiated in 1991 in El Batán in the semiarid, subtropical highlands of Central Mexico (2240 masl; 19.318 N, 98.508 W). The mean maximum and minimum temperature are 24 and 6°C, respectively (1991-2009) and the average annual rainfall is 625mm y^{-1}, with approximately 545mm falling between May and October. Short, intense rain showers followed by dry spells typify the

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summer rainy season and the total yearly potential evapotranspiration of 1550mm exceeds annual rainfall. The soil is a Haplic Phaeozem (Clayic). The irrigated experiment (initiated in 1993) is conducted near Ciudad Obregón, Sonora, Mexico (lat. 27.33°N, long. 109.09°W, 38 masl). The site has an arid climate with a mean annual temperature of 24.7°C and an average rainfall of 384mm (1971-2000). Rainfall is summer dominant and only 23% of total rainfall occurs during the wheat growing season from November to May (Servicio Meteorológico Nacional). The soil is a Hyposodic Vertisol (Calcaric, Chromic).

Results and discussion

Climate change predictions for Mexico

Analyses of climate data for Central America of the past 30 to 50 years show patterns of changes consistent with a general warming (Magrin et al, 2007). The occurrence of warmer maximum and minimum temperatures has increased, while incidences of extremely cold temperature events have decreased (Aguilar et al, 2005). There is also a positive tendency for more intense rainfall events and consecutive dry days (Aguilar et al, 2005; Groisman et al, 2005). Groisman et al (2005) found a substantial decrease in precipitation over the Central Plateau of Mexico over the last 30 years. In the same period, the frequency of rain events above 75 mm increased substantially by 110% $(30\ y)^{-1}$.

Climate models predict that Mexico will continue to warm during this century. Averaging the predictions of 19 models with emission scenario A2 (commonly known as “business as usual”), the predicted increase in annual average temperature by the 2050s (the period 2040 to 2069) ranges from 1.6-2.0°C on the Yucatán peninsula to 3.1-3.5°C in northern Mexico (Figure 1a). Temperatures will increase less in the coastal areas than in inland regions. Annual minimum and maximum temperature show the same trend with higher increases in maximum temperature (between 1.6 and 4.0) than in minimum temperature (between 1.6 and 2.5°C) (data not shown). Annual precipitation is predicted to decrease in most of Mexico, with the largest decrease (10 to 25%) on the Yucatán peninsula and in north-eastern Mexico (Figure 1b). Only the Baja California peninsula (currently the driest region) is predicted to have substantial increases in annual rainfall (Figure 1b). The predicted changes in climate could severely affect agricultural production in Mexico. According to Parry et al (2004), grain yields in Mexico could be reduced by 30% by 2080.

