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1 **Slumping dynamics in tilled sandy soils under natural rainfall and**  
2 **experimental flooding**

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19

## 1 **Abstract**

2        Compaction of tilled layers under the single effect of rainfall or irrigation was called slumping.  
3        Slumping affects strongly root development and plant biomass production and was observed in  
4        different soil types but sandy soils appear particularly prone to this physical degradation. Our  
5        objectives in this study were (i) to monitor in the field the changes in soil structure and water status  
6        simultaneously, (ii) to study the effects of rainfall and management practices on slumping and (iii)  
7        to propose a conceptual model for sandy soil slumping.

8        An experimental site was selected in Northeast Thailand and we tested the effect of tillage  
9        depth and initial water content on slumping dynamic. Plots (9 m×15 m) were tilled at (i) two depths  
10       (20 and 40 cm, called S and D respectively) in dry conditions, (ii) at 20 cm depth in dry or wet  
11       conditions (called Y and W respectively). These plots were submitted to natural rainfall for 20 or  
12       61 days to get different total rainfall amounts (114 and 212 mm respectively). In addition, smaller  
13       plots (0.24 m<sup>2</sup>) were used for experimental flooding irrigation (equivalent to measured rainfalls, i.e.  
14       100 and 200 mm). Soil bulk density, soil surface elevation, soil water content and matric potential  
15       were recorded.

16       A decrease in soil elevation was observed in all treatments. In the absence of erosion it was  
17       interpreted as a loss of porosity which resulted from slumping. Bulk density increased in all layers  
18       of the tilled profile (from 1.38 to 1.57 g cm<sup>-3</sup>). In the surface layer (0-5 cm) this increase was  
19       systematically higher compared to deeper layer. No significant difference in final bulk density was  
20       found between the S and W treatments, and between the Y and W treatments. Bulk density  
21       increased more rapidly in the Y and W treatments than in the S and D treatments, even though the  
22       cumulative rainfall was lower. After flooding experiments, bulk density was higher than after  
23       natural rainfall despite similar water amount brought to the soil.

24       The existence of a layer with 50 % porosity straight after tillage was explained by the capillary

1 forces developed by water bridges between the elementary grains. Models of wet granular material  
2 indicate that a drastic loss of cohesion can occur when the liquid phase becomes continuous.  
3 Indeed slumping was observed during the downward movement of the water front inside the  
4 profile which is consistent with this hypothesis. As the existence of a continuous liquid phase along  
5 the profile is the most determinant factor of slumping, all rainfall characteristics determining the  
6 existence of such a continuous liquid phase will affect slumping, i.e. rainfall intensity, duration and  
7 frequency. For given rainfall characteristics, slumping dynamic and intensity depend on the bulk  
8 density at the onset of the rainfall or irrigation event. The high variability recorded in earlier field  
9 result from the many possible interactions between these determining factors.

10

11 **Keywords:** Recompeaction; Bulk density; Matric potential; Northeast Thailand; Tillage;

12 Overburden pressure

## 1 **1. Introduction**

2 Soil tillage aims at creating favorable physical conditions for crop growth by modifying the soil  
3 structure and associated properties of the tilled layer (Guérif et al., 2001). However, the desired  
4 loose structure tends to be structurally unstable and is susceptible to structural collapse thus leading  
5 to a loss of the benefits for root development provided by soil (Hartmann et al., 2008a; Hamza and  
6 Anderson, 2005). Soil recompaction (i.e. bulk density increase to initial level) is a general  
7 phenomenon which has several causes related to external and internal forces. External force is  
8 defined as loading from outside the soil profile, such as tractor loading, rainfall kinetic energy;  
9 internal force is defined as force inside the soil profile, such as overburden pressure, capillary force.  
10 Soil recompaction is commonly attributed to mechanized agriculture alone because the weight of  
11 the agricultural and forestry machinery has been increased three- to fourfold as well as the  
12 frequency of wheeling during recent decades (e.g. Soane et al., 1981a, b; Soane et al., 1982; Soane,  
13 1990; Horn et al., 1995; Soane and Van Ouwerkerk, 1995; Soane and Ball, 1998; Hamza and  
14 Anderson, 2005). The phenomenon of bulk density increase recorded after wetting and without  
15 application of any external load was termed ‘slumping’ (Kemper and Rosenau, 1984; Mullins et  
16 al.1990). While compaction, i.e. the bulk density increase resulting from mechanical loading was  
17 widely studied, much less attention has been paid to slumping.

18 For coarse-textured soils, Kemper and Rosenau (1984) suggested that slumping is related to  
19 soils saturation or matric potential  $\psi$  close to 0 hPa. Slumping is a ubiquitous phenomenon and was  
20 recorded under a wide range of conditions. It was recorded after a single rainfall event (20 mm in  
21 one hour) (Mead and Chan, 1988), two natural rainfall events (80 mm in 160 min) (Hartmann et al.,  
22 1999), eight weeks of measuring (Osunbitan et al., 2005), and a cropping season (Hamblin and  
23 Tennant, 1979). Moreover, slumping can affect the whole tilled layer (such as down to 40 cm depth  
24 in Moffat and Boswell, 1997), and can have similar adverse effects on crop development as well as

1 compaction resulting from mechanical loading (Kozłowski, 1999). Despite its ubiquity and  
2 importance, no study has provided yet a detailed description of the dynamics of slumping and its  
3 main field characteristics. In the context of the extension of cultivated lands to marginal areas,  
4 which often include a high proportion of sandy soils (Eswaran *et al.*, 2007), it is a challenge to look  
5 for soil management that could minimize the occurrence of slumping. As a first step in this  
6 direction, the objectives of our study were: (i) to monitor the changes in soil structure and water  
7 status simultaneously at the field scale; (ii) to study the effects of rainfall and management  
8 practices on slumping and iii) to propose a conceptual model of sandy soil slumping.

9

## 10 **2. Material and Methods**

### 11 *2.1. Field description*

12 Northeast Thailand is a sandy alluvial plateau covered by an aeolian deposit (approximately  
13 1 m thick) mainly made of quartz grains. More than 80% of the grains belong to the sand fraction  
14 (50-2000  $\mu\text{m}$ ) and about 10% to the silt fraction (2-50  $\mu\text{m}$ ) (Lesturgez *et al.*, 2004; Bruand *et al.*,  
15 2004). The clay fraction ( $<2\mu\text{m}$ ) is less than 10% and contains phyllosilicates (mainly kaolinite and  
16 small amount of smectite) but also quartz grains (Bruand *et al.*, 2004). An experimental site was  
17 selected in a village named Baan Nong Sang (WGS84: 16°10' N, 102°48' E), 30 km south of the  
18 city of Khon Kaen. The soil is representative of the region with a sandy texture ( $<4\%$  clay), low  
19 organic matter content ( $<5\text{ g kg}^{-1}$ ) and high bulk density ( $\rho_b \geq 1.6\text{ g cm}^{-3}$ ) (Table 1 and 2). This field  
20 was planted with cassava in 2006 and harvested in February 2007. To minimize the effect of coarse  
21 crop residues fragments (cassava branches and leaves, weeds, etc.) on the different soil physical  
22 characteristics, they were removed from the plot before tillage operations. To prevent weed growth,  
23 an herbicide was applied three times during the experiment.

