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Productivity and energy efficiency of three tillage systems for maize (*Zea mayz L.*) production

Productividad y eficiencia energética de tres sistemas de labranza para la producción de maíz

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ABSTRACT: The amount of inputs and dry matter yields of grain, stover and weeds were quantified in six sites located in the districts of Zaachila and Etla, in the Central Valleys of Oaxaca Region, México. The tillage systems evaluated, which are the most widely used for corn production in this region, were full animal traction (FAT), mixed traction (MXT) and mechanical traction (MT). The higher productivity was achieved in the MT system, followed by the MxT system. According to the energy balance, the largest energy efficiency (EE) was achieved in the FAT system with a value of 34.4 and the least one with the MT system. The lowest EE of the MT system was associated to a higher use of machinery operations and the use of petrol derivate products. No significant differences in EE were found between the FAT and MxT systems; when the weed's dry matter production was considered, EE in this last system was increased 14%, while in the FAT system an 8% increase was observed. Therefore, besides the FAT system, MxT is also recommended because it is common to have plots smaller than 1 ha in the region and mechanical plowing is more efficient for primary tillage operations, while animal power can be used as a renewable source of energy for tasks such as weeding and transport.

RESUMEN: La cantidad de insumos utilizados para la producción de maíz (*Zea mays L.*) fueron cuantificados, así como el rendimiento de grano, forraje y malezas en seis parcelas comerciales ubicadas en los distritos de Zaachila y Etla, pertenecientes a los Valles Centrales de Oaxaca, México. Los sistemas de labranza evaluados fueron: labranza con tracción animal (LTA), labranza mixta (LMx) y labranza mecanizada (LM), los más empleados para la producción de maíz en esta región. La mayor productividad en cuanto a rendimientos de biomasa la obtuvo el sistema LM, seguido por LMx. De acuerdo con el balance energético, la mayor eficiencia energética (EE) se alcanzó en el sistema LTA con un valor de 34.4 y la menor con el sistema LM. La menor eficiencia de éste último se asoció con un mayor uso de operaciones con maquinaria, así como de insumos derivados del petróleo. No existieron diferencias significativas en EE entre LTA y LMx, cuando se consideró a las malezas, en este último sistema se produjo un incremento en la EE del 14%, contra un 8% observado en LTA. Por lo tanto también se recomienda utilizar LMx, ya que en la región predominan parcelas menores de 1 ha y con éste se obtuvieron niveles de rendimientos por jornada mayores durante la labranza primaria y se utiliza la tracción animal como fuente renovable de energía para laboreo secundario y transporte.

1. Introduction

In about most of the rain-fed agricultural area of the state of Oaxaca, Mexico, is planted to corn *Zea mays L.* either as a monocrop or in the "milpa" agroecosystem where corn is associated with beans and squash [1]. Some weeds growing in the plots are also used for human consumption, but most are used as forage for livestock. Traditional tillage systems, such as tilling with oxen-wooden plows in different degrees of combination with mechanical plowing, are used.

Despite being a region of traditional agriculture, and where there is a high cost for acquiring farm machinery and equipment [2] many farmers prefer plowing with tractor and carry up to five primary tillage operations (plowing, cross plowing, harrowing, cross harrowing, and furrowing). There are possibilities of replacement of traditional technologies

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by alternative tillage practices such as minimum tillage, zero tillage [3, 4] or carrying out several tasks in one step [5], which may lead to reduce the processes of soil compaction, erosion and organic matter loss.

The use of inappropriate tillage techniques has increased soil erosion and loss of fertility of agricultural soils in the Central Valleys of Oaxaca [6], which has contributed to the unsustainability of maize production systems, as mechanized tillage requires a greater amount of energy input for an equal output per unit of cultivated area [7]. Both soil degradation and high costs have contributed to motivate the search for alternative tillage methods with greater energy use efficiency and productivity.

