Field Crops Research 153 (2013) 12–21

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Maize stover use and sustainable crop production in mixed crop–livestock systems in Mexico☆

Jon Hellin[a,*], Olaf Erenstein[b], Tina Beuchelt[a], Carolina Camacho[a], Dagoberto Flores[a]

[a] International Maize and Wheat Improvement Center (CIMMYT), Apartado Postal 6-641, 066000 Mexico, D.F., Mexico
[b] International Maize and Wheat Improvement Center (CIMMYT), c/o ILRI, P.O. Box 5689, Addis Ababa, Ethiopia

ARTICLE INFO

Article history:
Received 2 December 2012
Received in revised form 15 May 2013
Accepted 20 May 2013

Keywords:
Crop–livestock farming systems
Maize
Smallholder farmers
Mexico

ABSTRACT

Mixed crop–livestock farming systems prevail in Mexico – typically rain-fed and smallholder systems based on maize and ruminants and spanning diverse agro-ecologies. Maize grain is the key Mexican staple produced for home consumption and the market. Maize crop residues (stover) are an important by-product, primarily for feed use, often through in situ stubble grazing and/or as ex situ forage. This paper explores maize stover use along the agro-ecological gradient and the potential trade-offs, particularly the widespread use of maize stover as feed against its potential use as mulch (soil cover) to manage soil health within the context of conservation agriculture. The paper builds on three case study areas in Mexico in contrasting agro-ecologies: (semi-)arid, temperate highland and tropical sub-humid. Data were obtained through expert consultation and semi-structured farmer group/community surveys. Although in situ grazing is found in all three study sites, it represented the bulk of stover use in only one site (70% of stover in the sub-humid tropics), with ex situ feed dominating in the other two sites (>80%). Maize stover commercialization is limited and mainly restricted to households with no livestock and often within the local context. Farmers are generally hesitant to adopt conservation agricultural practices that require the retention of stover as mulch, as this competes with their livestock feed needs and purchased feed is expensive. To reduce trade-offs, a portfolio of options could be adapted to these mixed systems, including partial residue retention, cover and feed crops and sustainable intensification. Promising but yet to be explored, are investments in the genetic improvement of maize stover feed quality.

1. Introduction: changing maize stover demands in Mexico

Mexico is the center of diversity for maize and farmers grow the crop in a variety of production environments in terms of altitude, temperature, moisture regimes, land, soil types and production technologies. Maize is Mexico's most important crop and continues to play multiple functions in farmers' livelihoods. It occupies the largest area planted to any crop in the country, and many small-scale farmers are engaged in its production (Barkin, 2002) mostly in rain-fed areas for self-consumption and to varying degrees for the market (De Janvry et al., 1995). Maize is a source of food, income, cultural identity, social status and part of a safety net (Perales et al., 2005). Maize plays a key role in local people's diets, not least the *tortilla* which is made from specially treated (*nixtamalized*) maize flour and which has been a staple food since pre-Columbian times. Poor consumers in both rural and urban areas register higher levels of *tortilla* consumption. Since the 1980s, Mexico has been increasingly dependent on imports, especially yellow maize imports for animal feed and industrial uses (Améndola et al., 2006).

The livestock sector is very important in Mexican agriculture. In 2004, Mexico produced 1.5 million tons of beef, making the country the world's ninth largest producer, and around 9 million tons of milk. Mexico is also the world's fourth largest producer of chicken (2.3 million tons) and ranks 17 in the world list of pig meat producers (1 million tons). The ruminant sector is dominated by cattle with 30.6 million head compared to 8.7 million goats and 6.1 million sheep (Améndola et al., 2006). Mixed crop–livestock systems span a wide agro-ecological gradient, including (semi-)arid, (sub-)humid and temperate/tropical highland areas, covering 18%, 8% and 7%, respectively, of Mexico's total land area of 2 million km^2. Of the mixed crop–livestock systems, grassland-based livestock production systems[1] comprise 38%, mixed crop–livestock

* Corresponding author. Tel.: +52 55 5804 2004x1153.
E-mail address: j.hellin@cgiar.org (J. Hellin).

[1] Thornton et al. (2002:17) defined grassland-based systems as follows: ">90% of dry matter fed to animals comes from rangelands, pastures, annual forages and purchased feeds and <10% of total value of comes from crops [. . .] i.e. high degree of importance of livestock in farm household economy".

0378-4290/$ – see front matter © 2013 The Authors. Published by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.fcr.2013.05.014

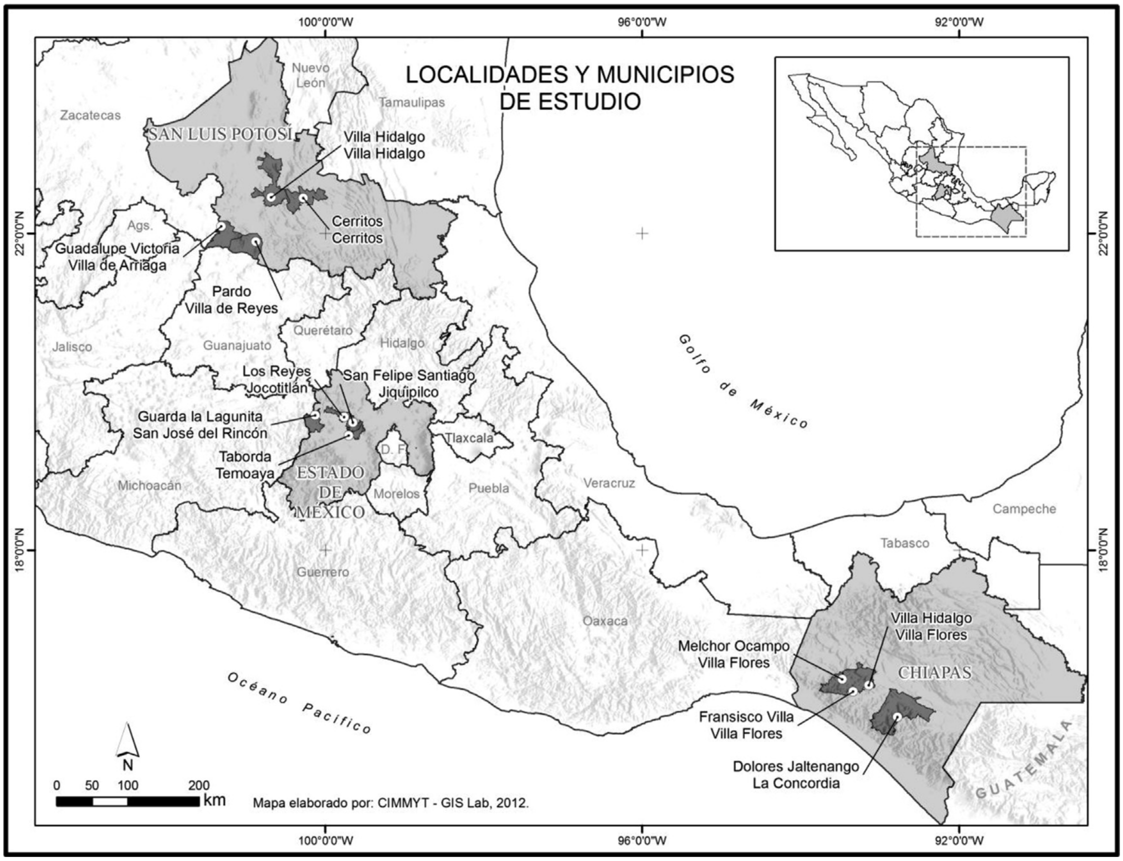

Fig. 1. Survey locations in Mexico.

systems[2] 33%, and other systems 29% (Thornton et al., 2002). The mixed systems are often based on maize and ruminants, with three-quarters being rain-fed (Thornton et al., 2002).

