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GREEN MANURE AS A SOIL FERTILITY AND ENVIRONMENTAL OPTION IN SEMIARID AGROSYSTEMS: MINERALIZATION RATE AND N CONTENT

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ABSTRACT

Green manures are an adequate alternative for improving the availability of nitrogen and phosphorus for crop nutrition, within a global context of decreasing soil fertility and the urgent need to care for the environment. Mixteca region, covers a wide area of central Mexico, characterized by a semi-arid climate, eroded calcareous soil, and rural poverty. With the aim of proposing technologies for improving soil quality and increasing the availability of nitrogen and phosphorus, an experiment was conducted using green manures: *Canavalia ensiformis*, *Dolichos lablab*, *Leucaena leucocephala* and *Avena strigosa* and *Phaseolus vulgaris*, that would ensure a balance between N and P release and the requirements of maize cultivation. The rate of enriched soil mineralization with green manures was determined through incubation, controlled for 15 days with CO_2 emissions using an OxiTop OC110® kit as an indicator of decomposition. CO_2 emissions were greatest in the soil established with *Leucaena leucocephala* and least in the soil with no fertilizer, with emissions descending in the following order: *Leucaena leucocephala* > *Canavalia ensiformis* > *Avena strigosa* +*Phaseolus vulgaris* > *Dolichos lablab* > soil without green manure. It is assumed that a greater flow of CO_2 is accompanied by greater mineralization and release of nutrients. The N_{total} in the soil treated with green manures was similar and greater than that of the soil without fertilizer. Soil treated with *Avena strigosa*+*Phaseolus vulgaris* contained the highest values of $N_{mineral}$ (N-ammonium + N-nitrate). P_{Olsen} content in soils with green manures was double that of the soil without fertilizer. Incubation provided the opportunity of identifying those green manures with higher agronomic potential in the area under study. The biomass comprising *Leucaena leucocephala* leaves and tender stems constitute an alternative for improving soil by providing OM. However, when considering the availability of N and P, the *Avena strigosa*+*Phaseolus vulgaris* combination is a superior alternative for meeting the needs of maize cultivation.

Keywords: P soil content, maize, *Leucaena leucocephala, Avena strigosa+Phaseolus vulgaris.*

INTRODUCTION

Agricultural soil in Mexico has high levels of degradation, particularly chemical degradation. This is due to unnecessary or irrational practices, such as the excessive use of agro-chemicals, over-exploitation, over-grazing and changes in land use (SEMARNAT, 2015a). It is well known that degradation is worse in arid and semi-arid zones, causing desertification (Garchinbyamba and Kang, 2013). Sixty three percent, or 125.3 million hectares, of the national territory suffers from desertification (report of the National Commission for Arid Areas in the Mexican Republic, SEMARNAT, 2015b).

Production of biomass is insufficient to provide the soil with organic material while simultaneously providing feed for livestock, with the latter being a priority for livestock producers. Foraging above its carrying capacity, together with compaction by livestock results in soil degradation. Generating management alternatives to repair this deteriorating condition is fundamental. Green manures, although under studied, offer the possibility of providing greater soil coverage and improving the physical, chemical and biological properties of soil, while also providing nutrients and limiting losses due to leaching or erosion. At the same time, green manures contribute to conserving soil humidity and, in some cases, are an economical alternative for rural producers who can sell these as forage (Florentín *et al*., 2011; Yang *et al*., 2012; Chen *et al*., 2019). The most commonly utilized plants for green manures belong to the families of Fabaceae, Poaceae, Cruciferae and Caryophyllaceae (Florentín *et al.*, 2011). Fabaceae species are particularly notable for their capacity to accumulate fixed N from the atmosphere in their biomass, which, on decomposing once incorporated into the soil (mineralization), releases nitrogen for crops (Couedale *et al.*, 2018).

The efficient management of an agrosystem through the use of green manures would mean a balance between the availability of nutrients released through mineralization and the requirements of the established crop (Ngetich *et al*., 2012). Adequate nutrition for plants would thus be ensured and losses of elements to the environment would be reduced (Brady and Weil, 2010; Hobley *et al.*, 2018). Thus, the planned introduction of green manures to agrosystems has the double function of providing the physical, chemical, and biological conditions for crop development and feed for animals, and thereby contributing to food sovereignty in regions with limited conditions, and at the same time, providing environmental services in terms of infiltration of quality water and C retention in the soil (Tribouillois *et al*., 2016).