An excessive use of machinery for soil preparation is related to higher soil compaction and rate of organic matter oxidation [8]. A reduction in soil tillage intensity can decrease soil moisture losses and the quantity of fine (< 2 mm) clods, which reduces crusting on the soil surface and soil erosion [9]. Soil and nutrients losses can be decreased by using conservation tillage, but under a limited availability and high opportunity cost of crop residues, reduced tillage can be an alternative to have profitable crop yields in maize [10].

Energy efficiency expresses the ratio between the amount of energy units produced and the energy invested as inputs [3, 4] while energy productivity relates the amount of product obtained with the energy invested in the production process [11]. Energy performance is the relationship between revenues and input of energy units [12].

Numerous studies have been conducted to quantify the power consumption in farming systems in temperate areas [13, 14], and in the tropics [15, 16]. There have been energy savings when conventional inputs are replaced by organic inputs or by improved cultural practices [17, 18]. Other studies integrate the analysis of energy, labor and financial profitability in conventional and alternative production systems [17].

The objective of this research was to evaluate the energy efficiency of three tillage systems: Full Animal Traction (FAT), mixed tillage (Mx) and mechanical tillage (MT), which may provide information for a more sustainable management of the land under rain-fed maize in the central valleys of Oaxaca.

2. Experimental procedure

2.1. Characteristics of the experimental sites

The research was conducted in five locations at two districts of the Central Valleys in the state of Oaxaca, namely Etla and Zaachila, in 2007 and 2010. The climate in Etla and Zaachila is a semi-warm type (BSh), with an average rainfall of 635.9 mm concentrated in the period May-October. The average annual temperature for this period is 20.2 ° C, with a minimum of 13 ° C and a maximum of 27.5 ° C [19].

Six pilot sites that were planted to maize using the native landrace "Bolita" were selected. In all cases, the planting and fertilization were done manually and the fertilizer used was ammonium sulfate (20.5% N) applied at a rate of 300 kg ha^{-1} prior to the first weeding.

Sites 1-4 were established in 2007, while sites 5 and 6 they were planted during 2010. These sites were located geographically and classified into hills and plains. After harvest, based on the evaluation of the soil profile at each site, its pedogenetic classification was determined (FAO). The characterization of the sites showed ranges in altitude from 1599 to 1718 m, slopes < 1% in floodplain soils and up to 15% in the hills. In the latter the Cambisol soil unit predominated, while in the plains the Fluvisol unit was more frequent, followed by Pheozem [20]. To characterize the soils of the experimental sites, sampling at depths of 0-20 and 20-40 cm were taken, obtaining a composite sample from five subsamples taken at the corners and center of the plots. Each sample was subjected to standard soil analysis to determine soil organic matter, major nutrients, pH, texture, and bulk density.

In the mechanized tillage system (FM) energy inputs were grouped into 1) indirect use, where labor was included, size of equipment and machinery working hours, and amortization and depreciation of the equipment and 2) direct use, which included the fuel, lubricants and fertilizers applied. When the source of traction was draft animals, the pulling force of the oxen teams in each experimental site was measured using the load cell LCCA -750 coupled to the wooden plow. Thus, in the MxT and FAT systems the values of tensile strength for plowing, furrowing and weeding were measured in the central rows of each plot, using four replicates per experimental site. The energy equivalence of other inputs was obtained from the literature (Table 1).

Energy efficiency was calculated considering the energy required for tillage as the energy input to the system and the crop yields obtained as the output energy of the system by the following Eq. (1):

$$EE = E_{rL} \times E_{RT}^{-1} \tag{1}$$

where EE = energy efficiency of tillage; E_{rL} = energy required for tillage (MJ ha-1); E_{RT} = energy contained in grain, stubble or weeds (MJ ha^{-1}).

