

2.4 SOIL AGGREGATION, WATER-HOLDING CAPACITY, AND BIOLOGICAL ACTIVITY UNDER NO-TILL SYSTEMS AND CROPPING SEQUENCES IN THE LAO PDR

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Abstract

In the four southern districts (Kenthao, Paklay, Boten, and Thongmixay) of Xayabury province, the current cropping systems are based on cash crop production. Maize is the main crop under rainfed conditions and covers more than 30,000 ha in the region. Land preparation is based mainly on plowing, which degrades soil and destroys infrastructures (paddy fields and roads). These deteriorations result from growing pressure on agricultural systems and farmers' lack of access to affordable labour. This study sought to analyze soil aggregation, soil water-holding capacity, and soil biological activity under tillage and no-tillage conditions in relation to the cropping sequence. Three cropping sequences were investigated: 1. maize monoculture; 2. two-year rotational sequence, maize – rice bean; 3. two-year rotational sequence, maize + *Brachiaria ruziziensis* – rice bean.). Each year of the sequence was represented under no-till (NT) and tillage (CT) practices. Independent of depth, soil aggregation was greater under no-till conditions and enhanced by crop rotation and higher dry matter production (maize + *B. ruziziensis* / rice bean). Soil macrofauna, that is, the number of species and amount of biomass, was increased with no-till and the cropping sequence. Earthworms increased with no-till and for some cropping sequences amounted to more than 50% of the total macrofauna biomass. The cropping sequences produced a limited amount of dry matter. The main challenge was to increase biomass productivity (above-ground and below-ground) to recover ecosystem functions (recycling of nutrients, carbon sequestration, high biological activity, integrated weed and pest management, etc.) in a medium-term process (five years). Generating and adapting intensive cropping sequences (high production of aboveground and belowground biomass combined with a high diversity) under no-tillage systems with smallholders is an essential step in achieving long-term land sustainability, to obtain more reliable harvests and higher farm profits.

Introduction

In the four southern districts (Kenthao, Paklay, Boten and Thongmixay) of Xayabury province, the current cropping systems are based on cash crop production. Maize is the main crop under rainfed conditions and covers more than 30,000 ha in the region. This development has been enhanced by Thai demand and transfer of technologies (different means of production, such as tractors, plows, hybrid maize seeds, and pesticides). Land preparation is based mainly on plowing (up to a slope of 45%), which generates severe soil degradation and infrastructure destruction (paddy fields and roads). Herbicides are widely used for land preparation and weed management. These deteriorations result from growing pressure on agricultural systems (to increase their productivity and generate marketable commodities) and farmers' lack of access to affordable labor.

Soil potentials in the Kenthao, Paklay, and Botene districts are closely related to the soil parent materials (igneous rocks, schist, and sandstone). Soil organic carbon (SOC) under 'natural' vegetation is estimated at 86.5 and 13.8 MgC.ha⁻¹ (0-20 cm) under basaltic and sandstone parent materials, respectively. Under basaltic conditions, SOC in cultivated fields (rotational swidden system over several decades and tillage for 15 years) is half (43.6 MgC.ha⁻¹) of the amount under 'natural' vegetation. This region has experienced strong rural growth (income generation, road construction) related to the Thai market demand. However, even very good soils with high potential for agricultural development can be rapidly degraded.

The National Agriculture and Forestry Research Institute (NAFRI) of Lao PDR, in partnership with CIRAD, implemented the Lao National Agro-Ecology Program to create, adjust, and optimize smallholder alternative cropping systems based on the principles of conservation agriculture and direct seeding mulch-based cropping systems. The main objectives were to develop innovative systems that can help preserve soil, water, and nutrients in order to achieve long-term land sustainability, so as to obtain more reliable harvests and higher farm profits. This study sought to analyze soil aggregation, soil water-holding capacity, and soil biological activity under tillage and no-tillage conditions in relation to the cropping sequence.

Materials and methods

Experimental design

A range of no till systems was implemented in 2004 in a demonstration field of Nongpakbong (sandstone parent material, Botene district, Xayabury province, 17°40'47.74"N, 101°10'48.37"E), integrating local species (rice bean) as a first step.

Table 1: Soil characteristics of the 0-30 cm horizons, experimental site of Nongpakbong.

Soil depth (cm)	C (g.kg ⁻¹)	N (g.kg ⁻¹)	pH	CEC (cmol.kg ⁻¹)	Particle size distribution (g.kg ⁻¹)		
					Sand	Silt	Clay
0-10	22.9	1.83	5.53	27.9	295	296	409
10-20	19.9	1.59	5.54	27.6	293	280	427
20-30	16.5	1.36	5.48	26.7	281	267	451

A criss-cross design was used (two factors: land management and cropping sequence) and each cropping sequence, and each year of the sequence, was represented under no-till (NT) and tillage (used as a reference – CT) practices. Cropping sequences: 1. maize monoculture; 2. two-year rotational sequence, maize – rice bean; 3. two-year rotational sequence, maize + *Brachiaria ruziziensis* – rice bean. Twenty five days after sowing (under no-till management), was intercropped with maize at a rate of 15 kg.ha⁻¹. Under tillage, cropping sequence 3) was maize – rice bean.

