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Lupines-Invaded Pine Forest and Cultivated Scrublands in Volcanic Ash Soils in Mexico: Dry-Sieved Aggregation and Instability Indices

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Abstract: A field study was conducted to investigate the effectiveness of wild lupines invasions and planted pastures on improvement of soil structural aggregation and to determine the macroaggregate instability indices for environmental impact assessment on the sustainability of traditional cropping management practices. Dry aggregate size distribution (ASD), macroaggregate instability indices (CoES), soil-water retention (SWR), total organic carbon (TOC), soil pH and particle size distribution were determined from air-dried soil under the long-term intensive cultivations (CA), natural oak forest (VN), lupines invaded disturbed pine forest (BL), planted pastures (PP), lupines invaded meadows (PL), lupines invaded fallows (SDL) and freshly-tilled lupines invaded fallows obtained by converting SDL to CA (BRDL). The higher moderate-acid pH and total clay content increased with depth, except for the SDL soils. The lowest amount of microaggregates (MicAg) at 0-20 cm depth was observed for the SDL soils than for the VN and BL soils. The small macroaggregation (SmMag) was the highest for the CA and VN soils at 20-40 cm depth, but the lowest for the SDL and PL soils at 0-20 cm depth. The VN soils caused higher medium macroaggregation (MeMag) at 0-20 cm depth as compared to the BL soils. The large macroaggregation (LaMag) was the highest for the BRDL soils at both depths and for the CA soils at 0-20 cm depths while was the lowest for the BL soils at both depths. The macroaggregate instability (CoES) indices for the TMag, SmMag and MeMag size classes were the lowest for the SDL soils and for the LaMag for the PL soils at 0-20 cm depth, while were the lowest for all the macroaggregate size classes for the VN soils at 20-40 cm depth, but were the highest for all microaggregate size classes for the BL soils at both depths. The linear regression analysis indicated strong negative association between CoES, pH and total clay content, but a positive relationship was observed between CoES and TOC. High yielding grain lupines genotypes could be considered for future inclusion in the cropping management practices to improve the physical soil fertility and socio-economic sustainability of the traditional farming systems.

Key words: Dry macroaggregation, macroaggregate instability indices, sustainable environmental assessment, volcanic ash soils

INTRODUCTION

Volcanic soils (Andisols) are among the most productive soils for agriculture and forestry in the world (Ugolini and Dahlgren, 2002). The pyroclastic volcanic ash materials are progressively transformed by climate in conjunction with the vegetation and time of exposure to weathering processes. Andisols are typically dominated by varying amounts of noncrystalline inorganic clay-size materials depending on diverse weathering environments of both humid temperate and tropical climates, mainly with grass vegetation and is altered to other soil orders with aging and degree of weathering (Ugolini and Dahlgren, 2002). Changes in landuse management practices lead to the variation in organic matter content which contribute to differences in soil pH and allophane content (Huygens *et al*., 2005). With high organic C-content and enhanced acidification by organic acids in A-horizons, the amount of allophane-imogolite was decreased because, humus preferentially complexes exchangeable Al

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to form Al/Fe-humus complexes and the soil pH varied with soil depth from 4.9 to 6.2 under *Miscanthus sinensis* grassland and from 5.6 to 6.0 for *Fagus crenata* forest (Ugolini and Dahlgren, 2002). Raising soil pH to neutral values in the range 6.1 to 7.3, would significantly cause the hydrated [$Fe/Al(OH)^{2+}$] oxides to precipitate and their removal increase the amount of negative charges on the surfaces of crystalline silicates (2:1-type) minerals and humus on which they are always found as coatings that block exchange sites (Brady and Weil, 1999). The soils dominated by 1: 1 kaolinite and oxide clays rapidly formed high amounts of unstable macroaggregates through electostatic interactions at low organic matter levels, while the soils dominated by 2: 1 type clays slowly formed more stable macroaggregates at high organic matter levels (Denef *et al*., 2002).

In Trans-Méxican Volcanic Belt (TMVB) region of central Mexico, the forested highland Andisols extend beyond 2500 m altitude and are progressively being subjected to rain-fed cultivated agriculture for fodder and cereal crop production, to an extent that the natural black oak forests vegetation is limited to ravines (Campos-Cascaredo *et al*., 2001). The Federal Forestlands Reserves Stewardship Council (FFRSC) has approved traditional farming systems that are monitored through the local administration of Ecological Commissions for lands allocation and certification of conservation compliance (Pulido and Bocco, 2003). The land use at altitudes between 2750 and 2920 m is for Traditional Cultivated Management-systems (TCM) and between 2920-3300 m is for Community Forestry Management (CFM), that involves the long and short-term fallow-crop rotational management practices (Pulido and Bocco, 2003). These land use systems and their respective cropping management practices have been summarized in this study (Table 1). The short and long-term fallow-rotational cropping management practices in TCM landuse are established with scrublands vegetation that increases organic matter content in the soil; But are often negatively perceived as abandonment of cultivated rain-fed agricultural lands due to low soil productivity (López *et al*., 2006). No drastic emigration patterns have been observed when converting scrublands fallows to avocado orchards, because of new variety of economic opportunities that provided relatively higher peasants family incomes (López *et al*., 2006). Perhaps this abandonment of TCM landuse provides strong evidence

Table 1: Representative traditional farming systems in the trans-Mexican volcanic belt (TMVB) chosen from the two land use systems

Altitude (m a.s.l.)	Land use systems	Land management areas	Plants or tillage sequences	Sampling code/Cropping management practices	Slope/Position/Area studied
2920-3200	Community Forestry Management (CFM)	Natural pine forest+dense herbaceous pasture and shrubs	Diverse *Pinus* sp. forest vegetation+*Muhlenbergia* sp.	NPF (natural pine forest)	15-30%/summit/not determined
		Pinus+*Lupinus uncinatus* invaded open field of disturbed pine forest	Clearing of forest litterfall for fire control+adapted *Pinus* sp.+*Muhlenbergia* sp.+cattle razing+wood logging	BL (lupines invaded disturbed pine forest)	8-20%/summit/0.26 ha
		Relict *Quercus* sp. on buffer strips and ravines	Cattle grazing+wood logging+*Abies religiosa*	VN (relict oak forest, reference soil)	8-20%/upper backslope/0.13 ha
2765-2920	Traditional Cultivated Management (TCM)	Short-term (14 months) fallows alternating with maize/beans intercrop production (milpa)	Furrow-dikes+direct sowing-forage crops: *Avena sativa* and *Brassica napus* fallows	FF (forage fallows)	Not determined
			Disk-plow+furrow-dikes+sowing maize/faba of 2 plant tufts+hilling+weeding cultivation+harvesting	CA (intensive cultivations)	8-15%/upper backslope/0.49 ha
		Long-term (4-12 years) scrubland fallows or subtropical deciduous shrubs	Fallows+>11 years weedy *Lupinus uncinatus* invasion	SDL (lupines invaded fallows)	8-15%/upper backslope/0.21 ha
			Fallows+>11 years weedy *Lupinus uncinatus* invasion+freshly tilled	BRDL (freshly-tilled lupines invaded fallows)	8-15%/upper backslope/0.42 ha
			fallows+>11 years tall oats grass pastures+weedy *Lupinus uncinatus* invasion	PL (lupines invaded meadows)	8-15%/middle backslope/0.67 ha
			Fallows+>11 years pure tall oats grass pastures	PP (pure meadows)	8-15%/middle backslope/0.34 ha

that unsustainable physical and chemical soil environments resulted in major decline in economic crop yields (Pulido and Bocco, 2003; Lopez *et al*., 2006) and in soil fertility as a consequence of topsoil erosion and desertification (Solleiro-Rebolledo *et al*., 2002). The latter indicates that TCMs practices have promoted the deterioration in soil quality which could be manifested as accelerated degradation of soil structure, mostly concerning low aggregates stability, hydraulic conductivity, or structural biopore space.