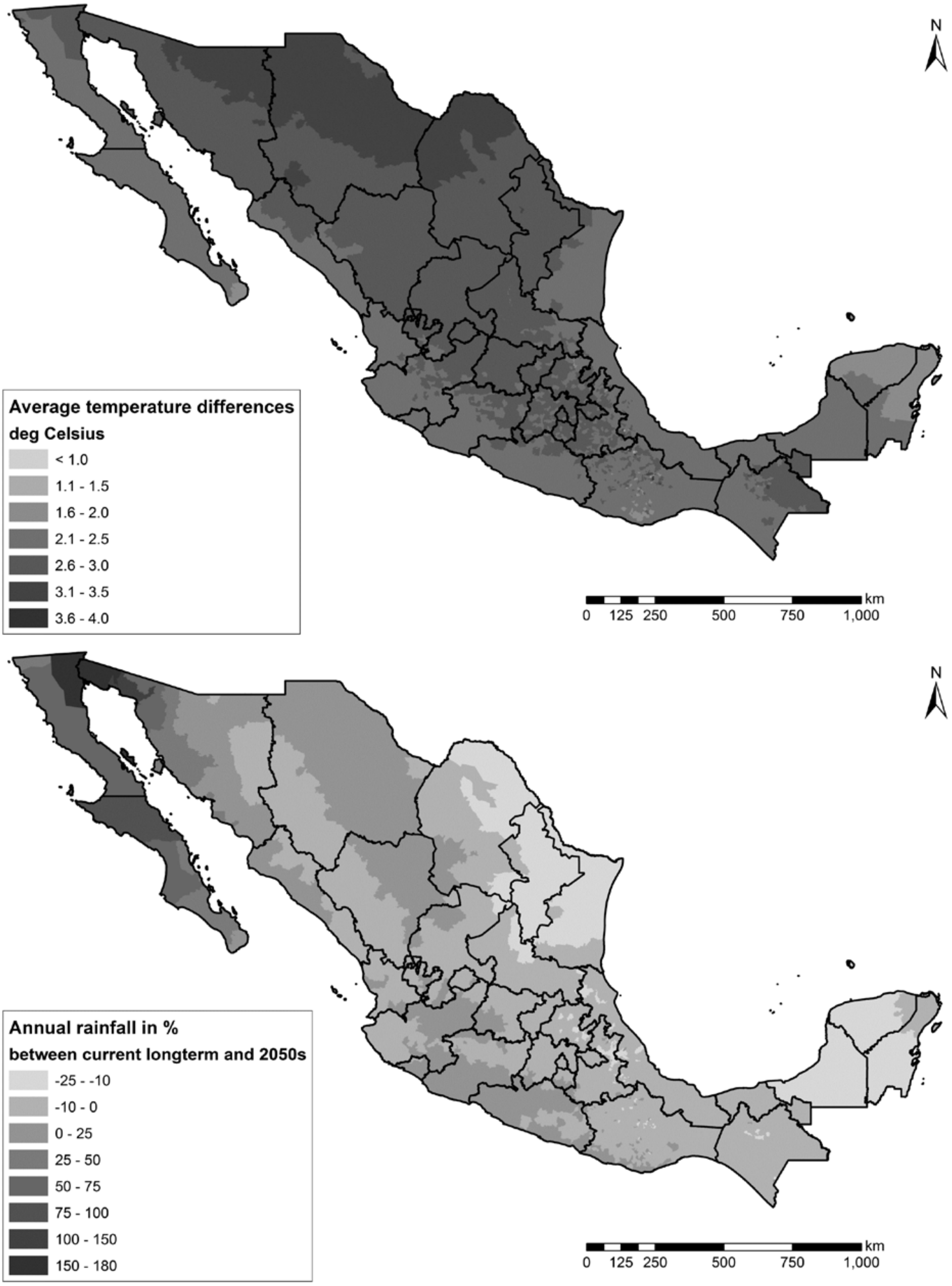

Figure 1 *Predicted annual (a) average temperature difference (in °C) and (b) rainfall difference (in %) between current long-term average (1951-2002) and the 2050s (average of 19 models for emission scenario A2)*

Rainfed conditions in the semi-arid highlands of Mexico

Conservation agriculture as an adaptive measure

Soil quality

Principal component analysis (PCA) of chemical and physical soil characteristics grouped treatments in three clusters: Zero tillage (ZT) with residue retention, ZT with residue removal and conventional tillage (CT) (Govaerts et al, 2006a). Plots with ZT and residue retention were separated from the other plots by high nutrient status, whereas plots with ZT with residue removal had a low nutrient status and high Mn concentration. Plots with CT had an intermediate chemical soil quality and the difference between residue retention and removal was small (Govaerts et al, 2006a). The physical soil quality data showed that ZT with residue retention resulted in a good topsoil structure, whereas ZT with residue removal had a less favourable topsoil structure and high penetration resistance. Conventional tillage had the lowest penetration resistance, but also a deficient topsoil structure (Govaerts et al, 2006a). Additional studies showed that ZT with residue retention also had higher water infiltration and soil moisture content than ZT with residue removal and practices involving tillage (Govaerts et al, 2007a, 2009; Verhulst et al, 2011a).

The effect of tillage practice, crop rotation and residue management on biological soil characteristics was also evaluated (Govaerts et al, 2006b, 2007b, 2008; Chocobar-Guerra, 2010). Earthworms strongly influence soil structure and aggregation (Lavelle, 1997). Chocobar-Guerra (2010) found equal number of earthworms in CT and ZT with residue retention and crop rotation, but when looking at the more determinant factor for soil structure, i.e. earthworm biomass, significantly higher biomass was found in ZT with residue retention. In 12 monitored years (since 1997), maize roots had a higher incidence of rotting under ZT with residue retention as compared to CT (Govaerts et al, 2006b). Wheat showed a low level of root rot incidence under all treatments. No correlation between yields and root rot incidence was found, indicating that CA had other advantages that determined the yield of wheat and maize in the target environment (Govaerts et al, 2005; Table 1).