Commercial beef and dairy systems tend to use livestock feed based on cereals, sown and conserved forages, crop residues and industrial by-products. Especially in the semiarid north, pastoral use of land is widespread (Améndola et al., 2006). Mixed systems, typically small-scale family-based farms, tend to graze their cattle on crop residues and at roadsides, complemented with purchased concentrates, pastures and forage crops. Sheep production and goat production are usually extensive. Feeding is based on crop residues, grazing native grassland or along roadsides and there is limited use of supplementary feeding with chopped crop residues and maize grain during dry season (Améndola et al., 2006). Research from the south of Mexico (Yucatan) shows that mixed smallholder sheep farms are characterized by a large diversity, including different methods of feeding, varying intensity levels of crop and forage production as well as differences in infrastructure investments (Parsons et al., 2011).

Maize residues are a widespread source of forage especially during the dry season. They are the most important crop residue which is used as fodder (an estimated 48.1 million tons per annum), followed by sorghum stover (6.5 million tons per annum) and wheat straw (2.7 million tons per annum) (Améndola et al., 2006). Maize residues are often left in farmers' fields for in situ stubble grazing or are harvested for ex situ use and used as green or dry forage (with various degrees of processing and feed supplements). Arriaga-Jordán et al. (2005) found that in two rural communities in central Mexico, the main factor determining herd size was maize stover supply (collected and purchased). Maize processed into silage (fermented grain and green plant matter) is used as feed for livestock in high input systems. Maize residue use/market options and residue rights are interdependent, and the latter may vary from open access to common property to private property. However, although partly addressed in prior research (Erenstein, 1999), there has been no systematic assessment of these often informal and localized maize stover markets in Mexico.

Although the value of crop residues as fodder is widely recognized and relatively easy to assess, there is less understanding of the value of crop residues as a soil protection and improvement measure. Such an understanding is important in light of natural resource degradation. In traditional maize-based cropping systems of the central Mexican highlands and of the mid-altitude mountainous landscapes in the Southeastern part of the country, burning and grazing of crop residues, heavy tillage, and lack of crop rotations lead to soil degradation and erosion. Soil degradation is a major constraint to crop production, aggravating farmers' vulnerability to climate risks. State governments have progressively introduced laws banning the burning of crop residues and secondary vegetation along with environmental protection policies (e.g. creation of natural reserves). These have resulted in a decline of migrant slash and burn systems, leading to a shift to more intensive production systems.

This shift from relatively extensive to intensive production systems implies an intensification of natural resources management. Crop residue management in these production systems has become more critical especially in the case of (semi-)arid environments and/or in systems under low maize production levels where less than optimum soil cover can lead to soil and land degradation.

[2] Thornton et al. (2002:17) defined mixed farming systems as follows: ">10% of the dry matter fed to animals comes from crop by-products and stubble or >10% of the total value of production comes from non-livestock farming activities".

Table 1
Survey sites.

Agro-ecological zone[a]	State	Municipality	Site	Rainfall (mm)	Altitude (m)[b]	Soil type[c]	Focus group social status[d]
(Semi-)arid	San Luis Potosi	Cerritos	Cerritos	669	1174	Vertisol	Rich
		Villa de Arriaga	Guadalupe Victoria	396	2111	Xerosol	Poor
		Villa de Reyes	Pardo	383	1790	Feozem	Medium
		Villa Hidalgo	Villa Hidalgo	333	1669	Litosol	Medium
Temperate highland	Estado de Mexico	San José del Rincón	Guarda la Lagunita	909	2959	Andosol	Poor
		Jocotitlán	Los Reyes	727	2593	Planosol	Medium
		Jiquipilco	San Felipe Santiago	755	2554	Planosol	Medium
		Temoaya	Taborda	830	2596	Vertisol	Rich
Subhumid tropical	Chiapas	La Concordia	Dolores Jaltenango	1900	626	Acrisol	Poor
		Villa Flores	Fransisco Villa	1223	581	Luvisol	Medium
		Villa Flores	Melchor Ocampo	1063	637	Cambisol	Medium
		Villa Flores	Villa Hidalgo	1260	540	Livosol	Rich

[a] Based on Améndola et al. (2006) and adapted from Thornton et al. (2002).
[b] Fieldwork data.
[c] CONAGUA.
[d] CENSO (2010).
[e] FAO/UNESCO Soil Classification.

Adequate levels of residue retention are essential to ensure crop productivity as well as to maintain soil health/quality (Govaerts et al., 2006; Hellin and Haigh, 2002). The various uses of maize stover on-farm (fodder, mulch, fuel, construction materials) and off-farm (commercialization particularly as feed, but also handicrafts, etc.) imply a complex array of trade-offs. This requires analysis of these trade-offs so that researchers and development practitioners can make appropriate policy recommendations for a sector that has undergone considerable change in Mexico in the last two decades.

Until recently, the dominant opinion was that a modernization of the agricultural sector was beneficial to all even though it would mean that some of the rural poor move away from maize farming and into other activities, including wage labor (Bellon and Hellin, 2011). The North American Free Trade Agreement (NAFTA), ratified in 1994, epitomized the modernization paradigm whereby government focused support on maize farmers who were economically efficient while resource-poor maize producers were encouraged to switch crops and/or to seek non-farm livelihood options (Keleman et al., 2009). Since the implementation of NAFTA, Mexico's rural population has decreased from 28.7% in 1990 to 23.5% in 2010 (INEGI, 2011) and the population employed directly in agriculture has declined more sharply, dropping from 26.9% in 1992 to 13.3% in 2008. However, rather than witnessing a mass exodus from maize farming the area planted to maize in 2010 decreased only 13.5% over 1995 levels, and maize production increased by 26.9%.

The Mexican government is demonstrating renewed interest in the maize sector and in sustainable management practices such as conservation agriculture (CA). There is also increased interest in CA worldwide due to its potential to conserve soil and water, reduce soil erosion and enhance soil health. The adoption and adaptation of CA have so far been more successful for larger-scale agriculture in relatively temperate environments, e.g. Brazil, Argentina, the United States, and Australia and uptake has been less evident amongst smallholder farmers in tropical environments (Knowler and Bradshaw, 2007). Mulching is absolutely critical to making CA successful (Erenstein et al., 2012), especially in (semi-)arid and subhumid regions. It is the principle of retention of soil cover in CA systems that potentially exacerbates the trade-offs between using maize stover as feed and its use as mulch. These trade-offs are particularly important due to their impact on soil fertility as well as erosion processes (Erenstein, 2002).

Depending on the agro-ecology and farming system, CA with its emphasis on soil cover may not be compatible with farmers' current cropping systems in Mexico wherever crop residues are intensively used to feed cattle. A more systematic assessment of maize stover use across agro-ecologies is, hence, necessary along with a better understanding of stakeholders' decision-making vis-à-vis stover use.