The wild *Lupinus* sp. invasion is a common phenomenon in scrublands fallows with low soil fertility, less productive rain-fed farmlands or degraded forest in the highlands volcanic-ash soils of the TMVB region (Medina-Garcia *et al*., 2000). Clearly, a need to evaluate the impact of these leguminous invaders in different cropping management phases within the TCM and CFM landuse systems is warranted by the necessity to guide the formulation of better cropping systems with suitable plant genotypes of higher economic value, as well as to improve soil structural aggregation for the long-term sustainable productivity. Certainly, the wild lupines invasion in scrublands reflects a satisfactory suitability for introducing improved florally-determinate lupines genotypes in several temperate regions of the world (Robson *et al*., 2002). In this study, it was hypothesized that the influence of wild perennial lupines root growth functions and physiology improve soil structural aggregation of volcanic soils in the forest and cultivated ecosystems. The objectives in this study were to assess the development of structural aggregation for different phases of the CFM and TCM with and without wild lupines invasion along a topographical biosequence of pine and oak forest ecosystems and to determine the macroaggregates instability indices for assessing environmental sustainability of lupines invaded cropping management practices in San Pablo Ixayoc, Texcoco, the State of Mexico, Mexico.

MATERIALS AND METHODS

Site, climate and soil description: The study was conducted in the Trans-Mexican Volcanic Belt (TMVB) region (Fig. 1) and geographically situated between 19°27′15′′ N and 19°25′51′′ N latitudes and between 98° 47′10′′ W and 98°42′43′′ W longitudes (Fig. 2) on the eastern side of the Central Valley of Mexico, about 25 km along a country gravel-road Texcoco-San Pablo Ixayoc, in the State of Mexico, Mexico.

The semi-cool temperate climate is characterized by mean annual summer rainfall (MAR) ranging from 620 to 770 mm occurs between June and September with mean monthly amounts varying from 30 to 75 mm and the early-morning daily fog and dew fall provides a substantial amount of humidity above the 2750 m altitude. The mean annual temperature (MAT) ranges from 12-18°C with a mean minimum (T-min) of 4°C in November

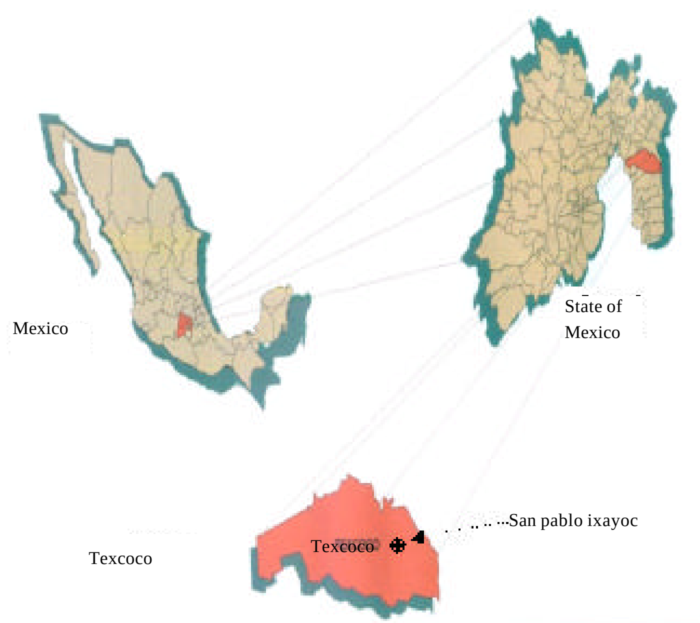

Fig. 1: Location of the study area in San Pablo Ixayoc, Texcoco, México

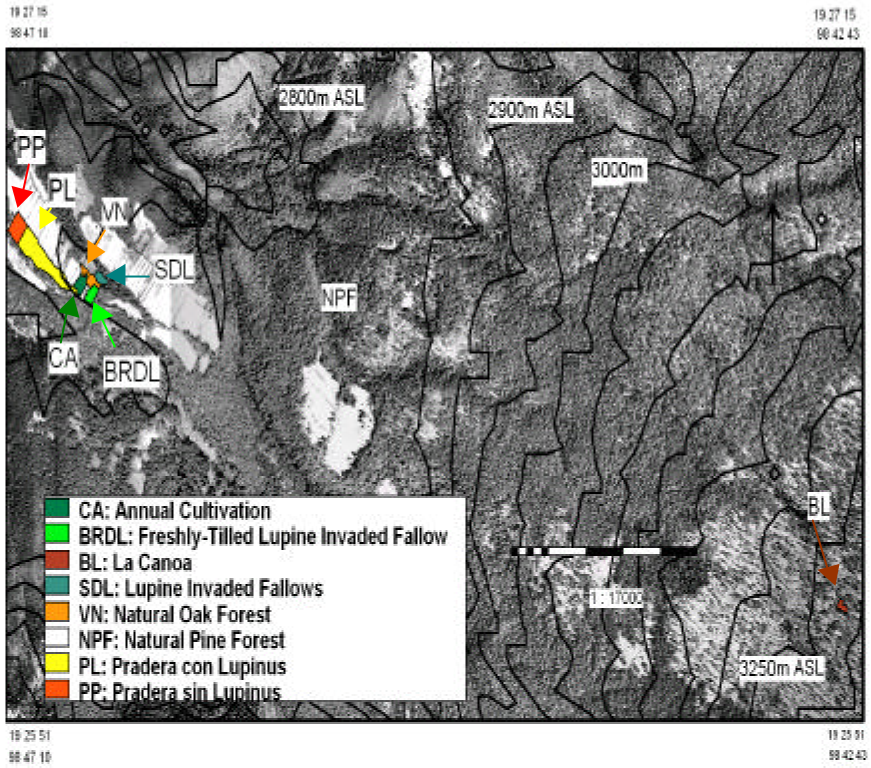

Fig. 2: Cropping management practices since 1994 within the two major Traditional Farming Systems in San Pablo Ixayoc México (Source Author, 2007)

and mean maximum (T-max) of 23°C in July on the north western Rio Frio mountain range that includes the Tlaloc volcano.

The volcanic ash soil of Tlaloc volcanic soil series on the north western shoulder slopes of Tlaloc volcano could be grouped into altitudes from 2750 to 2920 m and from 2920 to 3300 m, according to the land use systems adapted to the initially identical and homogeneous volcanic ash soils (Pulido and Bocco, 2003). Gutiérrez-Castorena *et al.* (2007) have classified the Tlaloc volcano soil series as Haplic Andosols, according to the FAO-ISRIC-ISSS (1998) taxonomic procedures and observed that these soil series presented the 2: 1 smectite clays at 0-7 cm soil depth in A-horizons, a mixed clay mineral soil having 1: 1-kaolinite and 2: 1-smectite clays at 7-40 cm soil depth in Bw-horizons, whereas the 2: 1-smectite were mixed with 1: 1-halloysite which replaced kaolinite at 40/60/90/115 cm depths in 2ABb-horizons, with a uniform distribution of anorthite, silica (as cristobalite) and iron-hydroxides (as ferrihydrite) in different amounts, which indicates abundant source of Al, Si and Fe oxides. The underlying red tepetates (Luvisols) were formed by Fe-enriched Si-indurations in the 2Bs-horizons at 90/115-120 cm depths and 2Bt-2Crt-horizons below 120-150 cm depths and were characterized by a calcareous paleosolic illuvial fragipan consisting of mixed clay minerals of halloysite, metahalloysite and large amounts of 2:1-smectite (Gutiérrez-Castorena *et al*., 2007). These morphological features were used to guide the choice of soil depths for the present study.

Land use systems, cropping management practices and sampling

Landuse systems: In Mexico, the higher mountain forestlands are dominated by natural *Pinus* sp. and *Quercus* sp. and are under the jurisdiction of the FFRSC. The administration of communal (ejidatorial) land tenure allocation policy through local ecological landuse commissions or agencies, is based on compliance to technical principles of landuse management and training for implementation of approved management practices. On the northwestern shoulder of Tlaloc volcano, two land use systems are operated at two contiguous slope positions, namely: (i) Community Forest Management (CFM) in La Canoa, at the 2920-3300 m altitudes, dominated by pine forest (*Pinus* sp.) and (ii) Traditional rain-fed Cultivated-agriculture Management (TCM) in La

Era, at the 2750-2920 m altitudes, dominated by natural black oak forest (*Quercus* sp.) in marginal buffer strips and ravines, respectively (Fig. 2). A participatory field approach using questionnaires was carried out to identify the cropping management practices and was complemented by semi-detailed topographic maps and aerial photographs to determine the cropping management history in the study area (Fig. 2), as summarized in Table 1.