24

## 1 2.2. Control of the rainfall pattern and amount

2 Three experiments were conducted at different periods to get different rainfall distribution and  
3 rainfall amount:

4 - Experiment 1 (Exp. 1): plots were tilled on 25 May, i.e. at the beginning of the rainy season  
5 that is generally characterised by storms separated by several dry days. The experiment was  
6 stopped on 1 August;

7 - Experiment 2 (Exp. 2): plots were tilled on 6 July, i.e. in the middle of the rainy season to get  
8 a different rainfall pattern (more regular distribution of the rainfalls and thus less frequent dry  
9 spells). The experiment was also stopped on 1 August;

10 - Experiment 3 (Exp. 3): mini-plots (0.24 m<sup>2</sup>) were artificially flooded; the amount of water  
11 added was similar to the rainfall amount recorded in Exp. 1 and Exp. 2. The experiment was  
12 done between 18 to 26 July.

13 Rainfall was recorded daily using the average readings from two rain gauges ( $\pm 1$  mm precision)  
14 that installed inside the experimental field.

15

## 16 2.3. Experiment 1

17 The objective of Exp. 1 was to study the effect of tillage depth on slumping characteristics. Soil  
18 preparation treatments consisted of two tillage depths: 20 and 40 cm, called shallow (S) and deep  
19 (D) treatments respectively. Each treatment was applied to five elementary plots (9 m $\times$ 15 m each).  
20 Tillage was performed using a 120-horse-power tractor equipped with a set of disk plough. In order  
21 to increase the homogeneity of the resulting soil structure, the large clods left by mechanical tillage  
22 were broken into smaller pieces by labourers using rakes. To mimic the practice of farmers who  
23 want to avoid flooding of the seed rows, ridges were built by hand two days after tillage. The  
24 interval between ridges was 40 cm and their height ranged from 12 to 17 cm.

1 MonitorMeasuring days were identified by the number of days after ploughing (DAP, thus  
2 DAP 0 meaning the 25 May) and by accumulated rainfall (AR in mm) since DAP 0. Soil water  
3 potential was measured using a set of ceramic tensiometers each equipped with an electronic  
4 transducer (model 2150 and SMS-2500S, SDEC Company, France). They were installed at 5 cm  
5 intervals from 10 to 20 or 40 cm depth according to tillage depth in two different locations:  
6 underneath either the ridge or the furrow. The zero level (soil surface) was counted from the surface  
7 of the ridge or the furrow according to the location of the tensiometer. Two sets of tensiometers  
8 were installed for each treatment (S and D) as replicates. Water matric potential ( $\psi$ ) was measured  
9 after each major rainfall event or after 3 to 7 days if no rainfall event occurred.

10 Changes in soil level were measured using a horizontal frame as a stable benchmark. It  
11 consisted of a  $1 \times 1 \text{ m}^2$  frame horizontally put on four metallic rods inserted 70 cm below the soil  
12 surface and fixed by cement. The distance between the frame and the soil surface was measured  
13 using a laser beam (Lasermeter Leica Disto 6A, Leica Geosystem, Switzerland) according to a  
14  $5 \times 5 \text{ cm}^2$  grid (total of 361 data points). The vertical precision was 1 mm. For both treatments (D  
15 and S), replicates were installed in three of the five elementary plots. To measure changes in  $\rho_b$  and  
16 soil water content ( $Wc$ ), after each major rainfall event, undisturbed cylinders of soil (5 cm in  
17 height and diameter) were collected every 5 cm in depth under furrows. They were weighted before  
18 and after putting in an oven for 24 h at  $105^\circ\text{C}$

19

#### 20 *2.4. Experiment 2*

21 The objective of Experiment 2 was to study the effect on slumping of the water content at  
22 tillage. Five plots ( $9 \times 15 \text{ m}^2$ ) were left under rainfall, while five other plots were protected from  
23 rainfall using greenhouses. These greenhouses were built with bamboo sticks and covered by  
24 plastic sheets (0.8 m high); to avoid overheating and water condensation, they were opened at both



1 ends so that air could circulate. To prevent preferential water infiltration along the plots, rainwater  
2 falling on the surface of greenhouses was drained out of the field. The greenhouses were removed  
3 on the 6 July and water content was measured after putting the soil sample in an oven for 24 h at  
4 105°C.

5 The soil was tilled on the 6 July (DAP 0), at one depth only (20 cm) using the same tractor as in  
6 Exp. 1. Therefore the treatments consisted in two different  $W_c$  during tillage; the treatments were  
7 named ‘dry’ (Y) (plots under greenhouse before tillage) and ‘wet’ (W) (plots that were submitted to  
8 rainfall before tillage). Five replicates were used for each treatment. Ridges and furrows were  
9 prepared using the same procedure as in Exp. 1.

10 In both treatments (Y and W), a set of four tensiometers was installed below the furrow at 5 cm  
11 intervals from 10 to 25 cm depth. Changes in soil level were measured using a 1 m long horizontal  
12 board as a stable benchmark, which was supported by metallic rods as “legs” inserted into soil at  
13 70 cm depth as in Exp. 1. One replicate of this device was installed in each of the ten subplots. The  
14 distance from the benchmark to the soil surface was measured using the laser beam every 2.5 cm  
15 (total of 38 data points). The  $\rho_b$  and  $W_c$  were measured using the same procedure as in Exp. 1.

16

### 17 *2.5. Experiment 3*

18 The objective was to mimic a continuous rainfall and to measure the consequences on slumping  
19 characteristics. Three supplementary plots were covered by greenhouses to keep the soil dry.  
20 Metallic rings (55 cm in diameter) were inserted deeply in the soil (60 cm) to be used as stable  
21 benchmark for soil level recording. The soil inside the ring was hand tilled using a small paddle and  
22 rake to mimic the soil tractor tillage and hand raking as in Exp. 1 and 2. Soil preparation treatments  
23 consisted of two tillage depths: 20 and 40 cm, called “shallow-tillage flooding” (Sf) and  
24 “deep-tillage flooding” (Df) respectively. Three rings were installed for each treatment. Unlike Exp.

1 1 and 2, the soil surface was flat (no ridges and furrows were built). Tensiometers were not used  
2 because the time was too short to obtain a good equilibrium between tensiometer and soil.