Table 2: Summary of cropping systems studied.

Cropping system	Land management	Land preparation	Sowing	Intercropping	Harvesting
1. Maize monoculture	CT	Disk plowing - April	From 25 th of April to 5 th of May	No	End of September
	NT	Weed management			
2. Two-year rotational sequence Maize – <i>Vigna umbellata</i>	CT	Disk plowing - April	Maize: from 25 th of April to 5 th of May Rice bean: end of May	No	Maize: end of September Rice bean: end of December
	NT	Weed management			
3. Two-year rotational sequence Maize + <i>B. ruziziensis</i> – <i>Vigna umbellata</i>	CT	Disk plowing - April	Maize: 25 th of April to 5 th of May Rice bean: end of May	No	Maize: end of September Rice bean: end of December
	NT	Cover-crop management (rolling and use of systemic herbicide – Roundup®)		<i>B. ruziziensis</i> : 25 days after maize sowing	

In 2008, undisturbed soil samples were collected to measure soil aggregation, soil water holding capacity, and soil biology activity. The distribution of soil aggregates was recorded at three depths (0-10, 10-20, and 20-30 cm) as were bulk density, soil water-holding capacity, and soil macrofauna activity. Each parameter was also recorded under forest ecosystem.

Bulk density (Da)

Da was measured on undisturbed soil samples using soil samplers and cylinders of 94.12 cm³. Three soil replicates were collected at depths of 0-10, 10-20, and 20-30 cm. The soil contained in cylinder was dried for 48 hours at 105°C. The dry weight of the sample was measured to express bulk density (kg.dm⁻³).

Soil Water Holding Capacity (SWHC)

Undisturbed soil samples for Da determination were used for SWHC determination. Samples were humidified to reach the full capacity, weighed, and then dried at 105°C for 24 hours. Results of soil water holding capacity had to be interpreted carefully because water available for plants (between 0.03 MPa to 0.42 MPa) was not measured. The volume of water contained in each sample (94.12 cm³) was used to express SWHC (mm H₂O) per soil layer.

Water Stable Aggregates (WSA)

Three undisturbed soil samples that were replicates from each plot were collected from trenches at depths of 0-10, 10-20, and 20-30 cm to record WSA. A sample of 100 g was used to obtain the aggregate size fractions through the wet sieving method (Yoder, 1936); a sub-sample was weighed and dried at 105°C for 24 hours to determine the soil moisture content to be used in the aggregation index calculations. Samples were dried in the shade to allow just the loss of excess moisture, but care had to be taken not to dry out the soil excessively. The total soil mass of each replicate was then passed through a 19 mm mesh sieve; clods greater in diameter than the sieve mesh were broken along their natural cleavage planes. The samples were moistened by capillarity by placing them on a filter paper at the top sieve (8 mm). The water volume was then raised inside the water tank to wet the filter paper and consequently the soil. The time taken to moisten the soil was 5 min. The filter paper was then removed and the wet sieving process was carried out. Each test used six sieves of 8, 4, 2, 1, 0.5 and 0.25 mm mesh; the wet sieving process lasted 10 minutes. The sieves were then removed from the tank, and the aggregates were removed from each sieve to measure the dry weight. The aggregates retained in each sieve were weighed after 24 h in a drier at 105°C.

MWD was calculated according to the following formula:

$$\text{MWD} = \sum_{i=1}^n \frac{P_i}{P_t} \cdot d_{mi} \quad \text{where } d_{mi} = \frac{(d_i + d_{(i+1)})}{2}$$

With:

- n = number of sieves
- P_i = dry weight of the soil fraction measured on the d_i grille sieve.
- P_t = Total dry weight measured on all sieves
- d_{mi} = mean soil particle diameter on the sieve
- d_(i+1) = grille of the sieve above d_i grille sieve.

Soil macro fauna

Fauna sampling was done on squares of 25 cm x 25 cm on three replicates and four depths: top soil, 0-10, 10-20, and 20-30cm. Total fauna was collected at each depth using pliers and put into alcohol for identification in laboratory. Fauna identification and accounting was done under binocular glass. Fauna weight was recorded for each treatment at every depth and for each species by a electronic balance. In relation with animal weight losses in alcohol, final weight was adjusted using a specific coefficient for each species (from 6 to 24%).

Statistical analysis

Graphic representations and calculations of confidence intervals for regressions and standard deviation (SDEV) were carried out with SigmaPlot 9.0 for Windows (Jandel Scientific). Statistical analysis was done with SPSS 9.0 for Windows.