Cropping management practices: The CFM and TCM land uses were opened for communal lands allocation tierras ejidatoriales since ~1970 in the forest ecosystem consisting of *Pinus montezumae*, *P. leyophyla*, *P. michoacana* and *Alnus* sp. trees (Piludo and Bocco, 2003). The impact of soil disturbance through forest clearing (e.g., cutting and burning) and extensive summer cattle grazing with subsequent degradation of vegetation and soil properties was evident in open wood fields.

The CFM Landuse in La Canoa, at 2920-3300 m altitude consists of:

- Dense patches of wild lupines (*Lupinus uncinatus* Schldl) invasions in disturbed pine forest plantations, designated as lupines invaded disturbed pine forest (BL).

The TCM land uses in La Era catchment area between 2750 m-2920 m altitudes consist of:

- Relicts of natural vegetation consisting of black oak forest *Quercus* sp. and *Abies religiosa* on the buffer strips were considered as a reference soil (VN) (Fig. 2).
- Annual intensive cultivations (CA) are major soil disturbance (Fig. 2) characterized by intercropped grain maize (*Zea mays*) with faba beans (*Vicia faba*), which may alternate short-term fallow cycles of 14 months or año y vez under minimum-tilled winter forage cover oats (*Avena sativa* L.) or canola (*Brassica napus* L.).
- Scrublands cropping management practices were characterized as long-term fallows abandoned cycles of 4 to 12 years, even up to or over 25 years with the emigrant peasants (López *et al*., 2006) and were intended for compliance with the ecological conservation policy to accumulate soil organic carbon (TOC) for improving soil fertility and rehabilitating biological processes that promote formation of soil structural pores and aggregates under the *ejidatorial*-land uses (Pulido and Bocco, 2003). Scrubland management practices that were encountered could be summarized in Table 1 as:

- Planted pastures of tall oatsgrass (PP)
- Lupines invaded meadows of tall oatsgrass (PL)
- Weedy lupines invaded fallows on cultivated farms (SDL)
- Converting lupines invaded fallows (SDL) to intensive cultivations (CA) using tractor crater+disk-ploughing was designated as, freshly-tilled lupines invaded fallows (BRDL)

Sampling: The sampling plot units within every cropping management practice were selected from the lupines invaded patches with the high plant population density. Three sampling plot units (16×20 m surface area) were selected as pseudo-replicates within each of the seven cropping management practices (Fig. 2). Sampling was carried out at 2 rooting depths (0-20 and 20-40 cm) for two randomly selected target plants chosen at vegetative and flowering growth stages within each sampling plot unit and were considered as the main factors; Thus, a total of 84 samples were taken for analysis. However, the plant growth stages were later treated as replicates since no significant differences were found, which confirmed that plant growth stage could not be an easily controlled physiological parameter under ecological field conditions for the stolon root sprouting wild perennial lupines. Therefore, the plant growth stage data were treated as replicates for their corresponding sampling depths. All samples were collected during both wet and dry seasons for each of the seven cropping management systems and were air-dried under shade in the warehouse. The time of sampling could not show any detectable differences in the preliminary statistical analysis, which indicated that air-drying of the soil samples has helped to standardize the potential variations that might be caused by initial field-soil water content (Kemper and Rosenau, 1986).

Chemical and physical analysis: Total soil organic carbon (TOC) was determined by Walkley-Black method and titration with Fe_2SO_4 after wet oxidation with $K_2Cr_2O_7$, using the pulverized (250 μm sieve size) dry soil samples, as described by Nelson and Sommers (1996). Soil pH was determined from a 1:2.5 v/v soil-deionized water extracts; Using a pH and conductivity meter, according to Thomas (1996). Soil texture was determined by the hydrometer method as described by Gee and Bauder (1996). The soil-water retention (SWC) at -33 and -1500 kPa tensions were determined from the <2 mm diameter sieve size of air-dried whole-soil samples by the pressure plates apparatus (Klute, 1986). The depth of water retained at each tension was correct for the soil bulk density in separate soil depths studied.

Dry-aggregate size distribution: The dry-sieving method was adopted from Kemper and Rosenau (1986) for aggregate size distribution (ASD) after air-drying the soil samples for 2 weeks to standardize the soil-water conditions. Dry-sieving was performed without destroying the aggregates of the larger fractions in the soil collected at 0-20 cm and 20-40 cm soil depths from every replicate sampling plot unit for each cropping management practice. The aggregates were separated by placing the 500 g of air-dried bulk-soil subsamples in a stack of 20 cm diameter sieves containing 11.5, 4.76, 3.36, 2.00, 1.00, 0.50, 0.25 and <0.25 mm diameter screen openings attached to a Tyler rotary-tap sieve shaker (Combustion Engineering, Inc., Mentor, OH.). The sieve stacks were shaken at 200 oscillations min^{-1} for 15 min. The soil aggregates retained on individual sieves and passed through the sieves were weighed and their proportions to that of the air-dried bulk soil sample were obtained as dry aggregate-size distribution (ASD) classes. A graphical examination of these 8 ASD classes (data not shown), resulted in the distinct patterns of four dry ASD classes for all cropping management practices, as follows: Microaggregates (MicAg, <0.25 mm diameter), small macroaggregates (SmMag, 0.25-2.00 mm diameter), medium macroaggregates (MeMag, 2.00-4.76 mm diameter) and large macroaggregates (LaMag, >4.76 mm diameter).

Dry-macroaggregate instability (CoES-) indices: The dry-macroaggregate instability (CoES-) indices were determined using the method described by Boix-Fayos *et al.* (2001) and Cammeraat and Imeson (1998) to assess the environmental sustainability of various cropping management practices. The CoES- indices were calculated as a quotient of the weight of microaggregates size class (MicAg, <0.25 mm) in the sample soil to the weight of the macroaggregates size class(es) (MacAg) in the reference soil. The relict natural oak forest (VN) soils were collected from the nearby buffer strips and were used as the reference soil (Fig. 2), instead of a bare soil (Cammeraat and Imeson, 1998). If the CoES index, that is, ($MicAg^{sample}/MacAg^{reference}$) becomes less than 1.0, then we accept null hypothesis that the cropping management practices have promoted the formation and stabilization of macroaggregates. It was hypothesized that mechanical-sieving of a dry soil could be an appropriate method to measure the macroaggregate instability (CoES-) for different ASD classes in the soil. This method was chosen because farmers carried out the primary tillage operations during dry season for removal of crop residues following the fallow periods which could subject the soils to highly catastrophic wind erosion losses. Agricultural sustainability can be limited by the loss of the wind erodible soil aggregate size fractions <0.84 mm (Campbell *et al.*, 1993). The CoES- index is a parameter intended to express the relative magnitude of the undesirable friability in volcanic ash soils, by calculating the proportion of free microaggregates released from the breakdown of each macroaggregates size class during the disruptive forces of mechanical dry-sieving, in order to simulate the effect of tillage operations.

Statistical analyses: ANOVA was performed with the use of SAS for window version 8.1-(8e) software by GLM procedure (SAS, 2002) at significant level of $p<0.05$. Both cropping management practices and soil depth were considered as the main factors. Because the cropping management practices could not be replicated within the watershed area, three subsamples obtained from the sampling plot units within every cropping management practice were treated as pseudo-replicates. Least-significant differences were calculated at $p<0.05$ level to separate the means. Correlations were determined by a simple linear regression analysis to determine the relationships between the soil properties and the amount of dry macroaggregates parameters and instability indices.