3 The amount of added water was 100 mm and 200 mm for Sf and Df treatments respectively.  
4 The soil surface was covered by a straw textile and water was added by increments of 25 mm water.  
5 To avoid kinetic energy, the water was poured on a hand as a buffer so that it gently felt on the  
6 textile over the whole surface. Infiltration time was recorded and after each addition of 25 mm  
7 water, the soil surface level was measured every 5 cm along a horizontal “board” that was put on  
8 the top of the metallic ring (10 measurement points each time) using the lasermeter. After the last  
9 addition of water and measurement of soil level, a small pit was opened inside the ring. The bulk  
10 density and water content were measured with 5 cm interval from surface to 20 and 40 cm depth in  
11 Sf and Df respectively. Three replicates samples were taken inside each ring.

12

### 13 2.6. *Statistical analysis*

14 The data were analyzed statistically using ANOVA by SPSS 13.0 (SPSS Inc., 2004). The least  
15 significant difference (LSD) at  $P = 0.05$  was used to establish the significance of differences  
16 between treatment means. When applicable, paired-samples T tests were done.

17

## 18 3. Results

### 19 3.1. *Rainfall characteristics*

20 Fig. 1 presents the daily rainfall events and the accumulated rainfall (AR). During 61 days for  
21 Exp. 1, AR was 212 mm, approximately twice as much as in Exp. 2 (114 mm) which lasted only  
22 20 days. Exp. 2 was done during the middle of the rainy season and had higher average daily  
23 rainfall than Exp. 1 which started earlier:  $5.7$  and  $3.4 \text{ mm d}^{-1}$ , respectively. More than half of AR in  
24 Exp. 2 resulted from two successive big rainfall events (22 and 36 mm) which occurred at the end

1 of the experiment.

2

### 3 3.2. Experiments 1 and 2

#### 4 3.2.1. Soil matric potential ( $\psi$ ) and water content ( $Wc$ )

5 For Exp. 1 and Y treatment (dry protected plots) in Exp. 2,  $Wc$  was ranging 0.04 to 0.06 g g<sup>-1</sup>; or  
6 W (unprotected wet plots) in Exp. 2,  $Wc$  was significantly higher ( $p < 0.05$ ), ranging 0.08 to 0.10 g  
7 g<sup>-1</sup> (data not shown).

8 Fig. 2 presents the matric potential ( $\psi$ ) measured under furrows and ridges in Exp. 1 (D  
9 treatment), under furrows in Exp. 2 (W treatment). During Exp. 1, minimum and maximum matric  
10 potential (*i.e.* driest and wettest soil respectively) were -120 and -40 hPa respectively. No  
11 significant difference was observed between tensiometers installed under a furrow or under a ridge,  
12 and no significant difference was observed between the D and S treatments (data not presented). At  
13 a given time, we recorded similar minimum and maximum  $\psi$  in Exp. 1 and Exp. 2. Moreover, no  
14 differences were observed with the W and Y treatments compared with the D treatment in the 0-20  
15 cm layer (data not presented).

16 In the top layers (0-20 cm), a rapid increase in  $\psi$  was observed after rainfall events (e.g. DAP  
17 41 and DAP 58), but a slow and regular  $\psi$  decrease was observed during the different dry spells (e.g.  
18 from DAP 47 to 51). In the 35 cm layer, changes were buffered: the  $\psi$  was significantly affected  
19 only by the two successive big rainfall events recorded at the end of the experiment (DAP 59 and  
20 60, 22 and 36 mm respectively).

21 For Exp. 1 and 2, it is noteworthy that at the end of the experiments (DAP 59 and 60), the  
22 highest  $\psi$  at 10 cm depth was recorded after the first rainfall event (-40 and -50 hPa respectively in  
23 the top layer) while higher  $\psi$  was expected after the second rainfall event (approximately twice as  
24 much water input as the first event). This discrepancy is a consequence of manual monitoring: at

1 DAP 59,  $\psi$  was recorded shortly ( $< 1$  h) after the rainfall event; while at DAP 60, it was recorded  
2 more than 10 h after the rainfall event. For the latter, the water front had already drained deeper in  
3 the profile as indicated by the drastic increase in  $\psi$  in the 35 cm deep layer, an increase which was  
4 not observed after the first rainfall.

5 At the end of the experiment, in all plots, whatever the initial  $W_c$  at the tillage depth,  $W_c$  ranged  
6 from 0.08 to 0.13 g g<sup>-1</sup> (data not shown). There was no significant difference between D and S, and  
7 between Y and W.

8

### 9 3.2.2. Soil surface elevation and bulk density

10 After each major rainfall event, a decrease in soil roughness was observed: the height of ridges  
11 decreased while furrows were filled with sandy material, and consequently the field became more  
12 flat (Fig. 3). This change in the topography of the soil surface indicated movements of solid  
13 particles from the top of ridges to the bottom of furrows, but we didn't observe any erosion  
14 (particles moving outside the field). The average soil level was calculated for the different  
15 treatments (Fig. 4). A level decrease was observed in all plots (ranging from 1.2 to 1.7 cm), but no  
16 significantly difference was found between the different treatments.

17 Average  $\rho_b$  profiles under furrows are shown in Fig. 5. Immediately after tillage, all profiles  
18 were characterised by a regular increase with depth. For shallow tillage (S, Y, W treatments, 20 cm  
19 depth), the differences between  $\rho_b$  at top and bottom of tilled layer ranged from 0.05 to 0.10 g cm<sup>-3</sup>.  
20 For deep tillage (D treatment, 40 cm depth), this increase was higher (0.15 g cm<sup>-3</sup>) indicating an  
21 effect of tillage depth. When the soil was tilled in dry conditions (S, D and Y treatments), a shift  
22 towards higher  $\rho_b$  values was observed at all depths with increasing AR. Initial bulk density in the  
23 profile was already higher when ploughing was performed at wet conditions. The shift was higher  
24 in the top layer than in deeper layers. When the soil was tilled in wet conditions (W treatment), no

1 change in  $\rho_b$  was observed in relation with increasing AR, except in the top layer (0-5 cm) at the  
2 end of the experiment.

3

### 4 *3.3. Experiment 3*

5 During the first addition, the infiltration rate was 450 and 600 mm h<sup>-1</sup> for Sf and Df respectively  
6 (Fig. 6a). During the following additions, IR decreased until it was stabilised around 100 mm h<sup>-1</sup>.  
7 The same value was observed in both treatments, suggesting that tillage depth did not influence the  
8 infiltration rate. For the first three water inputs, the sinkage rate increased at each input (-1.0, -1.2,  
9 -1.4 cm in Df treatment) (Fig. 6b). For all the following water inputs it decreased continuously  
10 (from 0.6 cm with 100 mm input to 0.1 cm with 200 mm input in Df treatment). Tillage depth  
11 affected the soil level decrease: at 100 mm water input, it was only 2.7 cm for Sf compared to  
12 4.2 cm for Df treatment. Just after tillage,  $\rho_b$  profile increased with depth: at the bottom of the tilled  
13 layer  $\rho_b$  was about 0.3 g cm<sup>-3</sup> higher than at the surface (Fig. 7). At the end of the experiment, for  
14 both Df and Sf,  $\rho_b$  shifted to higher values on all the profile,  $\rho_b$  being higher close to the surface  
15 than at the bottom (about 0.5 and 0.2 g cm<sup>-3</sup> respectively).