Results

Soil aggregation under forest showed the largest macro water-stable aggregates (> 8 mm) at each depth (Fig. 1). Under system 1, no-till was characterized by larger water-stable aggregates (WSA) at 0-10 cm (Fig. 2) than tillage, with average WSA of 4.7 mm and 3.0 mm, respectively. No significant differences were observed for 10-20 and 20-30 cm depths (Table 3). No-till showed a larger proportion (52.8%) of macro (> 2 mm) water-stable aggregates. In contrast, tillage showed fewer large macro aggregates (40.5%) and more small (1 to 0.25 mm) water-stable aggregates (59.5%). For system 2, differences between tillage and no-till at 0-10 cm depth were significant, with WSA of 3.3 and 4.9 mm, respectively (Table 3). Under no-till system 2 (Fig. 3), large macro water-stable aggregates (from 2 to 8 mm) at a depth of 0-10 cm amounted to 53.9% while under tillage they represented 38.6 %. For system 3, differences between tillage and no-till were significant at the three depths (Table 3). Under no-till, this rotational sequence showed a large proportion of large macro water-stable aggregates (Fig. 4). Aggregate size from 2 to 8 mm represented 62.7 % under no-till and 46.4 % under tillage. In comparison with natural ecosystem (Fig. 1), aggregate size distribution was irregular (Fig. 4), and no continuity was observed between aggregate size. Soil aggregation was influenced by land preparation and by cropping sequence (dry matter input and quality of residues). At 0-10 and 10-20 cm (Table 3), WSA were larger under no-till conditions and enlarged by crop rotation and greater dry matter production (maize + *B. ruziziensis* / rice bean). Significant differences were recorded in relation to the cropping sequence with greater water-stable aggregates produced under system No. 3 under no-till and at 0-10 cm. Independent of depth, soil aggregation under this system was close to that of the natural ecosystem. Soil aggregation was rebuilt probably due to an increase in temporary (roots hairs) and transient (polysaccharides) binding agents, which are the most important aggregation components. Distribution of the soil aggregation size is a global indicator of a cropping system's potential to rebuild soil cohesion, protecting soil organic carbon through soil biology enhancement.

Table 3: Water-stable aggregates for three cropping sequences and two soil managements (no-till and plowing) plus the results of the Duncan test (0.05). The water-stable aggregates with the same letters are not significantly different at $p < 0.05$.

Land preparation	Cropping sequence	Water Stable Aggregate (mm)		
		0-10 cm	10-20 cm	20-30 cm
Tillage	maize monoculture	3.0 ^c	4.6 ^{ab}	4.3 ^{abc}
No-till		4.7 ^b	5.0 ^a	4.2 ^{abc}
Tillage	maize - rice bean	3.3 ^c	3.6 ^c	3.8 ^{bc}
No-till		4.9 ^b	4.0 ^{bc}	3.8 ^{bc}
Tillage	maize + <i>B. ruziziensis</i> - rice bean	3.6 ^c	3.7 ^c	3.4 ^c
No-till		6.0 ^a	5.0 ^a	4.8 ^{ab}
Forest		5.6^a	5.3^a	5.1^a

Bulk density (Da) was affected by the treatment and soil depths (Table 4). Da values were lower under no-till for 0-10 cm and 10-20 cm depth, except for system 3. For this system, no significant differences were observed between tillage and no-till at 10-20 cm depth. Under tillage, system 2 showed the highest Da at the 0-10 cm depth. By contrast, under no-till, systems 1 and 3 showed lower bulk density at 0-10 cm depth resulting in a favorable environment for root penetration. We can reasonably conclude that these changes were related to biological soil improvement. At 20-30 cm depth no differences were observed between treatments

Table 4: Bulk density for three cropping sequences and two soil managements (no-till and plowing) plus the results of the Duncan test (0.05)

Land preparation	Cropping sequence	Bulk density (kg.dm ³)		
		0-10 cm	10-20 cm	20-30 cm
Tillage	1. maize monoculture	1.372 ^{ab}	1.514 ^a	1.456 ^a
No-till		1.320 ^c	1.365 ^b	1.464 ^a
Tillage	2. maize - rice bean	1.430 ^a	1.509 ^a	1.495 ^a
No-till		1.346 ^{ab}	1.387 ^b	1.444 ^a
Tillage	3. maize + <i>B. ruziziensis</i> - rice bean	1.384 ^{ab}	1.399 ^b	1.470 ^a
No-till		1.321 ^c	1.365 ^b	1.534 ^a
Forest		1.367 ^{ab}	1.420 ^b	1.427 ^a

Soil water-holding capacity (SWHC) was affected by land preparation, with higher SWHC recorded under no-till (Fig. 5). However, no clear differences were observed between rotational sequences. Under no-till, SWHC was significantly higher at 0-10 cm depth for system 1 and 3. At 0-10 cm, the increase in SWHC (between no-till and tillage) ranged from 6.6 mm for system 3; 7.1 mm for system 2, and 8.6 mm for system 1. The increase in SWHC was mainly in the 0-10 cm layer. At 0-30 cm, higher SWHC was observed under no-till except for system 3, which showed no significant differences between tillage and no-till management. No-till system 3 showed higher value than the natural ecosystem (125,5 mm), with a SWHC of 134.6 mm, but it was similar to those of systems 1 and 2.