This paper has two objectives. First, it aims to provide a preliminary assessment of maize stover use in mixed systems along Mexico's agro-ecological gradient. Indeed, despite the prevalence of maize stover use as feed in Mexico, there has been no systematic or recent assessment of its use in mixed systems. This paper thereby complements similar recent studies in South Asia and Sub-Saharan Africa (Erenstein and Thorpe, 2010; Erenstein et al., 2011; Valbuena et al., 2012). It builds an initial assessment based on farmer group/community surveys in three case study regions in Mexico in contrasting agro-ecologies: (semi-)arid, temperate highland and tropical sub-humid. Second, this paper aims to provide a preliminary assessment of the potential trade-offs between the use of maize stover for feed and soil health. It thereby sheds light on the dynamics and trade-offs of maize stover use as the basis for exploring ways to reduce conflicts between crop residue retention and demand for animal feed. With this empirically based analysis, our paper complements other papers in this special issue "*Potential for multi-purpose maize varieties to meet changing maize demands*" on ways to improve whole plant utilization of maize particularly for food and livestock feed in mixed crop–livestock systems.

2. Study region and methods

2.1. Case study sites

The authors selected three case study regions in contrasting agro-ecologies: the (semi-)arid State of San Luis Potosi in north-central Mexico; the temperate highlands in the central State of Mexico; and the (sub-) humid tropical lowlands in the south-eastern State of Chiapas (see Fig. 1). Field research took place in 12 communities (four communities in each of the three regions) (Table 1). There are socio-economic differences between the regions even though all have mixed (crop–livestock) systems. Rural poverty tends to be least in the State of Mexico, which benefits from its central location and proximity to the capital. Rural marginalization tends to be higher in San Luis Potosi and even higher in Chiapas.

The surveyed municipalities in the State of Mexico are predominantly agricultural (74% of land), versus less than a third in the two other study regions (Table 2). In contrast, the San Luis Potosi survey region has a third of its area classified as desert vegetation.

Table 2
Characteristics of study regions (secondary data).

	San Luis Potosi	Estado de Mexico	Chiapas
Agro-ecological zone[a]	(Semi-)arid	Temperate highland	Subhumid tropical
Land use (%)[b]			
Grassland	12	8	19
Agriculture	27	74	30
Forest	5	13	27
Desert	33	0	0
Fallow	23	5	25
Population density (inhabitants/km^2)[c]	32	286	43
Average farm size (ha)[d]	10.3	1.5	9.0
Maize area share of cultivated (%)[b,*]	20	57	67
Maize area share irrigated (%)[b,*]	7	20	1
Cattle density (head/ha)[b,*]			
Per ha cultivated	0.77	0.64	1.94
Per ha maize	3.80	1.12	2.91

Note: Based on averages at municipality level (survey locations only), except * at state level.
[a] Based on Améndola et al. (2006) and adapted from Thornton et al. (2002).
[b] INEGI. México en cifras. Información nacional, por entidad federativa y municipios.
[c] CENSO (2010).
[d] Based on data at a county level in Censo Agropecuario (2007).

The Chiapas region is relatively similarly divided into agricultural land, forest, fallow and grassland. The topography in both the State of Mexico and Chiapas survey regions primarily comprises valleys with hills – albeit in a highland and lowland setting, respectively. The population density in the surveyed municipalities of the State of Mexico is markedly higher than in the two other study regions, associated with an equally marked divergence in terms of farmers' average landholdings (only 1.5 ha in the State of Mexico region versus 9–10 ha in the other regions).

Maize occupies a fifth of the cultivated surface in the San Luis Potosi survey region compared to more than 50% in the two other regions. Maize production is primarily rain-fed, although a fifth of the maize area in the State of Mexico survey region was irrigated. In Chiapas, there are relatively high livestock densities per unit area cultivated, 2.5–3 times those for the two other regions. However, the relatively limited maize area share in the San Luis Potosi survey region implies it overtakes Chiapas in terms of livestock densities per unit maize area. The three study regions also have elements in common, including a longstanding tradition of maize cultivation and stover use as cattle feed. The mixed systems also face problems of soil degradation and low profitability and often competing demands for maize stover.

2.2. Methods

The study aims to provide an initial assessment of maize stover use and associated trade-offs based on 12 farmer group/community surveys in the three case study regions. The authors selected four representative communities in each of the three regions – including a relatively poor and a relatively rich community and two relatively medium-income communities. The site selection process included consultation with researchers from the National Institute of Agricultural, Forestry and Fisheries Research (INIFAP) and from the State of Mexico Autonomous University. It also builds on current and past relevant studies conducted in Mexico (Erenstein, 1999; Bellon et al., 2005).

All selected communities were *ejidos*: agrarian communities created by land distribution through the post-revolutionary agrarian reform (1917–1992). The choice of *ejidos* reflects a number of

Table 3
Income and crop indicators surveyed communities.

	San Luis Potosi	Estado de Mexico	Chiapas
Main household income sources	Remittances main, farming and livestock activities	Farming and livestock, also commerce, industry, remittances	Farming and livestock activities
Main crops	Maize, sorghum, oats	Maize, oats, vegetables	Maize, beans, sorghum
Cultivated area share (%)			
Irrigated	4	54	5
Maize	47	68	39
Share households using (%)			
Hybrid seed	0	13	82.5
Chemical fertilizer	0	100	100
Mechanization			
Maize establishment	Mainly tractor tillage	Mainly tractor tillage and seeder	Manual
Maize harvest			
Grain	Manual	Manual	Manual
Stover	Sometimes mechanized	Mechanized	Mainly in situ
Maize grain yield (ton/ha)			
Good year	1.9	4.1	6.1
Bad year	0.8	2.4	2.5
Share maize grain sold (%)	0	53	83
Maize straw yield (ton/ha)			
Good year	2.0	3.5	–
Bad year	0.7	1.5	–

Source: Survey data.

considerations, including that they represent the bulk of Mexico's crop land and farmer households and that their members are prevailingly resource poor mixed farmers and by their nature already organized. In each selected community, two research tools were implemented: a focus group discussion with farmers and a key informant interview, both using a semi-structured questionnaire. Focus group discussants numbered from eight to 18 members for each group, with participants from different age groups, but concentrated between 40 and 60 years old. Researchers collected qualitative and quantitative data on farming systems, household characteristics and crop reside management. A thematic analysis was applied to the qualitative data by developing an individual code system for data-reduction. The quantitative data were analyzed based on frequencies, means and ranges complemented by secondary data from official statistics.

3. Results: maize stover use in Mexico

The present section provides an assessment of maize stover use for each of the three case study regions in Mexico in consecutive sub-sections. Table 3 contrasts the three study regions in terms of the main income and crop indicators for the surveyed communities. Table 4 does the same in terms of livestock indicators, whereas Table 5 contrasts stover management.

3.1. Maize–livestock systems in (semi-)arid regions

In the sparsely populated surveyed communities of San Luis Potosi, water availability is a key constraint. The communities are located in a (semi-)arid region spanning mid-altitude to highlands (from 1100 to 2100 m above sea level – m.a.s.l.). Average annual rainfall is 445 mm and occurs between May and September. Water scarcity distinguishes this region from the study regions in the State of Mexico and Chiapas both of which have higher rainfall as well as more irrigation in the State of Mexico. There are also large differences between rich and poor communities in San Luis

Table 4
Livestock indicators surveyed communities.