RESULTS AND DISCUSSION

Chemical and physical soil characteristics: Total Organic Carbon (TOC) content ranged from 14.3 to 64.9 g kg^{-1} at 0-20 cm depth and also ranged from 13.4 to 24.8 g kg^{-1} at 20-40 cm depth (Table 2). The TOC contents were classified as recommended by the Institute of Natural Resources (IRENAT, 2006) (Table 2). Higher humus accumulation in the surface soil layers is a major characteristic of Andisols for supplying organic acids that are responsible for lowering soil pH strong adsorption of active Al and Fe onto humic substances to form stable Al/Fe-humus complexes, that hinders their reaction with silica and prevents the formation of aluminosilicate clay materials, such as allophane (Ugolini and Dahlgren, 2002).

Soil pH ranged from 5.86 to 6.86 at 0-20 cm depth and ranged from 5.93 to 7.02 values at 20-40 cm (Table 2). The soil pH data was classified according to Brady and Weil (1999) (Table 2). The SDL soils had exceptionally higher soil pH values at 0-20 cm than at 20-40 cm depth. Higher soil pH at 20-40 cm depth than at 0-20 cm depth was indicative of the contribution of organic acids in enhancing soil acidity in the surface soil layers with higher TOC content.

Total clay content increased which varied from 18.8 to 32.6% at 0-20 cm depth and ranged from 20.8 to 34.3% at 20-40 cm depth, but the sand and silt fractions showed no distinct patterns (Table 2). The surface layers

Table 2: General soil characteristics as influenced by different cropping and soil management systems determined at two soil depth

Altitude (m a.s.l.)	Cropping systems	Sand (Sa %)	Silt (Si %)	Clay (Cl %)	cm of water retention (SWR) -33 kPa	-1500 kPa	§pH (H_2O)	†TOC (g kg^{-1})
0-20 cm depth								
2765-2920	VN	35.0f	32.7d	32.3b	5.45c	4.18b	6.86b	64.9-ha
	PL	32.7c	32.8c	29.2e	6.10b	3.90c	6.11f	28.3-ld
	SDL	37.0d	30.8e	32.2b	6.00c	3.82c	6.38c	33.4-lc
	BRDL	37.3c	32.0d	30.7d	5.45c	4.47b	6.40c	24.5-lf
	CA	37.5c	30.1f	32.6b	5.93b	3.82c	6.31d	14.3-vlh
	PP	36.5d	33.1e	30.0d	6.57a	4.96a	6.42c	30.8-ld
3100-2920	BL	42.8a	38.2a	18.8f	3.88d	2.58d	5.86g	60.4-mb
20-40 cm depth								
2765	VN	33.2g	32.3d	34.3a	5.43c	4.15b	7.02a	24.8-lf
	PL	36.8d	33.0c	30.2d	6.31a	4.25b	6.23e	18.1-lg
	SDL	38.5b	29.8f	31.7c	5.98b	3.66c	6.32d	15.4-vlg
	BRDL	35.3f	31.0e	33.8a	5.27c	3.49c	6.41c	13.4-vlh
	CA	36.3e	31.0e	32.7b	5.95b	3.67c	6.32d	10.7-vli
	PP	36.4d	33.6c	30.4d	6.55a	4.70a	6.43c	15.9-vlg
3100-2920	BL	42.5a	36.3b	20.8f	3.88d	2.46d	5.93g	37.2-mc
Means		37.40	32.60	30.00	5.62	3.87	6.36	28.01
LSD ($p<0.05$)		0.64	0.75	0.84	0.34	0.45	0.07	3.01

Values of means for the same dependent-variable followed with the same letter are not significantly different according to Tukey studentized range test at $p<0.05$. §Soil pH classified according to Brady and Weil (1999): Strong-acid, pH = <5.0; Moderate-acid, pH = 5.0-6.5; Neutral, pH = 6.6-7.3; Moderate-alkaline, pH = 7.4-8-4 and strong-alkaline, pH = >8.5. †TOC = Total soil organic carbon (g kg^{-1}) recommended by IRENAT (2006): vh = Very high (>9.34%), h = High (6.38-9.33%), m = Medium (3.54-6.37%), l = Low (2.38-3.53%), vl = Very low (<2.37%)

(0-20 cm depth) appeared to have lower total clay content than subsurface layers (20-40 cm depth) because of higher TOC content. The formation of allophane and imogolite is favoured by dominant carbonic acid weathering environment at lower horizons with lower-TOC content and higher soil pH range of 5 to 7; Whereas organic acids activity can suppress the carbonic acid dissociation in the surface horizons with higher-TOC content and lower soil pH (Ugolini and Dahlgren, 1991; Nizeyimana *et al*., 1997). Campos-Cascaredo *et al*. (2001) reported that allophane content was strongly related with increasing soil pH and also was increasing with soil depth in volcanic ash soils at Cofre de Perote volcano, in Mexico. As indicated earlier, soil pH tended to increase at 20-40 cm soil depth under low TOC content derived from translocated dissolved and biologically active TOC and appeared to favour increased total clay content. Although there were good negative correlations between clay and TOC contents (Table 5a), the differences in slope and intercept of the linear relationships could indicate that the total clay mineral constituents were probably interacting with different TOC pools at different soil depths.

The depth of soil-water retention (Daw) at -33 kPa and -1500 kPa tensions varied from 3.88 to 6.57cm water and from 2.46 to 4.96 cm water, respectively (Table 2). Depth of available water retention capacity at -1500 kPa increased with increasing total clay content (Table 5a). However, the smallest Daw at both depths in the BL soils at higher altitudes than in other soils at the lower altitudes (Table 2) could reflect the deficiency of total clay content at both soil layers. Water retention at -1500 kPa level>18.5% has been attributed to dominant allophane/imogolite content due to its fine particles and hollow structure (Wada, 1989).

Soil structural aggregation: Dry-soil aggregate size distribution classes (ASD_d) were obtained by using a graphical analysis of the soil mass proportions of all the eight dry-sieved aggregate-size classes according to their cropping management practices and consequently resulted in four distinct parabolic distribution patterns of new soil mass proportions of dry-soil aggregate size classes (Fig. 3).

Microaggregates: The amount of microaggregates (MicAg) at 0-20 cm depth ranged from 135.0 to 546.2 g kg^{-1} and from 183.6 to 673.8 g kg^{-1} at 20-40 cm depth (Table 2). Although, the CA, SDL and VN soils had similar highest total clay content, the SDL soils had the lowest amount of MicAg at 0-20 cm depth and to an even greater extent than in both the VN and CA soils, probably because a rise in soil pH at this depth was accompanied by increased total clay content (Table 3). Lupines are known to have a relatively high demand for P and K nutrients uptake (Robson *et al*., 2002). An exceptionally higher soil pH at 0-20 cm than at 20-40 cm depth in the SDL soils than in all other soils was likely caused by high uptake of cation-bound phosphorus and the subsequent redistribution of the base-forming cations through the lupine foliage. The high outburst of exudates by lupines roots and associated microbial polysaccharides

Table 3: Dry microaggregate and macroaggregate size fractions as influenced by different cropping management systems determined at two soil depths

Altitude (m a.s.l.)	Cropping systems	MicAg<0.25 mm	SmMag 0.25-2.00 mm	MeMag 2.00-4.76 mm	LaMag>4.76mm
		------------	------------ g kg^{-1}	------------	------------
0-20 cm depth					
2765-2920	VN	291.4e	326.3d	518.29a	90.66c
	PL	178.9g	259.6f	465.19b	108.70b
	SDL	135.0h	268.9f	458.26b	88.18c
	BRDL	177.8g	347.3c	360.83d	132.92a
	CA	328.9d	394.9b	173.97h	140.39a
	PP	177.3g	357.6c	424.69c	93.55c
2920-3200	BL	546.2b	297.7e	115.03i	62.69d
20-40 cm depth					
2765-2920	VN	183.6g	441.5a	349.46d	57.89d
	PL	331.2d	342.2c	273.44f	59.24d
	SDL	224.6f	333.3d	340.54d	120.02b
	BRDL	197.3g	355.5c	320.58e	144.00a
	CA	221.7f	468.9a	236.15g	123.08b
	PP	486.7c	412.2b	107.51i	18.76e
2920-3200	BL	673.8a	263.7c	80.45j	9.18e
Means		296.74	347.82	301.74	69.23
LSD (p<0.05)		23.40	20.88	23.32	16.13