Soil macrofauna, as the number of species and amount of biomass, was positively enhanced with no-till and the cropping sequence (Figure 6). Over 2,000 individuals per m² were recorded with no-till. Earthworms increased with no-till and amounted to more than 50% of the total macrofauna biomass (two-year rotational sequence maize – rice bean).

Figure 1. Mean frequency \pm SDEV (six replicates) of soil water-stable aggregate distribution for three depths, under forest

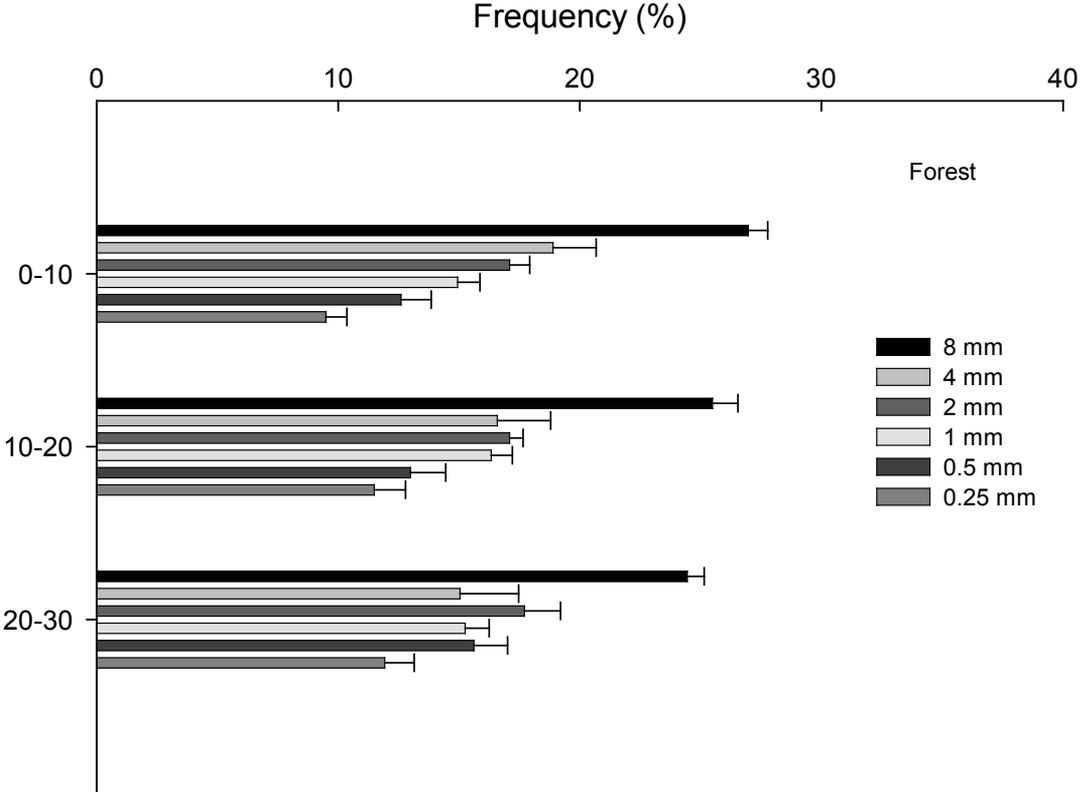


Figure 2. Mean frequency \pm SDEV (six replicates) of water-stable aggregate distribution for three depths, tillage and no-till, in maize monoculture

