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Seedbed structure of major field crops as affected by cropping systems and climate: Results of a 15-year field trial

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Abstract

Seedbed structure directly or indirectly affects crop establishment by modifying seed-soil contact, acting as mechanical obstacles or modifying temperature, moisture and oxygen contents of seedbed as well as the dynamic of pests, pathogens and weeds. However, very few detailed descriptions of seedbed's structure of major field crops exist to date, in terms of precise aggregate size distributions in relation to different factors including the cropping system (CS), soil and climatic conditions and their interactions. Here, we characterized seedbeds of major European field crops across three CSs over a 15-year period (1991-2005) of a long-term field experiment. CS I was the succession of spring pea/winter wheat/oilseed rape/winter wheat. Likewise, CSs II and III were the succession of sugar beet/winter wheat/maize/winter wheat with different sowing dates based on two different decision rules aimed at: minimizing the risk of soil compaction in the CS II or maximizing the duration of the crop in the CS III. We classified three types of seedbed structure, namely fine (with >20mm soil aggregates <15%), intermediate (with >20mm soil aggregates >15<25%), and coarse (with >20mm soil aggregates >25%). We found a statistically significant effect of CSs ($P<0.05$), crops ($P < 0.001$), previous crops ($P < 0.01$) and year ($P < 0.001$) while no significant effect of wheel traffic ($P>0.05$) and tillage ($P>0.05$) was observed on the soil aggregates > 20 mm. No irreversible effect of the CSs was observed over the study period on seedbed structure and the consequent risks of generating coarser seedbeds, which is unfavorable for crop establishment. This dataset offers a unique description of the seedbed structure variations for major European field crops. This information can be used for future simulation studies of crop emergence, using, for example, the SIMPLE model that has seedbed structure as one of the input variables.

Key words: seedbed preparation, seedbed structure, soil aggregates, cropping systems

1. Introduction

Seedbed structure can significantly affect early growth and development of the crop, by altering abiotic components of the seedbed including soil-plant contact, mechanical forces exerted on plant or plant parts, soil aeration, thermal regime and water balance (Dexter 1988, 2004a). In addition, seedbed structure can also affect the impact of early biotic stresses and the effectiveness of weed control (Glen et al. 1989; Bale et al. 1992; Otten and Gilligan 2006; Finney and Creamer 2008; Melander and Kristensen 2011). A seedbed containing a high proportion of large soil aggregates not only leads to a poor seed-soil contact but it also cools down more rapidly thereby slowing down the seed imbibition and germination process (Brown et al. 1996; Håkansson et al. 2002). Consequently, the time interval between the seed germination and seedling emergence phase in a seedbed comprising bigger soil aggregates is longer, due to the increased tortuosity of the seedling path before reaching the soil surface (Boiffin et al. 1992). Likewise, the risk of seedling death before emergence is higher in coarser seedbeds as seedlings can be trapped under the soil aggregates encountered during its elongation from the sowing depth (Dürr and Aubertot 2000). Delayed emergence also increases the risk of seedling death in an indirect way; for example, by increasing the probability of attacks due to soil-borne pests and pathogens owing to longer heterotrophic phase or topsoil crust formation impeding the emergence (Gallardo-Carrera et al. 2007). Lastly, delayed emergence may lead to a reduced growth rate (Tamet et al. 1995; Durr and Boiffin 1995). On the other hand, a high proportion of very fine aggregates in the topsoil layer is not always beneficial as it induces a higher sensitivity to crust formation under rainfall (Boiffin 1986). The soil structural state of a given field plot evolves over time because of a dynamic combination of compaction and fragmentation process (Richard et al. 1999; Obour et al. 2017;). This evolution results from the interaction between climate and crop management history including crop rotation, management techniques applied to these crops such as sowing and harvesting operations, equipment used for these operations, and the soil water content at the time of field operations (Guérif et al. 2001; Boizard et al. 2002; Dexter 2004b; Tagar et al. 2020). Following the harvest of a crop, the soil profile contains a more or less important volume of compacted zones created by wheel tracks, especially when harvest or antecedent field operations occur under wet conditions and with heavy machineries. Beginning from this "initial" structural state, seedbed structure of the following crop results from a more or less simplified sequence of tillage operations, including (or not) mouldboard ploughing, and, finally, the action of the driller itself. Depending on the soil moisture profile and on the related soil consistency, these tillage operations not only induce fragmentation of previously compacted soil volumes and big clods but also compaction or coalescence of fine aggregates, especially across deep layers located under wheel tracks. In addition to tillage, other types of field operations with a passage of wheel tracks may also lead to soil compaction (e.g. spraying fertilizers). Soil structure can also be greatly altered by climatic alternations (e. g. freezing–thawing or wetting-drying), which exert a more or less intense and deep effect of fragmentation, depending on soil texture, and on the frequency and amplitude of these alternations (Stengel et al. 1984; Kværnø and Øygarden 2006). Taken together, the seedbed structure obtained with a given set of tillage equipment reflects the combined prints of the last sequence of tillage and/or drilling, the recent intercultural phase, and the anterior history of the field. Based on these factors and their interactions, cropping systems (CSs) could result in different and more or less favorable trends affecting seedbed structure. These trends may or may not be reversible. For example, a progressive increase of the compacted volumes in the soil profile results in an increased occurrence of seedbeds with a coarse or heterogeneous soil structure (Boizard et al. 2002) and this could affect the quality of crop establishment. Therefore, it is important to describe and analyze the inter-annual variability of seedbed structure, in relation to contrasted and well-characterized CSs, especially in order to detect potential patterns of progressive evolution.

A previous study (Boizard et al. 2002), based on a field experiment, investigated cumulative effects of CSs on the structural state of the tilled layer, in particular the proportion of compacted zones in a loamy soil that is characteristic of northern European soils. The authors showed that the compaction level of a soil was dependent on the soil moisture at the time of field operations as well as the characteristics of the machinery used and that there was no indication of irreversible cumulative degradation. Another study (Boizard et al. 2013), compared the impact of conventional *versus* reduced tillage on the soil structure evolution and showed that the soil structure in the untilled layer mainly depends on the soil compaction intensity and that regeneration of this compacted layer over time was slower compared with that of the tilled layer. Although seedbeds in this long-term experiment were characterized, no study yet reported whether and to what extent the seedbed structure of major field crops can be affected by crop management history of a plot in interaction with climate. Seedbed characterization is not only time consuming and resource intensive but also difficult to perform due to limited field access, especially under rainy seasons and high moisture conditions. Only little knowledge is available to date concerning precise numerical data characterizing seedbed structure and its variations (Braunack and Dexter 1989; Braunack and McPhee 1991; Aubertot et al. 1999; Gallardo-Carrera et al. 2007). Therefore, the key objective of this work was to characterize seedbed structures of major field crops grown in Europe, and analyze how they are affected by CSs, climate and their interactions. The generated information will be useful for future simulation studies concerning crop establishment in a context of climatic and agricultural change.

2. Material and methods

2.1. Study sites

Most of the data presented in this study comes from a long-term field experiment (1991-2005) carried out at Mons-en-Chaussée (49°52′44″N 3°00′27″E), Northern France. A detailed description of the study site and soil texture and chemical characteristics have been published (Boizard et al. 2002). The soil is a Haplic Luvisol (FAO classification). Briefly, the soil at the 0-30 cm soil horizon had the following characteristics: 0.197 $g.g^{-1}$ clay, 0.747 $g.g^{-1}$ silt and 0.056 $g.g^{-1}$ sand; 0 $g.g^{-1}$ $CaCO_3$, 0.095 $g.g^{-1}$ C, 0.001 $g.g^{-1}$N, C/N ratio 9.3, and pH 7.7. Soil water contents at -10, -50, -100 and -1500 kPa were 0.252, 0.213, 0.164 and 0.083 $g.g^{-1}$, respectively. Water content at field capacity, measured during winter in field 2–3 days after excess water had drained away (Hillel 1971), was 0.24 g $g_{-}1$. The average annual air temperature and cumulative rainfall were 9.6 °C and 690 mm, respectively. The cumulated rainfall one week before seedbed preparation for each crop is presented in **Table 1**.