2.2. Estimated dry matter yield

The dry matter yields (DM) of crop and weeds were estimated from measurements taken in 4 randomly chosen sectors per site, an area of about 12 m^2 sampled from the two central rows. Other parameters determined were harvest index, number of grains per ear, number of ears

Table 1 Energy equivalency for several inputs used in maize-beans production

Inputs and units		*Equivalences (MJ per unit)*	*Source*
Animal work (h)		5.9	[21]
Human work (h)	Tractor operator	1.05	[22]
	Manual labor	1.95	[23]
Diesel (L)		40	[22, 24]
Nitrogen (kg)		55.4	[21]
Insecticides (kg)		77.2	[25]
Herbicides (kg)		214	[24]
Fungicides (kg)		99	[26]
Organic fertilizer (kg)		0.3	[21]
Maize (kg)		16.2	[27]
Stover (kg)		13.1	[27]
Electricity (kW h)		5.65	[24]
Plow (kg)		22.3	[28]
Harrow (kg)		42.8	[13]

per plant and one hundred kernel weight. To determine the content of DM, a subsample of five plants were dried in an oven for 48 h at 72 ° C.

2.3. Experimental design and statistical analysis

To compare DM yields and energy efficiency among tillage systems, analyses of variance were performed for a nested factorial design with four replications, using the Tukey test ($P \leq 0.05$) for comparison of means by the SAS [29] package.

3. Results and discussion

3.1. Tillage systems

The number of operations or activities performed in each tillage system, the source of tension and implements used

Table 2 Number of operations carried out per tillage system and location

Tillage system	*Site number and locality*	*Tillage Operations and harvest*	*Traction Source and implements*
FAT[†]	1, San Pablo, Etla 5, Cuilapam, Zaachila	Ploughing (3 times), furrowing, 1st cultivation, 2nd cultivation.	Oxen team, Wooden plow
MxT[¥]	2, San Gabriel, Etla 4, Guadalupe, Etla	Ploughing (2 times), harrowing, furrowing (2 times), 1st cultivation, 2nd cultivation.	New Holland 6610 Tractor, Ford 6600 Tractor, Oxen team, Wooden plow
FM[§]	3, Guadalupe, Etla 6, San J. de Dios, Etla	Ploughing (2 times), harrowing (2 times), furrowing, 1st cultivation, 2nd cultivation, harvest.	New Holland 6610 Tractor, cultivator, International 720 harvester.

[†] FAT: Full Animal Traction, [¥] MT: Mix Traction, [§] FM: Mechanized traction

are described in Table 2. The FAT system can have up to 6 operations requiring traction and MxT had a similar number of operations, but in the MT system up to 9 operations were made, which had immediate effects on increases in energy consumption and deterioration of the soil resource [30]. In the Oaxacan Mixteca Region, very similar to the Central Valleys region , up to 3 primary tillage operations have been reported on fine-textured soils, the so called plowing, crossing and re-crossing [31].

3.2. Statistical analysis

The tillage systems factor was significant ($P \leq 0.05$) for grain yield, while forage, weeds and total dry matter were highly significant ($P \leq 0.01$). The effect of systems within locations was highly significant for all these variables, which is attributed to each system showing high or low yields in each location due to limiting site conditions, such as drought and low fertility.

The statistical model was also highly significant ($P \leq 0.01$), with coefficients of variation (CV) between 8.45 to 27.5%. The lowest CV was obtained for total DM, while the highest was observed for weed DM.

3.3. Yields of grain, forage (stover) and weeds

Sites 6 and 3, under the FM system produced the highest forage yields, while higher grain yields were observed in sites 6 and 1 (Table 3). The highest yield of total dry matter was reached on site 6, a high proportion of this came from the forage dry matter and weeds with statistical differences compared to the other sites. Most of these weeds were classified as "arvenses" which are weeds used for forage or for human consumption, ocassionally, these species may have a higher value than the maize crop [32].