Planned application is understood as that done in accordance with the particular conditions of the agrosystem and biogeoclimactic region and not as a hegemonic technology. For complete success in areas with limited conditions, such as in arid and semi-arid zones, understanding the process and impact of the use of green manures in the agrosystem and the environment is crucial. The objective of this study is to evaluate the potential of four Fabaceae species (*Canavalia ensiformis*, *Dolichos lablab*, *Leucaena leucocephala*, *Phaseolus vulgaris)* and one grass (*Avena strigosa*) as green manures, in order to propose a management system that balances the availability of N and P nutrients, products of mineralization, with the requirements of maize cultivation.

MATERIALS AND METHODS

This research forms part of a broader study to diagnose and propose agrosystem management by the *Grupo Cooperativo Qualy*, located in the municipality of Zapotitlan, state of Puebla, Mexico, who seeks to improve amaranth production under organic management. The challenging conditions, linked to production, were found to be the poor soil quality and lack of nutrients for the crops. Compost and manure, in addition to being limited, carry potential dangers, such as secondary salinization. It was thus decided to explore the potential use of green manures in the region and thereby create a proposal for managing self-sufficient crops in the area, such as maize. The green manures chosen were Fabaceae species: jack bean (*Canavalia ensiformis*) and *Dolichos lablab*, which are highly recommended for organic agriculture in semi-arid and arid areas; white lead tree (*Leucaena leucocephala*) for recovering nutrients in deep soil layers and producing forage throughout the year; and the common bean (*Phaseolus vulgaris*) as it is a local plant. As the latter's low production of biomass is unable to cover the ground, this was interspersed with black oat *(Avena strigosa)*.

Study site

The region has a semi-dry temperate climate (BS1k); it is considered an arid zone; evapotranspiration is greater than precipitation: in the last 40 years, it has had an average annual precipitation of 559 mm and 1.4 mm daily, with a daily average evaporation of 5.5 mm. The average temperature is above 20 °C (CNA and SMN, 2020). The dominant soils are leptosols (INEGI, 2005) and limestone ($CaCO_3$) forms the dominant bedrock: soils have a high pH, generally between 7.5 and 9 (Ruiz *et al.*, 1998). Seasonal agriculture on small land extentions (1 – 5 ha) predominates in the area, combining plant production with small-scale livestock farming; sheep manure is used as compost. The main crops for family consumption are maize, beans and wheat. Amaranth (*Amaranthus hypochondriacus*) is mainly used as an income generating crop together with others such as cacti, flowers and herbs.

Soil mineralization experiment

The mineralization experiment was conducted *in vitro.*

*Soil and green manure sampling***.** A soil sample was obtained comprising 11 subsamples collected in a 1500 m^2 plot that had been cultivated with amaranth in previous years and fertilized with sheep manure (10 Mg ha^{-1} per hectare with a density of 18,000 plants and 0.55 kg of manure per plant). Soil sample was taken in May, before the first sowing and 7 months after the last fertilization. Green manures were planted in the same area and collected for use in the incubation experiment (Table 1).

Mineralization experiment

An experiment involving controlled incubations of green manures incorporated into the soil (Sumner, 2000) was conducted with OxiTop OC110® equipment to measure CO_2 emissions, using the rate of decomposition (mineralization) as proxy. Treatments

Table 1. Green manure plants used in the mineralization experiment.

Plant species	Supplier	Previous information
Avena strigosa	Rafaela (local producer)	This is one of the most utilized species for green manure in the world. It favors the complete coverage of cultivated crops in combination with other plants. When planted, only 100 kg ha^{-1} of seed is used. Its combination with *Phaseolus vulgaris* has not been reported in the literature.
Canavalia ensiformes	Local ONG	This is one of the most broadly used Fabaceae specie in the world for green manure due to its high N contribution (up to 60 kg ha^{-1}). Its incorporation into the soil three months after planting when crops are flowering is recommended. A planting density of 54 kg ha^{-1} of seed is recommended.
Dolichos lablab	Local ONG	This Fabaceae specie tolerates drought and adapts well to semi-arid conditions. It yields up to 60 t ha^{-1} (fresh matter). Its incorporation into the soil as green fertilizer before flowering or up to 10 % of flowering is recommended.
Leucaena leucocephala	Local ONG	A Fabaceae specie tree that grows also as bush in hot and arid zones throughout the world, including Mexico. Its use as forage and green manure has been studied in various regions of the world (Bacab *et al.*, 2013). Yields of between 3 and 30 Mg ha^{-1} of dry material have been reported. IThe species grows in the Mixteca region.
Phaseolus vulgaris	Rafaela (local stakeholder)	This is a widely used Fabaceae specie in Mexico and other parts of the world as a source of protein for rural populations. It is used as a green manure given its rapid growth rate.