Values of means for the same dependent-variable followed with the same letter are not significantly different according to Tukey studentized range test at p<0.05

production (Jonhson *et al*., 1996) act to bind the silt and clay particles into microaggregates (Oades, 1993; Haynes and Beare, 1997). The increased soil aggregates stability index (GMD) was positively related to the biologically active hydrolysable organic carbon pool (McLauchlan and Hobbie, 2004). The soil solutions beneath the lupines canopy with elevated biological (roots and microbial) CO_2 respiration are often found to contain high carbonic acid concentrations that promotes both a rise in soil pH (>5.6) and the formation of allophane/imogolite (Ugolini and Dahlgren, 2002). A rise in soil pH can also lead to increased amount of electronegative charges on the surfaces of some 1: 1-type clays, humus and amorphous clay constituents (allophane, imogolite and some Fe/Al oxides) for cation exchange capacity (Brady and Weil, 1999).

The highest amount of MicAg at both depths in the BL soils than in the SDL soils could be the most direct indication of a medium-TOC level in the BL soils that inhibited total clay formation through enhanced soil acidification by dominant organic acid weathering processes, while depress the carbonic acid dissociation in the entire soil profile (Table 3). Higher humic acid concentration in soils with high TOC content has been found to increase active Al and Fe contents in soil solutions by dispersing allophanic clay compounds (Farmer and Lumsdon, 2002). The active Al and Fe are often preferentially retained on humus in most oxide-rich soils, which have high humus accumulation to form humus-Al complexes (Huygens *et al*., 2005) that hinders their reaction with silica and thus preventing the formation of aluminosilicates, such as allophane/imogolite (Ugolini and Dahlgren, 2002). The adsorption mechanisms between the humus-Al complexes and the amorphous clay materials (such as allophane, imogolite and ferrihydrite) is believed to occur through a ligand exchange on organic-carboxyl groups with inorganic Al/Fe hydroxyl groups and can have both an aggregating and TOC-stabilization effects, that leads to stabilizing high amounts of TOC in microaggregates (Sollins *et al*., 1996; Six *et al*., 2000a).

At 20-40 cm depth, the prevailing low content of dissolved TOC and the apparent rise in soil pH in the VN soils than in the BL soils could indicate a dominant carbonic acid weathering environment that resulted in increased total clay content and was positively accompanied by the lowest amount of MicAg in the former (Table 3). As a result, an increase in soil pH from moderate-acid to neutral conditions at 20-40 cm depth could demonstrate that the oak forest ecosystem might have a greater capacity for promoting *in situ* weathering of the abundant mafic parent materials, such as anorthite and volcanic glass, than the pine forest ecosystem.

As predicted, the amount of MicAg was positively correlated with TOC content (r>0.54), but was negatively correlated with the soil pH (r>-0.43) and total clay content (r>-0.77, Table 5a and b; p<0.05). This pattern could indicate that high amount of MicAg at 20-40 cm depth was released rapidly from unstable macroaggregates developed under low content of root-derived TOC inputs; whereas low amount of MicAg at 0-20 cm depth was released slowly from rather stable macroaggregates developed under high content of TOC from the decomposing particulate organic matter.

Small macroaggregates: The amount of small macroaggregates (SmMag) at 0-20 cm depth ranged from 297.7 to 394.9 g kg^{-1} and from 263.7 to 468.9 g kg^{-1} at 20-40 cm depth (Table 2). Although, the CA, SDL and VN soils had similar highest total clay content, the former resulted in the highest amount of small microaggregates (Table 3). This could indicate that the clay-rich volcanic-ash derived soil environments had a greater capacity to form higher amounts of SmMag at very low-TOC content for the CA soils than at low- or high-TOC contents for the SDL and VN soils. These results are consistent with other studies made by Denef *et al*. (2002) and Denef and Six (2005), who reported that a high clay content in kaolinitic soils enriched with the amorphous clays and oxides or oxy-hydroxides of Fe/Al had a potential to form macroaggregates through electrostatic interactions in the absence of organic matter inputs. The lower total clay content at 0-20 cm depth was related to a lower soil pH at this depth. Decreased clay content in surface horizons has been associated with the preferential extraction of Al/Fe oxides from the allophane/imogolite at lower-pH levels by the less-soluble TOC (humic/organic acid) compounds, leading to the formation of humus-Al complexes (Nizeyimana, 1997; Campos-Cascaredo *et al*., 2001). By contrast, in the absence of the less-decomposable TOC compounds at 20-40 cm depth, a rise in soil pH led to increased total clay content. Other studies indicated that the allophane/imogolite content was increasing parallel with a rise in soil pH and pH increased with increasing soil depth (Campos-Cascaredo *et al*., 2001; Huygens *et al*., 2005). The SmMag showed the best correlations with the soil pH and total clay content than with TOC (Table 5a, b), but the closest absolute values were at 20-40 cm depth than at 0-20 cm depth.

The similar amount of SmMag at 0-20 cm depth for the PL and SDL soils could indicate that their differences in total clay content at 0-20 cm depth had no effect on decreasing the SmMag formation, but was dependent mostly upon other positive stabilizing effects of actively growing roots (i.e., physical entanglement of soil particles, production of cementing exudates, periodic rootzone drying-wetting cycles induced by higher root-water uptake), besides enhanced microbial activity. The SmMag increased by depth and was the lowest at 0-20 cm depth for the PL and SDL soils than for the PP and BRDL soils probably because the lupines root exudation could enhance greater microbial activity than grass-type genotypes, such as wheat (Haynes and Beare, 1997). Greater reduction in SmMag formation for the SDL soils than for the BRDL soils suggest that increased SmMag resulted from the disruptive forces of the recent tillage operations and decreased SmMag resulted from the entanglement of soil particle by the long-term actively growing lupines roots and at a higher-TOC input level, rather than from the remaining roots and incorporated lupines residues. Besides a distinct dry season, such periodic rootzone soil drying-wetting cycles of the rooting zone could lead to enhanced formation of crystalline layer silicate clays at the expense of amorphous clay materials in volcanic soils, as has been found in other studies (Ugolini and Dahlgren, 2002). Only in the subsurface Si-rich environments having Al / Si < 2, was halloysite abundant than kaolinite (Gutierrèz-Castorena *et al*., 2007), indicating that halloysite has been converted to kaolinite as the surface horizons become more weathered (Nizeyimana *et al*., 1997). This could help for explaining that biological processes in the PL and SDL soils led to decreased SmMag formation at 0-20 cm depth in the presence of 1: 1-type clays at lower-pH levels, while increased SmMag at 20-40 cm depth could be associated with increased proportions of pH-dependent amorphous clay materials at higher-pH levels. As discussed earlier, total clay content increased with increasing soil pH and both clay and pH increased with depth. Denef and Six (2005) concluded that biological processes were highly effective in forming more stable macroaggregates through stronger organic bonds between the illitic than kaolinitic clay soils. Detailed investigations are however warranted on the changes in clay mineralogy for these cropping management systems.

Medium macroaggregates: The amount of medium macroaggregates (MeMag) at 0-20 and 20-40 cm depth ranged from 115.0 to 518.29 g kg^{-1} and 80.5 to 349.5 g kg^{-1} respectively (Table 2). Although total clay content was similar at 0-20 cm depth or even higher at 20-40 cm depth for the CA than SDL soils, the lower amount of MeMag formation at both depths for the CA soils than for the SDL soils demonstrated that the increased amount and long-term stability of MeMag formation was highly dependent upon the presence of actively growing biological cementing processes, resulting in stronger organic bonds, rather than only upon electrostatic interactions, between the total clay mineral constituents and oxides. According to Six *et al*. (1998), soils subjected to frequent and intensive cultivation suffered aggregate degradation due to loss of readily-decomposable TOC by microbial activity and consequently resulted in decreased production of cementing agents.