	San Luis Potosi	Estado de Mexico	Chiapas
Main livestock	Cattle, sheep, goats	Cattle, sheep	Cattle
Share of households with livestock	66	73	33
Herd size (cow equivalents per household)	1.1	1.0	2.7
Herd composition (% in cow equiv.)			
Dairy cattle	0	16	12
Double purpose cattle	70	50	83
Beef cattle	0	12	0
Draft animals	1	7	3
Sheep (+goats)	23 (+5)	13	0
Pigs	2	1	2
Livestock feeding composition	Dried fodder and desertic plants (Opuntia and agave)	Dried fodder, maize grain, fodder oats	Grasses in paddocks, crop residues in situ
Livestock management system			
Grazing	Sheep, goats		Double purpose cattle
Combination (stall feeding and grazing)	Cattle	Double purpose cattle, sheep	Dairy cattle
Stall feeding		Dairy/beef cattle	

Source: Survey data.

Potosi. For example, in the relatively affluent community of Cerritos, it is common for rich farmers to have 250 ha of land with sophisticated drip irrigation systems. In contrast, in Guadalupe Victoria there are only resource poor farmers and there is no irrigation.

Agriculture and livestock contribute in different ways to household income. For some communities like Guadalupe Victoria they are the main sources of income complemented by remittances. In Villa Hidalgo and Cerritos, however, remittances make the bigger contribution and agriculture and livestock play a minor role in household income. In all the communities studied, maize is the most important crop although sorghum and oats are also relevant. Maize is primarily cultivated under rain-fed conditions (Table 3).

Wealthier farmers with large landholdings used mechanized tillage and most of these farmers own their tractors. In relatively affluent communities like Cerritos, some farmers also have mechanical sowers and threshers. Nevertheless, farmers from this region do not tend to use herbicides or fertilizers and prefer to apply manure. This distinguishes farmers in the San Luis Potosi region from those in the State of Mexico and Chiapas where farmers commonly use fertilizers. Farmers in San Luis Potosi also prefer to use traditional varieties of maize due to the risk of drought. Farmers harvest the grain by hand and maize is largely for home consumption.

In good years farmers reported average maize grain yields of 1.9 ton/ha – with substantial variations between rich communities like Cerritos with 2.5 ton/ha and poor localities like Guadalupe Victoria with 0.7 ton/ha. Our reported average maize yields for a good year is somewhat lower than Mexico's national average for rain-fed maize (2.2 tons/ha). Maize grain yields in bad years reportedly averaged 0.8 ton/ha. Maize cultivation is particularly precarious in San Luis Potosi and crop failure is common. Farmers reportedly often only harvest half of the sown maize area. This is in sharp contrast to the State of Mexico and Chiapas study regions where farmers harvest most of their maize area sown.

The main livestock types are cattle, sheep and goats (Table 4). Two-thirds of households reportedly owned livestock with an average herd of 1.1 cow equivalents per farm household. Cattle are mainly for dual purpose (meat and milk) and farmers maintain

Table 5
Stover management in surveyed communities.

	San Luis Potosi	Estado de Mexico	Chiapas
Stoveruse shares (% of stover volume)			
Ex situ feed use	81	85	
In situ grazing	15	10	70
Incorporate to the soil	4	5	
Soil cover			20
Burn			10
Reported stover transaction practices (% households using)			
Self-consumption	95	56	80
Sale	15	44	20
Buy	35	28	14
In kind payment	No	No	No
Given away	No	No	No
Stover transaction practices			
Sale for in situ grazing	Yes	No	Yes
Duration grazing contract (months)	2		5
Origin buyers in situ grazing	Neighbors (same community)		Neighbors (same or nearby communities)
Sale for ex situ use	Mainly no	Yes	Limited
Ex situ form of sale	Whole plant	Stover bale	Whole plant
Origin buyers ex situ use	–	Normally neighbors (same or nearby communities), sometimes regional	Neighbors (same community)
Main sales period ex situ use	March–June	March–June	January–February
Duration stover storage for ex situ use (months)	6	8	4
Stover prices			
Price for in situ grazing (M$/ha)	100–150		125–600
Price for ex situ use (M$/ha)		1400–1600	1260
Seasonal prices	Yes	Yes	No
Typical stover balance at community level (net sales/purchases)	Self-sufficient, deficit (net purchase) in drought period	Surplus (net sales)	Self-sufficient – surplus (limited net sales)

Source: Survey data.

them in a system that combines grazing and stall feeding ('zero grazing'). They are mainly local breeds that can feed on desert plants while they graze in available desert vegetation areas and grasslands. Cactus plants are also fed ex situ to cattle together with maize and other crop residues. Sheep and goats traditionally graze common desert areas and crop stubbles. Forage is scarce resulting in overgrazing. Cattle numbers have decreased due to the high cost of forage and sheep numbers have increased because it is easier to feed them. Cattle still prevail in the relatively affluent community whereas sheep prevail in the poorer community.

Farmers harvest around 80% of the maize stover by hand and use it ex situ to feed their livestock (Table 5). In good years farmers harvest an estimated 2 ton/ha of stover and in bad ones 0.7 ton/ha. Sheep and goats graze the remaining stubble with little remaining at the time of land preparation: farmers estimated that they incorporated only about 4% of the stover into the soil. Most of the maize stover is for self-consumption with storage averaging six months. Fodder is in short supply and 35% of farmers reportedly still had to buy maize stover to feed their livestock, whereas only 15% of farmers reportedly sold stover. Sales often are for in situ grazing against a payment of 100–150 Mexican pesos[3] per ha for a two-month grazing period. Two communities (Guadalupe Victoria and Villa Hidalgo) reported such sales of grazing rights, often to neighbors in the same community. In the other two localities, maize stubble is free for communal grazing. Surveyed farmers reported that they are seeking ways to classify the land of the *ejido* into grazing and non-grazing areas and this may stimulate a more vibrant trade in maize stover. In response to longer drought periods and limited rains, they are also replacing maize with other crops such as sorghum, oats and barley with reduced water requirements, shorter cycle and less labor needs. They are also testing crops like triticale as alternatives feed to maize stover.

The experience with CA techniques differs between communities. Farmers from Cerritos indicated that they have been practicing reduced tillage and this helps to reduce production costs, improve soil texture and maintain soil humidity. They recognize the importance of leaving crop residues to provide soil cover, maintain humidity and reduce soil compaction. However, farmers mentioned the conflict between CA and the fact that most farmers use crop residues as fodder and that free grazing is common. Similarly, in Guadalupe Victoria farmers are practicing reduced tillage and leaving crop residues as cover. Nevertheless, farmers recognize that information is lacking on how CA can be readily combined with the practice of free grazing and that this is restricting its adoption. Contrarily, farmers from the other two communities knew very little about CA although they recognized the potential benefits of leaving crop residue in the field.

3.2. Maize–livestock systems in temperate highlands

The surveyed communities in the State of Mexico are located in temperate highlands that are densely populated. Land fragmentation characterizes the study areas and farm size averages only 2 ha. Most of the land is in agriculture use. Agriculture and livestock contribute 60–70% of household income in two communities (both relatively poor Guarda la Lagunita and relatively rich Taborda), but only about 30% in the other two communities. In all four communities, farmers are also engaged in off-farm activities like construction, industry and commerce.