Changes in tillage, residue management, and rotation practices also induced shifts in the number and composition of soil fauna, including pests and beneficial organisms. After more than a decade, the effects of the different management practices on groups of beneficial soil micro-flora (total bacteria, fluorescent *Pseudomonas*, actinomycetes, fungi and *Fusarium* spp.) were studied with different techniques (Govaerts et al, 2007b, 2008). Residue retention under ZT and CT induced greater microbial diversity, especially higher total bacteria, fluorescent *Pseudomonas* and actinomycetes both for maize and wheat cropping systems. The continuous uniform supply of carbon from crop residues serves as an energy source for microorganisms (Govaerts et al, 2008). Retaining crop residues also increases microbial abundance. Zero tillage as such, is not responsible for increased microflora, but rather the combination of ZT with residue retention. The favorable effects of these two components are due to increased soil aeration, cooler and wetter conditions, less temperature and moisture fluctuations and increased carbon content in the topsoil (Govaerts et al, 2008;). Functional diversity and redundancy are signs of increased soil health. It allows an ecosystem to remain stable when facing changes in environmental conditions (Wang and McSorley, 2005).

Crop yield and system resilience

Small-scale maize and wheat farmers may expect yield improvements through ZT, appropriate rotations and retention of sufficient residues (average maize and wheat yield of CA practices was 5.94t ha^{-1} and 5.50t ha^{-1}), compared to the common practices of heavy tillage before seeding, monocropping and crop residue removal (average maize yield of 3.76t ha^{-1} and wheat yield of 4.83t ha^{-1}; Table 1). Again, leaving residue on the field is critical for ZT practices, since ZT with residue removal drastically reduced yields, except in the case of continuous wheat. Conventional tillage with or without residue incorporation resulted in intermediate yields. Zero tillage treatments with partial residue removal gave yields equivalent to treatments with full residue retention. This indicates that part of the residue can be removed for fodder while sufficient amounts can be retained to provide the necessary ground cover. This could make the adoption of ZT more acceptable for small-scale, subsistence farmers in systems where crop residue is used for fodder or fuel. Overall, CA practices had an average yield advantage of approximately 2.0t ha^{-1} for maize and 0.6t ha^{-1} for wheat compared to practices involving tillage or ZT with complete residue removal (Table 1).

Table 1 *Effect of tillage practice, crop rotation, residue management on grain yield (t ha^{-1} at 12% H_2O) averaged since 1997 in CIMMYT's long-term sustainability trial in El Batán, Mexico.*

Management practice	Maize			Wheat		
Core treatments						
Rotation, ZT, Keep	5.65	(0.03)	A	5.96	(0.09)	A
Rotation, ZT, Remove	4.43	(0.38)	B	3.92	(0.32)	F
Monoculture, ZT, Keep	4.80	(0.36)	B	5.89	(0.10)	AB
Monoculture, ZT, Remove	2.52	(0.06)	E	4.95	(0.11)	DE
Rotation, CT, Keep	4.59	(0.08)	B	5.31	(0.20)	CD
Rotation, CT, Remove	4.31	(0.32)	BC	5.04	(0.17)	DE
Monoculture, CT, Keep	3.91	(0.19)	CD	5.53	(0.02)	BC
Monoculture, CT, Remove	3.76	(0.04)	D	4.83	(0.33)	E
CA treatments						
Rotation, ZT, Keep	5.65	(0.03)	A	5.96	(0.09)	A
Rotation, ZT, KeepM1/2W	5.78	(0.09)	A	4.93	(0.07)	B
Rotation, ZT, Keep1/2	6.37	(0.57)	A	5.59	(0.23)	A

Keep *all residue kept in the field,* KeepM1/2W *all maize residue kept and 25cm wheat stubble,* Keep1/2 *maize stubble left until below ear and 25cm wheat stubble*

Rainfall in the Mexican Highlands is erratic and water shortage can occur at any time during the growing season, resulting in high yield variability and changes in farmer income over the years. In ZT with residue retention the increased aggregation and protection of the surface by the residue, maximizes the recharge of the soil profile during rainfall events, which are often afternoon storms with high rainfall intensity. Additionally, the residue cover decreases evaporation. As a result, ZT with residue retention has higher soil water contents than practices with CT and ZT with residue removal, providing a buffer for dry spells during the growing season. For example, in 2009, the total amount of rainfall during the growing season was close to the long-term average (420mm), but there was an extended dry period in July-August. In ZT with residue retention, the soil water content stayed above or near wilting point during the whole dry period, whereas in the other practices, values were below wilting point from 62 to 83 days after planting with severe implications for maize growth (Verhulst et al, 2011a). This resulted in the large yield differences, i.e. 4.71t ha^{-1}, between the treatments with the highest and the lowest yield. These results show that the increased soil quality in CA practices results in a more resilient system than ZT with full residue removal or CT.