2.2. Cropping systems

The long-term field experiment was set up to investigate the potential impact of contrasted CSs on soil structure changes, in the tilled or non-tilled layers (Guérif et al. 2001; Boizard et al. 2002). Three CSs were designed taking into account key agricultural features of the region. These factors included possible crops and rotations, and time schedule for field operations. The rotation in the cropping system I was spring pea (SP; *Pisum sativum* L.)/winter wheat (WW; *Triticum aestivum* L.)/winter oilseed rape (OR; *Brassica napus* L.)/ WW. Sowing and harvesting were always carried out either in summer or early autumn, *i.e.* during the dry period of the year, except for pea sowing in early spring. SP was sown between 7 March and 7 April, OR was sown between 10 and 31 August, while WW was sown between 8 and 20 October. The rotation in the CSs II and III was sugar beet (SB; *Beta vulgaris* L.)/WW/maize (M; *Zea mays* L.)/WW. The CS II was managed to avoid possible soil compaction during sowing and harvesting of the three crops. Consequently, SB was sown between 20 March and 30 April, M was sown between 3 April and 4 May while WW was sown between 8 October and 19 November. The soil water content was measured for each field operation by taking samples at 0-5, 5-10, 10-15 et 15-20 cm soil horizon (four replicates at each depth) per plot, weighed and dried 24 h at 105 °C as described previously (Boizard et al. 2002). When the decision had to be made quickly during the day, drying is carried out with a microwave on a reduced sample (60 g). The decision-making rules applied for seedbed preparation and sowing of SB and M in the CS I and CS II were with <0.20 g g^{-1} and <0.22 g g^{-1} water content in the 0–10 cm and 10–20 cm soil layer, respectively. In contrast, the CS III was managed to maximize light interception and yield by SB and M canopies without taking into account any possible compaction during field operations. The decision rules applied for seedbed preparation and sowing was with <0.25 g g^{-1} water content in the 0–10 cm soil layer. Therefore, SB and M were sown in early spring (between 4 and 17 March and between 1 and 23 April, respectively) and harvested in late autumn, during wet periods of the year. Consequently, sowing of WW in the CSs I and II occurred earlier and they were very similar in terms of dates while WW in the CS III occurred later (i.e. between 4 and 21 November) compared with the previous two CSs. The harvesting dates of WW were similar independent of the CSs.

Each crop from each CS was grown every year leading to four plots per CS (12 plots in total) that were replicated in two blocks (24 plots in total). As explained above, the rules for decision making in each CS, depended on a combination of crop physiology requirements and field access for seedbed preparation (Boizard et al. 2002). The key agronomic rule consisted in avoiding soil compaction by considering pre-determined thresholds of soil water content at the 0-10 and 10-20 cm soil horizons. Major field operations used following the harvest of a preceding crop and before tillage were: chopping (only for M) and stubble disking (only for SP and OR). Seedbed preparation was followed by sowing within a maximum of 24 hours for all crops.

A detailed description of the equipment used for seedbed preparation and sowing is presented in **Table 2**. Conventional tillage was applied to each crop every year from the beginning of the experiment up to 1999. A new treatment, which consisted of reduced tillage at a 4 to 8 cm depth, was introduced in 1999 into the experiment in order to compare the effects of conventional and reduced tillage on soil structure evolution. For conventional tillage treatment, the field plots were subjected to a 30 cm depth mouldboard ploughing (for all crops) followed either by seedbed preparation with a combination harrow (for SB, M and OR), or combined seedbed preparation (for WW and SP). Mouldboard ploughing before spring crops was carried out between November and January to take advantage of the effect of climatic conditions (freezing thawing and wetting drying) on the soil surface horizon. Mouldboard ploughing for WW and OR was carried out just before sowing. The depth of the seedbed layer ranged from 3 to 9 cm (average 5.5 cm). Stubble tillage was performed every year after WW, M, SP and OR at a depth ranging from 6.5 to 10 cm (average 8 cm). Seedbed preparation was performed with a combination harrow (with several rows of small tines and two rows of rollers) at 6-8 cm depth, for SB, M and OR. WW and SP were sown using a combined rotary harrow and disc drill carrying out tillage and sowing in one pass. The equipment used for seedbed preparation had similar characteristics in terms of weight (6.5–8 Mg), tire width (0.70 m), working widths (3 m), and inflation pressure (70 kPa). In contrast, the harvesting equipment was much heavier (about 15 Mg) with a high inflation pressure (200-300 kPa), and a wide variation in the percentage of the experimental plot covered by wheel tracks (29–77%). In reduced tillage treatment, the only difference was that a compact disc cultivator at 6 cm average depth (ranging from 4 to 8 cm; **Table 2**) replaced mouldboard ploughing.

2.3. Cumulated rainfall before seedbed preparation and sowing

Rainfalls were daily recorded at the meteorological station located at the study site. Rainfalls one week before seedbed preparation were cumulated to get an indicator of the soil moisture conditions for soil tillage and sowing.

Cumulated rainfall values 7 days before sowing for all three CSs are presented in **Table 1**. These values could markedly vary between years, especially for WW sowing (0 to 52 mm). As expected, the highest and the most variable cumulated rainfall values were observed in the CS III while the lowest and least variable values were registered in the CS I, because of the sown crops and the decision rules. For all CSs, the highest cumulated rainfall values were for WW while the lowest values were in the CS I for OR

2.4. Characterization of soil compaction level

The soil compaction level caused by soil traffic, in interaction with soil moisture, can affect the seedbed structure. A higher level of soil compaction may lead to the formation of bigger soil aggregates that may affect the quality of crop establishment with a higher rate of seedling mortality under clods. The soil compaction level was assessed following each crop establishment as previously described (Boizard et al. 2002, 2013). A morphological description of the soil structure of the 0–30 cm layer was carried after each sowing, from a randomly located 3 m wide soil profile perpendicular to the tillage and wheeling directions. We used the ‘‘profil cultural’’ method proposed by Manichon (1987) and presented in detail in Boizard et al. (2002, 2013) and Roger-Estrade et al. (2004), to map soil structure in this tilled layer. The highly compacted zones containing specific morphological features (no visible macro-pores, a massive structure and a smooth breaking surface) were identified in slight relief on the observation face. The proportion of highly compacted zones in the tilled layer under the seedbed was calculated. The working depth was measured by digging a pit perpendicular to the direction of tillage following each tillage operation (3 m wide at sowing and 1 m wide at stubble tillage). The tilled layer was visually delimited and its thickness was measured every 10 cm laterally.

In addition to assessing the soil compaction level at the plot scale, we investigated the potential effect of wheel-induced compaction along the row due to wheel traffic on seedbed structure, compared with the control treatment (*i.e.* the zone outside the passage of wheel) as described previously (Boizard et al. 2002, 2013). Working widths markedly differed from one operation to the others (2.7–5.4 m) that led to an important variation in the percentage of the experimental plot covered by wheel tracks (11–44%). The location of the wheel tracks was recorded after each field operation on a transect over the plot width.

2.5. Seedbed characterization

The distribution of seedbed aggregate size was characterized as described previously (Aubertot et al. 1999). Seedbed samples were taken just after sowing. A surface was delimited along the row of the seedbed with combs (20 length x 10 width x 10 cm depth) to determine either the numbers, mass or percentage of aggregates or all of them in a precise soil volume. The number of replicate/year/crop ranged from 10 to 48 for SP, 16 to 24 for OR, 10 to 48 for WW, 12 to 48 for SB, and 16 to 48 for M. Soil samples from all the treatments (i.e. the zones subjected and non-subjected to wheel traffic from conventionally tilled plots as well as from plots with reduced tillage) were carefully extracted with a spoon, brought to the laboratory, and air-dried. The samples were sieved with a gently shaking machine (30 s, 50-mm amplitude) and grades <5, 5-10, 10-20, 20-30, 30-40, 40-50, and >50 mm diameter were obtained. The number, the mass and the volume for each of these grades were determined. Finally, the observed variations, in terms of percentages of soil aggregates, measured for each seedbed class of crops belonging to the three cropping system, were used to define three types of seedbed structures: a fine seedbed (with >20mm soil aggregates <15%)), an intermediate seedbed (with >20mm soil aggregates >15<25%), and a coarse seedbed (with >20mm soil aggregates >25%). A visual aspect of these three seedbed types is reported in **Figure 1**.