The higher amount of MeMag at both depths in the PL and SDL soils than in the BL soils was likely caused by their higher total clay content and soil pH without accumulating as much TOC as in the BL soils (Table 3). The lowest amount of MeMag at both depths in the BL soils than in the VN soils could be a consequence of lower total clay content and soil pH conditions in the former (Table 3). An increase in total clay content occurred with both increasing soil pH and aggregate size (Table 5a). However, organic matter accumulation in volcanic ash soils led to increased organic acid concentration and resulting in lower soil pH levels that increased Al release from allophane compounds (Farmer and Lumsdon, 2002). The subsequent formation of humus-Al complexes (Huygens *et al*., 2005) hinders the formation of aluminosilicates, such as allophane (Ugolini and Dahlgren, 2002).

The highest amount of MeMag at 0-20 cm depths in the VN soils than in the PL and SDL soils may suggest that a rise in soil pH from higher moderate-acid to neutral conditions was needed to increase both the amount and electrostatic capacity of total clay constituents to counteract the negative effects of increased TOC inputs in the VN soils. The MeMag increased with increasing soil pH (r>0.61) and total clay content (r = 0.69; Table 5a). According to Brady and Weil (1999), a rise in soil pH can be also important for increasing the negative charges by removing the Al/Fe hydroxyl and hydrogen ion coatings from blocking the electrostatic variable exchange sites on the aluminosilicate clays on some 1: 1-type clays, humus and oxides.

The similar highest amount of MeMag at 20-40 cm depth for the VN and SDL soils may support the argument that lupines root growth was more effective in transferring positive biologically-active cementing agents to greater soil depths leading to higher MeMag formation, to an even equal extent as for the reference soil at lower-TOC level. The stronger positive correlations between the MeMag size fractions and TOC content were found only at the lower elevations where increased total clay content had occurred with a rise in soil pH, rather than at higher elevations (r>0.07 and -0.45), with the closest absolute values found at 0-20 cm depth (r = 0.76) than at 20-40 cm depth (r = 0.33; $p<0.05$; Table 5b). This implies that the role of increased TOC content in the formation of higher MeMag size fractions with long term stability was dependent upon increased total clay content with increasing soil pH levels. The higher amount of particulate organic-C (POC) was also associated with dry-sieved 4.75-2.00 mm (MeMag) fractions where the soils had higher total clay content (Sainju, 2006). Increased total clay content was found to increase the proportion of macroaggregates in the soil under pastures in southern Piedmont, USA (Franzluebbers *et al*., 2000).

The positive correlations were found between MeMag size fractions and Daw at -1500 kPa (r>0.23; Table 5a), suggesting that soil drying could have promoted MeMag formation. Soil drying to the wilting point could lower the soil pH and favour macroaggregate formation, by freeing off the water and oxy-hydroxides of Al/Fe from the permanent negative charges for cation exchange on the surfaces of 2: 1-type clays and allophane minerals, with a subsequent specific adsorption of organic molecules (Denef *et al*., 2002).

Large macroaggregates: The amount of large macroaggregates (LaMag) ranged from 62.7 to 140.4 g kg^{-1} and 9.2 to 144.0 g kg^{-1} at 0-20 and 20-40 cm depth respectively (Table 2). The amount of LaMag was the lowest at both soil depths among all the four macroaggregate size fractions (Fig. 3). The similar highest amount of LaMag at 0-20 cm depth for the BRDL and CA soils showed that, in clay-rich CA soils with very low-TOC levels, the depletion of TOC had less impact on the amount of LaMag. The LaMag formation for the CA soils was not bound by organic agents, since no increase in macroaggregates was observed with increasing TOC

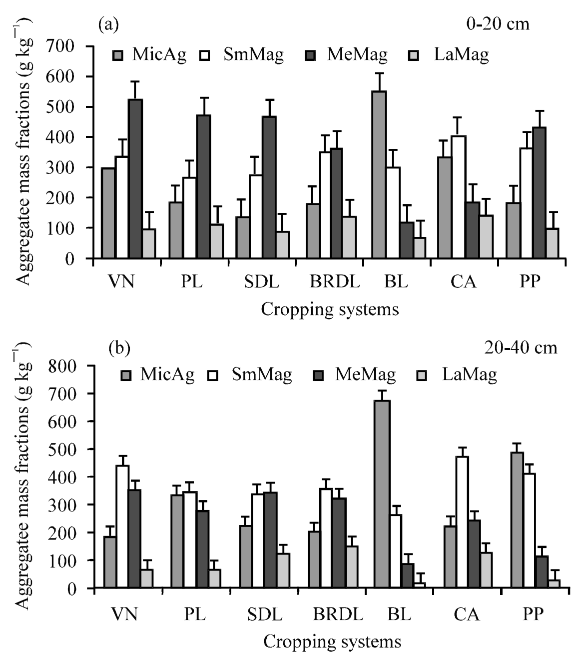

Fig. 3: Dry soil microaggregates and macroaggregate size fractions as influenced by different cropping management systems. Vertical bars represent ±SE (n = 3)

content. Therefore, the higher LaMag for the CA soils with their high total clay content could be bound through physical drying and electrostatic interactions between the abundant oxides and clay minerals, whereas after incorporating fresh lupines residues by tillage in the BRDL soils could lead to enhanced biologically active TOC cementing agents, resulting in higher amounts of LaMag with long-term stability (Table 3). These results are consistent with the findings of Denef *et al.* (2002) and Denef and Six (2005) who reported that macroaggregates were formed rapidly without adding residues or plant derived organic-C inputs in the kaolinitic soils, but could be bound through mineral-mineral bonds mediated by electrostatic interactions between the oxides and 1: 1-type clay minerals. The BRDL soils formed the highest amount of LaMag at both depths, to an even greater extent than the clay- and TOC-rich VN and SDL soils, suggesting that LaMag structure may be enhanced through the binding of biologically active TOC (i.e. fungal hyphae, roots and microbial-derived polysaccharides) inputs after incorporating fresh lupines residues, rather than leaving dead plant residues as mulches. These differences could not be related to drying after tillage operations because all the soil samples were air-dried to standardize the drying effects (Kemper and Rosenau, 1986). The lowest amount of LaMag at both depths in the BL soils than in the BRDL soils could be the most direct indication that increasing TOC inputs, with dead rather than freshly incorporated plant residues without raising soil pH, resulted in decreased LaMag formation.

The highest amount of LaMag at 20-40 cm depth in the BRDL soils than in the CA soils can be attributed to their higher total clay content under low TOC inputs released by the lupines roots, since increased total clay content was observed with increasing amount of LaMag. The similar amounts of LaMag at 20-40 cm depth between both the PL and VN soils, as well as between the SDL and CA soils, demonstrate the effectiveness of the lupines invaded meadows and fallows in promoting LaMag formation, to an even equal extent as in the clay-rich VN and CA soils.

Dry macroaggregate instability (CoES) indices: The macroaggregate instability (CoES) indices of the soil aggregates separated by dry-sieving was calculated as a quotient of the mass of free microaggregates plus silt-plus clay-size particles (<0.25 mm diameter) to the mass of a specified macroaggregate size class of the reference soil (Cammeraat and Imeson, 1998; Boix-Fayos *et al.*, 2001). The most sustainable cropping management practices were considered as those that contributed to the lowest CoES indices. Similarly, this criterion was used in this study as a parameter to evaluate the impact of traditional cropping management practices on environmental sustainability. Soils from all the seven cropping management practices had a very friable consistency at 0-20 cm depth and most at 20-40 cm depth and this could be the main limitation for achieving a stable structural aggregation in these volcanic ash soils. We identified the CoES indices for four macroaggregate size classes for the whole-soil, small-, medium- and large- macroaggregates (TMag, SmMag and MeMag and LaMag, respectively) at both soil depths studied. The CoES- indices for the TMag ranged from 0.143 to 0.583 at 0-20 cm depth and from 0.217 to 0.792 at 20-40 cm depth; and for the SmMag from 0.442 to 1.707 at 0-20 cm depth and from 0.423 to 1.110 at 20-40 cm depth; while for the MeMag this range was from 0.255 to 1.062 at 0-20 cm depth and from 0.527 to 1.937 at 20-40 cm depth and for the LaMag from 0.929 to 6.375 and from 0.486 to 11.64 at 0-20 and 20-40 cm depth respectively (Table 4).