Table 3 Maize crop yields, planting densities (P. dens.), and production of weed and crop dry matter per site

Site number	Grain (kg ha^{-1})	Stover (kg ha^{-1})	P. dens. (plants ha^{-1})	Weeds (kg ha^{-1})	Total DM[¥] (kg ha^{-1})
1	2360.3 a[†]	4935.5 ab[†]	39600 cb[†]	1817.0 b[†]	9112.3 b[†]
2	2103.3 b	4641.0 abc	35030 c	2042.0 b	8786.3 bc
3	612.3 c	5909.3 a	76786 a	1031.3 bc	7552.3 cd
4	813.5 c	4159.0 bc	35094 c	2004.5 b	6976.8 d
5	807.8 c	3332.0 c	43027 bc	113.5 c	4253.0 e
6	2249.3 a	5995.0 a	46786 b	3303.8 a	11547.8 a
CV (%)	23.9	13.3	10.2	27.6	8.1

[†]Tukey's Test, P< 0,05; [¥]Dry matter of maize and weeds

As seen below, the higher forage yields were related to the planting densities used, while grain yields were more related to the degree of soil fertility and total precipitation. The average rainfall for both growing seasons was 708.2 mm, but 2007 was drier with 459.5 mm and 2010 had 978.6 mm. Overall, rainfall was well distributed, except at site 3 in 2007 where there were severe deficiencies during the flowering stage (VT), and in 2010 at a site 5 with moderate deficiencies during the late vegetative stage [33].

Chemical analysis of sites 1 and 6 showed medium to high content of organic matter and phosphorus (Table 4). In the region of the Central Valleys of Oaxaca P contents are considered deficient (1.5-8 mg kg $^{-1}$), especially in soils located in sloping land [34, 35], which is associated with lower corn yields [6]. At P contents close to or below 10 mg P kg $^{-1}$ it is expected to have response to addition of P [36], in this study the average P content (0-40 cm) ranged from 3.49 - 31.25 mg kg $^{-1}$, with average pH values of 7.26. In soils with pH = 7.6 and 4.9 , higher yields were found in plants with higher content of N, P and K in the foliage measured 60 d after planting [37].

Table 4 Soil analysis results per location. 2007 and 2010. Oaxaca, Mexico

Location	pH	Organic matter (%)	Extractable P (mg Kg^{-1})
1	6.50	2.57	31.25
2	7.65	2.61	27.40
3	7.70	2.03	19.75
4	5.85	4.60	21.50
5	7.90	0.85	3.49
6	8.05	2.62	11.80

There were significant differences (P ≤ 0.05) between the densities of plants of the three tillage systems, but grain yields were significantly different between FAT and MT only (Table 5). When planting densities varied from 35062 to 41314 plants ha^{-1} grain yields ranged from 1692 to 1842 kg ha^{-1}, which were considered acceptable yields for this region [6]. For plain soils in the region of the Central Valleys of Oaxaca, optimum planting densities for grain production range from 33-43 thousand plants ha^{-1} [34], therefore the productivity of maize in the FAT and MxT systems was not limited by plant density.

Table 5 Maize grain and stover yields, planting densities and total dry matter production under three tillage systems

Tillage system	*Grain (kg ha^{-1})*	*Stover (kg ha^{-1})*	*P. density (plants ha^{-1})*	*Weeds (kg ha^{-1})*	*Total DM¥ (kg ha^{-1})*
FAT†	1841.6 a §	4133.1 b	41314 b	965.3 b	6941.0 c
MxT¶	1695.9 ab	4400.0 b	35062 c	2023.3 a	8119.0 b
MT§	1430.8 b	5952.1 a	61786 a	2167.5 a	9550.4 a
CV¤ (%)	22.9	12.1	9.0	26.4	6.1

† FAT: Full Animal Traction, ¥ MT: Mix Traction, § FM: Mechanized traction

†Means with the same letter are not different according to Tukey's Test, P< 0.05; ¥Dry matter of crops and weeds

3.4. Energy efficiency

Due to the requirement of personnel for all work, including the application of fertilizers, the use of labor was higher in the FAT system. In contrast, the MT system had the smaller use of human energy, but the higher use of agricultural machinery (Table 6). The amount of seed used in this system was also higher, since the aim of these producers was to obtain the largest possible amount of forage for dairy cattle feed. In similar systems, use of labor in planting wheat amounted to 20.9 MJ ha^{-1}, while the diesel used represented 12219.0 MJ ha^{-1} [38].