Conservation agriculture to mitigate climate change

Dendooven et al (2011) evaluated the effect of tillage practice and crop residue management on the net global warming potential (GWP) taking into account soil C sequestration, emissions of greenhouse gasses from soil, i.e. CO_2, CH_4 and N_2O, and fuel used for farm operations (tillage, planting and fertilizer application, harvest) and the production of fertilizer and seeds. Tillage and residue management had little effect on greenhouse gasses emitted from the soil. Maximum difference between the agricultural systems was 242kg equivalent- C ha^{-1} y^{-1}. However, the soil organic C content in the 0-60cm layer was affected strongly by tillage and crop residue management. The soil organic C content was 118×10^3kg C ha^{-1} in ZT with residue retention, approximately 40,000kg C ha^{-1} higher than in practices involving tillage or ZT with residue removal. Taking into account the almost 20-year duration of the experiment, approximately 2000kg C ha^{-1} y^{-1} was sequestered in the soil in ZT with residue retention compared to tillage or ZT with residue removal (Dendooven et al, 2011). Zero tillage reduced the C emission of farm operations with 74kg C ha^{-1} y^{-1} compared to CT. This may seem a small difference, but while the amount of C that can be sequestered in soil is finite, the reduction in net CO_2 flux to the atmosphere by reduced fossil-fuel use can continue indefinitely (West and Marland, 2002). The net GWP (taking into account soil C sequestration, emissions of GHG from soil and fuel used for farm operations and the production of fertilizer and seeds) was near neutral for ZT with crop residue retention (40kg CO_2-C ha^{-1} y^{-1}), whereas in the other management practices it was approximately 2000kg CO_2-C ha^{-1} y^{-1}.

Irrigated conditions in arid north-western Mexico

Conservation agriculture as an adaptive measure

Soil quality

Similar to the results in rainfed conditions of Central Mexico, a PCA of soil quality data from the arid north-west of Mexico distinguished three groups of tillage-straw systems: Permanent beds (PB)-straw burned, Conventionally tilled beds (CTB)-straw incorporated and PB-straw not burned (Verhulst et al, 2011b). The PB-straw burned system had the poorest soil quality with high electrical conductivity, Na concentration and penetration resistance and poor self-mulching ability and aggregation. As in Central Mexico, the absence of tillage (in this case

PB) without residue retention (in this case burning of residue) degraded soil quality and was not a sustainable management option. The CTB-straw incorporated system differentiated from the PB practices by its soil physical characteristics, especially the low direct infiltration and aggregate stability, indicating degradation of physical soil quality. This may have an effect on the efficiency of the use of resources, such as irrigation water. The PB with all or part of the residue retained had the highest soil microbial biomass C, total N, direct infiltration and aggregate stability and the lowest electrical conductivity and Na concentration. The practice of PB, where all or part of the residue is retained in the field, seems to be the most sustainable option for this irrigated wheat-based cropping system.

Crop yield and system resilience and flexibility

There have been marked annual changes in wheat yields in the long-term trial with 300kg N ha^{-1} applied at first node (Figure 2; Sayre et al, 2005). Low wheat yields in 1995 and 2004 were the result of extended warm, cloudy periods during the first half of the crop cycles. There were no significant wheat yield differences between any of the tillage-residue management practices for the first five years (ten crop cycles). However, yield differences between management treatments diverged after the first five years with an overall reduction in the yield for PB-straw burned. This reflected the soil degradation found in this management practice. It seems that for irrigated cropping systems (at least for tropical, semi-tropical and the warmer, temperate areas), the application of irrigation water “hides or postpones” soil degradation associated with continuous residue burning until they reach a level that can no longer sustain high yields. Again, both full retention and partial retention of residues resulted in similar yields, indicating that for irrigated systems associated with high amounts of crop residue, large parts of the residue can be removed for other uses without inducing a decline in yield.

