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Soil erosion control using agroforestry terraces in San Pedro Mixtepec, Oaxaca, Mexico

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ABSTRACT
The forest soils of San Pedro Mixtepec, Oaxaca, present water erosion problems. The loss of plant coverage by the opening of lands to planting and overgrazing in lands with slopes > 30% cause such difficulties. Current water erosion was evaluated in rangelands by establishing a runoff lot and using the Universal Soil Loss Equation (USLE/RUSLE). Results indicate that the affected soils displayed a severe erosion of 16.67 Mg/ha/ year. The establishment of an agroforestry system with *Leucaena lecocephala* (Lam.) de Wit and *Moringa oleiferous* (Lam.) in terraces, contained the removal of soil that was worked out to be of 2.17 ton/ ha/ year. The control method avoided the loss of 14.5 Mg/ha/ year of sediments. We conclude that agroforestry technology in terraces is an efficient method for the control of water erosion and of the sustainable soil management.

Keywords: agroforestry terraces, eutric regosols, soil conservation, water erosion.

INTRODUCTION
Humans base their agro productive development on soil use. However today, the inappropriate application of techniques in food production systems for an ever increasing global population is the main factor of pressure on the soil resource (Palacios and Gama 1994). The change in the use of forest lands to agricultural use, common in Third World countries, does not take into account the capability of the ecosystem to load and regenerate, and the soil is vulnerable to water and/or wind erosion, which, with time, induce soil loss, the reduction of its productive potential and economic and social damage to agrarian communities involved (Szabolcs 1994). The phenomenon is more intense in lands with a slope. Worldwide, over six million hectares per year present erosion and desertification problems (UNESCO 1979). In Mexico, an average of 365 million tons of soil is lost to water erosion. It is estimated that it affects 75% of the country's soils and it becomes more intense as the pressure increases on forest resources, with no adequate measures taken to control it (SEMARNAT 2008, Moreno 2008). The low relief of the microbasin of San Pedro Mixtepec, Juquila, Oaxaca, is composed of shallow regosols

and lithosols that support a medium subdeciduous rainforest vegetation, deteriorated by the opening of lands to agriculture and the establishment of grasslands for extensive cattle-raising (INEGI 2004). These are soils with a slope of 35%, which, in the rainy season, undergo a still unmeasured amount of water erosion. To evaluate the natural or induced water erosion, field methods have been created, such as marked rods, runoff lots, crevasse transects, and the soil profile analysis, which are empirical projections that, when not handled accurately, can subevaluate real erosion (FAO 1977, Michelena et al. 1989). In other cases, models are used to predict annual soil loss by water erosion based on the Universal Soil Loss Equation (Wischmeier and Smith 1978), developed for the weather and soil conditions of the United States, and which was revised by McCool et al. (1995) who redesigned calculating R factors (rainfall-runoff erosivity), L (slope-length), S (slope steepness), C (Cover management) and P (supporting practices) to more accurately estimate soil loss from crop and rangelands areas, based on computer programs. Then the equation was modified especially in the use and management factor to adjust it to conditions of other countries (Renard et al. 1991, Sharpley and Williams 1993, Sphor et al. 2009). In this regard Clérisi and García (2001) indicate that the estimation *in situ* of the rate of water erosion of a surface of land, by establishing the experimental fields and runoff lots under natural rainfall, and its comparison with the application of the Universal Soil Loss Equation (USLE/RUSLE), has turned out to be an adequate method to estimate the erosion that takes place under certain conditions of soil use and management. On the other hand, terracing has been used since ancient times to control the erosion of planted soils on steep slopes (Cristchley and Siegert 1997). In this sense, researchers such as Ayres (1960) and Troeh et al.(1980) point out the importance of setting up terraces as an efficient method for controlling soil loss, since terraces reduce sedimentary externalities in over 50%, particularly if they are used with appropriate planting and agroforestry techniques. Estralich et al. (1997) and Petit et al. (2005) indicate that an adequate control of soil erosion is feasible, combining terraces and forest shepherding technology. The use of multipurpose trees favors the stabilization of soils, due to the roots of the trees growing into the terraces, as well as the particles settling and the organic matter increasing in the soil from the contribution of plant residues (Torquebiau 1993). Likewise, the use of leguminous species can fix atmospheric nitrogen into the soil, which improves fertility conditions. The aim of this study was to evaluate the erosion of an experimental site on a steep slope affected by overgrazing in San Pedro Mixtepec, Oaxaca, by a runoff lot, as well as examine the erosion caused in a rainy season after a forest grazing system was established with *L. leucocephala* and *M. oleifera* bushes in terraces, and their validation using the Revised Universal Soil Loss Equation. Results will help conclude whether the proposed terrace and agroforestry system are efficients or not in helping reduce the rate of water erosion.