16

## 17 **4. Discussion and conclusion**

### 18 *4.1. Evidence of slumping*

19 The soil surface reorganisation which was recorded during Exp. 1 and 2 and which consisted  
20 in a decrease in the soil roughness (Fig. 3) was commonly observed in coarse-textured soils and  
21 discussed as closely related to their low structural stability when submitted to rainfall ([Mwendera  
22 and Feyen, 1994](#); [Rudolph et al., 1997](#); [Twomlow and Bruneau, 2000](#)). Our results show that soil  
23 reorganisation affected not only surface but also the whole tilled horizon. In the three experiments

1 and whatever the treatment, a soil sinkage was recorded, i.e. a decrease in soil surface elevation  
2 (Fig. 4 and Fig. 6b). As no erosion was observed during the experiment (i.e. no mass movement out  
3 of the field), such an elevation decrease in soil surface necessarily resulted from a loss of pore  
4 volume, i.e. from an increase in soil compactness. Soil sinkage did not happen regularly over time  
5 but was related to the occurrence of rainfall events, and consequently can be considered as an  
6 indicator of *soil slumping* as defined by Mullins et al. (1990). Soil sinkage cannot be observed by  
7 the naked eye even if it is probably a common phenomenon in coarse textured soils, thus explaining  
8 the rarity of its description (Wilton, 1964; Young et al., 1991; Moffat et al., 1997; Or and Ghezzehei,  
9 2002). Even if soil sinkage is a relevant indicator of slumping occurrence, it does not provide any  
10 information about how compactness evolves with depth in the soil.

11

#### 12 4.2. Soil structure after tillage

13 After tillage, the  $\rho_b$  profile presents two striking aspects. First, the  $\rho_b$  increased regularly with  
14 depth (from  $1.26 \text{ g cm}^{-3}$  at surface to  $1.44 \text{ g cm}^{-3}$  at 40 cm depth), thus indicating a closer packing  
15 of the soil particles when going deeper in the profile (Fig.5 and 7). Second, the  $\rho_b$  values  
16 (correspond to porosity ranging from 53 to 45%) were very low in sandy soils since it results  
17 mainly from the packing of coarse grains.

18 This loose packing was created by tillage: the energy developed by the disks was enough to  
19 separate most elementary particles which were lifted up, increasing their potential energy. This  
20 energy was dissipated when the particles moved downward under the effect of gravity. During the  
21 piling process, each time a contact occurred between neighbouring particles, the downward  
22 movement was hampered due to (i) mechanical friction, and (ii) capillary bridges developing  
23 between the grains. At  $W_c < 0.12 \text{ g cm}^{-3}$ , as measured before tillage (data not presented), water can  
24 be located only at the contact points between two particles, forming bridges (Willet et al., 2000;

1 Adams et al., 2002; Herminghaus, 2005). These bridges act as glue bonding the particles together  
2 in relation with the water interfacial tension and negative Laplace pressure (Kemper and Rosenau,  
3 1984). The development of water bridges hampered the flow of solid particles and blocked the sand  
4 grains into a loose packing. But during the piling process, the overburden pressure was gradually  
5 increasing with depth, forcing the grains to rearrange in a continuously closer packing, resulting in  
6 a regular  $\rho_b$  increase with depth. This could be a general behaviour in tilled sandy soils (Ampoorter  
7 et al., 2007). The stability of the tilled layer results from capillary bridges and is consequently low,  
8 but in the absence of mechanical loading, it is stable until occurrence of rain and subsequent  
9 slumping.

10

#### 11 4.3. Water characteristics inducing slumping

12 No relation was found between rainfall amount and slumping characteristics (occurrence,  
13 intensity, dynamic): (i) slumping was triggered by a small but variable amount of water (34 mm in  
14 Exp. 2 but only 25 mm in Exp. 3), (ii) despite similar large amounts of water brought to the soil  
15 (~200 mm), the intensity of slumping was much higher in Exp. 3 than in Exp.1 (soil sinkage of 4.6  
16 and 1.2 cm respectively), (iii) when at the end of Exp.1 and 2, AR were very different (200 mm and  
17 100 mm respectively), intensity of slumping was similar, i.e. same final  $\rho_b$  ( $>1.4 \text{ g cm}^{-3}$  below  
18 10 cm), and (iv) slumping was faster in Exp. 3 compared to Exp 1 (nearly finished after 75 mm  
19 water input in Exp. 3 when still observed after 132 mm water input in Exp.1) (Fig. 5).

20 The lack of a global relation between slumping and rainfall characteristics, suggests that not all  
21 rainfall events have the same potential to induce slumping. A soil material is stable as long as it  
22 meets the Mohr-Coulomb criterions:

$$23 \quad \tau = \mu\sigma + c \quad (1)$$

1 where  $\tau$  is the shear stress,  $\sigma$  is the normal force,  $\mu$  is the internal friction coefficient and  $c$  is  
2 cohesion. The cohesion is equivalent to the shear stress at zero normal force and it depends on (i)  
3 both the amount and type of clay and organic matter (i.e. permanent bonds), and (ii) the water  
4 content (Le Bissonnais et al., 1995). Sandy soils have low clay and organic carbon content,  
5 consequently water becomes a major factor of cohesion between the elementary particles and  
6 globally of structural stability (Panayiotopoulos and Mullins, 1985, Panayiotopoulos, 1989).  
7 Kemper et Rosenau (1984) suggested that slumping was related to soil saturation and resulting lack  
8 of cohesion between the elementary particles. Recent development on the physics of wet granular  
9 material, like sandy soils, suggest that slumping would occur before reaching water saturation.