Local ONG: Alternativas y Procesos de Participación Social A.C.

consisted of incorporating the four different green manures: 1) *Canavalia ensiformis*, 2) *Dolichos lablab*, 3) *Leucaena leucocephala*, 4) *Avena strigosa* + *Phaseolus vulgaris* and a control treatment without green manure. Thirty grams of dry soil sifted at 2 mm were used from each treatment, placed in the 500 mL bottles of the OxiTop OC110® kit, and mixed with 3.8 g of wet green manure (0.85 g dry base) finely sectioned (< 3 mm diameter). In the case of *Canavalia ensiformis, Dolichos lablab* and *Avena strigosa+Phaseolus vulgaris*, the whole plant was used, including previously washed roots, while in the treatment of *Leucaena leucocephala*, only the aerial parts (leaves and tender stems) with a diameter of less than 3 mm were used. The mixture was brought to field capacity and homogenized. Each treatment was conducted in triplicate.

The OxiTop OC110® kit bottles were hermetically sealed and left to incubate at 25 °C for 15 days. This equipment is a manometric respirometer designed to determine biological oxygen demand. The equipment electronically measures oxygen consumption or oxygen pressure loss in a closed system. It has been tested in previous studies with residual waters, soil and forest mulch (Kalamdhad *et al.*, 2008; Jiménez de Santiago, 2012; Barrales-Brito *et al.*, 2014). When the microorganism respiratory processes use all available oxygen, respiration stops. It was thus necessary to conduct aerations on days 2, 5, 7, 10 and 14 to ensure the presence of O_2. Aeration returns partial oxygen pressure to atmospheric levels. The loss of oxygen pressure within the bottle is transformed into soil respiration (R expressed in g CO_2 kg^{-1}) according to the following formula:

$$R = \frac{MO_2}{RxT} \times \frac{Vfr}{MAv + s} \times |\Delta P|$$

MO_2= molecular weight of O_2 (31998 mg mol), R = universal gas constant (83.14 l bar cm^3 mol^{-1} K^{-1}), T= temperature in Kelvin, Vfr= volume of available air (l) $MAv+s$= mass of green manure and soil, $|\Delta P|$= change in pressure (hPa).

N, P and C determinations at the end of soil incubation

After 15 days of mineralization, the soil was dried at environment temperature and the following were determined: (i) organic material (Walkley-Black; Bremner and Jenkinson, 1960); (ii) total nitrogen (Kjeldahl, semi-micro, wet digestion with sulphuric acid); (iii) ammonium and nitrates (extracted with KCl (2N) and steam distillation with magnesium oxide and Devarda alloy); and (iv) phosphorous (extracted with $NaHCO_3$ 0.5 M pH 8.5 (P Olsen) and colorimetric determination using blue molybdenum complex (molybdic phosphoric with ascorbic acid; Olsen) (Bremner and Keeney, 1966).

Statistical analysis

Results of the respiration experiment of soil treated with green manures, the N_{total}, phosphorus, ammonium and nitrates were subjected to a one-way ANOVA. When the effect of the treatments was statistically significant, a test of homogeneity of variance was conducted (Tukey; p<0.05). Analyses were done with the R package (R Studio Team, 2015).

RESULTS AND DISCUSSION

Mineralization rates of green manures

The daily CO_2 flow patterns of the four soil treatments mixed with green manure show three stages: first, high respiration rates between days 1 and 3; second, a fall in respiration between days 4 and 5 to zero due to oxygen depletion. On day 5, the bottles were opened to allow oxygenation, and mineralization returned to elevated levels. This behavior is similar to what occurs in arid zones where a reservoir of highly mineralized organic material is created due to the lack of water, which quickly degrades when wet and increased with Fabaceae species use (Austin *et al.*, 2004; Zavala *et al.*, 2018). In the experiment, with the lack of oxygen, the OM showed a similar process, i.e. accelerated CO_2 emission in the 24 hours after oxygenation, followed by regularization. The results of the mineralization were considered valid, despite when the sample had no oxygen, given its similarity to the described real-life experience. The third stage occurred in days 8 – 15, which was a period with an intermediate rate of respiration (Figure 1).