MATERIAL AND METHODS

Area under study

The study was carried out in low relief lands of the microbasin of San Pedro Mixtepec, District of Juquila, Oaxaca, Mexico, which is a part of the Río Colotepec water basin (INEGI 2004). The microbasin is located between 97° 05´ W and 16° 59´ N, has a surface of 8 km^2 and its natural limits are the hills “El Zopilote”, “El Ocote”, “La Campana” and “El Águila”. It is drained by the rivers Vaca and Sangre, tributaries of river Colotepec, the dendritic water pattern of which flows into the Pacific Ocean. Specifically, the property named “Los Nanches” is at an altitude of 196 masl; it has a surface of 10 ha and a 35% slope. Weather is warm subhumid, rainy in less-humid summers Aw_0 (w), and the average temperature is 27.4 ° C (the coolest month is January, with a temperature of 25.5°C, and the hottest is May, at 29.4 °C). Average yearly rainfall is 1057.8 mm; rain is torrential, distributed between May and October, and it reaches its peak in September. The area is formed by granite rock with powerful overlay thicknesses of gneiss metamorphic rock type, belonging to the complex geological Xolapa of Paleozoic age (Tolson 2005). Soils have gradually developed on this stone, giving rise to shallow and lateritic regosols with a forest vocation. The lithic phase of these soils determines a low capacity for infiltration and runoff rates of 20 to 30%. Its texture is sandy loam, its color is brown and it displays a content of organic matter below 4% (INEGI 2004). The land in study maintains grassy vegetation for extensive cattle grazing, which replaced the native lowland deciduous vegetation. As a consequence of deforestation, the hydroerosive processes are common in the area. Despite this problem, it is possible to notice in the area species such as *Bursera simaruba* (Gumbo-limbo), *Lysiloma acapulsence* (ebony), *Ceiba petandra* (Kapok), *Trichillia havanensis* (siguaraya), *Brosimum allicastrum* (breadnut), *Aphanante monoica* (palo de armadillo), *Enterolobium cyclocarpum* (guanacastle), *Parmentiera aculeata* (cuachilote), Swetenia humilus (cobano), *Hura poliandra* (haba de Guatemala), *Tabebuia rosea* (palo de rosa), *Vitex mollis* (zapotillo), *Acacia cornígera* (cuernitos) y *Acacia cochilacanta* (palo de cucharitas). Shrubby vegetation consists of *Andira inermis* (Cacajo de caballo), *Spondias sp* (Jocote), *Acacia cornígera* (cuernitos), *Cordia alliodora* (Suchicahue), *B. simaruba*, *H. Poliandra*, *Ficus sp*. (ficus) and *E. cyclocarpum*, which shed their leaves in the dry season.

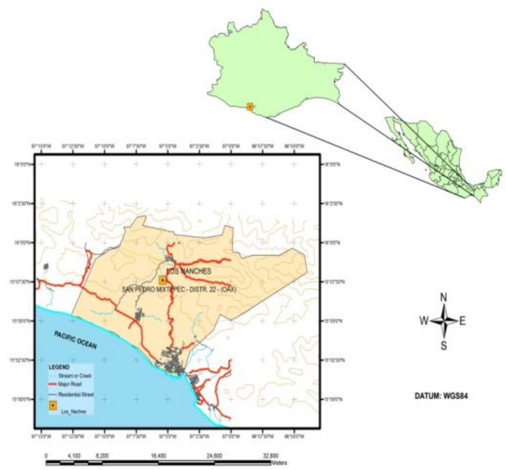

Fig.1. Localization of the study area

Soil sampling and analysis

In the dry season of 2008, before establishing the runoff lot, a soil monolith was dug in order to determine its physical and chemical properties. Samples of 1 kg of soil were gathered, each one 20 cm thick, and of a depth of up to 1 m (Palmer and Trohe 1979). Samples were placed in plastic bags, properly labelled and sealed for their transfer to the Universidad del Mar Research Laboratory, where they were dried in the open air. Infiltration speed was calculated by measuring the percolation of water in cm per minute in a PVC tube 15 cm wide and 20 cm long, placed 15 cm under the ground. In the lab, their dry and humid weights were measured using a grain scale and a muffle furnace at 104° C. The soil texture and apparent density (g/cm^3) were determined using the Bouyoucos hydrometer method (Richards 1985). The percentage of porous space was calculated with the equation: $100 - \frac{\varrho_a}{\varrho_r} \cdot 100$, where: $\varrho_a =$

apparent density of the soil; ϱ_r = real density of the soil. The color of the soil was estimated using Munsell soil color charts (2000). The Cation-Exchange Capacity or CEC (mEq 100 g^{-1} of soil) was calculated using the ammonium acetate method (SEMARNAT 2002). Electrical Conductivity, or EC (dS/m), and the pH of the soil saturation extract were taken using a multifunctional HI 98129 HANNA INSTRUMENTS ® apparatus, and the soluble cations and anions were calculated using the titrimetric method (Richards 1985). The three last parameters were also determined in the solution of sediments gathered in the runoff lot after the rainy season.

Establishing the runoff lot

The location was chosen by differentiating areas based on land maps and the aid of soil, vegetation and soil use thematic maps INEGI (2004). For this purpose, the forest perturbance, change in soil use and the slope of the land were considered. An analysis of the phenosystem helped identify that the terrain chosen had the ideal characteristics, since it was cleared in areas of decline for establishing grasslands for extensive cattle ranching. The lot was set up in the property named “Los Nanches”, lying in the jurisdiction of San Pedro Mixtepec, in the coordinates of 15° 57´42” north and 97° 05´20.1” west. Initially, the highest point of a small hill was chosen to calculate the slope of the property in an upstream-downstream direction using theodolite, estadal and measuring tape, and the equation quoted by Velasco (1991), which considers the relation as a percentage of the vertical and horizontal relief components: $S = \frac{IV}{IH} * 100$, where: S = land slope (%), VI = Vertical Interval (m), HI= Horizontal Interval (m). On the field, the measurements of the runoff lot were 2.5 m width by 5 m length, giving a surface of 12.5 m^2, which served as a base for calculating the location's percentage of runoff and erosion. The lot was set up from north to south (upstream-downstream from the microbasin) and was fenced using planks of wood, 5m long by 0.30 m tall, buried to a depth of 0.1 m. The southern end of the structure was connected in its lower part to a PVC tube, 1 m in length and 3 inches wide, which served as a transporter of sediments to a 100-liter steel container. This container was placed under the tube and buried to a depth of 0.20 m and contained the sediments removed during the process of erosion. Sediments gathered were monitored on a monthly basis. They were dried in the open air and weighed. Then they were added to obtain the total sediment weight. Following this, the sediments were transferred to the Universidad del Mar Research Lab in sealed plastic bags to obtain their real dry weight using a muffle furnace at 104° C. The mass obtained was extrapolated at a hectares as unit area, and using the data of the density, we worked out the volume of soil eroded per hectare. Likewise, based on weather, topography, soil conditions, and soil use in the study, the percentage of runoff for the microbasin was worked out. In order to determine the basic ionic makeup of the sediments gathered during the process of erosion, chemical analyses of soluble cations and anions were performed using the titrimetric method (Richards 1985).