10 Indeed, in a sandy material, the relation between soil cohesion and water content is not linear,  
11 two successive stages need to be considered (Pierrat and Caram, 1997; Iveson et al., 2002; Mitarai  
12 and Nori, 2006): at the first stage, water is located only at the contact between grains and is filling  
13 the packing pores between neighbouring grains creating separated clusters of grains (Kohonen et  
14 al., 2004; Scheel et al., 2008). The second stage starts after all the packing pores were filled with  
15 water when the liquid phase becomes continuous (Herminghaus, 2005). The second stage is  
16 characterised by a drastic decrease in development of air/water interfaces and thus a drastic  
17 decrease in macroscopic cohesion (Soulié et al., 2006; Grof et al., 2008). Such a model suggests  
18 that slumping in sandy soils would be triggered before reaching saturation, when rainfall amount is  
19 high enough to obtain a continuous liquid phase draining down in the profile. Compared to natural  
20 tilled sandy soil, the experimental and mathematical models studied by physicists are simplified  
21 (the particles size distribution is limited and the grains are in close packing). Even so, it is still a  
22 challenge to determine  $W_c$  or  $\psi$  that corresponds to a continuous liquid phase in these models and it  
23 is not yet possible for real soils. Anyway, such liquid phase continuity in sandy material can be  
24 observed during fast downward movement of the wetting front that correspond to a locally high  $W_c$



1 and  $\psi$  (Kawamoto et al., 2004)

2

#### 3 4.4. Slumping dynamics and water infiltration

4 In Exp.3 water supply was continuous, creating an infiltration and thus a downward movement  
5 of the wetting front. Soil and water characteristics were recorded during and immediately after  
6 (<1h) water supply. During the first water input, soil surface sinkage (indicating a rearrangement of  
7 elementary grains) was observed; sinkage intensity increased until the third addition of water, then  
8 it decreased again and even if it was small, sinkage was observed until the last water input (Fig. 6b).  
9 This result confirms that slumping occurred during the downward movement of the wetting front,  
10 i.e. before saturation, contrary to the suggestion of Kemper and Rosenau (1984). Similar fast  
11 rearrangement was already recorded in an independent field experiment during which the largest  $\rho_b$   
12 increase occurred within the first 10 min of rainfall (Bedaiwy and Rolston, 1993).

13 Exp. 1 and 2 were conducted under natural rainfall events and were characterised by slower  
14 slumping dynamic. Soil and water characteristics ( $\rho_b$ ,  $\psi$ ,  $Wc$ ) were monitored manually at the  
15 interval of one to seven days; consequently our device could not record any fast water front  
16 movement. Anyway, structural changes (soil surface sinkage and bulk density increased) were  
17 observed only after the limited number of major rainfall events, events that occurred similarly  
18 during Exp. 1 and 2 (Fig. 1). This observation is consistent with the hypothesis that all rainfall  
19 events do not have the same capability to induce slumping; in the context of our experiment, only  
20 events > 15 mm induced fast wetting front infiltration and significant structural changes (surface  
21 level decrease, bulk density increase).

22 In Exp. 3, a steady state was reached earlier for infiltration rate than for soil elevation decrease  
23 (Fig. 6a and Fig. 6b). This suggests that infiltrability is not a good indicator of slumping (direct  
24 observations of structural changes have to be preferred). On the other hand, these data can also

1 provide some indications on the characteristics of sand grains rearrangement at the onset of the first  
2 major rainfall. The steady state observed for infiltration when slumping was still on process  
3 indicates that the continuity of the porosity (a major factor of infiltration rate) decreased faster than  
4 total pore volume (Nimmo and Akstin, 1988; Meek et al., 1992). In a pile of grains that results from  
5 a loose packing of grains linked together only by capillary water bridges, the first grains to be  
6 unbalanced are probably the biggest ones. They are indeed the most strongly pulled by gravity and  
7 less strongly hold by capillary bridges. Once unbalanced, those grains can ‘fall’ in the large pores  
8 (with 50% porosity, the volume occupied by porosity is the same as occupied by particles). This  
9 reorganisation would explain the fast infiltration decrease related to (i) a decrease in the volume of  
10 large pores (i.e. that allows fast water movement), and (ii) a decrease in the continuity of the  
11 remaining smaller packing pores.

12

#### 13 *4.5. Soil factors affecting slumping*

14 Previous experiment demonstrated that under similar rainfall events, slumping could differ in  
15 relation with soil management (Meek et al., 1988; Bedaiwy and Rolston 1993, Hartmann et al,  
16 2008a,b). Our experiment confirmed that the relative change of  $\rho_b$  was inversely correlated with the  
17 initial  $\rho_b$  as already suggested by Bedaiwy and Rolston (1993). For exemple, compared to the  
18 shallow layers, the deep layers had the highest  $\rho_b$  after tillage, and they had also the smallest  $\rho_b$   
19 increase during the experiment. Less slumping was also observed when the soil was initially wet  
20 compared to when it was initially dry (Fig. 6). As the wet sandy soils are more sensitive to  
21 mechanical stresses than dry soils (Panayiatopoulos et al., 1989; Meek et al., 1992), during the  
22 tillage operations the W plots were probably more affected by mechanical constraints induced by  
23 the disk than the Y plots. This suggests that the factor hampering the slumping process in W  
24 compared to Y treatment was its higher initial  $\rho_b$  and not its higher  $Wc$ .

1 While inside the profile, the relative  $\rho_b$  change was inversely correlated to the initial  $\rho_b$ , the top  
2 layer behaved differently:  $\rho_b$  increase was constant and was finally huge compared to the  
3 underlying layers. In first estimate, a different behaviour of the top layer seemed to be related to a  
4 lateral sand movement from the ridge and accumulation on the surface of the furrow (Exp.1 and 2,  
5 Fig. 3). But similar increase was recorded in Exp. 3 which had a flat surface and where no lateral  
6 movement occurred. On a flat surface, the soil structure can also be degraded by vertical  
7 segregation of clay and sand fractions due to the kinetic energy of the raindrops and result in  
8 different surface crusts (Casenave and Valentin, 1992). Such crusts are only some millimeters thick  
9 (Biielders and Bavey, 1995; Roth, 1997; Fohrer et al., 1999; Ndiaye et al., 2005) and cannot explain  
10 changes at several centimeters depth and deeper in the tilled layer. Indeed, the surface layer is  
11 characterised by (i) a very small normal force  $\sigma$  (Eq (1)) due to quasi absence of overburden  
12 pressure, and (ii) a frequent occurrence of high  $W_c$ , even during minor rainfall events. These two  
13 specific characteristics can explain that the particle reorganisation at the surface is different from  
14 that observed below the surface layer.

15 Since surface heterogeneity can induce preferential water infiltration (Twomlow and Bruneau,  
16 2000), the presence of ridges and furrows has to be mentionned: slumping was perhaps also  
17 influenced by that specific surface topography, but we have not collected any data that allows a  
18 estimation on the effect of this factor .