In the first two stages (7 days), the four treatments with green manure behavior similarly, with more accelerated daily respiration rates than in previous days. During this period, 66.08 % of the total CO_2 registered in the 15 days was emitted. From day 7, differences were observed in the respiration rates of the treatments with green manure. The respiration of the control treatment (soil without green manure) was practically null for the 15 days (Figure 2). Soil biodegradation without the incorporation of green manure is slow as the limited organic matter in the soil corresponds to the organo-mineral or humic fraction, which is not readily available for microbiota as it is physically and chemically protected (Kemmit *et al.*, 2008; Marques Monroe *et al.*, 2021). This is corroborated by the poor chemical fertility of the soil in the study; the limited mineralization explains the poor availability of nutrients for plants. At the end of the incubation, the accumulated average respiration ($p<0.05$) of the treatments were ordered as follows: soil treated with *Leucaena leucocephala* > *Canavalia ensiformis* > *Avena strigosa+Phaseolus vulgaris* > *Dolichos lablab* > control soil. Treatments with green manure had a fast mineralization rate during the first 7 days, which was directly associated with the C:N ratio of the added material. Fabaceae green manures species mineralize faster than other plants such as Poaceae species or straw, a week after being incorporated when their C:N ratio falls in the range of 9 to 16 (Zavala-Sánchez *et al.*, 2018; Zhou *et al.*, 2020).

After 15 days of incubation, the soil with green manures in this experiment showed C:N ratios of between 9 and 11, less than that of the control soil (Table 2). This result

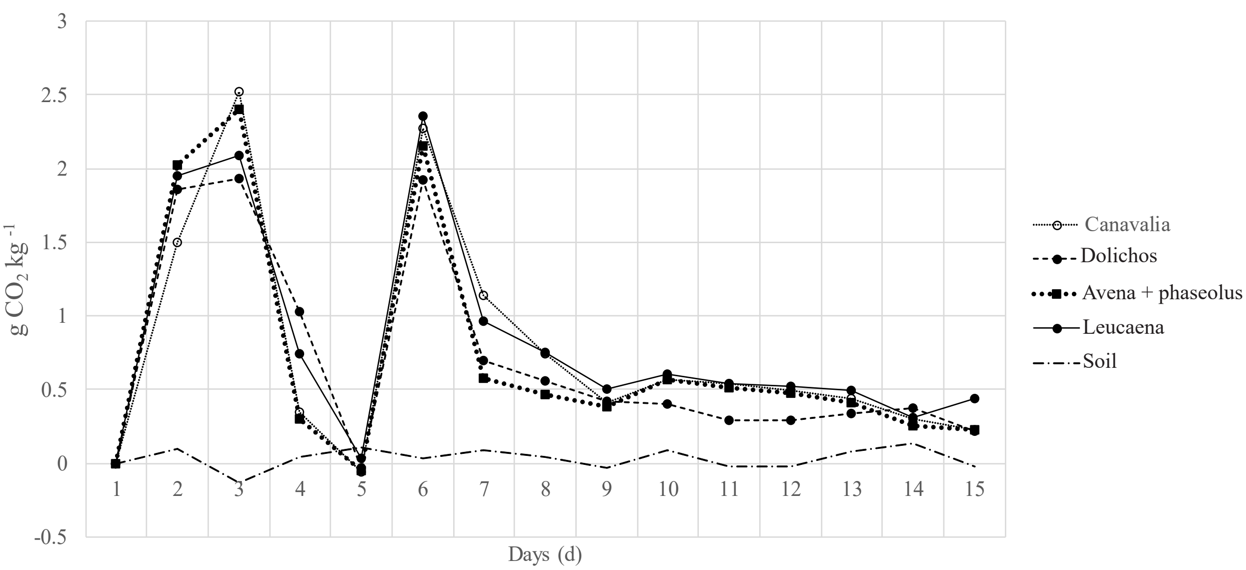

Figure 1. Daily CO_2 emissions in the mineralization laboratory experiment, as indicator of mineralization in the soil.