In order to compare the results for the erosion of the soil obtained using the runoff lot method, the potential erosion and actual erosion in the area of study were calculated using the Universal Soil Loss Equation (Wishmeier and Smith 1978), which is as follows:

A = R·K·LS·C·P, where:

A = Soil loss per surface unit (Mg/ha).

R = Rain erosiveness factor. Accumulated product of the kinetic energy times the highest intensity of rainfall in 30 minutes for the period of interest (a year in agroecosystems) with a slight probability of occurence (generally 50% or average) its units are $MJ\ \frac{mm}{h}$/year. In this respect, Trohe et al. (1980) consider that for simplicity R must be handled in energy units per surface J/ha.

K= Factor of soil erodability. Average amount of soil lost per unit of factor R (Mg/J), when the soil is kept bare permanently, with secondary tilling in the direction of the slope.

L = Factor of slope length. Relation between the erosion with a given slope length and that which occurs in the standard 22.1 m length, while the other factors remaining equal.

S = Factor of slope steepness. Relation between erosion with a given slope steepness and that which occurs in the standard 9% of steepness, the other factors remaining equal.

C: Factor of use and handling. Relation between soil erosion with a particular use and handling system, and that which occurs in the same soil placed under the standard conditions under which factor K was defined, the other factors remaining equal.

P = Factor of support mechanical practice. Relation between the erosion that takes place with a particular support mechanical practice and that which occurs with the standard condition of tilling in the direction of the slope, the other factors remaining equal. This equation was modified for Mexican soil conditions by the Colegio de Postgraduados-SARH (1977) based on erodability number curves that estimate the factor C based on 5 easily established variables: 1) coverage of the soil with stubble from earlier plants, 2) coverage of soil with leaf canopies, 4) content of organic matter in decomposition in the first 10 cm of the soil, and 5) water conductivity of the soil.

Construction of terraces

The experimental plot was established adjacent to the runoff lot. Banks were made following level curve with a slope of 0.5% to allow excess water to drain out. Every patch was formed with the soil removed from the vertical slope tune header. The terraces were stabilized in its lowest level with sacks filled with leftover dirt from the slope tune. The size of the patches was 10 m in length by 1.50 m in width. The distance between terraces was 2 m, following the formula used to find the Vertical Interval (CONAFOR 2004):

$IV = 0.6 + 0.075\ S$, where:

VI: Vertical Interval (m)

S: Slope (%)

0.6: constant to be used in areas with an annual rainfall of over 750 mm.

0.075: Constant

On the other hand, the Horizontal Interval was obtained using the equation $IH = \left(\frac{IV}{S}\right) * 100$, where:

HI: Horizontal Interval (m)

VI: Vertical Interval (m)

S = Slope (%).

Establishing the agroforestry system and experimental design

A system was established in terraces of forest grazing in multiple-use trees with grasslands, in which experimented leguminous species were "Guaje" (*Leucaena leucocephala L.*) and "Moringa" (*Moringa oleifera*). The guaje and moringa plants were taken from a greenhouse and transplanted in the patches 30 days after emergence. The plantation was in a real frame at a distance of 1.25 m between plants. The bowls were set up in the central area of the terraces that contained a total of 8 plants each. A random block design was established with seven terraces, six of which contained three treatments (T_1 Leucaena plants), (T_2 Moringa plants), (T_3 combination of Leucaena and Moringa plants), two repetitions and a terrace represented the control, giving a total of 48 experimental units. To evaluate plant growth, the parameter of height was used (measured with a SUNNTO CLINOMETER), along with treetop diameter and diameter at the root's neck both measured with measuring tape (Diéguez et al. 2003). The regression and variance analyses to determine significant differences in the control of erosion were carried out using the Statistical Analysis System SAS (2006).

RESULTS AND DISCUSSION

Physical and chemical characterization of soils

The studied soils display poorly-developed horizons with a moderate drainage that derive from the weathering of the metamorphic rock. Horizon A accumulates a decent amount of fresh plant residues that decompose rapidly due to solar radiation, temperature and microbial activity, which produce a thin, dark layer 4 cm thick (subhorizons Oa/Oi). Horizon B, approximately 1 m deep, presents eluviation and illuviation of clays, iron and aluminum hydroxides, in such a way that such materials move and accumulate in the mid and lower horizon. Horizon C contains high amounts of unweathered primary silicates in its thickness, with diverse gradings until it reaches the mother rock. Soil texture was established as sandy loam, and apparent density was 1.45 g/ cm^3. The content of organic matter varies from 4% to 1% as the profile descends. The color of the soil is 7.5 YR 4/2 reddish-brown and it indicates processes of oxidation of ferrous material, a common phenomenon in tropical soils with a forest vocation. The pH values of approximately 5.6 correspond to acid soils, the reactions of which give rise to the precipitation of iron and aluminum hydroxides. This explains their accumulation in horizon B, as well as the leaching of basic cations (Ca^{2+}, Mg^{2+}, Na^{1+} y K^{1+}) by the drained water. The diverse thicknesses present a low electrolytic concentration (< 202 ppm) and low EC < 1.0 dS/m, and they therefore do not present salinity problems (Richards 1985). Their low Cation-Exchange Capacity, which varies between 16.8 and 30.6 mEq/100 g of soil in the top and lower horizons, is related to the presence of kaolinitic clay determined by De Scerna (1965), and hence their low fertility. According to the soil classification by FAO (1998), the characterization corresponds to eutric regosoles that present a fragile balance with the forest vegetation.