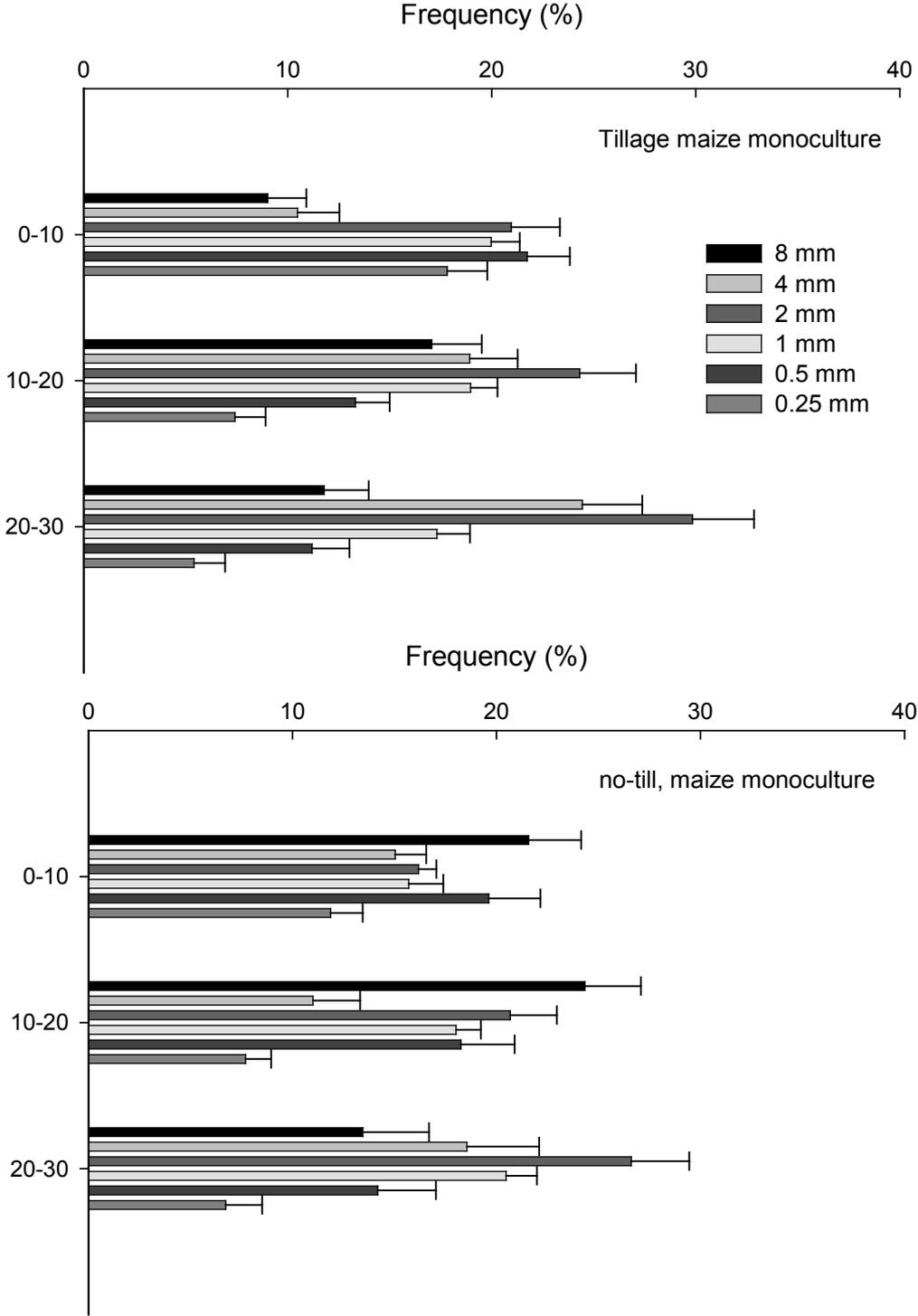


Figure 3. Mean frequency \pm SDEV (six replicates) of water-stable aggregate distribution for three depths, for tillage, no-till, in relation to the maize-rice bean rotational sequence