19

#### 20 4.6. A conceptual model of soil slumping

21 When Kemper and Rosenau (1984) and Mullins et al. (1990) suggested the existence of a  
22 specific degradation process named slumping, they did not provide any information about its  
23 kinetic, and the underlying processes and determinant factors. Here we suggest a scenario of  
24 slumping in sandy soils and a list of determinant factors based on our experiment. Slumping kinetic

1 can be separated in three main steps (Fig. 8): (i) creation of an initial loose profile with a regular  $\rho_b$   
2 increase with depth after tillage, the cohesion and stability of these layers resulting from the strong  
3 capillary forces between elementary grains (Fig. 8-a), (ii) during major rainfall events or under  
4 irrigation, a fast increase in  $\rho_b$  in all tilled layers, the loss of cohesion resulting from the  
5 development of a continuous (but transient) liquid phase along the profile (Fig. 8-b), and (iii) after  
6 each major rainfall, when the soil is gradually getting denser, the slumping intensity is decreasing  
7 because of steric constraints to reorganisation, except for the surface layer where bulk density  
8 seems to be continuously increasing (Fig. 8-c). As the existence of a continuous liquid phase along  
9 the profile is the most determinant factor of slumping, all rainfall characteristic determining the  
10 existence of such continuous liquid phase will affect slumping, i.e. rainfall intensity, duration and  
11 frequency. For given rainfall characteristics, slumping dynamic and intensity depends on the bulk  
12 density at the onset of the rainfall or irrigation event. The high variability recorded in earlier field  
13 works (for example: Mead and Chan, 1988; Meek et al., 1988, Hartmann et al., 1999 ; Osunbitan et  
14 al., 2005) result from the many possible interactions between these determining factors.

15 Further experiments should include a better control of experimental conditions associated to  
16 more accurate recording at the time scale of the rainy events to obtain new data enabling to  
17 establish a quantitative model and consequently improve our knowledge and prevision of the  
18 elementary mechanisms of slumping.

19

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6

7

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1 **Legend of the figures**

2

3 Fig. 1. Rainfall distribution and accumulated rainfall (AR) in Exp.1 and Exp.2. DAP is day after tillage for Exp.1,  
4 which started from 25 May 2007. DAP' is day after tillage for Exp.2, which started from 6 July 2007.

5

6 Fig. 2. Matric potential of a) Top: D (40 cm tillage) under furrow (—■—) and under ridge (—▲—); b) Bottom: S  
7 (under furrow). Average values (n=3) are shown.

8

9 Fig.3. Soil surface level recorded in Exp.1, example of one subplot; left side is DAP4 and right side is DAP60.  
10 Measurements were made along a regular grid 5x5 cm (i.e. 361 measurement points).

11

12 Fig.4. Mean soil height with cumulated rainfall. D and S are Deep (40 cm) and S shallow (20 cm) tillage  
13 respectively; W and Y indicate tillage made in wet and dry soil respectively. Each line is one replicate from the  
14 subplot. The numbers indicate mean values of level decrease with standard errors in the brackets. Note: The  
15 reference level was the board arm that support lasermeter. The arm was fixed with iron sticks fixed deep in the  
16 soil. The absolute value of soil height was not important, but the relative soil height that measured at different  
17 time was our aim.

18

19 Fig. 5. Bulk density collected under furrow after major rainfall events during Exp.1 and Exp.2. D and S are Deep  
20 (40 cm) and S shallow (20 cm) tillage respectively (n=5); W and Y indicate tillage made in wet and dry soil  
21 respectively (n=9). DAP and DAP' are the number of days after tillage for Exp.1 and Exp.2 respectively; AR is  
22 the accumulated rainfall since tillage day. Error bar indicates standard error of mean (SEM).

23

24 Fig.6. a) Soil infiltration rate decreased with added water amount, b) Soil surface level change with added water  
25 amount. The soil was protected from rainfall under plastic before tillage. Error bars indicate standard error of  
26 means (n=9). D-f is deep flooding; S-f is shallow flooding.

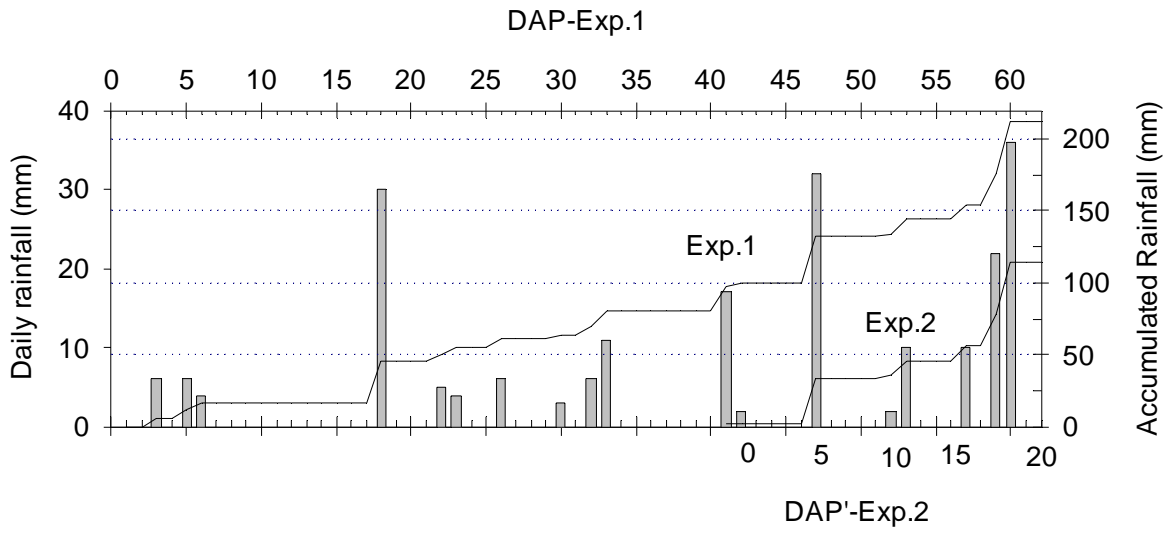
27

1 Fig. 7. Bulk density after flooding. 200 mm water was added into “D-f” and 100 mm water into “S-f”. Error bar  
2 indicates standard error of mean (SEM) (n=9). D-f is deep flooding; S-f is shallow flooding.