Determining the index of erosion by rain

The potential capacity of the region's rainfall to cause erosion in the soils of the area under study was calculated and the average rainfall intensity was considered, (amount of mm of rain that fell in an hour) during the period between May and November of 2008, with data provided by “La Ceiba” weather station. This average was 51.5 mm h^{-1}. Likewise, the Hudson equation, modified for tropical rainfall areas (Albuquerque 1993) was used in order to find the kinetic energy (KE) of the rain, such that:

$$KE = 29.8 - \frac{127.5}{I} \dots\dots\dots\dots (Ec\ 1.)$$

Where: KE = kinetic energy ($J\ \frac{m^2}{mm}$)

I = Rainfall intensity (mm/h).

Replacing in the equation the value I of 51.5 mm/h, we obtained a KE of:

$$KE = 29.8 - \frac{127.5}{51.5} = 27.32\, J\frac{m^2}{mm}$$

This KE value is high, therefore, according to Wischmeir & Smith (1978), this rain intensity is capable of producing erosion.

Determining the potential erosion (PE)

To determine this erosion, we used the terms R (rain erosiveness), K (susceptibility of the soil to water erosion), L (slope length factor) and (S) slope factor that indicate the influence of the area's physical factors, hardly modifiable by humans. These terms represent the loss of soil that would take place if the soil in the area of study were to remain bare the entire year (Irurtia and Cruzate 1984). Below shows the results of each term:

Determining rain erosiveness (R)

The average monthly and annual rainfall data reported for the area of San Pedro Mixtepec for a period of 30 years in the Geographical Summery for the State of Oaxaca (INEGI 2004) helped feed the equation by Lombardy Neto and Moldenhauer (1992), indicated below:

$R = 6.866 \frac{(p^2)^{0.85}}{P}$ Ec………(2),where:

R = average annual erosiveness index (Mg/ha)

p = average monthly rainfall =156 mm.

P = average yearly rainfall = 900 mm.

After substituting, we obtained the following:

$$R = 6.866 \frac{(156^2)^{0.85}}{900} = 113.22 \text{ Mg/ha}$$

According to criteria by FAO (1977), this result indicates a high risk of laminar erosion produced by factor R.

Determining soil vulnerability to water erosion (K)

Factor K represents the susceptibility of soil to the erosive action, and it depends on the physical characteristics of the soil: texture, structure, porous space, permeability, water conductivity, capacity of infiltration, organic matter contents, etc. In this case, the eutric regosoles are underdeveloped, with a sandy loam texture, a regular structure with a low content of organic matter, deficient drainage and a rate of infiltration of 2.7 cm/h. Hence according to the soil classification, due to its vulnerability to water erosion of the Soil Conservation Service of the United States (Mishra and Singh 2003), these soils belong to type B. That is, they are soils with moderate rate of infiltration and higher runoff values. This group contains sandy loam lands with a lower presence of colloidal matter.

To work out the value K, the equation established by Wischmeyer and Smith (1978) was used and modified for metric units (Irurtia and Cruzate 1984):

$77.4 \cdot K_m = 2.1[(\%\, of\ silt + very\ fine\ sand) \cdot (100 - \%\, of\ clay)]^{1.14} \cdot 10^{-4}(12 - \%\, OM) + 3.25(b - 2) + 2.5(c - 3)$………Ec (3).

where:

% silt= Percentage of the fraction from 2 to 50 μ

% sand = Percentage of the fraction from 50 to 100 μ

% clay = Percentage of the fraction lower than 2 μ

OM = % of organic matter of the surface layer of soil.

b = Grade of structure of the soil according to the following scale:

1: very good structure. Very fine granular.
2: good structure. Fine granular.
3: regular structure.
4: Bad structure. Regular or massive.

c: Permeability according to the following scale:

1: very fast > 12.5 cm/h.
2: moderately fast (6.25 to 12.5 cm/h].
3: moderate (2 to 6.25 cm/h].
4: moderately slow (0.5 to 2.0 cm/h].
5: slow (0.125 a 0.500 cm/h].
6: very slow: < 0.125 cm/h.

When replacing the values of the relative proportion of particles, of the structures and permeability obtained in the lab, the equation gives the following value for K_m:

$$77.4 \cdot K_m = 2.1[(96.4) \cdot (96.4)]^{1.14} \cdot 10^{-4} \cdot (2.2) + 3.25(1) + 2.5(0) = 20.36$$

Clearing: $K_m = \frac{20.36}{77.4} = 0.26$

Therefore, the value of factor K soil erosiveness is 0.26, which ends up in the interval of values (0.13-0.38] established by the Soil Conservation Service of the United States for a soil type B (Mishra and Sing 2003), which confirms the correct determination of the factor K for the soils studied.

Determining the topographical factor LS

The topographic factor establishes the contribution of relief to water erosion. To calculate it, we used the equation by Wischmeyer and Smith, modified by the FAO (1977). The equation requires data such as slope length (L) in m and its steepness (P) as a percentage, and it is as follows:

$$LS = \left(\frac{L}{22.1}\right)^{m} \cdot (0.0650 + 0.04536 \cdot P + 0.0065 \cdot P^2) \ldots\ldots Ec(4).$$

Where:

L = Length of the slope (m).