2.6. Statistical analyses

The variability of seedbed structure can be related to several fixed factors, mainly the CS, crop and year. These fixed factors influence seedbed structure by determining sowing equipment and the soil conditions at sowing, including soil moisture and compactness at the time of seedbed preparation. A 3-step statistical analysis was performed: i) the effect of the main fixed factors on soil moisture and compactness at sowing was tested through a one-way ANOVA, ii) possible relationships between seedbed structure and soil moisture or compactness were investigated through linear correlation tests, and iii) an ANCOVA, with the dependent variable (the seedbed structure represented by % soil aggregates >20 mm), the independent variables considered as fixed factors (the CS, crop, previous crop and year, and additionally, the type of tillage and the location of wheel tracks in the seedbed), and covariates (the % of soil moisture at 0-15 cm and that of the topsoil compaction level). All statistical analyses were computed using JASP version 0.13.0 (Love et al. 2019).

3. Results

3.1. Types of seedbed structure in relation to year, crops and cropping systems

The types of seedbed structure found over the 15 years of the experiment are reported in **Figure 2**. When analyzed crop-wise for each individual year, the fine seedbed structure was the most frequently found for SP, SB and M in all three CSs tested, followed by the intermediate and coarse seedbed structure. In contrast, the coarse seedbed structure followed by the intermediate one prevailed for WW, especially in the CS III and, to a lower extent, in the CS II. When analyzed year-wise for each CS, the intermediate seedbed structure was the most frequent followed by fine and coarse seedbed for all but in the CSs III for which coarse and intermediate seedbed structures were the most frequent and in equal number.

3.2. Topsoil moisture and compaction at sowing

Results of the seedbed moisture level at 0-15 cm soil horizon at the time of seedbed preparation are reported in **Figure 3**. The moisture level ranged from 19 to 21% and it was significantly higher ($P<0.001$) in the CS III followed by the CSs I and II. When analyzed by crop, the moisture level at 0-15 cm was significantly higher ($P<0.001$) for SP (22%), followed by SB (21%), WW (20%) and M (19%). No data were recorded for OR.

The topsoil compaction level, observed after sowing, as analyzed by ANOVA ranged from 0.17 to 0.41% for all crops and the CSs combined **(Figure 4)**. When individually analyzed by the CS, the compaction level was significantly higher ($P<0.001$) in the CS III (0.41%) followed by the CSs II (0.28%) and I (0.17%). Likewise, when analyzed by crop, the topsoil compaction level of SB (0.36%) and M (0.30%) was significantly higher (P<0.001) compared with that of WW (0.27%) and SP (0.20%).

3.3. Correlations between seedbed structure and soil moisture or topsoil compaction level

When analyzed by CSs, there was a positive correlation between the seedbed moisture at 0-15 cm soil horizon at the time of seedbed preparation and the % of soil aggregates > 20 mm **(Table 3)**. Likewise, a positive correlation was observed between the topsoil compaction level and the soil aggregates > 20 mm (Table 3). When analyzed by crop, the seedbed moisture level at 0-15 cm soil horizon was positively correlated with the soil aggregates > 20 mm (Table 4). Similarly, there was a positive correlation between the topsoil compaction level and the soil aggregates > 20 mm **(Table 4)**.

3.4. Combined effects of fixed factors and covariables on seedbed structure

ANCOVA showed a statistically significant effect (P < 0.001) of both the covariates (the % of soil moisture at 0-15 cm and that of the topsoil compaction level) on the soil aggregates > 20 mm **(Table 5)**. There was also a significant effect of CSs (P<0.05), crops (P < 0.001), previous crops (P < 0.01) and year (P < 0.001) while no significant effect of wheel traffic (P>0.05) and tillage (P>0.05) was observed on the soil aggregates > 20 mm**.** The seedbed structure, expressed as the % of soil aggregates > 20 mm, was the coarsest in the CS III (26 ± 15 %) followed by the CS II (22 ± 14 %) and the CSI (18 ± 10 %). Among crops, WW seedbeds were the coarsest (26 ± 14 %) followed by those of SB (19 ± 13 %), M (16 ± 10 %) and SP (15 ± 9 %). As for previous crops, WW seedbeds prepared after the harvest of SB were the coarsest (31 ± 19 %), followed by M (30 ± 18 %), SP (22 ± 13 %) and OR (20 ± 13 %). Finally, a significant (P < 0.001) inter-annual fluctuation of the seedbed structure was observed over the 15-year period with the least and most coarsest seedbed structure observed in 2003 (14 ± 14 %) and 2001 (30 ± 18 %), respectively.

4. Discussion

In this study we analyzed a unique dataset on seedbed structure, resulting from various crop types and CSs put in place and observed during 15 consecutive years. This combination of crops, CSs and years generated a wide range of soil structure dynamics and seedbed structures. Differences between CS and crop types, large inter-annual fluctuations, and a variable differentiation of the CSs according to year and crop types were the dominant features of the variability in seedbed structure.

Independent of the fixed factors, aggregate size in the seedbed was correlated to topsoil compactness and moisture at the time of seedbed preparation and sowing, with a tendency to coarser seedbeds associated with profiles that are more compact and wet. This trend is consistent with the initial hypotheses that (i) seedbed structure partly reflects the importance of continuous and compact soil volumes at the time of seedbed preparation, and that (ii) this influence is modulated by the loosening efficiency of tillage tools, which itself depends on soil consistency resulting from soil moisture. Starting from a dry soil with a maximum level of cohesion, the increase of soil water content decreases soil cohesion and facilitates fragmentation up to an optimal threshold value above which pressures exerted by the working utensils result in plastic deformations rather than ruptures (Guérif 1982; Guérif et al. 1988). Once this threshold is reached, any increase in soil water content should then reduce fragmentation, and induce the formation of new clods by coalescence of small aggregates.

The ranking of CS (III II and I, in decreasing order of coarseness) is consistent with the effect of these systems on soil compactness. Harvests and seedbed preparations generally occurred in wetter soil conditions in the CS III than in the CS I and II. They induced higher pressures on topsoil, as well as larger wheel tracks areas, for the CS II and III than for the CS I. Consequently, the CS III corresponded to higher levels of soil compaction, followed by the CS II and I, as previously mentioned by Boizard et al (2013) and confirmed here with supplementary data **(Figs. S1-S3)**.

The observed contrast between seedbeds of different crop types (coarser seedbeds for WW compared with those of SB and M) is commonly observed in the agricultural context of Northern Europe, in relation with the fact that emergence rate and seedbed structure requirements for precision sowing crops are higher than those for WW or OR. Consequently, tillage operations for preparing SB or M seedbeds are generally higher than for WW or OR (2 vs 1 in our case). The contrast also might result from two additional effects. First, a higher proportion of WW plots resulted from the late harvest of the preceding crop (SB and M) under wet conditions leading to a high level of soil compaction. Second, WW sowings followed shorter intercultural periods with less wetting-drying and no freezing-thawing alternations.

The seedbed types distribution does not reflect simple effects of CS or crop type, but a stronger differentiation of CS for WW than for SB and M seedbeds. Crop-specific modalities of seedbed preparation and sowing (autumn vs spring, 1 vs 2 tillage operations, specific sowing equipment) combined with different durations of the intercrop sequences (short *vs* long) can modulate the influence of antecedent compaction on seedbed structure. Short intervals between harvests and sowing dates of the preceding crop (case of WW) tend to maintain the antecedent contrasts in soil structure, while long intervals including freezing-thawing and wetting-drying alternations (case of SB and M) tend to reduce them.