Farmers practice agriculture mainly from 2500 to 3000 m.a.s.l. Annual rainfall averages 805 mm and occurs between May and October, and is followed by dry, frosty winters. Drip irrigation systems are common except in relatively poor Guarda la Lagunita. Maize is the dominant crop and is often grown every year. Other crops include (fodder) oats, vegetables, beans, wheat, barley and potatoes. Agriculture is very important in terms of fodder production and even when the maize crop fails due to frost, farmers still use the stover for fodder.

Maize is cultivated both as a rainfed and irrigated crop in a semi-intensive system. Farmers routinely use fertilizers and herbicides (Table 3). The use of agricultural machinery is also common for tillage and seeding and many farmers have their own tractors. The exception is Guarda la Lagunita where farmers do not own machinery and use animal traction. Farmers in all four communities reported that local maize varieties are the best option in terms of the dual purpose of grain production for household consumption/sale and maize stover for fodder. Grain harvest is done by hand and farmers indicated that maize grain yields in good years average 4.1 ton/ha – again with substantial variations between rich communities like Taborda with 5.5 ton/ha and poor localities like Guarda la Lagunita with 2 ton/ha. Maize grain yields average 2.4 ton/ha in bad years. Farmers pointed out that their tall local maize varieties are susceptible to lodging. They also complained about irregular rainfalls and problems with frost and hailstones.

Cattle and sheep are again the most common livestock types. Although dual purpose cattle still prevail, dairy and beef cattle are also present in the surveyed communities. In relatively rich Taborda, farmers have dairy cattle from a Swiss race, whereas local dairy cattle prevailed in relatively poor Guarda la Lagunita. In Los Reyes beef cattle was common. Farmers maintain dairy and beef cattle mostly through zero-grazing, with ex situ feed composed of crop residues (like maize stover), grains (from maize and other cereals) and fodder oat. Sometimes farmers invest in dairy cattle feed made of ground mixtures of residues, alfalfa, poultry litter and concentrates. Others give green fodder (maize silage) to their dairy cows. Dual purpose cattle are typically maintained in a system combining stall feeding and stubble grazing.

Sheep production is also important, especially in poor communities like Guarda la Lagunita. In some localities, sheep are managed in a combined system but in others, sheep graze the common areas and the field stubble. Problems have arisen due to the reduction of common areas for grazing and difficulties in feeding the livestock. Farmers from this region reported that this has led to a decrease in cattle numbers. They also indicated that sheep numbers from improved races have increased due to support from governmental programs.

Around 85% of maize stover is machine harvested and baled. In good years farmers harvest around 3.5 ton/ha of stover and in bad ones around 1.5 ton/ha. The remaining stubble is grazed mainly by small livestock like sheep and goats. Only about 5% of maize stover is incorporated into the soil. In contrast to San Luis Potosi and Chiapas, nearly half (44%) of farmers in the State of Mexico reported selling stover (primarily as bales) to their neighbors from the same community or from nearby communities for prices around 1400–1600 Mexican pesos per ha. In the surveyed communities 28% of farmers reported buying crop residues to meet feed shortfalls for their animals. Bale trade also occurs at a regional level and there is some trade with neighboring regions such as the Bajío.

Experiences around competing stover uses such as CA are limited to farmers from Los Reyes, San Felipe and Taborda. Farmers know that leaving the crop residues as cover reduces soil compaction, maintains humidity and improves soil structure. However, they also recognize major challenges to the maintenance of effective cover. Challenges include the strong winds that sweep the fields from February to April and the culture of free grazing. In situ grazing takes place in *ejido* common lands and in farmers' own fields after harvest. However, farmers reported conflicts on

[3] The exchange rate is approximately US$1: 12 Mexican pesos.

accessing farm fields. Traditionally, farmers did not claim private access to their fields after harvest, so that livestock could graze residues in any field in the community. Some farmers also mentioned the trade-offs between soil cover and the use of residues for animal feed as a reason for them not being able to establish fully functioning CA systems.

3.3. Maize–livestock systems in tropical lowlands

The surveyed communities in the State of Chiapas in southeastern Mexico are located in sub-humid lowlands. Land allocation and tropical conditions contribute to a particular maize–livestock system that shapes the way farmers manage maize stover. The system is characterized by a high production of biomass, by the use of grasslands as paddocks and by shifting cultivation that make use of fallows as well of agriculture land. The surveyed communities are located in La Frailesca – a region in the southwestern part of the state of Chiapas. The region has two distinct physiographic landscape units: (i) steep hillsides with a slope >20% and (ii) terraces and river plains with a maximum slope of 20%. The riverbeds occupy around 10% of the area, the terraces 56% and the hillsides 34%. The altitude in the surveyed communities averages 600 m a.s.l. annual rainfall averages 1360 mm between June and September. Agriculture (crop and livestock) contributes over 70% of household income in the surveyed communities – more than in the other case study regions.

Maize predominates in La Frailesca and productivity levels are higher than others parts of the State. Maize and, to a lesser extent, beans are produced in small areas. Other crops include squash, sorghum, peanut, rice and tomatoes. Farmers' maize cultivation practices depend on local topography. In a relatively poor community like Dolores Jaltenango where most of the fields are rain-fed and located on hillsides, mechanization is not suitable. Traditional land preparation consists of chopping maize stover, and burning crop residues, before planting with a stick (known as a *macana* or *espeque*) after the start of the rains. In recent years, the practice of burning crop residues has decreased in response to government legislation prohibiting the practice and there is now wider use of herbicides for land preparation. In river plain fields and gently sloping lands the conventional land preparation consists of 1–3 tillage operations (plough and cultivator), but planting is mostly still done manually with a stick

All the surveyed communities have rapidly taken up hybrid maize varieties and buy seeds every year. There is evidence that farmer adoption of improved maize seed has been stimulated by government seed subsidies (Bellon and Hellin, 2011). Farmers also apply fertilizers (and herbicides) but they do not apply manure because they tend to keep livestock in separate paddocks. Grain harvest is manual, and farmers save part of it for self-consumption and the balance is sold. In good years maize yields average 6 ton/ha but in bad years only 2.5 ton/ha. Reported problems with maize production in the communities included the control of pests and weeds, high production cost and the reduced governmental subsidies.

In terms of livestock, cattle predominate, although of late pig and chicken numbers are increasing with the support of government programs. Cattle ownership is often concentrated, and averages only a third of the farmers in the surveyed communities. Most cattle are dual purpose (meat and milk) and managed under an extensive system. Grazing in paddocks and maize stubble grazing are common, with maize stover being a major feed source during the dry season between January and May. Cattle numbers have reportedly decreased because of low produce prices (both meat and milk) and fodder shortages (due to grazing constraints). Using a combination of stall-feeding and grazing is becoming more common in some communities (Dolores Jaltenango and Francisco Villa), relying on fodder harvested from flat riverine areas. Some also indicated starting to mill the maize stover and starting to cultivate sorghum as a fodder alternative. The bulk of the maize stover (70%) is still grazed in situ, with some 10% burned (except Villa Hidalgo) and 20% remaining in the field (relatively common in Villa Hidalgo and Melchor Ocampo). Even though many farmers do not always harvest the stover, there is a trade in maize stover and farmers who do not have cattle may sell grazing rights to cattle holders. Grazing rights are sold for periods of some 5 months (the dry season) for prices ranging from 125 to 600 Mexican pesos per ha. The buyers generally come from the same community – except in the relatively poor Dolores Jaltenango where residues were sold to people from nearby communities.