P = Steepness in %

m = exponent that varies with the slope, as indicated as follows: for slopes up to 0.5% steep, m = 0.2; for slopes up to 1 to 3% steep, m = 0.3; for slopes between 4 and 5% steep, m = 0.4; for steepnesses > 5%, m= 0.5.

As a result of topographic works to establish the runoff lots, we obtained a length of 12 m for the slope and a steepness of 35%, and therefore replacing such values, equation (4) gives the following result:

$$LS = \left(\frac{12}{22.1}\right)^{0.5} \cdot (0.0650 + 0.04536\ (35) + 0.0065 \cdot (35^2) = 7.084$$

Based on the above, the PE was calculated by multiplying the values R, K, LS, where:

R = 113.22 Mg/ha

K = 0.26

LS = 7.08

Therefore, when multiplying the values, we obtained a PE of $208.41\ \frac{Mg}{ha}/año$. According to the classification of the PE given by Wischmeyer and Smith (1978), the soils under study present a high PE.

Determining actual erosion (A)

Working out A considered PE and factors C (soil use and management) and P (conservationist practices). To determine factor C, the indices considered were those pointed out by the Soil and Water Conservation Manual of the Colegio de Postgraduados-SARH (1977) contained in table 3.

In this case, the value chosen was C = 0.8, since it is an eroded terrain with sparse vegetation. On the other hand, coefficient P was chosen considering that the type of conservationist practice proposed was the use of terraces with agroforestry. The values for such a coefficient are indicated by the Soil and Water Conservation Manual of the Colegio de Postgraduados-SARH (1977) contained in table 4.

Therefore, if A = R·K·LS·C·P, then $A = (EP)(C)(P)$. Substituting values:

$$A = 208.41\ Mg\ ha^{-1}(0.8)(0.1) = 16.67\frac{Mg}{ha}/year$$

This loss of sediments indicates that the eutric regosols of the study area are very vulnerable to water erosion, and due to their depth (100 cm) and moderate structural condition, they are considered to have little tolerance to water erosion. Therefore, according to maximum tolerance values provided by the FAO (1977) for shallow soils and with substrates similar to the object of study, which is of 6.7 $\frac{Mg}{ha}/año$, the actual erosion obtained (A) is higher than the threshold of tolerance indicated. In this respect Irurtia and Cruzate (1984) and Clérici and García (2001) accede in pointing out that the comparison of the actual erosion rate (A) with the value of tolerance to erosion for each soil type helps evaluate if the farming systems in practice create erosion or not, thus indicating relative sustainability or unsustainability. In the case of agroecosystems established in the soils of foothills with slopes > 30% in San Pedro Mixtepec, the perturbance and erosion of the forest soils is intense due to the establishment of grasslands for extensive cattle farming and from the clearing of lands for agriculture by means of slash and burn (Sánchez et al. 2012a). This causes a drop in biological and productive potential of these soils, along with harmful impacts on the forest's ecosystem, which is why such farming systems are by all means unsustainable. Therefore it is necessary to replace these soil management techniques and methods for more appropriate and sustainable agrotechniques.

Table 1. Textural proportion, porous space, speed of infiltration and organic matter content, of the soil thicknesses analyzed.

Soil thickness (cm)	Textural proportion (%)	Total porous space (%)	Bulk density (g/cm^3)	Speed of infiltration (cm/h)	Organic matter content (%)
0-20	Sand: 84 Silt: 10 Clay: 6	44.23	1.45	2.8	4
20-40	Sand: 85 Silt: 13 Clay: 2	44.43	1.45	2.7	2.5
40-60	Sand: 84 Silt: 10 Clay: 6	44.23	1.45	2.7	2.1
60-80	Sand: 80 Silt: 18 Clay: 2	45.28	1.46	2.7	1.4
80-100	Sand: 81 Silt: 17 Clay: 2	45.28	1.46	2.7	1

Table 2. Electrolytic concentration and Cation-Exchange Capacity of the diverse soil thicknesses analyzed.

Soil thickness (cm)	pH	EC (dS m^{-1})	ppm	Anions (mEq/100 g of soil)				Cations (mEq/100 g of soil)				CEC mEq/100 g of soil
				HCO_3^{-1}	Cl^{-1}	SO_4^{-2}	Total	Ca^{2+}	Mg^{2+}	Na^{1+}	K^{1+}	
0-20	5.65	0.40	202	0.063	0.045	0.130	0.238	0.009	0.005	0.72	0.48	16.8
20-40	6.23	0.13	68	0.050	0.046	0.105	0.201	0.006	0.004	0.49	0.16	21.8
40-60	5.60	0.13	69	0.055	0.020	0.021	0.096	0.007	0.000	0.85	0.16	25.0
60-80	6.58	0.88	44	0.073	0.033	0.030	0.136	0.008	0.000	0.19	0.15	30.0
80-100	5.10	0.17	86	0.062	0.025	0.022	0.109	0.008	0.005	0.83	0.18	32.5

Estimating erosion using runoff lots

The mass of sediments removed in the runoff lot under evaluation during the rainy season was 11.54 kg in a surface of 12.5 m^2. When this was projected onto a surface of one hectare, it gave a mass of eroded soil of 9.2 Mg/ha. This value is less than that predicted by the universal erosion equation. However, it also exceeds the maximum value of tolerance to water erosion in the land under study, which is 6.7 Mg/ha (FAO 1977). For scientists such as Albuquerque (1993), this difference lies in the empirical simplicity of the calculation of the soil erosion with a runoff lot, but doesn't directly consider the coefficients of the potential erosion caused by the rain, nor soil erodability, nor those for soil use, management and conservation, which tend to sub evaluate actual erosion. However the method is useful in order to have an approximate idea of the degree of the erosion in a particular place. On the other hand, using the universal erosion equation is a more refined empirical reference point, since it predicts the rainfall based on soil texture, land slope, plant coverage, type of use, conservation management and practice, and the potential of erosion by rainfall in a region. In this regard, García and Durán (1998) point out that both methods are precise determinations of erosion on hillsides and high areas, yet they have the disadvantage of not quantifying erosion in a precise way in a basin because they do not include the factors of deposition and retransportation of sediments that take place downhill.