The influence of CSs and crop types on soil moisture at sowing is less contrasted than their effect on topsoil compaction level. Higher soil moisture in the CS III than in the II on average is again consistent with the differences in sowing times induced by the decision rules, with later sowing dates for autumn-sown crops and earlier sowing dates for spring-sown crops in the CS III, and consequently higher rainfall before sowing on average. Independent of the fixed factors and except for OR, most of the variation of topsoil moisture at sowing occur in a relatively narrow range of water potential (-100 to -50 kPa). For this type of soil texture, such range corresponds to well drained but still plastic soils. The trend to positive correlations between soil moisture at sowing and the proportion of coarse aggregates, which was observed on average, confirms that soil consistency at seedbed preparation varied within the plastic domain. Then higher soil moistures obtained some years in the CS III in relation to decision rules, were an additional cause of coarser seedbeds.

There was no difference in seedbed structure due to the presence or absence of wheel tracks during seedbed preparation. This confirms that the soil conditions for seedbed preparation and seeding were appropriately chosen to avoid significant compaction under the wheel tracks that, otherwise, may have led to reduced loosening and a coarser structure. This means that variations in seedbed structure were generally determined by the topsoil compaction generated before rather than during seedbed preparation. The type of tillage (conventional vs. reduced) did not have any effect on seedbed structure although, depending on the tillage system. The under representation of the reduced tillage treatment, introduced only in 2000, could explain the lack of significant effect that warrants an in-depth further investigation.

The importance of inter-annual fluctuations of seedbed structure, in interaction with the crop types and CSs, reflects the influence of climatic conditions on the different processes influencing soil structural dynamics, from the harvest of the preceding crop to the sowing of the following crop. Years with high or low levels of large aggregates in seedbed alternate in an apparently erratic way. Indeed, no irreversible trend could be obviously detected within or among the CSs and that the seedbed structural differences between the CSs observed at the end of the period **(Fig. 5)** were not larger from those detected at the beginning. The year sequences 1991-1995-1999-2003, 1992-1996-2000-2004, 1993-1997-2001-2005 (only for WW), exactly corresponded to the same groups of experimental fields in each case, and did not exhibit a progressive trend. However, for the year sequences 1994-1998-2002 and 1995-1999-2003, which again corresponded to the same groups of experimental fields, the largest differences between the CSs occurred at the end of the sequence. For these sequences, it is impossible to neither exclude nor emphasize a cumulative effect of the CSs, due to the lack of the monitoring and observations in 2006. This is again consistent with the fact that seedbed structure variability was mainly inherited from a relatively short-term soil dynamics. The impact of the CSs on seedbed structure was important, but essentially summed up to an effect of the antecedent crop on the subsequent seedbed structure. This antecedent effect not only depends on the crop species, but also on the decision-making rules applied to the different CSs. The different set of rules applied in the experiment have led to various conditions of harvest and seedbed preparation, with contrasted inter-annual rainfall accumulations the week before seedbed preparations, and contrasted soil moisture levels at 0-15 cm soil horizon. Our findings corroborate with a previous study that showed no long-term irreversible effect of CSs on the tilled soil layer (Boizard et al. 2002). The apparent reversibility of cumulative degradation of seedbed structure should be related to soil texture, and more precisely to the nature and amount of the clay content. This latter determines the soil aptitude to cracking (Stengel and Guérif 1985). However, this reversibility should not be extrapolated to soils with clay content <16%

neither to CS more aggressive than the CS III, as for example CS with sequences of successive maize with late harvests.

5. Conclusions

The results presented in this study represent an important dataset on seedbed structures obtained across a wide diversity of sowing contexts, in terms of sowing season (spring, summer and autumn), impact of cropping systems with regard to topsoil compaction risks, tillage intensity and climatic conditions during the year affecting seedbed preparation. Consequently, the observed variability of seedbed structure was large, with a higher proportion of coarser seedbeds when all three factors were combined. First, a high level of topsoil compaction at the time of seedbed preparation, related to harvest conditions of the preceding crop. Second, a short interval between sowing and harvest of the preceding crop, reducing the occurrence of climatic episodes able to induce fragmentation of compacted zones in the topsoil. Third, a high soil moisture at the time of seedbed preparation, resulting in less loosening and even clumping of previous aggregates.

Our results confirm the initial assumption of an influence of cropping systems on seedbed structure. Cropping systems with high risks of topsoil compaction correspond to coarser seedbeds, especially for crops sown in autumn following late harvests. However, no cumulative and irreversible differentiation between CSs could be detected in our experiment. This means that the impact of repeated soil degradation on seedbed structure does not prevail on the reversible and annually variable effects of the intercultural periods. Even so, the influence of CSs on seedbed structure is important, and involves not only the nature of crops included in the crop rotation, but also the strategies which determine the techniques of crop management, and especially the time period for field operations. The soil aptitude to cracking increases the reversibility of compaction that results from more or less aggressive CSs and therefore it should be considered as a key criterion for extending or restricting the trends observed in this experiment.

The dataset presented in this work represents an important input variable for simulation studies using the SIMPLE crop emergence models (Dürr et al. 2001), which takes into account the impact of seedbed structure on seedling emergence. The seedbed classification proposed in this study may also facilitate the identification of any seedbed structure, for which no data are available to date.

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Figure legends:

Figure 1. Characteristic seedbed structure of major field crops sown in Europe. Three types of seedbed structure are identified based on the percentage of soil aggregates >20 mm. Coarse seedbed (>25% of soil aggregates >20 mm; A), intermediate seedbed (>15<25% volume of soil aggregates >20 mm; B), and fine seedbed (<15% of soil aggregates >20 mm; C).

Figure 2. Percentage of mean annual soil aggregates >20 mm diameter in the seedbed of each crop for the three CSs. Results are based on the combined data measured from plots subjected to both conventional and reduced tillage. CS: cropping system; NT: not tested; SP: spring pea; WW: winter wheat; OR: oilseed rape, SB: sugar beet; M: maize. The values in each cell represents the percentage of soil aggregates >20mm diameter measured in the seedbed. Red, yellow and green colours indicate coarse, intermediate and fine seedbed, respectively.

Figure 3. Moisture level (%) at 0-15 cm soil horizon at the time of seedbed preparation as determined by cropping system (a) and crop (b). CS I: cropping system I (pea/wheat/oilseed rape/wheat), CS II: second cropping system (sugar beet/wheat/maize/wheat), and CS III: third cropping system (sugar beet/wheat/maize/wheat). Error bars on the graph represent standard deviation. Means followed by the same letter are not significantly different at P< 0.05

Figure 4. Topsoil compaction level (%) as affected by cropping system (a) and crop (b). CS I: cropping system I (pea/wheat/oilseed rape/wheat), CS II: second cropping system (sugar beet/wheat/maize/wheat), and CS III: third cropping system (sugar beet/wheat/maize/wheat). Error bars on the graph represent standard deviation. No data were available for oilseed rape. Means followed by the same letter are not significantly different at P< 0.05.

Figure 3. Correlation between the topsoil moisture (%) and the percentage of soil aggregates >20 mm (a), and the topsoil compaction level (%) and the percentage of soil aggregates >20 mm (b) as affected by cropping systems. Results are based on the combined data measured from plots subjected to both conventional and reduced tillage. CS I: cropping system I (pea/wheat/oilseed rape/wheat), CS II: second cropping system (sugar beet/wheat/maize/wheat), and CS III: third cropping system (sugar beet/wheat/maize/wheat). No data were available for oilseed rape. Specific values of Pearson's correlation coefficients are detailed in Table 3.

Figure 4. Correlation between the topsoil moisture (%) and the percentage of soil aggregates >20 mm (a), and the topsoil compaction level (%) and the percentage of soil aggregates >20 mm (b) as affected by tillage practice. Results are based on the combined data measured from all cropping systems. Specific values of Pearson's correlation coefficients are detailed in Table 3.