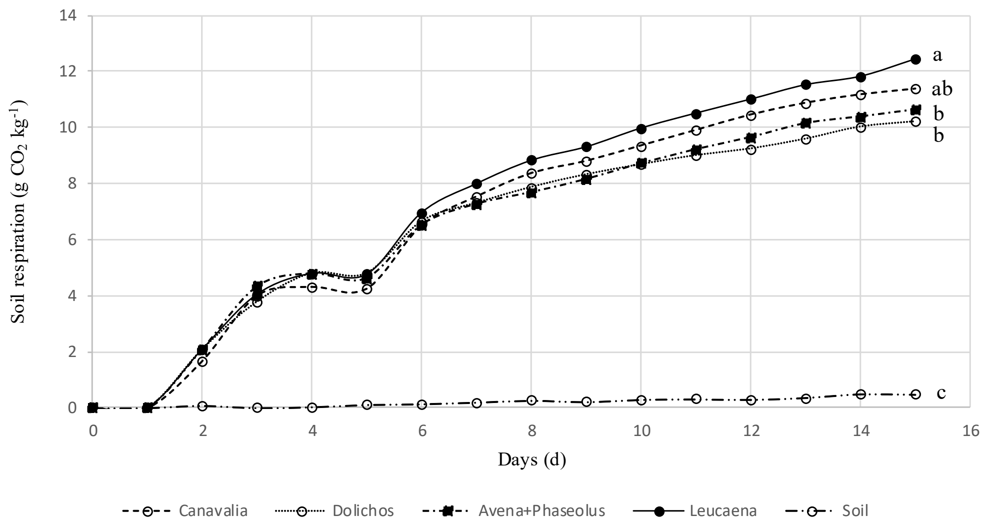

Figure 2. Cumulated respiration curves of treatments during 15 days of laboratory incubation. Different letters at 15th day indicate statistical differences among treatment means.

Table 2. Selected chemical properties (means ± standard error) for soil samples at the end of the mineralization experiment (n=3).

Variable	*Avena strigosa+Phaseolus vulgaris*	*Canavalia ensiformis*	*Dolichos lablab*	*Leucaena leucocephala*	Soil
SOM (g 100 g^{-1})	3.0 ± 0.30 b	2.8 ± 0.03 b	2.8 ± 0.14 b	3.9 ± 0.54 a	2.2 ± 0.09 b
N_{total} (g 100 g^{-1})	0.18 ± 0.004 a	0.17 ± 0.004 a	0.16 ± 0.005 a	0.19 ± 0.01 a	0.10 ± 0.013 b
$N_{ammonium}$ (mg kg^{-1})	25.5 ± 1.0 a	25.6 ± 2.6 a	25.6 ± 5.0 a	19.3 ± 1.1 a	22.4 ± 0.5 a
$N_{nitrate}$ (mg kg^{-1})	287.0 ± 19.6 a	266.0 ± 22.3 a	148.0 ± 6.8 b	19.3 ± 1.86 c	30.4 ± 5.6 c
P_{Olsen} (mg kg^{-1})	22.1 ± 3.32 a	25.0 ± 2.14 a	22.5 ± 3.33 a	15.0 ± 0.89 b	11.3 ± 1.06 b
C:N ratio	9.6 ± 0.58 b	9.5 ± 0.29 b	10.1 ± 0.52 b	11.7 ± 0.18 b	13.0 ± 1.99 a

SOM (soil organic matter), different letters (horizontal) indicate different mean groups (p<0.05)

is advantageous when compared with what occurs when manure and compost are added, which are more stable and require up to 300 days to release their nutrients (Brady and Weil, 2010; Rodriguez-Verde *et al.*, 2018). In this experiment, *Leucaena leucocephala* mineralized slightly but to a significantly greater degree than *Dolichos lablab* and *Avena strigosa+Phaseolus vulgaris*. Decomposition rates depend on the green manure, environmental conditions, but also on the activity of micro-organisms and enzymes (Elfstrand *et al.*, 2007; Masunga *et al.*, 2016).

Organic matter and soil nutrient supply by green manure treatments

After 15 days, the incubated soil that had been fertilized with *Leucaena leucocephala* had the highest content of organic material (Table 2). The organic composition of this green manure had less lability than the other three treatments tested due to the incorporation of woody parts (which was not done in the other green manures). *Leucaena leucocephala* leaves have a 4.4 % N content with a C:N ratio=11, reflected in its greater mineralization in comparison to the other green manures used, while the branches contain 2.6 % N and the C:N ratio is greater than 19. *Leucaena leucocephala* is an option for increasing the organic matter content in soils in arid and semi-arid zones with a view to conservation and resilience of soil properties, immobilization of N and C, can translate into an increase in the formation of new soil aggregates whose stability favors the water retention capacity and water retention (Ayangbenro and Babalola, 2021).

Differences in N_{total} content in the soils treated with green manure were not significant, however all had a greater proportion than the soil without fertilizer (Table 2). Consequently, the N_{total} is not a useful variable in deciding which green manure to use when aiming to improve the chemical fertility of the soil to produce maize and other crops in the region. The difference in $N\text{-}NH_4$ content was also not significant between the various treatments with green manure (Table 2). However, differences between the treatments in $N\text{-}NO_3$ levels in the soil after 15 days of incubation were significant (Table 2). Soil treated with *Canavalia ensiformis* and *Avena strigosa+Phaseolus vulgaris* had a greater $N\text{-}NO_3$ content than those treated with *Dolichos lablab*, and these three all had higher concentrations than *Leucaena leucocephala* and the soil without green manure. The latter two were statistically equal.

