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ABSTRACT

In France, agronomists have studied the effects of cropping systems on soil structure using a field method that is based on a visual description of the soil structure. This "profil cultural" method was

designed as a field diagnostic tool to identify the effects of tillage and compaction on soil structure dynamics. It is of great benefit to agronomists seeking to improve crop management and preserve soil structure and fertility.

However, the "profil cultural" method was developed and has mainly been used in conventional tillage systems with regular ploughing. As there has been an increase in the use of various forms of reduced, minimum and no-tillage systems in many parts of the world, it is necessary to re-evaluate this method's ability to describe and interpret soil structure dynamics in no-till or reduced tillage. In these situations, changes in soil structure over time are mainly driven by compaction and by regeneration through natural agents (climatic conditions, root growth and macrofauna), therefore it is important to evaluate the effects of these natural processes on soil structure dynamics.

These concerns have led to adaptations and amendments to the initial method based on field observations and experimental work in different cropping systems, soil types and climatic conditions. The description of crack types has been improved and a criterion of biological activity based on the visual examination of clods has been introduced.

To test this modified method, a comparison with the initial method was undertaken and its ability to make diagnoses tested in five experiments in France, Brazil and Argentina. The adapted method allowed an improved assessment of the impact of cropping systems on soil functioning when natural processes were integrated into the description.

1. Introduction

There are many soil visual assessment methods (SVA) used directly in the field to evaluate soil structure. These are of great use to agronomists and consultants when making soil management decisions related to soil structure. SVA techniques can be categorised into two kinds of methods:

spade methods and profile methods (Boizard *et al.*, 2005; Batey *et al.*, 2015). Spade methods are easy and quick to implement and are easily replicated, while profile methods allow a more detailed structural assessment. The "profil cultural" method is based on a soil profile evaluation directly in the field. The concept was proposed by Henin *et al.* (1969) to analyse the effects of tillage, compaction and weathering on soil structure and the impact of soil structure on plant development and growth. To do this, the method examines the soil structure, taking into account the spatial variability related to tillage and traffic (Gautronneau and Manichon, 1987; Roger-Estrade *et al.,* 2004). This method is of great interest not only to farmers and their advisors, but also to researchers in the identification of the compartments that should be considered when studying soil properties or the impacts of soil structure on production and the environment. Examples of such uses can be found in Richard *et al.* (1999), Dorel *et al.* (2000), Neves *et al.* (2003), Coquet *et al.* (2005) and Boizard *et al.* (2013).

The method was developed in conventionally tilled fields, where the main drivers of change in soil structure over time are tillage and compaction. Since the 1970s, there has been a rapid increase in simplified tillage systems worldwide. In South America, North America and Australia, these tillage systems, mainly no-till (NT) or reduced tillage limited to a depth of 10 cm (RT), currently represent a significant proportion of areas of cultivation: 55 M ha in South America, 40 M ha in North America and 17 M ha in Australia and New Zealand combined (Derpsch *et al.*, 2010). In France, NT and RT have developed slowly but steadily, from 10-20% of the wheat area in 1994 to about 40% in 2005. This proportion has remained stable, and the frequency of NT and RT systems for at least six successive growing seasons remains very low, at between 4 and 17% of crop areas (Labreuche *et al.*, 2007; Roger-Estrade *et al.*, 2014).

In NT and RT systems, the effects of crop residues on soil surface, soil macrofauna, root development and climatic conditions are the main drivers of change in soil structure over time, but the action of these natural factors is weak in comparison with fragmentation and compaction in conventional tillage. As the "profil cultural" method was not really designed to make an adequate assessment of these natural effects on soil structure, scientists studying conservation tillage have

introduced new criteria. For instance, Sasal *et al.* (2006) and Boizard *et al.* (2013) propose distinguishing a platy soil structure from the Φ structure used in the "profil cultural" method (see below). Many authors have also outlined the importance of macropores due to soil biota activity in the dynamics of soil structure regeneration in reduced tillage (Capowiez *et al.*, 2012; Piron *et al.*, 2012; Silva *et al.*, 2014) and developed their own system of description (Peigné et al., 2013; Piron et al., 2016 submitted). In Brazil, Tavares Filho *et al.* (1999) have adapted the method for no-till situations in tropical soils (such as oxisols, which are considered to have a particular behaviour).