Figure 5. Seedbed of spring (a) and winter (b) crops containing >20 mm aggregates over the period 1991-2005. Results are based on the combined data measured from plots subjected to both conventional and reduced tillage. Spring crops were represented by sugar beet and maize while winter crops were represented by wheat. The soil aggregate similarity observed between the beginning and the end of the period for all cropping systems indicates no irreversible effect of cropping system over time. Values related to every four year period correspond to the same groups of experimental fields. Error bars on the graph represent standard deviation.

Table 1. Cumulated rainfall (mm ± standard deviation) one week before seedbed preparation for each crop belonging to the three cropping systems tested from 1991 to 2005. The time range of the cumulated rainfall was 1st February for pea, 1st to 20th March for sugar beet, 1st to 20th April for maize, 25th August for oilseed rape, and 10th October for winter wheat. Seedbed preparation was followed by sowing within a maximum of 24 hours for all crops.

Year	Cropping system I				Cropping system II				Cropping system III			
	Pea	**Wheat**	**Oilseed rape**	**Wheat**	**Sugar beet**	**Wheat**	**Maize**	**Wheat**	**Sugar beet**	**Wheat**	**Maize**	**Wheat**
1990	ND	2 ± 0	ND	2 ± 0	ND	2 ± 0	ND	2 ± 0	ND	2 ± 0	ND	2 ± 0
1991	11 ± 2	5 ± 1	ND	5 ± 1	8 ± 1	5 ± 1	6 ± 1	5 ± 1	28 ± 7	9 ± 2	0 ± 0	9 ± 2
1992	2 ± 1	5 ± 2	ND	5 ± 2	3 ± 1	5 ± 2	6 ± 1	5 ± 2	22 ± 6	14 ± 3	16 ± 3	14 ± 3
1993	1 ± 0	28 ± 7	ND	28 ± 7	1 ± 0	28 ± 7	6 ± 1	28 ± 7	1 ± 0	6 ± 2	17 ± 2	6 ± 2
1994	10 ± 2	0 ± 0	ND	0 ± 0	7 ± 1	0 ± 0	1 ± 0	0 ± 0	8 ± 2	20 ± 2	19 ± 3	20 ± 2
1995	16 ± 2	1 ± 0	ND	1 ± 0	0 ± 0	1 ± 0	7 ± 2	1 ± 0	10 ± 3	1 ± 0	15 ± 4	1 ± 0
1996	0 ± 0	3 ± 1	ND	3 ± 1	1 ± 0	3 ± 1	0 ± 0	3 ± 1	1 ± 0	19 ± 4	1 ± 0	19 ± 4
1997	1 ± 0	24 ± 8	ND	24 ± 8	1 ± 0	7 ± 2	13 ± 3	7 ± 2	4 ± 1	17 ± 4	0 ± 0	17 ± 4
1998	0 ± 0	7 ± 2	1 ± 0	7 ± 2	1 ± 0	7 ± 2	2 ± 1	7 ± 2	4 ± 1	46 ± 8	1 ± 0	46 ± 8
1999	0 ± 0	4 ± 1	0 ± 0	4 ± 1	3 ± 1	4 ± 1	1 ± 0	4 ± 1	8 ± 2	1 ± 0	3 ± 1	1 ± 0
2000	3 ± 1	36 ± 6	ND	36 ± 6	4 ± 1	36 ± 6	ND	36 ± 6	ND	ND	11 ± 2	ND
2001	12 ± 2	33 ± 8	ND	33 ± 8	0 ± 0	1 ± 0	20 ± 3	1 ± 0	ND	32 ± 9	12 ± 2	32 ± 9
2002	0 ± 0	6 ± 1	ND	6 ± 1	0 ± 0	8 ± 2	0 ± 0	8 ± 2	10 ± 2	52 ± 10	0 ± 0	52 ± 10
2003	0 ± 0	11 ± 2	ND	11 ± 2	1 ± 0	11 ± 2	0 ± 0	11 ± 2	1 ± 0	11 ± 2	0 ± 0	11 ± 2
2004	2 ± 0	9 ± 3	ND	9 ± 3	ND	9 ± 3	ND	9 ± 3	ND	1 ± 0	ND	1 ± 0
2005	ND	ND	ND	ND	6 ± 1	ND	26 ± 5	ND	0 ± 0	ND	5 ± 2	ND

ND: not determined

Table 2. Main characteristics of the equipment used for tillage, seedbed preparation and sowing for different crops belonging to the three cropping systems

Cropping system	Previous crop	Crop	Conventional tillage[a]	Reduced tillage[b]	Seedbed prepar
I	Pea	Winter wheat	Mouldboard ploughing	NP	CSP & S (unique
	Winter wheat	Oilseed rape	Mouldboard ploughing	NP	CSP & S (unique
	Oilseed rape	Winter wheat	Mouldboard ploughing	NP	CH
	Winter wheat	Pea	Mouldboard ploughing	NP	CSP & S (unique
	Pea	Winter wheat	NP	Compact disc cultivator	CSP & S (unique
	Winter wheat	Oilseed rape	NP	Compact disc cultivator	CSP & S (unique
	Oilseed rape	Winter wheat	NP	Compact disc cultivator	CH (1st passage)
	Winter wheat	Pea	NP	Compact disc cultivator	CSP & S (unique
II and III	Sugar beet	Winter wheat	Mouldboard ploughing	NP	CH (1st passage)
	Winter wheat	Maize	Mouldboard ploughing	NP	CSP & S (unique
	Maize	Winter wheat	Mouldboard ploughing	NP	CH (1st passage)
	Winter wheat	Sugar beet	Mouldboard ploughing	NP	CSP & S (unique
	Sugar beet	Winter wheat	NP	Compact disc cultivator	CH (1st passage)
	Winter wheat	Maize	NP	Compact disc cultivator	CSP & S (unique
	Maize	Winter wheat	NP	Compact disc cultivator	CH (1st passage)
	Winter wheat	Sugar beet	NP	Compact disc cultivator	CSP & S (unique

[a] Conventional tillage was performed at 30 cm depth, using a 4-bottom mouldboard plough (41 cm wide) pulled by a tracto
[b] Reduced tillage was performed at 10 cm depth, using Rubbin (4m width) combining two rows of discs and two rows of ro
(MX 150)

CSP & S: Combined seedbed preparation and sowing was performed with an unique passage of Rotary harrow and seeder
IH 956) for winter wheat and pea; CH & S: Combination harrow, which was performed combining several rows of small tir
a tractor (Case IH 956) for oilseed rape, sugar beet and maize, followed by S: sowing (2nd passage) using a 12-row seeder p
(Renault 851.4 for oilseed rape and MF 575 for sugar beet); NP: Not performed.

Table 3. Pearson's correlation between soil moisture (%) at 0-15 cm and soil aggregates >20 mm (%), and between the topsoil compaction level (%) and soil aggregates >20 mm (%) as affected by cropping systems.

Treatment	**Correlation between soil aggregates >2 cm (%) and**	**All CSs combined**	**CS I**	**CS II**	**CS III**
Conventional tillage	Soil moisture at 0-15 cm (%)	0.25	0.08	0.21	0.31
	Soil compaction (%)	0.41	0.35	0.32	0.47
Reduced tillage	Soil moisture at 0-15 cm (%)	0.50	0.60	0.52	0.37
	Soil compaction (%)	0.20	-0.02	0.01	-0.12
Combined (Conventional & reduced tillage)	Soil moisture at 0-15 cm (%)	0.31	0.18	0.35	0.32
	Soil compaction (%)	0.34	0.21	0.24	0.33

CSs: cropping ststems; CS I: cropping system I (pea/wheat/oilseed rape/wheat), CS II: second cropping system (sugar beet/wheat/maize/wheat), and CS III: third cropping system (sugar beet/wheat/maize/wheat).

Table 4. Pearson's correlation between soil moisture (%) at 0-15 cm and soil aggregates >20 mm (%), and between the topsoil compaction level (%) and soil aggregates >20 mm (%) as affected by crops.