To calculate the N_{total} and $N_{mineral}$ contribution of the green manures to the soil, the value of the soil without added fertilizer was subtracted. The *Avena strigosa+Phaseolus vulgaris* mix provided the second highest quantity of N_{total} and the highest quantity of $N_{mineral}$ after 15 days of incubation, while the *Canavalia ensiformis* was located in third position in terms of quantity of N_{total} and second in inorganic N. *Dolichos lablab* contributed the least amount of N_{total} and was third in terms of inorganic N. Based on these results, it was concluded that *Avena strigosa+Phaseolus vulgaris* and *Canavalia ensiformis* contribute more inorganic nitrogen, quickly available for plants (15 days of incubation) than *Dolichos lablab* and *Leucaena leucocephala*. The latter provided the lowest amounts of nitrates (Table 2). As a result, it can be stated that *Avena strigosa+Phaseolus vulgaris* and *Canavalia ensiformis* respond to immediate crop N needs, while *Leucaena leucocephala* can be recommended as a source of gradually released N that is active for a longer period in comparison with the other experimental treatments. In addition, *Leucaena leucocephala* provides a greater SOM contribution than the others, reducing soil fertility loss and contributing to C capture in the field of ecosystem services (Srinivasarao *et al*., 2013; Ayangbenro and Babalola, 2021).

The quantity of phosphorus in the soil following the incubation period was significantly greater in the treatments with *Avena strigosa+Phaseolus vulgaris, Dolichos lablab* and *Canavalia ensiformis* than those with *Leucaena leucocephala* and soil without green manure ($\varrho<0.05$; Table 2). The proportion of P_{Olsen} in the soil without green manure was 11 mg kg^{-1}, which is considered low in soil fertility terms (Horta and Torrent, 2007). Soils incubated with green manures had double the P content in comparison to the soil without added green manure (Table 2). Another advantage of incorporating organic amendments, including green manures, into calcareous soils is that they lower the pH (8.5 in the soil under study) of the soil, thereby ensuring greater P availability for plants (Zhang *et al.*, 2022).

One of the traditional management options for maize cultivation in the area under study, when the use of synthetic fertilizer is either unwanted or unavailable, consists of applying 10 to 15 t ha^{-1} of sheep manure 25 days after seeding. Sheep manure with non-intensive feeding schemes, similar to those in the Mixteca, have an elevated C:N ratio, resulting in N immobilization. It has been shown that in the first 85 days after application, the low mineralization does not satisfy the N demand of maize (Azeez and Van Averbeke, 2010; Zarabi and Jalali, 2013; Li and Li, 2014) (Figure 3A).

Based on our study, an alternative is proposed that responds to the fertility requirements of maize production systems associated with livestock breeding in the Mixteca region. This consists of combining the use of green manures with the application of sheep manure (15 t ha^{-1}) to meet crop N needs. It is suggested that the sheep manure be applied at the ending of January, that is, 4 months before sowing the maize (beginning of June), incorporating it into the soil at a depth of between 5 and 10 cm, using disking.