Table 3. Index values of the factor C soil use and management.

Type of plant coverage	C index value
Affected forest	0.001
Unaffected forest	0.34
Eroded lands with scarce vegetation	0.8
Bare soil	1.0
Extensive plantations in rows	0.5
Yucca and sweet potato (first year)	0.2-0.8
Palm tree, coffee, cacao	0.1-0.3
Grasslands	0.07
Vegetables	0.3

Estimating surface runoff

To better understand the erosion that takes place in the area of study, the surface runoff was calculated, since it is an indicator of the transportation of sediments based on the distance they cover from the point in which erosion is generated to the place of deposition. For this purpose, the equation proposed by the National Resources Conservation Service (Pilgrim and Cordery 1993) was used and is given below:

$$Q = \frac{C \cdot I \cdot A}{3.6} \dots\dots.. Ec\ (5)$$

where:

Q = surface runoff (m^3/s)

C = runoff coefficient (adimensional. Ranged from 0.1to 0.7).

I = intensity of rainfall (mm/h).

A = Surface of microbasin.

3.6 = Factor of conversion from hours to seconds.

Initially, the intensity of the rainfall was evaluated for the time of concentration of the microbasin and, for this, maximum daily rainfall was calculated based on the rainfall data for the rainiest days of the year for about 30 years, which was 280 mm (INEGI 2004). Next, the daily maximum intensity I_d, was calculated as follows:

$$I_d = \frac{Maximum\ daily\ rainfall}{24} = \frac{280\ mm}{24} = 11.66\ mm$$

After this, the maximum intensity was worked out for any interval t and for this we obtained the maximum daily rainfall and, using statistical analysis, the maximum average rainfall intensity in an hour, which gave 93 mm h^{-1}. According to this, the intensity in the rainiest hour of the area is 8 times higher than the average intensity of the day.

Using this data, we estimated the intensity for any interval of time (t), using the formula indicated by Salas and Fernández (2006):

$$I_t = I_d \left(\frac{I_1}{I_d}\right)^{3.5287-2.5287 \cdot t^{0.1}} \dots. Ec\ (6)$$

where:

I_t = Intensity of rain for any time interval.

I_d = Daily maximum intensity.

I_1 = Intensity in the rainiest hour.

t = time of concentration.

Table 4. Index values of the factor soil conservation practices.

Technique	Factor P
Level curves (slopes from 5 to 20%)	0.1-0.7
Antierosion bands from 2 to 4 m (slopes between 5 and 20%)	0.1-0.3
Protection with straw	
Terraces of 80 cm combined with level curves (slopes from 15 to 30%)	0.01
	0.1

Preliminarily, we took the time of concentration (t) or time taken for a drop that landed in the point with water farthest away from the riverbed to reach a given section of its slope. In this regard, the length of the riverbed in the microbasin was considered to be 10 km, the highest point was considered 200 m, the lowest was 55 m, the surface was 8 km^2, maximum rainfall in a day (P_d) was 280 mm and the threshold rainfall (P_o) was 56 mm. Substituting these data in equation 7 indicated by Pylgrim and Cordery (1993), gave the following results:

$$T_c = 0.3\left(\frac{L}{J^{\frac{1}{4}}}\right)^{0.76} \quad \ldots . Ec\ (7),$$

T_c: time of concentration (h).
L: length of riverbed= 10 km
J: average slope $\left(\frac{Maximum\ elevation - Minimum\ elevation}{L}\right)$
Then:

$$T_c = 0.3\left(\frac{10000}{(0.014)^{\frac{1}{4}}}\right)^{0.76} = 3.88\ h$$

Therefore T_c is 3.88 h. This information helped determine the intensity of the time of concentration in equation 6:

$$I_t = I_d\left(\frac{I_1}{I_d}\right)^{3.5287-2.5287 \cdot t^{0.1}}$$

Id = 11.66 mm/h
t = 3.88 h

$$\frac{I_1}{I_d} = 8$$

When substituting, we obtain the following:

$$I_t = 11.66(8)^{3.5287-2.5287\ (3.88)^{0.1}} = 43.47\ mm/h$$

For its part, the runoff coefficient calculation, namely the ratio between the flow rate of water flowing through a section of the basin as a result of rain, and the volume of water to precipitate thereon, was obtained by formula of USDA Soil Conservation Service (Arnold et al. 1998) as follows:

$C = \frac{(P_d - P_o)(P_d + 23 \cdot P_o)}{(P_d + 11 \cdot P_o)^2}$, where:
P_d = Maximum daily rainfall
P_o = Threshold rainfall.
Substituting:

$$C = \frac{(280-56)(280+23 \cdot 56)}{(280+11 \cdot 56)^2} = 0.43$$

Finally, the volume of runoff (Q) gives the following result:

$$Q = \frac{C \cdot I \cdot A}{3.6} = \frac{(0.43)(43.47\ mm/h)(8\ km^2)}{3.6} = 41.53\ m^3/s$$

This indicates that runoff in the microbasin studied, induces intense processes of water erosion. Indeed, considering the surface of the land (10 ha), the soil use systems in the experimental property, out of which 10% are natural fields (NF), 75% are grasslands (Gr) and 15% are cattle crop rotations (Ccr) and the transportation coefficient of 0.43, the gross erosion estimated is 2081.4 Mg/year, of which 895 Mg/year migrate and are deposited in the low plain of the microbasin or are transported to the ocean (Table 5).