In order to unify these various attempts to adapt the method, this paper presents a renewed approach to the "profil cultural" method resulting from a collective approach. The original method was designed to understand how the soil structure is modified by farmers under the effect of tillage and compaction. The novelty of this approach lies in its improved description of soil structure when it is altered by weathering or soil biota. The objective was to enable a more accurate diagnosis of soil structure and its consequences on production and environment in situations where there is no-till, reduced tillage or localised tillage such as strip till.

This paper proposes a modified method of the "profil cultural". The initial method is outlined before the proposed improvements are presented in detail. The initial and amended methods are then compared in two situations, followed by an analysis of three experiments to identify whether the developments made to the method led to an improved soil structure assessment and thus a better diagnosis.

2. A brief presentation of the initial "profil cultural" method

The initial "profil cultural" method was developed by Manichon (1987) and is described in detail in Gautronneau and Manichon (1987), Peigné *et al.* (2013) and Roger-Estrade *et al.* (2004). The "profil cultural" concept was defined by Henin *et al.* (1969) as the part of the topsoil (i) whose structure is determined by tillage, compaction and weather conditions and (ii) where the main part

of organic carbon, plant roots, soil biota and mineral nutrients are located. The objective of the method is to describe the structure of this part of the soil.

The description of the structure begins with a lateral and vertical partition of the cultural profile, on the face of a soil pit dug perpendicularly to the tillage direction and large enough to encompass the spatial variability of the soil structure of the field studied (Fig. 1). Different horizons are delimited by the tillage depths of the successive cultural operations and a lateral partition is determined by the location of the wheel tracks after the last ploughing, as shown in Figure 1. In a second step, each compartment is defined by the intersection of the vertical and lateral partition. Morphological units with an homogeneous soil structure are delimited in each compartment.

At this stage, an initial description of the structural organisation of the soil is produced. The degree of compaction, the spatial arrangement of clods, aggregates, voids, cracks and organic residues are described on a morphological basis. Three types of units are distinguished. Morphological units of type 'O' are highly fragmented, with the presence of small aggregates or clods. Type 'B' units are characterised by the presence of decimetric clods, produced by limited fragmentation by tillage tools (mainly the plough). In these units, voids are often observed between the clods. In type 'C' units, the soil structure is massive and clods or aggregates are not distinguishable. When large vertical cracks are present in type 'C' units, the subscript 'r' is added to indicate a strong swelling/shrinkage activity in the soil.

Once this is done, samples of each morphological unit are broken apart in order to characterise the soil structure at a second organisation level. The soil structure is described focusing on the type of porosity within the soil fragments that is visible to the naked eye. The specific features of each identified type are shown in Figure 2a. Type Δ is characterised by high bulk density, a high tensile strength (De Leon, 1991; Guérif *et al.*, 1994) and altered hydraulic properties (Coutadeur *et al.*, 2002). In type Δ, structural porosity, as defined by Monnier *et al.* (1973), has been destroyed by severe compaction (Richard *et al.*, 1999; Boizard *et al.*, 2013; Sasal, 2012). Type Γ results from the agglomeration of small soil particles under the effects of climatic conditions, biological activity and organic matter; type Γ has a lower resistance to penetration and a higher infiltration rate than type

Δ (de Leon, 1991; Boizard *et al.*, 2013). Φ clods are Δ clods in which cracks have appeared due to weathering.

Finally, the two criteria (spatial arrangement of clods and type of porosity) are combined to characterise the soil structure of each morphological unit. Thus a soil structure with high structural porosity and small aggregates is characterised as ΟΓ and a highly compacted soil structure as CΔ. A ratio giving the proportion of areas with each structural type (ΟΓ, CΔ...) can be calculated as the ratio of the area of the structural type to the total area of the horizon, as described by Boizard *et al.* (2013).

3. The improved "profil cultural" method

Since the initial method consists in a rather simple description of the effect of weathering (cracks due to shrinkage of Δ clods and the subscript "r" added to morphological units of type C in the presence of large cracks) and does not take biological activity into account, the developments made to the method mainly focused on an improved description of these two processes. The nomenclature of the horizons and lateral positions were not modified. They remained similar to those of the initial method, except for the surface horizon. Given its importance in no-till, it was proposed that the surface horizon, including the mulch and the first centimetre of the soil under the mulch that are heavily influenced by climate and the activity of epigeic fauna, would be called H0. The description of the spatial arrangement of soil units also remained unchanged. The main changes concerned the second level of description based on the porosity, in order to take cracking and biological activity into greater account.