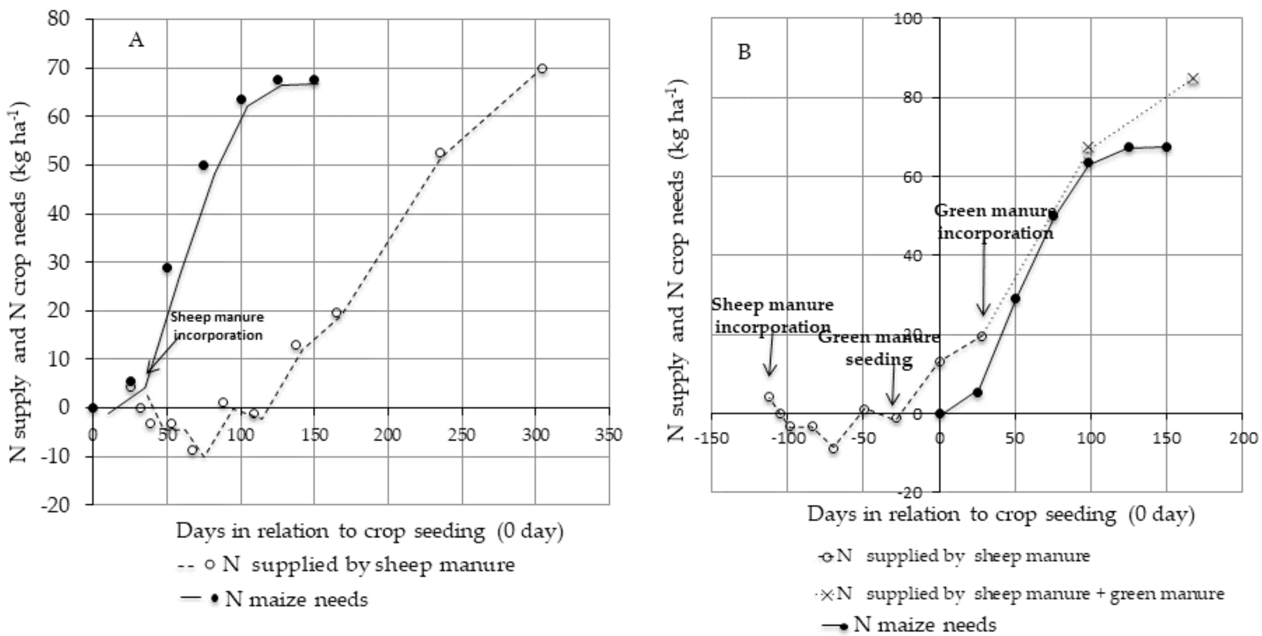

Figure 3. Simulated scenario of N supply from decomposition of sheep and green manure in relation to N maize crop needs. A) N supplied by sheep manure mineralization in relation to the N needs of maize; the sheep manure is applied 25 days after seeding as occurs in the semi-arid region (Tehuacan Valley, Puebla). B) The N is supplied by the combination of sheep manure applied 120 days before seeding and *Phaseolus vulgaris+Avena strigosa* green manure, incorporated 30 days after seeding, contributing to meet all the N needs of maize. Curve of sheep manure mineralization corresponds to Zarabi & Jalali (2013). Maize curve needs were calculated from Volke et.al, 1998 (yield 3 t ha^{-1}, native maize, Mixteca Region).

Three months after the application of manure, at the ending of the month of April, the *Phaseolus vulgaris+Avena strigosa* green manure should be sowed. In the experiment, this manure contributed the greatest quantity of $N_{mineral}$ to the soil (Table 2).

The proposed seeding density was 27 kg ha^{-1} *Phaseolus vulgaris* seed and 60 *Avena strigosa,* in 70 cm wide strips with 4 rows of oats and 2 rows of beans and leaving 30 cm spaces between each of the strips for the maize. In the Mixteca region, beans flower within a period of between 6 to 8 weeks after sowing; grow with the first rains of the year; and develop well with the N provided by the manure 85 days after its incorporation.

At the beginning of June, when the rains are more frequent (Figure 4), maize is established in the spaces left for this purpose, and thus the three species grow simultaneously. At the end of June, when the green manure reaches a height of between 20 and 30 cm, it is incorporated into the soil during the first weeding / hilling of the maize. At this point, the mineralization of the green manures will provide additional N to that of the sheep manure, which, at this stage, would have been incorporated for more than 145 days. In this way, the period of greatest N demand by the maize crop occurs simultaneously with the moment of greatest availability of mineralized N from both the sheep manure and the green manure (Fig 3B). This scenario depends on normal rain conditions in the area (Figure 4) and assumes that there is enough moisture in the soil for mineralization by the microbiota. It is important to mention that the microorganisms in semi-arid zone have developed biochemical, molecular and physiological mechanisms to adapt to abiotic and biotic stresses through assemblies in the rhizosphere that facilitate the availability of nutrients for plants. These assemblies act by promoting root growth and thus increase the absorption capacity of water and nutrients. These microorganisms also stimulate the production of plant hormones