Chiapas was one of the first states where CA was promoted at a large scale, by emphasizing the benefits of no-burning and providing the farmers with credits, and sprayers to help overcome the costs of change (Erenstein, 1999). Initial uptake was mainly on the terraces or river plains where an increasing number of farmers no longer plough the soil but instead use one or two passes with the cultivator only (reduced tillage) or no soil tillage at all (zero tillage). All communities recognized the advantages of retaining stover in the field. However, they also identified obstacles to retention: cultural barriers in terms of farmers being used to burning crop residues; agronomic barriers (such as increased pest problems in clay soils; difficulty of sowing due to soil mulch; a lack of adapted seeding machinery); and challenges such as farmers' forage needs and a decrease of yields in the first years. Farmers interviewed were unable to estimate stover yields. But to put the potential feed–mulch conflict in perspective, one may assume that $\geq$20% of the stover remains in the field after grazing and with a harvest index of 0.3, a minimum maize grain yield of 4.3 ton/ha is needed to result in a residue cover after grazing of $\geq$2 ton/ha, corresponding to $\geq$30% soil cover. This percentage of ground cover due to the high level of biomass production should be sufficient to ensure sufficient protection of the soil when it comes to splash erosion but "more would be better" in terms of improving soil organic matter.

4. Discussion and research and development (R&D) implications

4.1. Contrasting management of maize stover

The underlying research primarily assesses maize stover use in three contrasting mixed systems along Mexico's agro-ecological gradient and identifies the potential trade-offs in maize–livestock systems, particularly the widespread use of maize stover as feed against its potential retention as mulch (soil cover) to manage soil health. The paper highlights the diversity of maize stover management and underlying agro-ecological and socio-economic factors, as well as some ways to minimize the trade-off between residues for feed and for retention in farmers' fields.

In the (semi-)arid study region of San Luis Potosi, water availability is a major issue and consequently, maize yields in rain-fed areas are well below the national average. There is a shortage of biomass and fodder is in short supply. Although farmers harvest around 80% of the maize stover by hand and use it as ex situ feed – a third of the farmers still had to buy stover to feed their livestock. Free stubble grazing is a common practice – whereby only about 4% of the stover remains in the field and is incorporated into the soil. Improved land management practices such as CA would only add to the immediate demands on already scarce and intensively used stover. This would affect poorer farmers more as they are more dependent on agriculture (crops and livestock) than wealthier farmers whose livelihood security is enhanced by remittances. Furthermore, wealthier farmers are more likely to be able to afford and use alternative feed sources – especially as the region may well be too dry to introduce successfully alternative fodder sources such as cover crops (see below).

In the temperate highland State of Mexico, land fragmentation is a serious issue; average farm size is significantly less than in the other two regions. Drip irrigation systems are common amongst wealthier farmers but poorer farmers remain largely dependent on rain-fed agriculture. Farmers typically use stall-feeding systems to maintain dairy and beef cattle and ex situ feed is the norm. In situ stubble grazing takes place in *ejido* common lands and in farmers' own fields. Only an estimated 5% of maize stover remains in the field and is incorporated into the soil. Cattle herds are under pressure in view of reduced communal grazing areas and livestock feeding difficulties. There is a vibrant trade in maize stover, and interestingly, it is the poorer farmers without cattle who benefit from this trade in the short term. The promotion of CA would exacerbate the trade-offs between the retention and feed use of stover.

"Maize-livestock systems in the tropical lowlands of Chiapas are characterized by high plant biomass production and large numbers of cattle". Farmers predominantly feed their livestock in situ – i.e. cattle graze the fields following the harvest and in paddocks. Poorer farmers again tend to have fewer cattle, and often sell stubble grazing rights. The relative abundance of biomass means that the trade-offs between cover and feed are less pronounced than in the other two agro-ecological zones, and the prospects of stover retention are aided by the curtailing of burning crop residues at land preparation.

This paper provides a preliminary assessment of maize stover use and potential feed–mulch trade-offs. We did not intend to provide a comprehensive assessment but instead to raise issues and awareness – complementing studies elsewhere (Erenstein and Thorpe, 2010; Erenstein et al., 2011; Valbuena et al., 2012). Indeed, the robustness of the assessment would have been enhanced by casting the village surveys across a larger population and area – be it in terms of the sheer number of villages or the diversity of agro-ecologies covered. The study format is also less apt in bringing out within village diversity. One may hypothesize that poorer mixed farmers depend more on maize stover as fodder source than non-poor farmers. We did observe that farmers without livestock were typically poorer than their mixed farm counterparts and yet more likely to sell maize stover – i.e. monetize stover as a complementary income source. Stover management practices and implications may thus vary according to income group – and this would be one area that merits more substantive research.

Mexican smallholders' livestock fulfill several purposes including enrichment of diets (home consumption), financial capital, security assets/savings, insurance, traction and manure. These non-market functions of livestock tend to be at least as if not more important than the sale of surpluses (McDermott et al., 2010). These non-market functions of livestock are often ignored since they are difficult to value, yet they may contribute to a better understanding of existing mixed systems and farmers' management decisions. The high rates of non-cash contributions are likely to make mixed, low productivity, systems more stable in face of risks and shocks compared to more intensive production systems. This helps explain why farmers in mixed systems rarely seem to intensify livestock production. McDermott et al. (2010) posit that in the case of ruminants, there is no strong evidence of economies-of-scale in production. They base their arguments on the under-utilized family labor and the availability of ruminants to exploit low value roughage, including crop residues and that from public lands. The reliance of smallholders on household labor and the relatively low use of purchased inputs enable smallholders to be competitive in informal and traditional markets.

Our research in Mexico supports this argument. Crop residues are easily available without the need to adjust cropping patterns (as would be the case for e.g. cover crops or forage crops) and thus can be used without any immediate opportunity costs in terms of land use. Research results show that in addition, crop residues are a very cheap source of forage in comparison to purchased higher quality forage (McDermott et al., 2010). Crop residues indeed tend to be relatively easily and cheaply available on the farm or within the community with limited cash outlay compared to higher quality feed, especially if sourced from external sources.

Despite the lack of incentives to intensify crop–livestock systems, more R&D is needed on how to lower the costs of intensifying these heterogeneous production systems. Participatory action research can help to elaborate appropriate solutions adjusted to the complex livelihoods of smallholders. Sustainable intensification of maize production holds particular promise – as this would increase not only production of grain (food and cash) but also maize stover. Promising ways forward are the enhanced use of appropriate seed and fertilizer. More challenging perhaps are appropriate CA systems – but these ostensibly would allow both maize grain and stover yields to stabilize and increase over time relative to business-as-usual – thereby gradually further reducing trade-offs over time between stover retention and feed use. R&D into potential complementary solutions to reduce trade-offs can also look at the system level and include enhancing the feed value of stover, use of cover crops and forage crops, and improved crop residue management options.

These 'solutions' can also be seen in the context of a scenario whereby there is a reduction in livestock numbers but an increase in their productivity. Given the right incentives, livestock farmers could intensify and increase productivity via better-nourished and healthier livestock, and animals with higher reproduction and lower mortality rates, thereby potentially decreasing feed needs for herd maintenance, particularly of low value feeds like most crop residues. In some cases, this would be an economically viable option for farmers but R&D would need to ensure the intensification incentives are there and deal with the non-cash contributions of livestock, increased risks in case of losses and gender effects in terms of workload, distribution of income and other benefits. A case in point was one surveyed community in State of Mexico (Guarda la Lagunita) where high fodder costs and low milk prices reportedly induced dairy farmers to shift to meat production which required less investment. We discuss some of the options further below.