Treatment	**Correlation between soil aggregates >2 cm (%) and**	**Pea**	**Wheat**	**Sugar beet**	**Maize**
Conventional tillage	Soil moisture at 0-15 cm (%)	0.59	0.30	0.32	0.25
	Soil compaction (%)	0.42	0.65	0.49	0.12
Reduced tillage	Soil moisture at 0-15 cm (%)	0.67	0.73	0.31	0.20
	Soil compaction (%)	-0.36	0.23	-0.18	-0.26
Combined (Conventional & reduced tillage)	Soil moisture at 0-15 cm (%)	0.57	0.40	0.33	0.32
	Soil compaction (%)	0.28	0.48	0.35	0.07

Table 5. Mean (±SD) values of seedbed structure (% aggregates > 2 cm) computed by an analysis of co-variance (ANCOVA). The analysis was performed taking into account the soil moisture at 0-15 cm and the soil compaction level as a co-variables, and cropping system, crop, previous crop, wheel traffic, tillage, and year as fixed treatments.

					Effect of co-variables	
Treatment	**Fixed factor**	***n***	**Aggregates > 2cm ± SD (%)**	**Effect of treatment**	**Soil moisture at 0-15 cm (%)**	**Soil compaction level at 0-15 cm (%)**
Cropping system	CS I	230	18 ± 10	*	***	***
	CS II	258	22 ± 14			
	CS III	252	26 ± 15			
Crop	Maize	128	16 ± 10	***	***	***
	Pea	62	15 ± 9			
	Sugar Beet	130	19 ± 13			
	Wheat	390	26 ± 14			
Previous crop	Maize	680	30 ± 18	**	***	***
	Oilseed rape	342	20 ± 13			
	Pea	296	22 ± 13			
	Sugar beet	481	31 ±19			
Wheel traffic	Along the wheel traffic	369	22 ± 14	ns	***	***
	Outside the wheel traffic	371	22 ± 14			
Tillage	Conventional tillage	590	21 ± 12	ns	***	***
	Reduced tillage	150	24 ± 19			
Year	1991	199	16 ± 11	***	***	***
	1992	211	22 ± 17			
	1993	218	26 ± 18			
	1994	285	27 ± 16			
	1995	192	24 ± 14			
	1996	409	27 ±13			
	1997	128	17 ± 10			
	1998	220	17 ± 11			
	1999	294	21 ± 14			
	2000	178	24 ± 14			
	2001	176	30 ± 18			
	2002	196	25 ± 23			
	2003	177	14 ± 14			
	2004	191	15 ± 15			
	2005	154	21 ± 16			

***P < 0.001; **P < 0.01; *P < 0.05; ns: not significant; *n*: sample size; SD: standard deviation

Figure 1.

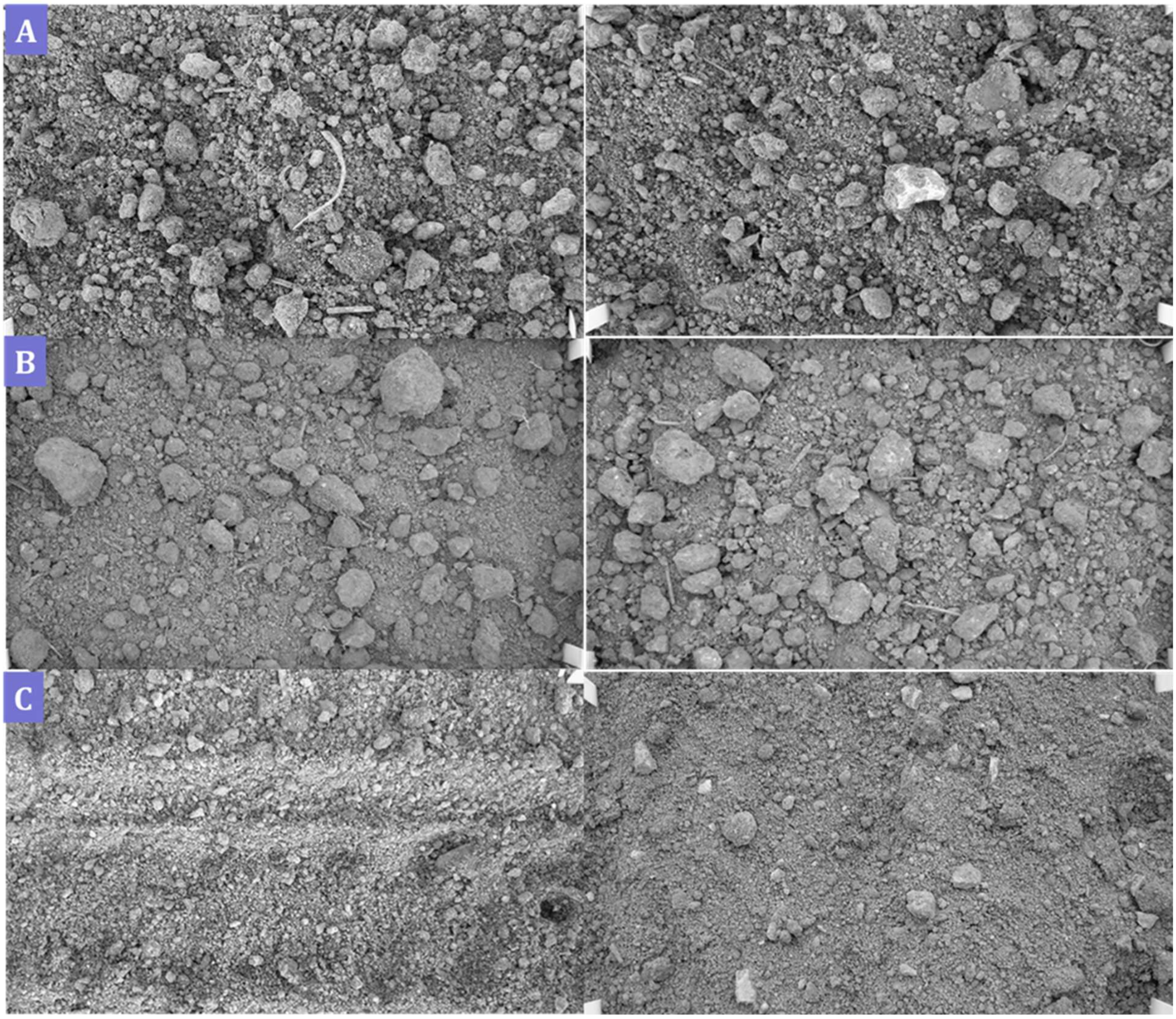
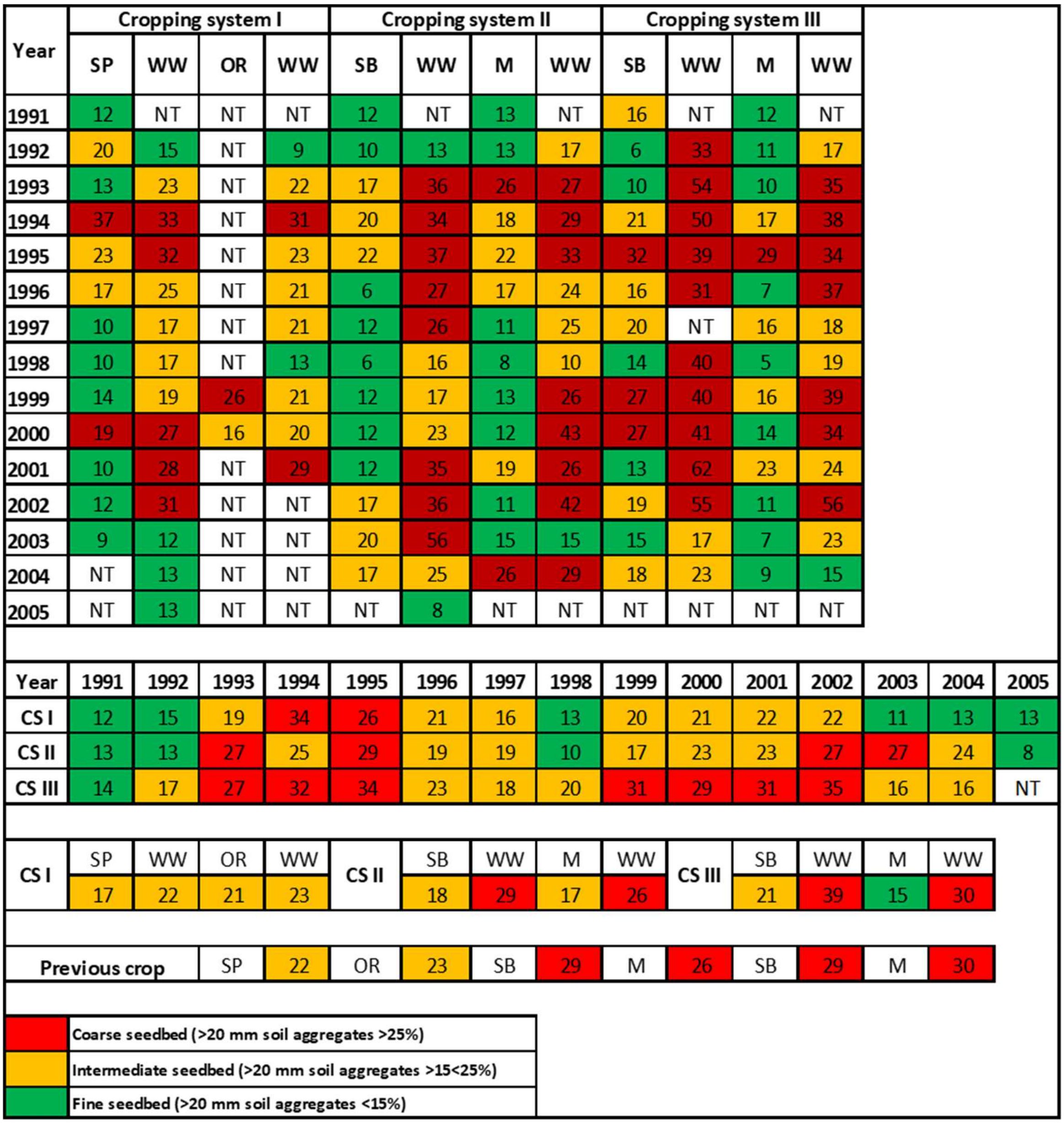