3

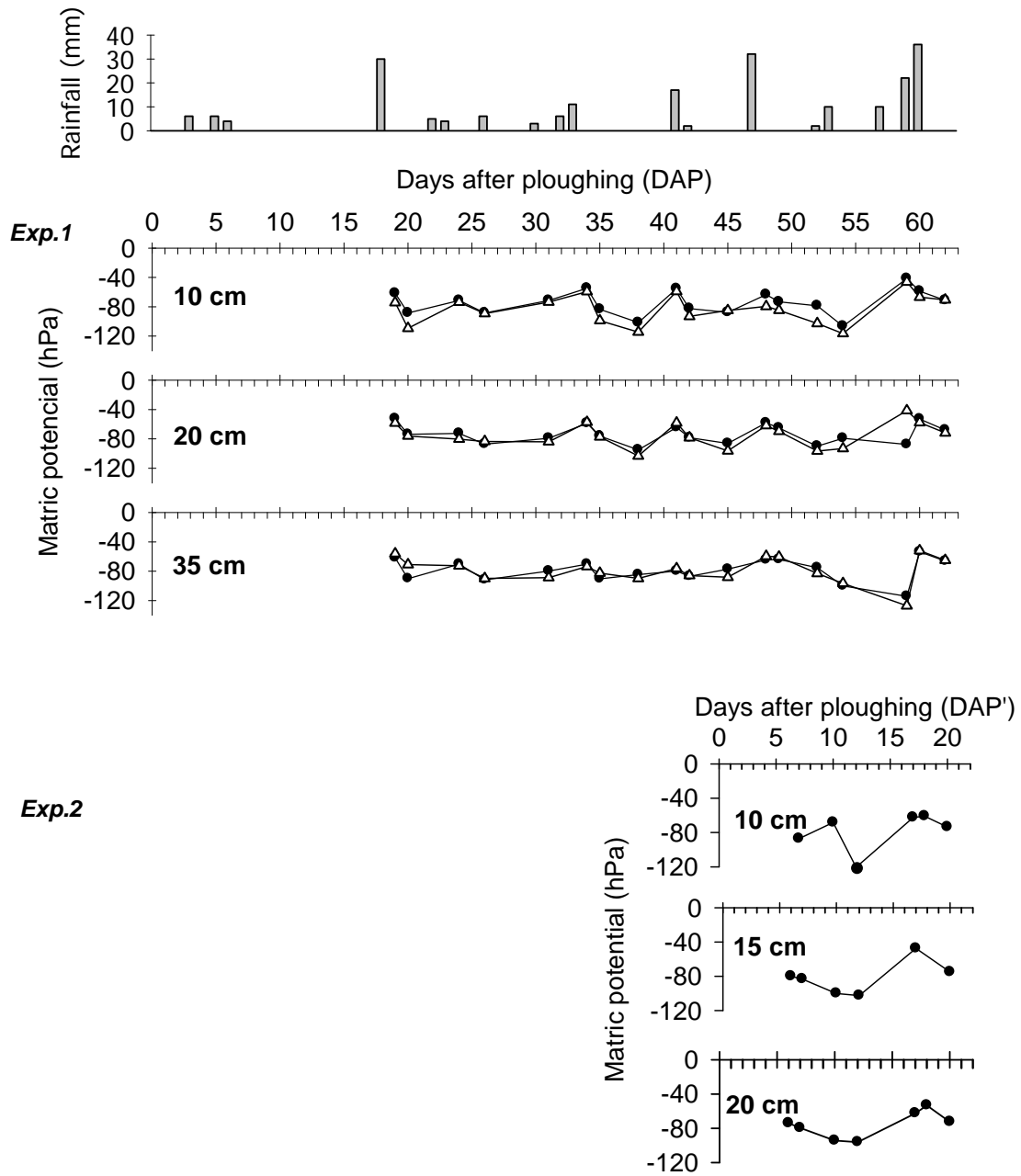
4 Fig.8. Schematic diagram of possible slumping dynamic profiles in tilled sandy soil. a) just after tillage, b)  
5 beginning of slumping, c) with maximum bulk density at surface and deeper layer, d) a comparison profile after  
6 mechanical compaction, maximum bulk density occurs in the intermediate layer.

1



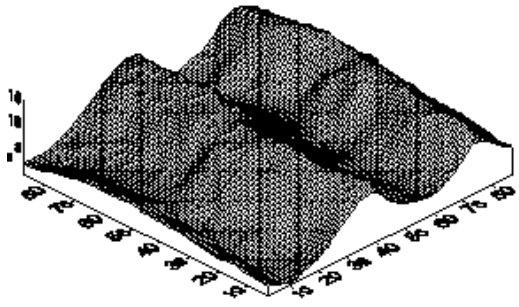
2  
3 Fig. 1

1 a)