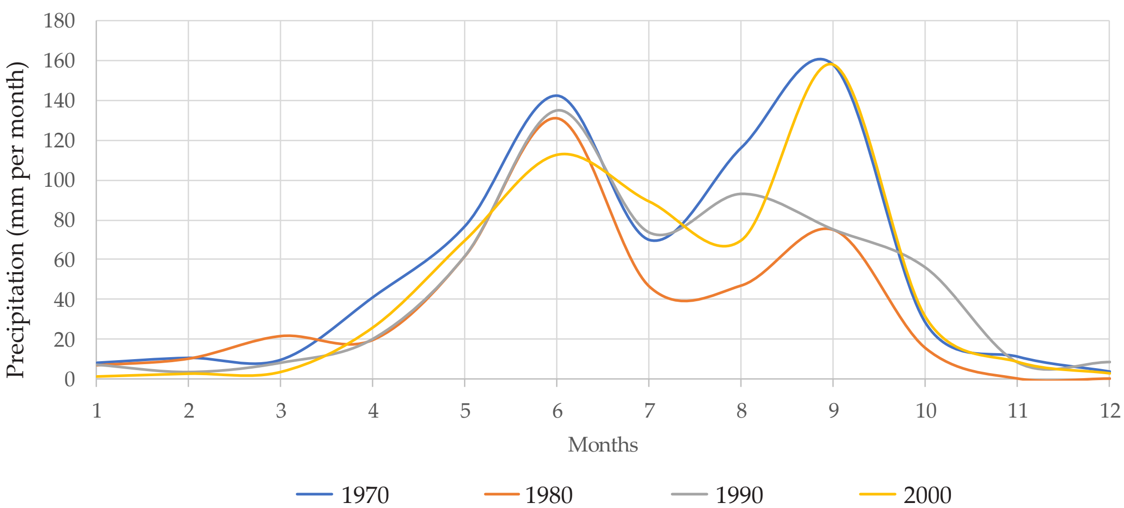

Figure 4. Average precipitation per decade, CNA weather station 21002, Acatepec (Caltepec, Puebla 18° 13’ 40” N, 097° 34’ 41” W)

and other compounds that reduce ethylene levels in plants, improving tolerance to water stress conditions. The mechanisms of action of these microorganisms in the rhizosphere contribute to carbon sequestration, N fixation and nutrient solubilization (Ayangbenro and Babalola, 2021).

Another option is to delay the planting of maize in order to synchronize it with the moment of greatest mineralization of the sheep manure and thus dispense with the green manure. However, this is risky if there is insufficient seasonal rain towards the end of the year, or early frosts in the higher zones. Furthermore, late planting of maize increases N loss, especially in the first 25 days after sowing, when N needs may still be low with respect to N mineralization from the manure in this period of the year. Using green manures facilitates the use of N from the manure at the beginning of the mineralization phase, to later be reintegrated into the soil with a more accelerated mineralization due to the lower C:N ratio of the green manure (Masunga *et al.*, 2016). In this way N availability in the soil is increased, provided by both sheep manure as well as green manure, during the period of greatest N demand of maize, without needing to increase the dose of manure. The use of this type of green manure interspersed with the maize crop, may contribute to the suppression of certain weeds in the first month of maize growth, as well as to the diversification of sources of N supply to the soil, through biological fixing carried out in beans one month after sowing. It is important to consider incorporating green manures to reduce losses to the atmosphere due to early mineralization (Florentín *et al.*, 2011; Masunga *et al.*, 2016).

The present investigation provided results of the mineralization rates of a selection of plant species (*Phaseolus vulgaris+Avena strigosa*, *Canavalia ensiformis*, *Dolichos lablab and Leucaena leucocephala*) with the potential to be used in rainfed agriculture in the maize production system (maize as staple crop and amaranth as cash crop) in the semi-arid region of the Mixteca (Mexico), in order to increase the amount of nutrients (N, P) available for these crops. In addition to the short-term contributions of N and P, the long-term objective that can be covered with the introduction of these green manures is the increase of organic matter in the soil, which requires long terms (several decades) and it supposes the care on the part of the producers of the growth and development of plant species adapted to each region at the plot level (Hobley *et al*., 2018).

In subsequent studies, N contributions should be tested in the field in synchronization with the needs of the crops of interest (corn and amaranth, for example) as well as the contribution of organic C to the soil of the species analyzed in this research. The alternative proposed in the present investigation of combining the contributions of N and P from sheep manure synchronized with the contributions of green manure should be tested in the field in further investigations. It is known that the dynamics of mineralization under field conditions can present large variations with respect to experimentation under controlled soil moisture and temperature conditions (Masunga *et al.*, 2016).

In the scenario of longer droughts that are already occurring due to climate change, the use of green manures emerges as a valuable alternative against desertification

(Ayangbenro and Babalola, 2021). Also, in the current context of rising prices of fertilizers of industrial origin, the research on green manures will take on greater relevance, (Masunga *et al*., 2016)

CONCLUSIONS

Of the four green manures used in the mineralization experiment, *Leucaena* offered the greatest added value in terms of CO_2 flow at the end of the 15 days trial. When considering $N_{mineral}$ (ammonium+nitrates), *Avena strigosa*+*Phaseolus vulgaris* and *Canavalia ensiformis* were the most promising green manure treatments (with 287 and 266 mg kg^{-1} of $N_{mineral}$ contributed, respectively). Regarding phosphorus contribution (Olsen), the four green manures almost doubled the reference content of the soil without organic contributions (ranging between 15-25 mg kg^{-1}). Taking the results of $N_{mineral}$ contributions in their totality, better fertility management of maize production systems can be achieved by combining sheep manure (15 t ha^{-1} dry base) and *Avena strigosa*+*Phaseolus vulgaris* to meet the needs of maize crops. The results of this investigation demonstrate the usefulness of the short-term controlled incubation method in selecting plant species with the potential to be used as green manures.

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