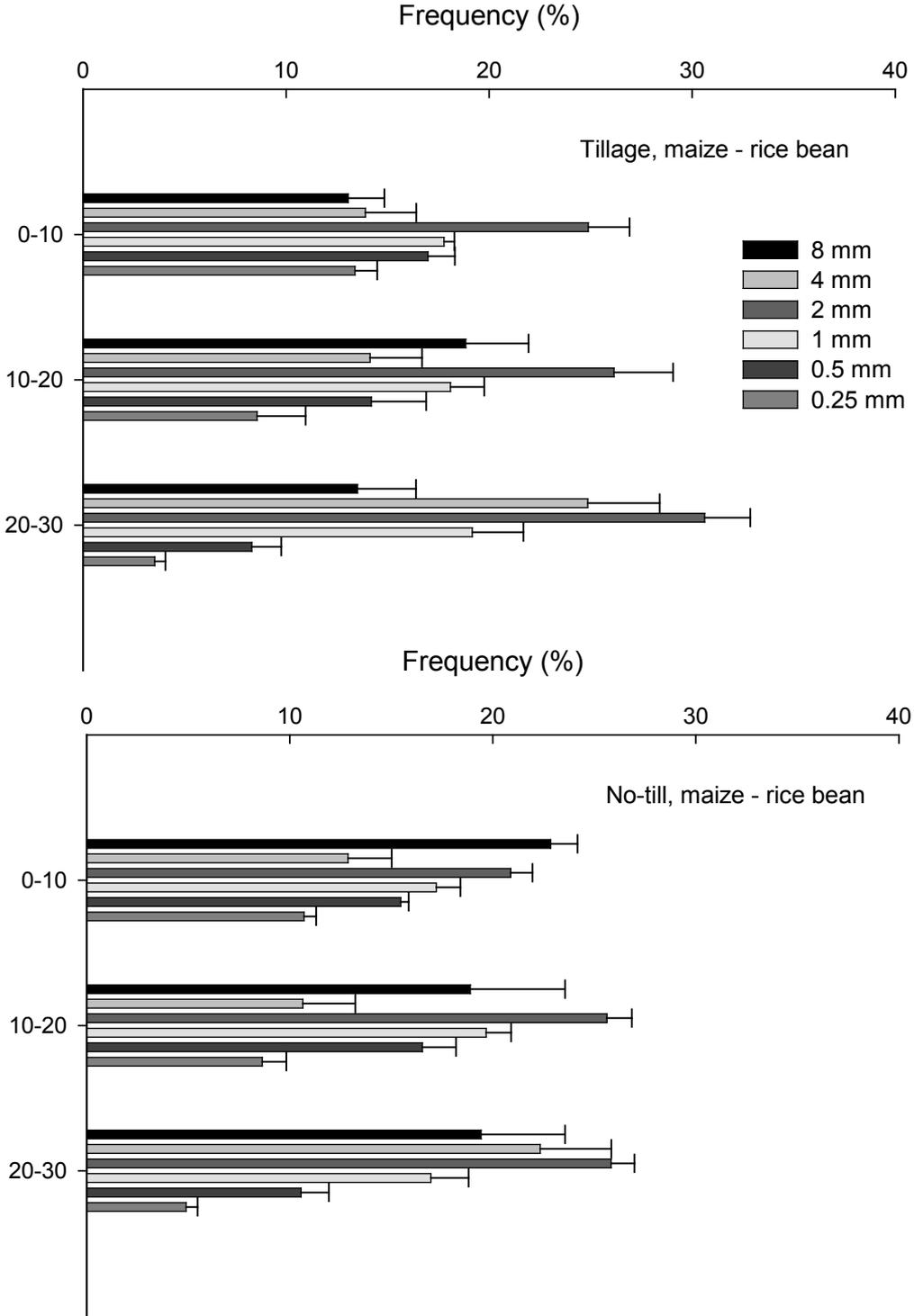


Figure 4. Mean frequency \pm SDEV (six replicates) of water-stable aggregate distribution for three depths, for tillage, no-till, in relation to the maize + *B. ruziziensis* - rice bean rotational sequence

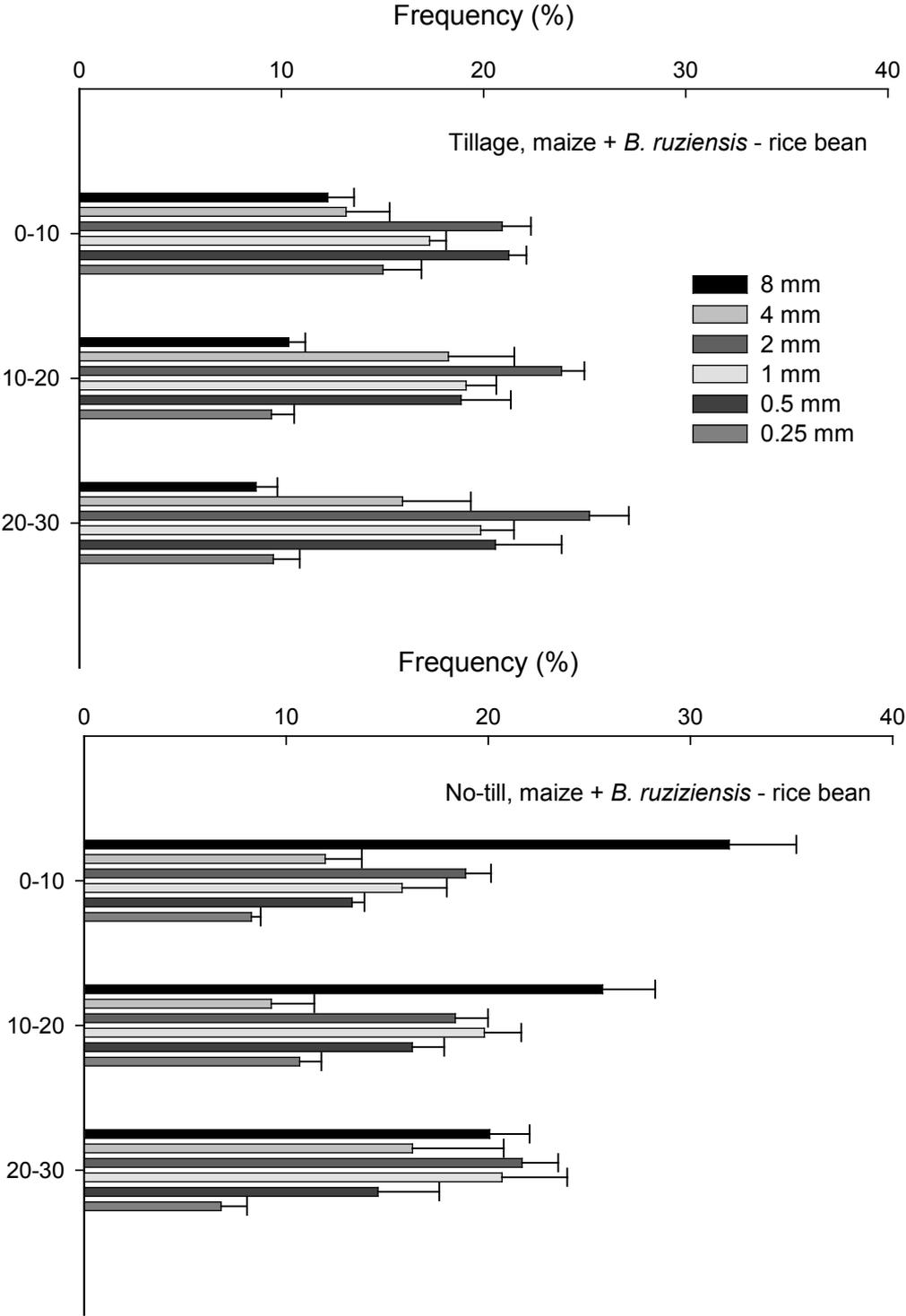


Figure 5. Box and whisker representations of the soil water-holding capacity (SWHC) in forest, cropping sequence combined with conventional tillage (CT) and no-tillage (NT). The median is illustrated in the box. The bottom of the box is at the first quartile, Q1, and the top is the third quartile, Q3. Red dashed lines indicate the mean SWHC; same letters are not significantly different at $p < 0.05$ (Duncan test). Depths of 1) 0-10 cm and 2) 0-30 cm, $n = 6$.