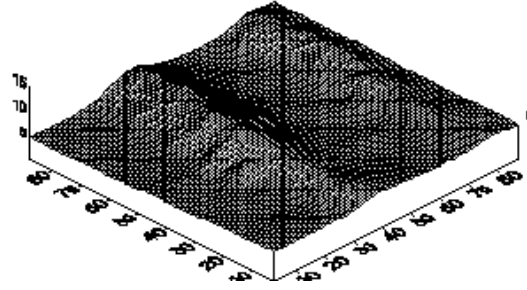
2  
3 b)  
4 Fig. 2

1  
2

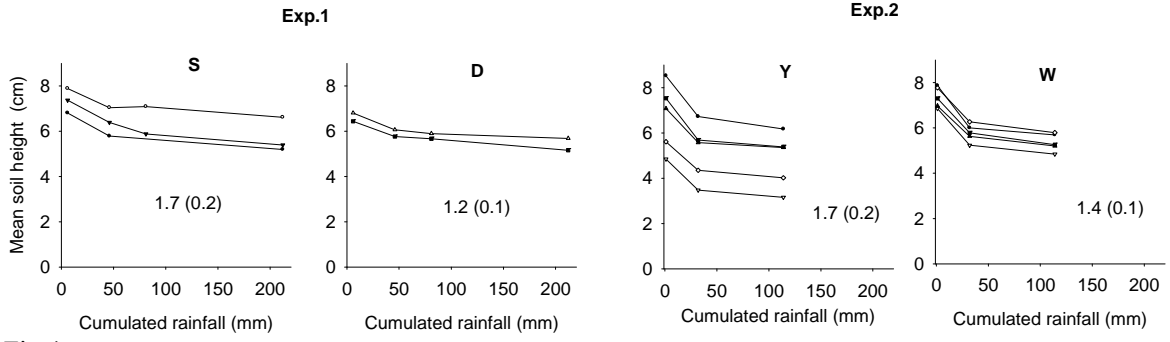


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Fig.3



1

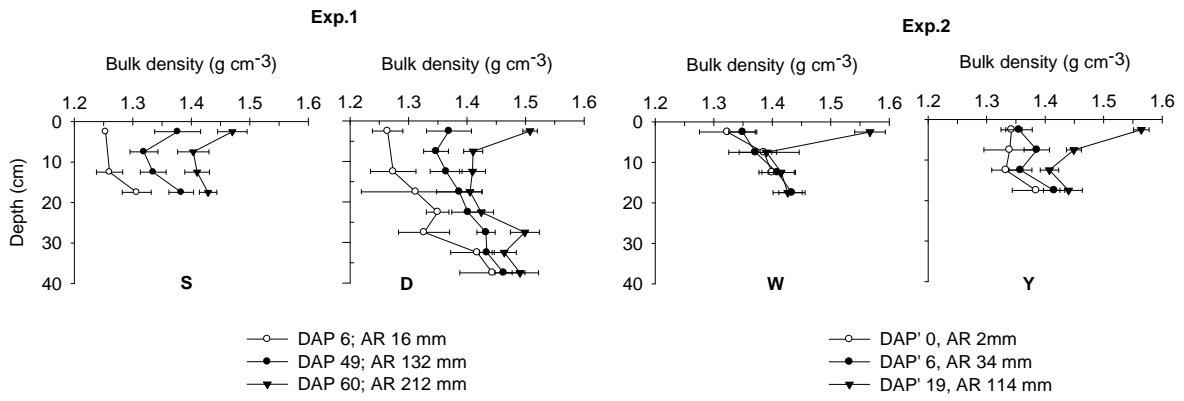


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Fig.4



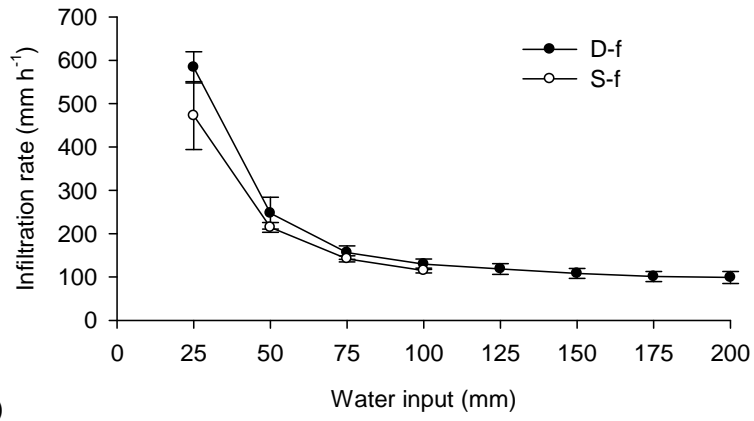
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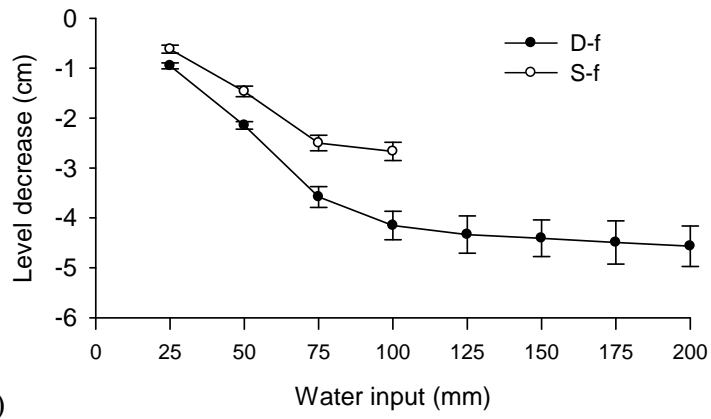
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Fig. 5

1



2 a)

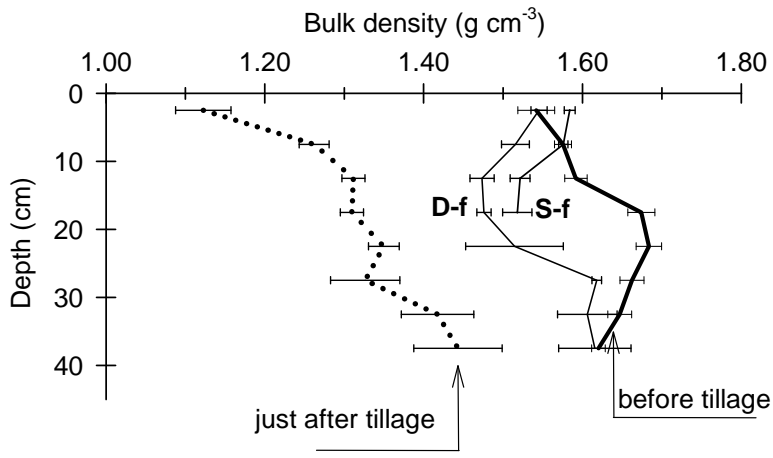


3 b)

4

5 Fig.6

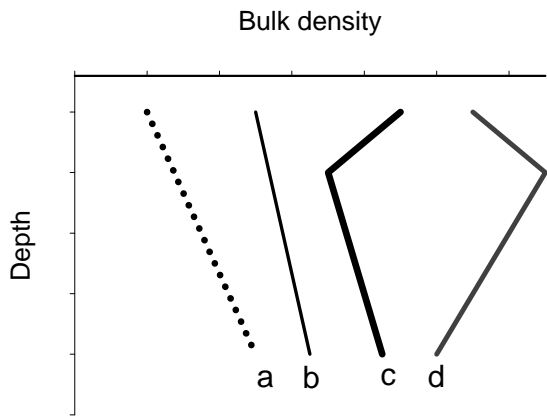
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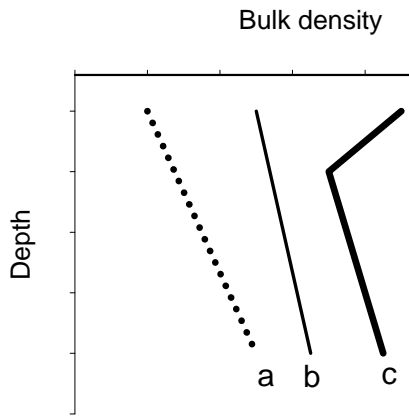
2  
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Fig. 7

1



2



3

4 Fig.8

1 **Tables**

2  
3  
4

5 Table 1. Selected physical and chemical properties of soil measured one day before tillage.

6

Depth	Sand (%)	Silt (%)	Clay (%)	Organic mater	Bulk density	RP	SS
(cm)	50-2000 $\mu\text{m}$	2-50 $\mu\text{m}$	<2 $\mu\text{m}$	(g kg <sup>-1</sup> )	(g cm <sup>-3</sup> )	(kPa)	(kPa)
0-20	90	9	1	4.5	1.60	13	4.6
20-40	86	11	3	4.6	1.65	33	5.6
40-60	86	11	3	1.9	1.62	32	5.1

7

8 RP: Resistance to penetration, measured by datalogger penetrometer.

9 SS: Shear strength, measured by Hand Held Field Vane Shear Test (Helwany, 2007).

10

11

12

13 Table 2. Particle size distribution of soil (g kg<sup>-1</sup>) at 0-20 cm layer. It was measured by laser  
14 diffraction granulometer (Malvern Instruments).

15

	Clay	Silt	Sand					
Size ( $\mu\text{m}$ )	0-2	2-50	50-100	100-150	150-200	200-250	250-500	500-2000
Content	26	101	205	176	209	171	112	3

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