4.2. Enhancing the feed quality of maize stover

Promising but relatively unexplored in the Mexican context are genetic improvements in main food crops like maize to enhance the feed value of stover (Muttoni et al., 2013). Maize grain production has generally been the prime and sole objective of maize improvement efforts across the (sub)tropics (Herrero et al., 2010). Mexico is no exception: despite the prevalence of maize stover use as feed, no systematic or recent breeding effort has considered the feeding value of maize stover. Instead, selecting on grain yield in tropical maize may actually increase the harvest index and consequently reduce available stover quantities to the mixed farmer (Hay and Gilbert, 2001). During our research, farmers said that they often differentiate stover quality based on maize variety: typically preferring traditional (criollo) over hybrid varieties as livestock consume it more readily.

The need to consider the feeding value of crop residues in crop breeding is not new (Byerlee et al., 1989; McIntire et al., 1992; Kelley et al., 1993; Erenstein et al., 2011). Especially for drier areas where feed is a major constraint, multi-objective crop improvement programs can contribute to increase feed availability and quality in terms of digestibility and palatability (McDermott et al., 2010). Recent research on other cereals has shown the potential to incorporate feeding value of residues into crop improvement programs without compromising grain yield (Hall et al., 2004; Hash et al., 2006; Herrero et al., 2009, 2010). Most such cases refer to scenarios where feed is relatively scarce and has a correspondingly high value. In these cases, contributions of residues to gross production often range from 29 to 48% (Erenstein, 1999). With past R&D mainly having looked into (semi-)arid environments and cereals such as sorghum and millet there appears potential to look into the implications of investing in enhancing the feed quality of maize stover through breeding, particularly in contexts of widespread and intensive maize stover use for feed such as in Mexico. The potential scalability of appropriate multi-purpose varieties is another particular advantage: they can be relatively easily scaled-out through public and private crop breeding and seed systems (McDermott et al., 2010).

Others have looked into options to enhance stover feed quality through direct residue treatment and silage – including in Mexico (e.g. Arriaga-Jordan et al., 2002; Estrada-Flores et al., 2006; Garcia-Martinez et al., 2009). Although earlier studies have flagged potential technological enhancement options of using fibrous crop residues as feed these have typically had limited impact at the farm level because of limited incentives and scalability (Erenstein et al., 2011).

For instance in the USA, maize stubble grazing plays an important role in efficient beef production but stover harvesting and/or chemical treatment although feasible, were not economical (Klopfenstein et al., 1987). Stover management practices may ostensibly also be improved to reduce wastage and enhance use efficiency. For instance, partial residue removal/grazing may only use the more palatable components for feed and less palatable ones for soil health. In the case of stubble grazing this could be achieved by managing its intensity and duration through confinement.

4.3. Increasing biomass and animal feed

One prospect to reduce the tradeoff between feed demands and soil cover is partial residue harvesting while retaining adequate amounts of crop residue in the field to ensure some soil cover. This is only feasible in areas where sufficient biomass production is possible. Further options to reduce such trade-offs are to provide substitutes for the soil cover function of crop residues (via the use of cover crops inter-cropped with maize or used in rotations) and/or their feed function (e.g. through forage crops).

Some cover crops can also be used as animal feed. Although most species cannot be grazed well, many can be used for cutting and carrying even after months of drought but it implies high labor input which is not always available or affordable. Seeds potentially also provide feed, as with velvet bean in Campeche, Mexico. In principle it should be possible to substitute the stover's feed function through forage crops. Unfortunately, the incentives to do so are often lacking in Mexico's mixed systems, and forage crops are typically limited to specialized livestock producers. More R&D is called for to improve and adapt forage varieties in Mexico and, hence, to reduce feed demands from maize stover.

5. Conclusions

Mexico's predominantly rain-fed mixed systems often integrate maize production with livestock – yet suffer from soil degradation, low economic profitability and competing demands for maize stover. Improved land management practices such as CA rely on retaining stover to ensure soil cover – but unless the practical and economic constraints of stover use in mixed systems receive adequate attention, farmers are likely to remain reluctant to adopt. Indeed, the demand for stover as livestock feed is now increasingly recognized as a major constraint to farmers' retention of crop residues in Mexico. One promising option is the use of partial stover retention in areas with sufficient biomass production: only an appropriate level of stover is left to protect the soil and increase yields, and part of the stover is sold/used for fodder. Other options include the production of appropriate dual purpose maize varieties with higher feed quality and complementary forage crops; as well as dual purpose green manure/cover crops for feed and mulch.

The present study was scoping in nature and research gaps remain. To better assess the scope for improved farm profitability and soil health through changes in residue management, there is a need for a more robust characterization of the existing diversity of production systems and crop residue uses. This includes information about the economic value of crop residues when used for different purposes, which then enables us to analyze the economic trade-offs (or compatibilities) of contrasting residue uses. Those trade-offs will be affected by agro-ecological conditions as well as farmer characteristics in terms of economic resources and livelihood strategies. In the end though, public pro-poor policies should reduce underlying trade-offs by increasing the productivity of smallholder mixed systems. This calls for public investments in R&D to generate viable crop and livestock technologies and an overall enabling environment for agriculture that includes adequate risk management options, intensification incentives and access to stable markets.

Acknowledgements

The underlying case studies benefitted from financial assistance provided by CGIAR Systemwide Livestock Programme and also funding from the Mexican Government's Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación via the Sustainable Modernization of Traditional Agriculture (MasAgro) Initiative. The authors acknowledge the contributions of many individuals from NARES partners (INIFAP and State of Mexico Autonomous University) and CIMMYT colleagues, including Antonio Castellanos, Dagoberto Flores, Alejandro Ramirez, Pedro Aquino, Roberto La Rovere and Mirjam Pulleman. The authors are also very grateful to two anonymous reviewers and the Guest Editor for invaluable comments on an earlier version of this paper. The views expressed in this paper do not necessarily reflect the views of the authors' institutions or the donor. The usual disclaimer applies.

References

Améndola, R., Castillo, E., Martínez, P.B., 2006. Country Pasture/Forage Profiles. Food and Agriculture Organization, Rome, Italy.

Arriaga-Jordán, C.M., Pedraza-Fuentes, A.M., Nava-Bernal, E.G., Chávez-Mejía, M.C., Castelán-Ortega, O.A., 2005. Livestock agrodiversity of Mazahua smallholder Campesino systems in the highlands of Central Mexico. Hum. Ecol. Interdiscip. J. 33, 821–845.

Arriaga-Jordan, C.M., Albararan-Portillo, B., Espinoza-Ortega, A., Garcia-Martinez, A., Castelan-Ortega, O.A., 2002. On-farm comparison of feeding strategies based on forages for small-scale dairy production systems in the highlands of central Mexico. Exp. Agric. 38, 375–388.

Barkin, D., 2002. The reconstruction of a modern Mexican peasantry. J. Peasant Stud. 30, 73–90.