For Clérici and Préchac (2001), and Sphor et al. (2003) this estimation procedure has been used successfully in the basins of the main courses and bodies of water in Argentina and Uruguay.

From a geochemical point of view, the migration of sediments induced by runoff water must be seen as the transportation of ions that make up the colloidal complex of the soil undergoing erosion. This is relevant given that the ionic migration involves the loss of soil fertility (Bertol et al. 2003). Table 2 shows the low concentration of soluble cations and anions in different soil thicknesses as a consequence of their removal and migration to the lower area of the microbasin by water erosion. In this context, scientists such as Szabolcs (1994) and Sánchez et al. (2012b) have pointed out the excess ionic mobility in the lixiviation water such as Na^{1+} and Cl^{-}. This is due to the chemical characteristics of each ion, such as their ionic energy coefficient, valence, ionic and hydration radius. Precisely Na^{1+} is considered one of the most mobile ions in nature (Kovda 1977, Velázquez et al. 2010). Basically, the results of the chemical analysis of sediments gathered in the runoff lot after the rainy season indicate a reconcentration of cations Ca^{2+} and Mg^{2+} and anions HCO_3^{-1}, Cl^{-1} and SO_4^{-2}, which shows the ionic transportation and accumulation in the lower areas of the microbasin. In this case, the ion Na^{1+} was not found in the sediments gathered, due to its excessive mobility in the runoff water (Table 6).

Erosion caused by agroforestry treatments in a system of terraces.

The erosion produced in each experimental terrace gave average results of 2.68, 2.74, and 2.70 kg of sediment removed for terraces in which Leucaena and Moringa trees were planted, along with a combination of plants belonging to both leguminous species, respectively. On the other hand, erosion in the control treatment was 11.54 kg in all cases in a surface of 12.5 m^2. The statistical analysis indicates a significant difference between the control treatment and the rest of the treatments. For example, there was a significant drop in the erosion of agroforestry terraces in comparison to the control, although there was no difference between the agroforestry treatments, implying that they were statistically equal. In general, the average erosion for the three treatments was 2.70 kg of soil eroded in 12.5 m^2, which, projected at a level of one hectare, gives an approximate erosion of 2.17 Mg/ha. After comparing this result with the erosion obtained in the control terrace projected to one ha (10 Mg) which had no vegetation, as well as with the actual erosion obtained using a universal equation which was 16.67 Mg/ha, we find that with the system of terracing, combined with the proposed agroforestry treatments, the transportation of particles by water erosion fell by 7.83 Mg/ha and 14.5 Mg/ha respectively, accounting for 78% and 87% of erosion control. These results coincide with those of Morgan (1997), Troeh and Donahue (1980) and those of Clérici and García (2001), who point out that setting up terraces with agroforestry systems reduce the sedimentary externalities by more than 50%. The reduction of erosion brings about a series of benefits caused by the establishment of terraces on steep slopes, such as: 1) the reduction of surface runoff, 2) the increase in infiltration and in amounts of humidity in the soil, 3) sediment retention, crucial for soil conservation, and 4) less washing away of nutrients that are necessary for soil fertility and, consequently, its productive potential. The effects of the leguminous species establishment is also worth pointing out, since these species create a pivotal root system during their growth, which allow sedimentary particles to settle and be contained in the patch. Furthermore, through their leaf canopy and the cushion formed by the continuous deposits of vegetable waste, the upper layer of soil is protected against the wind and rain (Petit 2005). They also promote the formation and fertilization of the soil due to the biological interaction of the roots with the microorganisms of the rhizosphere and the fixation of nitrogen, findings that correspond with Hudson (1982) and Parrota (1992) (Table 7).

Table 5. Estimations of the gross erosion and that which would migrate downstream in the current condition of the property named "Los Nanches".

Soil use	Gross erosion Mg/year	Migration and deposition of sediments downstream (Mg/year)	Proportion of erosion to the low plain.
NC	208.14	89.50	0.10
Pa	1561.05	671.25	0.75
A_{lr}	312.21	134.25	0.15
Total	2081.4	895	1.00

Note: NC: Natural condition; Pa: Pastureland; A_{lr}: Agriculture livestock rotation

Table 6. Electrolytic concentration of the sediment gathered after the rainy season, in a ratio of soil-water extraction1≈0.2-0.6

Soil sample	Parameters	Value	Units
	pH	6.8	-
	EC	3.30	dS/m
	DRC	1655	mg/L
	Anions		mEq/100 g of soil
	CO_3^{-2}	0.00	"
	HCO_3^{-1}	0.82	"
Sediment	Cl^{-1}	0.04	"
	SO_4^{-2}	0.14	"
	Total	1.00	"
	Cations		mEq/100 g of soil
	Ca^{2+}	0.48	"
	Mg^{2+}	0.18	"
	Na^{1+}	0.00	"
	K^{1+}	0.43	"
	Total	1.09	"

*EC = Electrical conductivity, DRE = Dry Residue Calcined.