Yield differences between CTB-straw incorporated and PB-straw retained were small in this experiment: 7.05t ha^{-1} in CTB vs. 7.21t ha^{-1} in PB averaged over 1998 to 2009. In this trial planting dates have been kept similar for all treatments (Sayre et al, 2005). However, in the real field situation like in the training/extension module managed in cooperation with the local farmer association, it was possible to plant the permanent beds 10-15 days early than the tilled beds. This resulted in a yield difference of 0.58 t ha^{-1} between PB and CTB, averaged over 2001 to 2004 (in the long-term trial, the difference between both practices was 0.12t ha^{-1} averaged over the same period) (Sayre et al, 2005). Timely planting is important because in March and especially April (during grainfilling), average temperature and the frequency of heat events (>30°C) increase substantially, affecting yield. With increasing temperatures, timely planting will become even more important in the future.

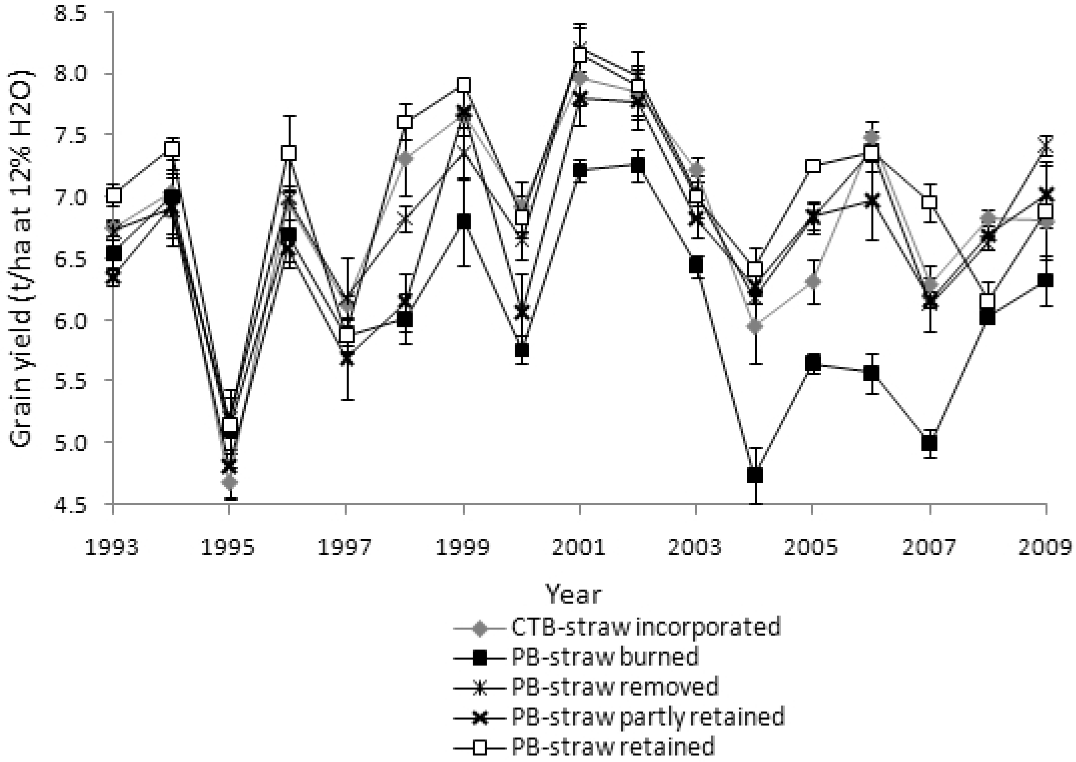

Figure 2 *Effect of tillage-residue management system on wheat grain yield (t ha^{-1} at 12% H_2O) when 300kg N ha^{-1} are applied at the first node stage in the long-term trial, Yaqui Valley, Mexico (adapted from Sayre et al (2005)). Bars indicate standard errors of the mean.*