Bellon, M.R., Hellin, J., 2011. Planting hybrids, keeping landraces: agricultural modernization and tradition among small-scale maize farmers in Chiapas, Mexico. World Dev. 39, 1434–1443.

Bellon, M.R., Adato, M., Becerril, J., Mindek, D., 2005. Impact of Improved Germplasm on Poverty Alleviation: The Case of Tuxpeño-Derived Materials in Mexico. CIMMYT, Mexico, D.F.

Byerlee, D., Iqbal, M., Fischer, K.S., 1989. Quantifying and valuing the joint production of grain and fodder from maize fields: evidence from northern Pakistan. Exp. Agric. 25, 435–445.

De Janvry, A., Sadoulet, E., de Anda, G.G., 1995. NAFTA and Mexico's maize producers. World Dev. 23, 1349–1362.

CENSO (Censo de población y vivienda), 2010. Instituto Nacional de Estadistica. Geografia e Informatica, Mexico, D.F.

Censo Agropecuario, 2007. Instituto Nacional de Estadistica. Geografia e Informatica, Mexico, D.F.

Erenstein, O., 1999. The Economics of Soil Conservation in Developing Countries: The Case of Crop Residue Mulching. Wageningen University, Wageningen, The Netherlands.

Erenstein, O., 2002. Crop residue mulching in tropical and semi-tropical countries: An evaluation of residue availability and other technological implications. Soil Tillage Res. 67 (2), 115–133.
Erenstein, O., Sayre, K., Wall, P., Hellin, J., Dixon, J., 2012. Conservation agriculture in maize- and wheat-based systems in the (sub)tropics: lessons from adaptation initiatives in South Asia, Mexico, and Southern Africa. J. Sustain. Agric. 36, 180–206.
Erenstein, O., Samaddar, A., Teufel, N., Blummel, M., 2011. The paradox of limited maize stover use in India's smallholder crop–livestock systems. Exp. Agric. 47, 677–704.
Erenstein, O., Thorpe, W., 2010. Crop–livestock interactions along agro-ecological gradients: a meso-level analysis in the Indo-Gangetic Plains, India. Environ. Dev. Sustain. 12, 669–689.
Estrada-Flores, J.G., Gonzalez-Ronquillo, M., Mould, F.L., Arriaga-Jordan, C.M., Castelan-Ortega, O.A., 2006. Chemical composition and fermentation characteristics of grain and different parts of the stover from maize land races harvested at different growing periods in two zones of central Mexico. Anim. Sci. 82, 845–852.
Garcia-Martinez, A., Albarran-Portillo, B., Castelan-Ortega, O.A., Espinoza-Ortega, A., Arriaga-Jordan, C., 2009. Urea treated maize straw for small-scale dairy systems in the highlands of Central Mexico. Trop. Anim. Health Prod. 41, 1487–1494.
Govaerts, B., Sayre, K.D., Deckers, J., 2006. A minimum data set for soil quality assessment of wheat and maize cropping in the highlands of Mexico. Soil Till. Res. 87, 163–174.
Hall, A., Blummel, M., Thorpe, W., Bidinger, F.R., Hash, C.T., 2004. Sorghum and pearl millet as food-feed-crops in India. Anim. Nutr. Feed Technol. 4, 1–15.
Hash, C.T., Blümmel, M., Bidinger, F.R., 2006. Genotype × environment interactions in food-feed traits in pearl millet cultivars. Int. Sorghum Millet Newsl. 47, 153–157.
Hay, R.K.M., Gilbert, R.A., 2001. Variation in the harvest index of tropical maize: evaluation of recent evidence from Mexico and Malawi. Ann. Appl. Biol. 138, 103–109.
Hellin, J., Haigh, M.J., 2002. Better land husbandry in Honduras: towards the new paradigm in conserving soil, water and productivity. Land Degrad. Dev. 13, 233–250.
Herrero, M., Thornton, P.K., Notenbaert, A.M., Wood, S., Msangi, S., Freeman, H.A., Bossio, D., Dixon, J., Peters, M., van de Steeg, J., Lynam, J., Parthasarathy Rao, P., Macmillan, S., Gerard, B., McDermott, J., Seré, C., Rosegrant, M., 2010. Smart investments in sustainable food production: revisiting mixed crop–livestock systems. Science 327, 822–825.
Herrero, M., Thornton, P.K., Gerber, P., Reid, R.S., 2009. Livestock, livelihoods and the environment: understanding the trade-offs. Curr. Opin. Environ. Sustain. 1, 111–120.
Instituto Nacional de Estadística y Geografía (INEGI), 2011. http://cuentame.inegi.org.mx/poblacion/rur urb.aspx?tema=P
Keleman, A., Hellin, J., Bellon, M.R., 2009. Maize diversity, rural development policy, and farmers' practices: lessons from Chiapas, Mexico. Geogr. J. 175, 52–70.
Kelley, T.G., Rao, P.P., Walker, T.S., 1993. The relative value of cereal straw fodder in the semiarid tropics of India: implications for cereal breeding programmes at ICRISAT. In: Dvorak, K.A. (Ed.), Social Science Research for Agricultural Technology Development: Spatial and Temporal Dimensions. CAB International, Wallingford, pp. 88–105.
Klopfenstein, T., Roth, L., Rivera, S.F., Lewis, M., 1987. Corn residues in beef production systems. J. Anim. Sci. 65, 1139–1148.
Knowler, D., Bradshaw, B., 2007. Farmers' adoption of conservation agriculture: a review and synthesis of recent research. Food Policy 32, 25–48.
McDermott, J.J., Staal, S.J., Freeman, H.A., Van de Steeg, J.A., 2010. Sustaining intensification of smallholder livestock systems in the tropics. Livest. Sci. 130, 95–109.
McIntire, J., Bourzat, D., Pingali, P., 1992. Crop–Livestock Interaction in Sub-Saharan Africa. World Bank, Washington, DC.
Muttoni, G., Palacios-Rojas, N., Galicia, L., Rosales, A., Pixley, K.V., Leon, N.de., 2013. Cell wall composition and biomass digestibility diversity in Mexican maize (Zea mays L) landraces and CIMMYT inbred lines. Maydica 58, 21–33.
Parsons, D., Nicholson, C.F., Blake, R.W., Ketterings, Q.M., Ramírez-Aviles, L., Cherney, J.H., Fox, D.G., 2011. Application of a simulation model for assessing integration of smallholder shifting cultivation and sheep production in Yucatán, Mexico. Agric. Syst. 104, 13–19.
Perales, H.R., Benz, B.F., Brush, S.B., 2005. Maize diversity and ethnolinguistic diversity in Chiapas, Mexico. Proc. Natl. Acad. Sci. U.S.A. 102, 949–954.
Thornton, P.K., Kruska, R.L., Henninger, N., Kristjanson, P.M., Reid, R.S., Atieno, F., Odero, A.N., Ndegwa, T., 2002. Mapping Poverty and Livestock in the Developing World. International Livestock Research Institute, Nairobi, Kenya.
Valbuena, D., Erenstein, O., Homann-Kee Tui, S., Abdoulaye, T., Claessens, L., Duncan, A.J., Gérard, B., Rufino, M.C., Teufel, N., van Rooyen, A., van Wijk, M.T., 2012. Conservation agriculture in mixed crop–livestock systems: scoping crop residue trade-offs in Sub-Saharan Africa and South Asia. Field Crops Res. 132, 175–184.