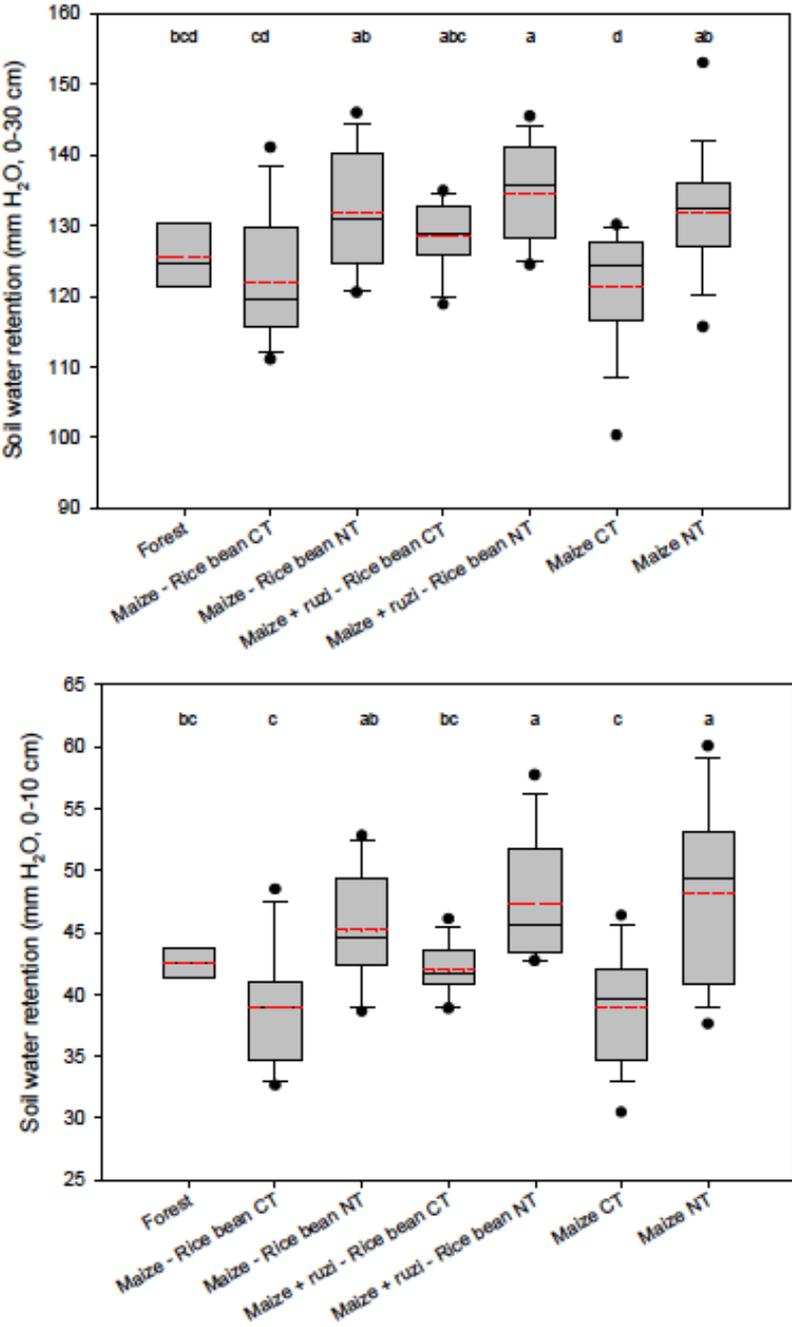
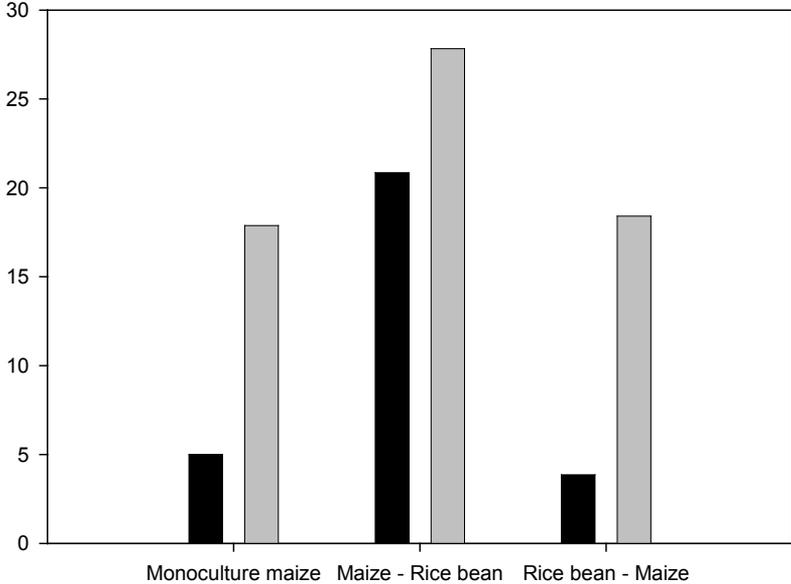
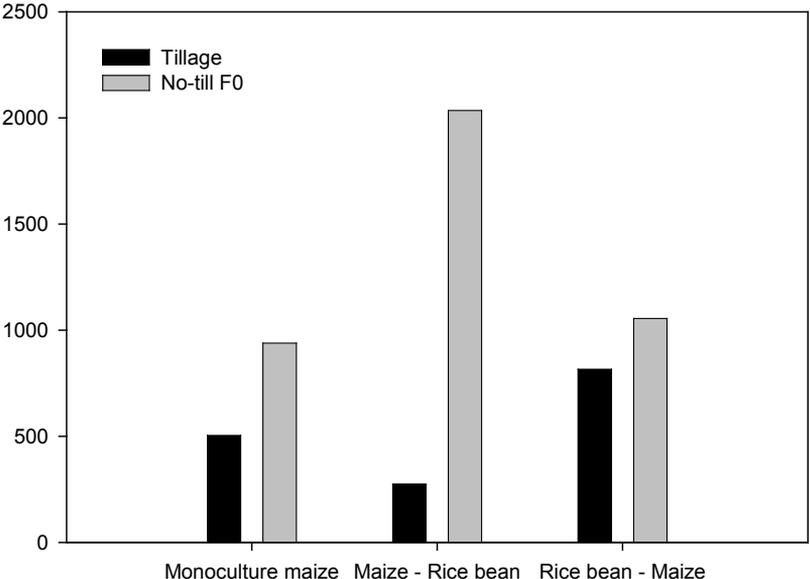