Figure 2.



Year	Cropping system I				Cropping system II				Cropping system III			
	SP	WW	OR	WW	SB	WW	M	WW	SB	WW	M	WW
1991	12	NT	NT	NT	12	NT	13	NT	16	NT	12	NT
1992	20	15	NT	9	10	13	13	17	6	33	11	17
1993	13	23	NT	22	17	36	26	27	10	54	10	35
1994	37	33	NT	31	20	34	18	29	21	50	17	38
1995	23	32	NT	23	22	37	22	33	32	39	29	34
1996	17	25	NT	21	6	27	17	24	16	31	7	37
1997	10	17	NT	21	12	26	11	25	20	NT	16	18
1998	10	17	NT	13	6	16	8	10	14	40	5	19
1999	14	19	26	21	12	17	13	26	27	40	16	39
2000	19	27	16	20	12	23	12	43	27	41	14	34
2001	10	28	NT	29	12	35	19	26	13	62	23	24
2002	12	31	NT	NT	17	36	11	42	19	55	11	56
2003	9	12	NT	NT	20	56	15	15	15	17	7	23
2004	NT	13	NT	NT	17	25	26	29	18	23	9	15
2005	NT	13	NT	NT	NT	8	NT	NT	NT	NT	NT	NT

Year	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
CS I	12	15	19	34	26	21	16	13	20	21	22	22	11	13	13
CS II	13	13	27	25	29	19	19	10	17	23	23	27	27	24	8
CS III	14	17	27	32	34	23	18	20	31	29	31	35	16	16	NT

CS I	SP	WW	OR	WW	CS II	SB	WW	M	WW	CS III	SB	WW	M	WW
	17	22	21	23		18	29	17	26		21	39	15	30

Previous crop	SP	22	OR	23	SB	29	M	26	SB	29	M	30

🟥	Coarse seedbed (>20 mm soil aggregates >25%)
🟨	Intermediate seedbed (>20 mm soil aggregates >15<25%)
🟩	Fine seedbed (>20 mm soil aggregates <15%)

Figure 3.

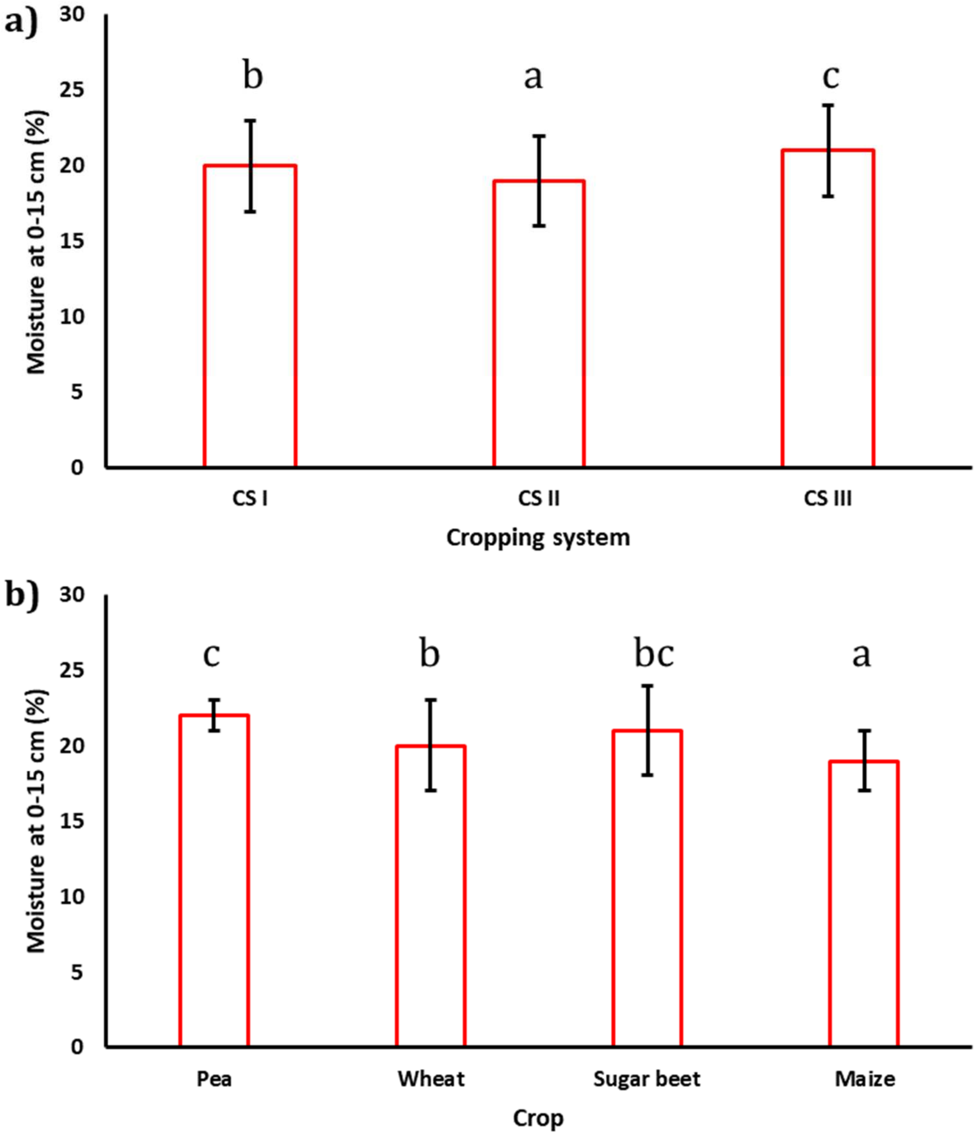

a)
Moisture at 0-15 cm (%)
0
5
10
15
20
25
30
b
a
c
CS I
CS II
CS III
Cropping system
b)
Moisture at 0-15 cm (%)
0
5
10
15
20
25
30
c
b
bc
a
Pea
Wheat
Sugar beet
Maize
Crop

Figure 4.