The CoES- indices for all the dry-macroaggregates sizes were decreased with increasing soil pH ($r>-0.42$; Table 5b) and total clay content ($r>-0.77$; $p<0.05$; Table 5a), but were increased with increasing TOC content ($r>0.51$; $p<0.05$; Table 5b). As discussed earlier, the MicAg were also associated with TOC content ($r>0.54$; Table 5b). The CoES indices represent the MicAg release rate as the macroaggregates breakdown, but it is not clear if this TOC can be considered non-hydrolyzable C. It has been hypothesized that, high organic C content in volcanic-ash soils resulted from biochemical stabilization of the slowly-decomposable C through the formation of Al/Fe-humic acid complexes and chelates with allophane/imogolite clay materials (Wada and Aomine, 1973) and can also be physically-associated with clay- and silt-size fractions in MicAg within macroaggregates (Six *et al.*, 2000b). This could be a possible explanation for the observed lowest CoES indices for all the macroaggregate size classes at both depths for the SDL soils than for the BL soils. This shows that biologically active TOC cementing agents from fresh lupines residues for the SDL soils rather than from dead pine forest litter for the BL soils, led to stronger organic bonds between total clay constituents at a higher than a lower soil pH (Table 2, 4). Similarly lower CoES- indices at 0-20 cm depth for the all macroaggregate size classes for the PL, SDL and BRDL soils than for the clay-rich VN and CA soils suggest that the lower total clay content for these practices was likely not the only factor controlling their reduction in CoES indices. This can be

Table 4: Macroaggregate instability (CoES) indices for the whole soil (TMag), small (SmMag), medium (MeMag) and large (LaMag) size classes as influenced by different cropping management practices

		Macroaggregate instability indices (CoES-)			
Altitude (m a.s.l.)	Cropping systems	CoES-TMag^R	CoES-SmMag	CoES-MeMag	CoES-LaMag
0-20 cm depth					
2765-2920	VN	0.310f	0.923e	0.567e	3.360e
	PL	0.192i	0.547g	0.352g	0.929h
	SDL	0.143j	0.442h	0.255h	1.472g
	BRDL	0.192i	0.570g	0.340g	1.988f
	CA	0.350e	1.020d	0.643e	3.863d
	PP	0.190i	0.567g	0.343g	2.027f
2920-3200	BL	0.583b	1.707a	1.062c	6.375c
20-40 cm depth					
2920-3200	VN	0.217h	0.423h	0.527f	0.486h
	PL	0.390d	0.745f	0.958d	0.880h
	SDL	0.267g	0.517g	0.638e	3.935d
	BRDL	0.233h	0.455h	0.563e	3.445e
	CA	0.260g	0.500g	0.637e	3.827d
	PP	0.577c	1.110c	1.397b	8.443b
2920-3200	BL	0.792a	1.528d	1.937a	11.640a
Means		0.335	0.790	0.730	4.385
LSD ($p<0.05$)		0.026	0.079	0.066	0.456

Values of means for the same dependent-variable followed with the same letter are not significantly different according to Tukey studentized range test at $p<0.05$

due to the fact that a reduction in cultivation intensity with PL, SDL and BRDL practices has resulted in the increased fresh hydrolyzable C in macroaggregates with long term stability than for the VN and CA practices. The TOC-depleted soil environments, such as for intensive cultivations, can lead to a loss of organic C-rich macroaggregates accompanied by an increase in C-depleted MicAg release (Six *et al*., 2000a). Present results demonstrate that despite the fact that the macroaggregates were bound by weaker electrostatic interactions between 1:1-type clays and oxides rather by the stronger organic cementing processes, higher CoES indices at 0-20 cm depth for the CA soils were achieved along with the corresponding decrease in amounts of MeMag. Denef *et al*. (2002) and Denef and Six (2005) also reported that a significant increase in amount of stable macroaggregates was induced by actively growing biological processes which led to longer-term stabilization of macroaggregates in 2:1- than in 1:1-type clay soils for the planted treatments. Therefore, actively growing lupines in the PL, SDL and BRDL practices led to decreased CoES probably through more soluble organic cementing agents (i.e. root exudates and associated microbial polysaccharides production) and were likely contributing to stronger organic bonds that promoted long-term macroaggregates stabilization, whereas the mineralization of dead and mature oak forest residues in the VN soils could lead to the non-soluble or less-decomposable organic cementing agents (i.e., lignocellulose compounds). This is in agreement with Denef and Six (2005), who observed that actively growing plant root exudates stimulated significant microbial activity which simultaneously promoted the formation of large macroaggregates in illitic clay soil than in kaolinitic clay soil.

Many studies have shown that allophane content was increased by increasing soil pH which in turn increased by soil depth in several other volcanic ash soils (Campos-Caredo *et al*., 2001; Huygens *et al*., 2005). The total clay content and pH measured in this study showed the same pattern. Secondly, the lowest CoES- indices at 20-40 cm depth for the TMag, SmMag, MeMag and LaMag in the VN soils than in the scrubland (PL, BRDL, PP and SDL) soils (Table 4) could indicate that a rise in soil pH from higher moderate-acid to neutral conditions has resulted in significantly higher amounts of total clay constituents that promoted more stable macroaggregates. The preferential sorption of humic-types of TOC on clay particles and sesquioxides at 0-20 cm depth resulted in TOC fractionation, leading to the lack of humic-types of TOC inputs at 20-40 cm depth. The increase in TOC content led to increased CoES- indices for all the macroaggregate size fractions ($r>0.51$; $p<0.05$; Table 5b). Decreasing the humic-type TOC content resulted in increased total clay content with increasing soil pH at 20-40 cm depth for the VN soils which suggest that a stronger adsorption of dissolved TOC content was probably favoured by increased allophane/imogolite content and consequently helped in the formation of stable macroaggregates of all size classes. These conclusions were supported by the negative correlations between CoES-indices for both total clay content ($r>-0.70$) and soil pH ($r>-0.42$); but positive correlations with TOC content ($r>0.73$; $P<0.05$), while the closest

Table 5a: Correlation coefficients (r) and regression equations relating total organic carbon content (TOC), total clay content (clay) and soil pH, as independent variables, to the dry-sieved macroaggregate size classes, microaggregates and macroaggregate instability indices

Dependent variable	§Regression equations	r
Clay	$Clay^1$ = -0.1262 TOC+34.08	-0.49
	$Clay^2$ = -0.3955 TOC+38.16	-0.78
Clay	$Clay^1$ = 0.1139 pH-42.69	0.72
	$Clay^2$ = 0.1043 pH-36.04	0.75
MicAg	$MicAg^1$ = -22.87 clay+935.88	-0.77
	$MicAg^2$ = -37.89 clay+1487	-0.94
SmMag	$SmMag^1$ = 3.107 clay+230.25	0.31
	$SmMag^2$ = 11.257 clay+30.49	0.73
MeMag	$MeMag^1$ = 19.63 clay-218.55	0.61
	$MeMag^2$ = 19.03 clay-336.49	0.79
LaMag	$LaMag^1$ = 3.526 clay-1.412	0.63
	$LaMag^2$ = 7.889 clay-164.7	0.68
CoES-TMag	CoES-$TMag^1$ = -0.0245 clay+1.00	-0.78
	CoES-$TMag^2$ = -0.0445 clay+1.748	-0.94
CoES-SmMag	CoES-$SmMag^1$ = -0.071clay+2.91	-0.77
	CoES-$SmMag^2$ = -0.086 clay+3.36	-0.94
CoES-MeMag	CoES-$MeMag^1$ = -0.0446 clay+1.823	-0.77
	CoES-$MeMag^2$ = -0.109 clay+4.28	-0.94
CoES-LaMag	CoES-LaMag ^{1} = -0.268 clay+10.75	-0.70
	CoES-$LaMag^2$ = -0.0722 clay+26.69	-0.82
MicAg	$MicAg^1$ = -201.9 pH+1539.7	-0.43
	$MicAg^2$ = -369.84 pH+2693.5	-0.65
SmMag	$SmMag^1$ = 56.10 pH-33.18	0.35
	$SmMag^2$ = 145.92 pH-558.11	0.67
MeMag	$MeMag^1$ = 348.69 pH-1846.7	0.69
	$MeMag^2$ = 257.57 pH-1401.1	0.77
LaMag	$LaMag^1$ = 29.69 pH-85.43	0.34
	$LaMag^2$ = 38.77 pH-171.65	0.24
MeMag	$MeMag^1$ = 136.37 Daw-180.75	0.65
	$MeMag^2$ = 36.07 Daw+108.08	0.23