Conservation agriculture to mitigate climate change

Studies of the net GWP of agronomic systems in the long-term trials in the Yaqui Valley are pending. In high-input systems like the one in the Yaqui Valley, N fertilizers are a significant direct source of emissions of N_2O and NO_x in the field and an indirect source through fossil fuel energy consumption associated with manufacturing and transport of fertilizers (Ortiz-Monasterio et al, 2010). Adequate fertilizer management can play an important role in reducing N_2O and NO_x emissions in the field and increasing the fertilizer efficiency, thereby reducing the necessary fertilizer and associated manufacturing emissions. Sensor-based N management in wheat and maize is a new technology that uses an optical sensor, which measures the normalized difference vegetative index of the canopy. The use of this vegetative index in conjunction with an N rich strip (a well fertilized part of the field) and a crop algorithm can be used to establish the optimum N fertilization rate (Raun et al, 2009). This technology optimizes N rates and minimizes the risk of excess fertilizer application. In addition, the N fertilizer is applied at the time of high demand by the crop, which in turn reduces the probabilities of generating favourable conditions for N_2O emissions. Conservation agriculture may adjust C and N cycling compared to conventional systems (Govaerts et al, 2006c) and thus research is needed to determine whether dose, method and timing of application should be adjusted depending on management system.

The use of agricultural inputs such as irrigation carries a `hidden´ carbon cost (West and Marland, 2002). As mentioned above, the degradation of physical soil quality in CTB may have an effect on the efficiency of the use of resources, such as irrigation water. The decreased infiltration in CTB might result in lower irrigation efficiency. Additionally, a better water conservation due to reduced evaporation in PB systems with residue retained may decrease the irrigation requirements compared to CTB. However, more research is needed to determine irrigation water requirements in CA systems compared to conventional systems.

The economic potential of conservation agriculture for climate change mitigation and adaption, beyond direct incentives

In the Mexican Highlands, production parameters (production cost and returns) were determined for both the newly introduced CA practices and the conventional tillage-based practice in 2009. As mentioned above, the 2009 growing season was characterized by an extended dry period in July-August. Conservation agriculture had higher yields than the conventional practice in farmers' fields under these adverse conditions. Averaged over six locations (30 fields for both treatments), maize yield was 31% higher under CA (6.4t ha^{-1} under CA vs. 4.8t ha^{-1} under the conventional practice) (Figure 3a). These higher yields combined with the lower costs of CA resulted in a net return that was almost twice as high for CA as for the conventional practice averaged over the six locations: average net return was 9940MXN ha^{-1} (813US\$ ha^{-1}) under CA compared to 5019MXN ha^{-1} (420US\$ ha^{-1}) under the conventional practice (Figure 3b).

Numerous authors have demonstrated that apart from the on-farm benefits, CA created also off-site public benefits. Many soil and water conservation technologies have been implemented at very low rates by farmers (in many cases only when direct incentives were provided) because such practices do not always result in direct short-term benefits for the farmer (Hellin and Schader, 2003). Conservation agriculture has the win-win combination of being a soil and water conservation technology that also increases productivity in most cases.