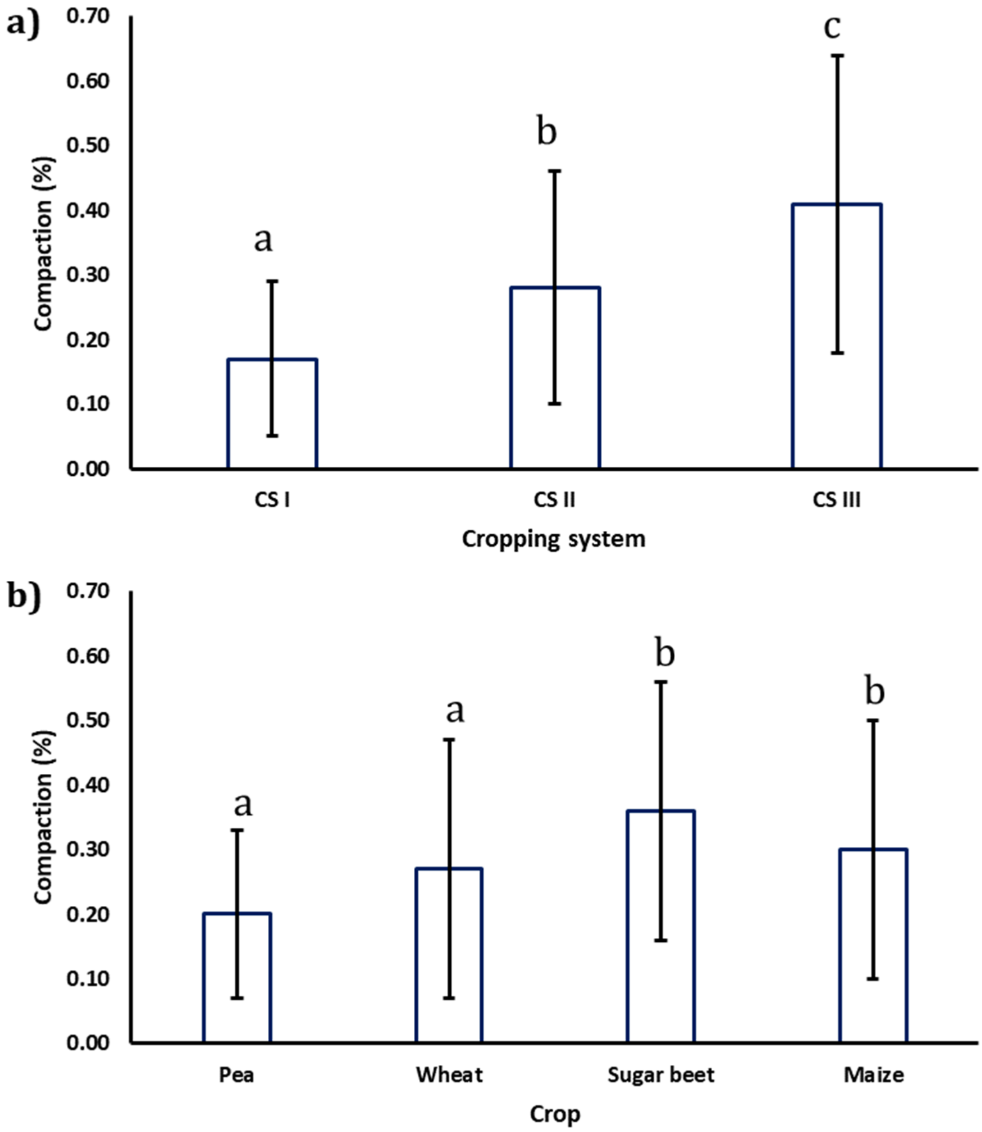
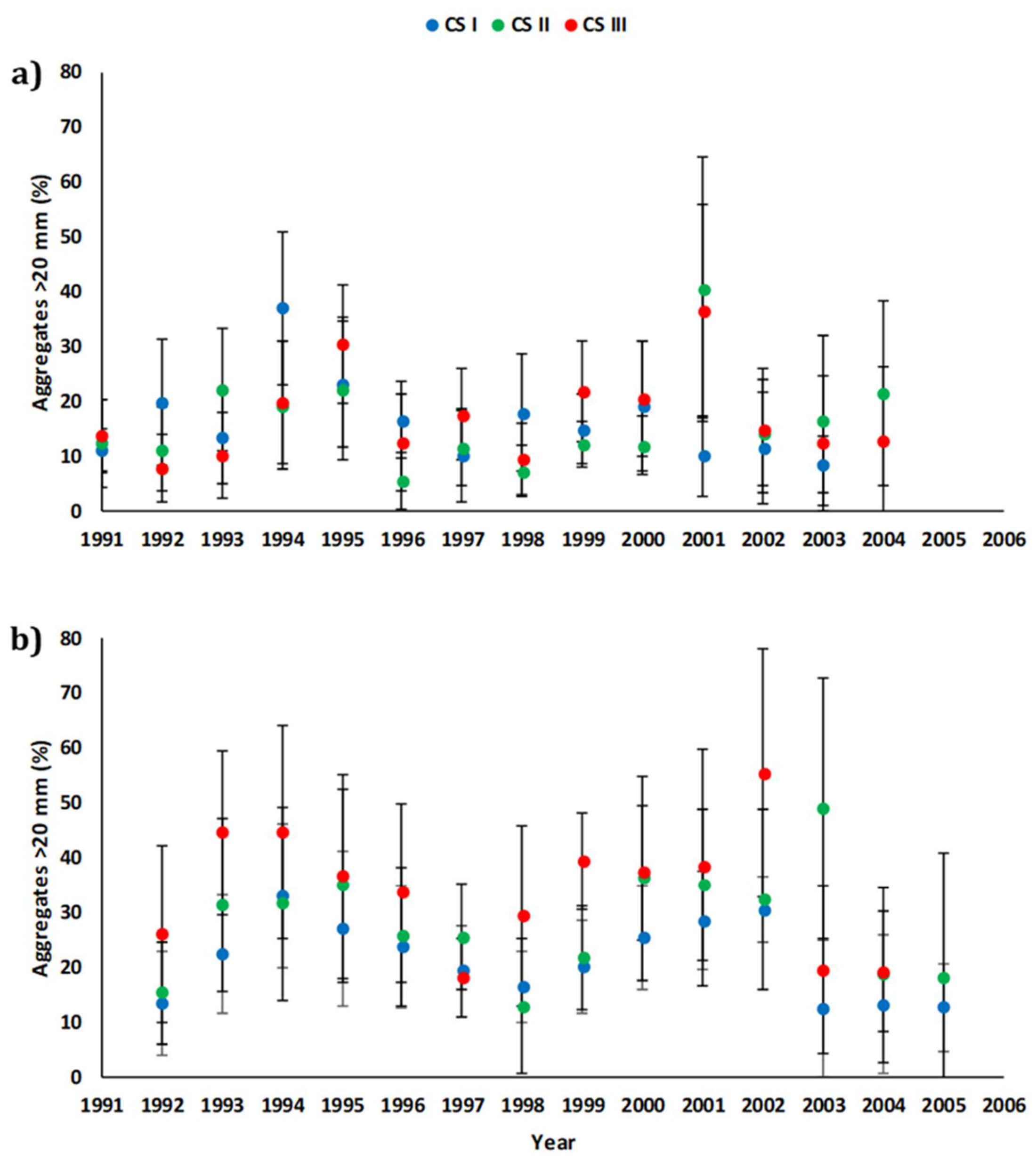

a)
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Compaction (%)
a
b
c
CS I
CS II
CS III
Cropping system
b)
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Compaction (%)
a
a
b
b
Pea
Wheat
Sugar beet
Maize
Crop

Figure 5.



● CS I ● CS II ● CS III
a)
b)
Aggregates >20 mm (%)
0
10
20
30
40
50
60
70
80
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
Year