Table 6 Mean energy inputs per tillage system (MJ ha-1). Oaxaca, Mexico

Tillage system	*Fertilizers*	*Human labor*	*Traction energy*	*Animal work*	*Machinery*	*Seeds*
FAT†	2212.0 a	73.630 a	13.0 b	30.2 a	n.a. b	247.9 b
MxT¶	2212.2 a	64.350 b	673.0 a	12.2 b	11832 ab	210.4 b
MT§	1169.1 b	0.263 c	1171.8 a	n.a. b	23945 a	370.7 a

† FAT: Full Animal Traction, ¥ MT: Mix Traction, § FM: Mechanized traction; b not applied.

†Means with the same letter are not different according to Tukey's Test, P< 0.05; ¥Dry matter of crops and weeds.

In a study aimed to evaluate sustainability, fossil inputs ranged from 11.2 to 46,0 GJ ha $^{-1}$; the highest values were due to the high use of machinery and chemical inputs. The efficiency factor in energy transformation (an indicator of the dependence of food and feed production on non-renewable energy) ranged from 5.0 to 12.2 [39].

In all cases, the MT system produced the lowest efficiency values of energy efficiency (EEL) with respect to the FAT system, but it was significantly different (P ≤ 0.05) from the MxT system when grain yield, forage and weeds were included (Table 7). This value is strongly linked to an extra use of fuel required for tillage operations with tractor in

Table 7 Indicators of partial and total energy efficiency per tillage system

Tillage system	*PE1†*	*PE2¥*	*EET§*
FAT	10.0 a	31.7 a	34.2 a
MxT	5.2 ab	18.1 ab	20.7 a
MT	1.2 b	4.7 b	5.2 b

† PE1: Partial energy efficiency includes grain yield only.

¥ PE2: Partial energy efficiency, includes grain and stover yields,

§ EET: Total energy efficiency, includes grain, stover and weed yields.

†Means with the same letter are not different according to Tukey's Test, P< 0.05

areas smaller than 1 hectare, because of the large number of dead time required to make turns. In other systems, it has been found that low energy efficiency was associated with the use of fossil fuels and inadequate management of tillage methods [3, 40].

When the energy of forage was considered, the EE increased significantly in all systems, reaching a maximum value of 34.3 at the FAT system. However, in percentage terms, the increase in efficiency was higher in the MT system (292%). The contribution of weeds to the increase in EE was 7.9-14.4%, with the highest value in the MxT system, In some cases, the contribution of dry matter of weeds in the milpa agroecosystem can be greater than that of corn silage [32].

The non-mechanized production system of flooded rice in Thailand reaches 38.0 efficiency values, while the mechanized agriculture of U.S. corn have values close to 3.0 [41]. These values are similar to those obtained in the present study for the FAT and MT systems. In studies on tillage intensities EE values from 7.7 to 8.6 have been obtained, but these were not proportional to the energy used in the preparation of the soil, but less tillage operations tended to give higher values of EE [42].

It has been noted that EE is a critical issue for food sovereignty in most countries [43], so that under a condition of smallholding and production for home consumption is advisable to use animal traction or a mixture of it with mechanical traction. In this study there were no differences in EE between the tillage system with animal traction and mixed tillage system, which validates the latter as a viable alternative [3, 44].

4. Conclusions

In the present study, the low EE for the fully mechanized tillage system was largely determined by the use of a larger quantity of machinery and implements and energy inputs such as fuels and lubricants. The full animal traction system produced the highest values of energy efficiency with significant differences with the mechanical tillage but not with the mixed tillage systems. However, as in the region it is common to have plots smaller than 1 ha, the mixed tillage system is recommended, because mechanical plowing is more efficient for primary tillage operations and animal power can be used as a renewable source of energy for tasks such as weeding and transport.

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