Figure 6. Density and biomass of soil macrofauna for tillage and no-tillage in relation to two cropping sequence (system 1 and 2)



Discussion

Soil aggregation, water holding capacity, and macrofauna are affected by soil and crop management (tillage, no-till, and rotational sequence). Under tillage, water-stable aggregates are disrupted, which enhance aggregate turn-over and increase decomposition of soil organic carbon (Tiessen et al. 1994; Six et al. 1998). By disrupting the soil and reducing soil organic carbon (SOC) content, tillage negatively affect the chemical, physical, and biological parameters, which cause unfavorable conditions for crop growth. In contrast, SOC content increases under no-till, rotational sequence, and use of cover crops (Sá et al. 2001; Bayer et al. 2001; Séguy, Bouzinac et al. (2001, 2006).

Soil aggregation improves soil cohesion, decreasing soil susceptibility to erosion and loss of organic matter. These effects are linked to biological activity (mycorrhizal symbionts), root exudates, polysaccharides and humic compounds, all of which are promoted by undisturbed soil and biomass production (Puget et al., 1999). Plants provide energy that fuels biological processes and either directly or indirectly creates structure within soils (Perry et al, 1989). For example, a large proportion of photosynthates is allocated to roots and much of that is diverted to mycorrhizal symbionts or exuded into the surrounding rhizosphere (Morel et al. 1990; Nguyen 2003; Jones et al. 2009). Polysaccharides produced by mycorrhizal fungi and rhizodeposition glue mineral particles together into water-stable aggregates (Aiguo Liu et al., 2005; Gobat et al. 1998; Lynch and Bragg 1985). Aggregation is the one of the main ways to protect the carbon within soil aggregates and stimulate the interactions among soil chemical, physical, and biological attributes (Tisdall and Oades, 1982; Elliot, 1986; Elliot and Coleman, 1988; Six et al, 1988).

Soil aggregation is a non-equilibrium phenomenon that is maintained and increased by periodic influx of fresh extra-cellular polysaccharides. Soil aggregation is influenced by the dynamic interaction of the below-ground ecosystem (microbial activity, rhizodeposits) and above-ground species (Perry et al, 1989; Kong et al., 2005). The beneficial functions of each species may be shown for soil aggregation, nutrient uptake and changes in SOC (Ryan et al. 2001; Jones et al. 2004).

However, the cropping sequences presented in this study produced a limited amount of dry matter. As already proposed for other tropical conditions (Séguy and Bouzinac, 2008), the main challenge is to increase biomass productivity (above-ground and below-ground) to recover ecosystem functions (recycling of nutrients, carbon sequestration, high biological activity, integrated weed and pest management, etc.) in a medium-term process (five years). Generating and adapting intensive cropping sequences under no-tillage management with small-holders is an essential step in achieving long-term land sustainability, to obtain more reliable harvests and higher farm profits.

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