§Superscript 1 is for 0-20 cm and 2 is for 20-40 cm soil depth

Table 5b: Correlation coefficients (r) and regression equations relating total organic carbon content (TOC) and soil pH, as independent variables, to dry microaggregate and macroaggregate size classes and macroaggregate instability indices (CoES).

Dependent variable	Regression equations‡	r
MicAg	$MicAg^1$ = 4.10 TOC+112.12	0.54
	$MicAg^2$ = 14.23 TOC+55.75	0.70
SmMag	$SmMag^1$ = -0.896 TOC+354.61	-0.34
	$SmMag^2$ = -4.574 OC+462.46	-0.58
MeMag	$MeMag^1$ = 0.576 TOC+338.34	0.07
	$MeMag^2$ = -5.512 TOC+350.75	-0.45
MeMag ‡	‡$MeMag^1$ = 5.45 TOC+222.15	0.76
	‡$MeMag^2$ = 6.16 TOC+170.35	0.33
LaMag	$LaMag^1$ = -0.918 TOC+139.06	-0.69
	$LaMag^2$ = -5.765 TOC+181.54	-0.57
CoES-TMag	CoES-$TMag^1$ = 0.004 TOC+0.12	0.54
	CoES-$TMag^2$ = 0.017 TOC+0.07	0.69
CoES-SmMag	CoES-$SmMag^1$ = 0.013 TOC+0.35	0.55
	CoES-$SmMag^2$ = 0.032 TOC+0.13	0.70
CoES-MeMag	CoES-$MeMag^1$ = 0.008 TOC+0.22	0.53
	CoES-$MeMag^2$ = 0.041 TOC+0.16	0.70
CoES-LaMag	CoES-$LaMag^1$ = 0.052 TOC+0.94	0.53
	CoES-$LaMag^2$ = 0.228 TOC+0.26	0.51
CoES-TMag	CoES-$TMag^1$ = -0.215 pH+1.64	-0.43
	CoES-$TMag^2$ = -0.492 pH+3.53	-0.74
CoES-SmMag	CoES-$SmMag^1$ = -0.622 pH+4.79	-0.43
	CoES-$SmMag^2$ = -0.944 pH+6.78	-0.74
CoES-MeMag	CoES-$MeMag^1$ = -0.390 pH+2.98	-0.43
	CoES-$MeMag^2$ = -1.203 pH+8.63	-0.74
CoES-LaMag	CoES-$LaMag^1$ = -2.572 pH+19.13	-0.42
	CoES-$LaMag^2$ = -10.212 pH+69.89	-0.82

Superscript 1 is for 0-20 cm and 2 is for 20-40 cm soil depth. ‡Regression analysis was done only with data from the lower altitudes (2750-2920 m a.s.l.).

absolute values were observed at 20-40 cm than at 0-20 cm depth (Table 5a, b).

The lower CoES- indices at 20-40 cm depth for all the four macroaggregate sizes in the PL soils than in the PP soils and to an even similar lowest extent for CoES-LaMag at 20-40 cm depth for the VN soils could indicate that total clay content was not the only factor controlling CoES. At a lower soil pH, cation adsorption reactions tend to be dominated by 2:1-type clays more than some pH-dependent 1:1-type clays and amorphous clay materials (Brady and Weil, 1999). The similar lowest CoES-indices for the TMag and SmMag at 20-40 cm depth for the VN and BRDL soils (Table 4) was likely caused by their higher total clay content. Increase in total clay content for the two soils resulted from significantly different soil pH levels, suggesting that their similar CoES indices were more likely influenced differently at this soil depth by different mixtures of variable and constant charged colloids. Similarly, a significantly lower CoES-LaMag indices at both depths for all the size classes for the SDL and PL soils than for the PP soils could indicate that biologically active processes from the lupines invasions fallows and meadows led to stronger organic bonds than from the pure pastures (PP). A higher pH at 20-40 cm depth was important since it could determine the amount of variable charge on colloidal constituents, of which allophane is often more abundant than humus content, since no increase in CoES indices was observed with increasing total clay content.

CONCLUSIONS

This study examined long-term effects of the wild lupines invasions in various traditional cropping management systems on dry-soil aggregate size distribution and macroaggregate instability indices at two depths in volcanic ash soils. The data suggested that increasing soil pH resulted in increased total clay content independent of the TOC content. Compared to other cropping management practices, the lupines invaded fallow soils demonstrated higher total clay content with increased soil pH at 0-20 cm than at 20-40 cm depth, showing that the lupines have a unique capacity to redistribute the base-forming cations through foliage. The microaggregate formation at 0-20 cm depth was highest in the pine forest soils under dead plant residues TOC inputs, but was lowest in the lupines invaded fallow soils under biologically active soluble TOC inputs. In the absence of dead plant derived-TOC inputs at 20-40 cm depth, the amount of microaggregates release was then decreased with increased total clay content and soil pH from higher moderate-acid to neutral conditions in the oak forest soils than in the lupines invaded fallows. The lupines invaded fallows and meadows had similar lowest amounts of SmMag at 0-20 cm depth in the (PL and SDL) soils and also lowest at 20-40 cm depth in the lupines invaded disturbed pine forest (BL) soils. The highest amount of SmMag at both depths was formed under very low TOC inputs in the annually cultivated soils. This indicates that high total clay soils have a potential to form SmMag through electrostatic reactions rather than through biologically active TOC cementing processes, since TOC did not increase with increasing amount of small macroaggregate. The highest amount of MeMag formation at both soil depths in the VN soils than in the SDL and PL soils was significantly enhanced by a rise in soil pH from higher medium-acid to neutral conditions. The highest amount of LaMag at both depths upon fresh-lupines residues incorporation (BRDL) could indicate a rapid response of LaMag formation to biologically active cementing TOC processes after adding fresh lupines residues into the soil. The highest amount of large macroaggregates (LaMag) were formed in annually cultivated (CA) soils with very low TOC input through electrostatic adsorption reactions between the clays and oxides, rather than through biologically active TOC cementing processes.

Incorporating fresh lupines residues (BRDL) had the lowest amount of medium macroaggregate instability (CoES-MeMag) indices at both depths. Lupines invaded fallows (SDL) had greater capacity to decrease dry macroaggregates instability indices in whole soil, small and medium macroaggregates at 0-20 cm depth than at 20-40 cm depth more than did the other scrublands soils, but the trend reversed in the reference oak forest soils. This was due to physical entanglement and biologically active TOC cementing processes associated with lupines roots growth and a rapidly fresh residues decay throughout the rooting zone. The clay-rich annually cultivated (CA) soils can form large macroaggregates due to electrostatic interactions without accumulating TOC, but had higher macroaggregate instability indices for all the macroaggregate size classes which may pose a very serious threat to sustainable agricultural systems.

We concluded that lupines invaded fallows and meadows can stabilize all the macroaggregates size classes. Hence these findings will be relevant for future inclusion of lupines in cropping management practices with high yielding grain lupine genotypes in order to improve both physical soil fertility and socio-economic sustainability of the traditional farming systems.

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