In the case of the studied agroforestry treatments, both the *L. leucocephala* and the *M. oleifera* plants showed satisfactory growth in the nursery phase, despite presenting slight variations in their growth and development behavior due to their being species with different phenotypes and physiologies. After the transplant and during its adaptation to the terraces (30 to 120 days), the L. leucocephala plants adapted faster to the soil than the M. oleifera plants. This was reflected in their height increase during the first four months, which was slightly higher than in Moringa plants (Figure 2). It is important to point out that L. leucocephala is native to the area and therefore it is perfectly adapted to the dry conditions of semiarid and subhumid tropical climates (Petit 2005). After this period (120 to 180 days after the transplant) L. Leucecephala presented a slightly unsustained growth, due to the physiological stagnation the plant develops as a mechanism to tolerate water stress caused by the dry season (Parrota 1992). In this last period, the growth and development of *M. oleifera* plants was slightly higher than that of *L. leucoephala* plants in height as well as in diameter of the treetop and diameter at the neck, although there is no significant statistical difference between treatments for these growth variables. On average, the *L. leucocephala* plants reached a height of 1.35 m, 54.8 cm in the diameter of the top and

11.23 mm for the diameter of the neck, whereas *M. oleifera* plants reached a height of 1.47 m, 58.6 cm in the diameter of the top, and 18.3 mm in diameter for the neck. This coincides with results by Medina et al. (2007), who evaluated the initial growth of both leguminous plants in experimental fields and found no significant differences in plant height, number of branches, or growth rate. The results obtained have a strong relation with the short time period in which the growth of both leguminous plants was evaluated, since, due to their being shrubs, will tend to differentiate during their life cycle.

Table 7. Erosion caused by rain in the agroforestry treatments

Treatment	Surface	Average soil removal (kg)
Control A[1]	12.5 m^2	11.54
T_1 = Leucaena B[1*]	12.5 m^2	2.68
T_2 = Moringa B[1*]	12.5 m^2	2.74
T_3= Leucaena-Moringa B[1*]	12.5 m^2	2.70

A, B= Test of averages between agroforestry treatments for the variable of soil erosion (Pr >F = 0.0001). Note: averages with the same letter are not significantly different (*) Duncan statistical significance (0,05).

The Leucaena – Moringa relationship presented an intermediate behavior. In sum, the plantation of one or another leguminous species created a positive ecological interaction in the conservation of soils affected by erosion. This is based on the plant's capability to grow and establish themselves in uneven and rocky grounds in short time periods as well as its capability to adapt to adverse humidity and poor nutrient conditions in soils, characteristics which are very desirable in agroforestry systems used in the recovery of soils with steep slopes (Torquebiau 1993, Petit et al. 2005). Likewise, these soil-use practices tend to be sustainable since, along with the beneficial environmental impacts mentioned, it is possible, in a timely manner, to take advantage of its woody (which can be sold for firewood) and herbaceous components (nutritious leaves for cattle and humans). These are positive economic interactions that give undoubtable benefits for farmers' families in the region.

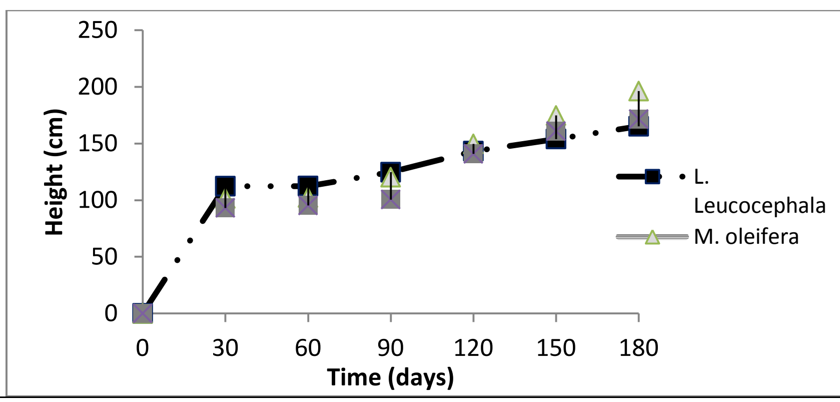

Fig. 2. Height of *L. leucocephala* (Lam.) de Wit and *M. oleífera* (Lam.) plants, and a relation of both during the initial growth in terraces. The bars indicate standard error and stars indicate significant difference with P = 0.05.

CONCLUSIONS

The rangelands of "Los Nanches" in the municipal area of San Pedro Mixtepec, Oaxaca, used as grasslands for extensive cattle-ranching, are affected by intense water erosion processes, as indicated by PE values (208.14 $\frac{Mg}{\square a}/year$) and AE values (16.67 $\frac{Mg}{\square a}/year$). These results were obtained using the Universal Soil Loss

Equation (USLE/RUSLE). Soil removal surpasses its threshold, which is why they are considered as having little tolerance to water erosion.

The systems of slash-and-burn and burning for clearing lands for planting, as well as overgrazing in the area upset and erode the forest lands intensely, with adverse effects on the environment, such as the loss of its physical and chemical properties, and its biological and productive potential. Consequently, such farming systems tend towards unsustainability.

The estimation of soil erosion with a runoff lot (9.2 $\frac{Mg}{ha}/year$) is less than that obtained in the AE of the soil loss equation. Although both evaluations clearly indicate the scale of the erosion caused by surface runoff that takes place in the rainy season in the area studied, was calculated to be 41.53 m^3/s.

The establishment of terraces related to the agroforestry technique of planting leguminous species *L. Leucocephala* (Lam.) de Wit and *Moringa Oleifera* (Lam.), produced an efficient control of water erosion by reducing sedimentary externalities by 87% for the rainy season analyzed. Consequently, it is considered a feasible agrotechnique to be transferred to cattle crop rotation farmers in San Pedro Mixtepec, Oaxaca.

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