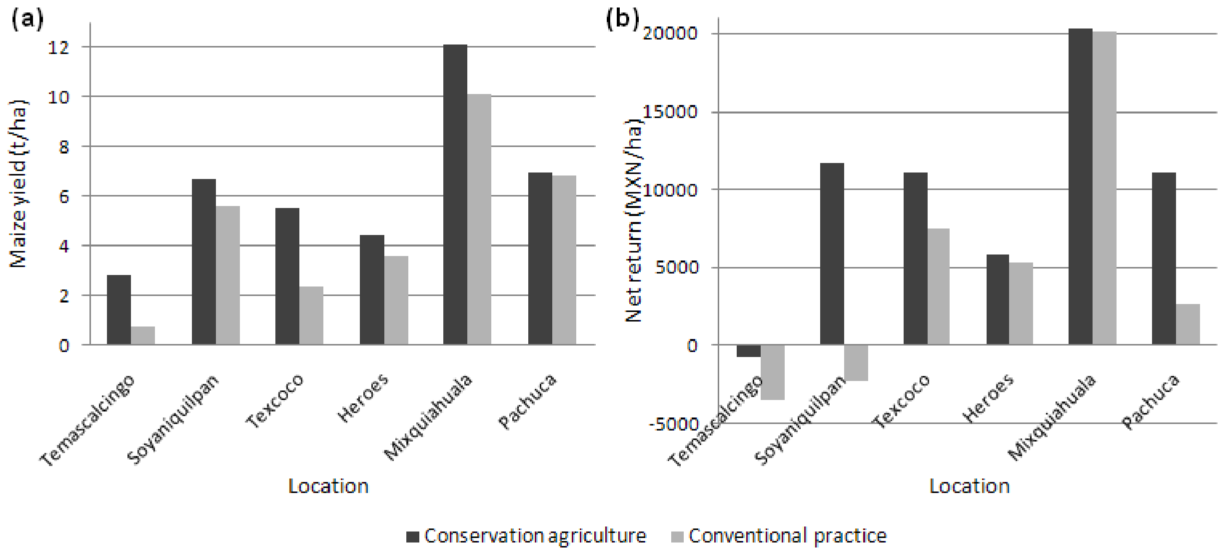

Figure 3 (a) *Average maize yields (t ha^{-1}) and (b) comparative net returns (MXN ha^{-1}) for famers' plots under conservation agriculture and the conventional practice at six different locations in the Central Mexican Highlands in 2009 (Source: CIMMYT's survey data).*

Conservation agriculture adoption and the need of new extension approaches: the efforts in Mexico

The CA adoption process is complex. It is unlikely that complex, multi-component technologies, such as CA, can be successfully scaled out through traditional linear models of research and extension. Instead, this effort requires the development of innovation systems to adapt technologies to local conditions that includes functioning networks of farmer groups, machinery developers, extension workers, local business and researchers (Hall et al, 2005). To this end, decentralized learning hubs within different farming systems and in key agro-ecological zones are being developed (Sayre and Govaerts, 2009). At the hubs, intensive contact and exchange of information is organized between the different partners in the research and extension process with a large feedback component. Because of the multi-faceted nature of CA technology development and extension, activities should be concentrated in a few defined locations representative of distinct farming systems, rather than making lower-intensity efforts on a wide scale. Through research and training, regional CA networks are established to facilitate and foment research and the extension of innovation systems and technologies. Research at the hubs also provides an example of functioning CA systems, helping to break down the culture of the plough with locally-adapted successful examples. Furthermore, the hubs act as strategic science platforms operated by international centres and national research institutes, enabling the synthesis of a global understanding of CA, and its adaptability to different environments, cropping systems and farmers' circumstances.

Conclusions and recommendations

Climate models predict an increase in annual average temperature by the 2050s ranging from 1.6-2.0°C on the Yucatán peninsula to 3.1-3.5°C in northern Mexico. Annual precipitation is predicted to decrease in most of Mexico. The predicted changes in climate could severely affect agricultural production in Mexico if adequate measures are not taken.

In the highlands of Mexico, conservation agriculture (zero tillage with at least partial residue retention and crop rotation) has the potential to mitigate and adapt to climate change. Conservation agriculture results in high physical, chemical and biological soil quality that favours larger yields and reduces the net global warming potential compared to the traditional agricultural system (tillage, residue removal and monoculture of maize). The high physical soil quality ensures that the cropping system is optimized to cope with both heavy rainfall events and prolonged drought, events that are likely to increase in frequency due to climate change. Residue retention under zero and conventional tillage induces greater microbial diversity, especially higher total bacteria, fluorescent Pseudomonas and actinomycetes both for maize and wheat cropping systems. This diversity allows an ecosystem to remain stable when facing changes in environmental conditions. The net global warming potential is near neutral in conservation agriculture, whereas systems involving conventional tillage or zero tillage contribute to global warming. Conservation agriculture requires the retention of at least part of the crop residue in the field. Therefore, research on the integration of conservation agriculture and mixed livestock systems is needed, focusing on the trade-offs for residue use.

In the irrigated arid north-western part of Mexico, the practice of permanent beds, where all or part of the residue is retained in the field, seems to be a more sustainable option for this irrigated wheat-based cropping system than conventional tillage with incorporation of the residues. Timely planting of wheat might help to prevent negative effects of global warming. Optimizing application fertilizer rates and synchronizing them with crop development will further increase yields while reducing costs and emissions of N_2O. More research is needed to determine net global warming potential of different practices and to further develop conservation agriculture systems and irrigation strategies with reduced irrigation requirements.

Complex, multi-component technologies, such as conservation agriculture, can be successfully scaled out through an innovation systems approach. The case studies described in this chapter highlight the importance of key investments to establish several of those innovation systems in contrasting cropping systems in different agro-ecological environments in Mexico and world-wide to corroborate the results obtained and develop conservation agriculture practices tailored to local conditions.

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