An additional type of porosity for an enhanced description of cracking

The clods in type Φ are composed of fragments separated by flat cracks oriented in all spatial directions (Fig. 2a). However, a special facies of porosity, characterised by a dense network of horizontal cracks, frequently appears on top of compacted volumes in situations of direct seeding or reduced tillage. This facies, called platy soil structure, has often been described in NT systems in the first ten centimetres of the topsoil in the Pampas region of Argentina (Sasal *et al.*, 2006;

Alvarez *et al.*, 2009). Other authors have also reported the same facies in silty topsoils under NT in other areas (Pagliai *et al.*, 1983; Ball and Robertson, 1994). In France, Boizard *et al.* (2013) revealed the development of a platy soil structure on top of compacted volumes in RT, which becomes deeper over time.

There has been limited research but nevertheless ongoing debate about the origin of this platy soil structure. Pagliai *et al.* (1983) attributed the striated orientation of aggregates to the effect of pressures and tensions caused by wetting and drying. Laboratory studies aiming to recreate this facies in an experiment suggested that its origin could be related to the alternation of wetting and drying cycles, inducing very high moisture gradients on top of compacted volumes (Sasal *et al.*, 2012; Sasal *et al.*, 2016a submitted). In terms of properties, Boizard *et al.* (2013) showed that shear strength decreases with platy soil structure development because horizontal cracking introduces planes of weakness, while vertical penetration resistance remains unaffected. The creation of horizontal cracks impedes vertical water transfer and thus infiltration rates in the platy soil structure, which is no different from those measured in the Δ structure. In a long-term experiment in Parana (Argentina), platy structure has been found to alter the drainage pattern, restrict water entry into the soil and favour surface runoff according to its proportion in the soil profile (Sasal *et al.*, 2012; Sasal *et al.*, 2016b submitted).

The importance of this process and its impact on water infiltration and rooting growth encouraged the introduction of a new type of porosity, called P, which is distinct from type Φ (Fig. 2b). Type Φ is related to the shrinkage of the clay from the drying (or freezing) of Δ clods, with the appearance of shrinkage cracks oriented in all spatial directions, individualising polyhedral aggregates, while type P is related to the alternation of drying and wetting cycles in the upper part of the compacted soil where drainage is slow. Although the development of the platy soil structure may be a step towards the regeneration of a Δ structure, the elongated and horizontally-oriented pores are less effective for water movement and gas exchange, and probably less effective in promoting downward proliferation of plant roots than vertically-oriented pores of the same size and shape.

An additional criterion to describe the effect of biological activity on soil porosity

In soil, macrofauna (earthworms, ants, termites) or mesofauna (enchytraeids) perforate or ingest the soil and thus alter the soil structure. Piron *et al.* (2012) studied earthworm biostructures in the field to be able to describe soil structure more effectively and proposed a typology of soil-structure patterns coming from biogenic sources. The action of earthworms can involve either perforating and creating macropores, or rejecting casts (Fig. 3). Earthworms are important actors in the recovery of soil macroporosity after compaction, leading to the recovery of soil water infiltration (Capowiez *et al.,* 2012). In the tropics, Silva *et al.* (2014) noted the abundant presence of macrofauna, mainly the Oligochaeta, Formicidae, Melolonthidae, Diplopoda and Chilopoda families, leading to intense biological activity with a huge number of macropores and chambers. Oliveira *et al.* (2012) observed that termites transform soil structure and are likely to create new microstructures and aggregates. Similarly plant roots contribute to the maintenance or modification of pore space and can penetrate compacted zones (Unger and Kaspar, 1994; Gubiani *et al.,* 2010). It is important to consider the action of these natural agents on modifications of soil structure through the creation of a macropore network and/or the deposition of casts because these modifications play an important role in soil functioning and root access to the subsoil (Ehlers *et al.*, 1983; McKenzie *et al.*, 2009; Peigné *et al.*, 2013).

Given the action of biological activity, it was proposed that the description of porosity be complemented by a criterion b (as in biology) when biological activity is identifiable in types Γ, Δ, Φ and P. To make it easy to apply, it was decided that the criterion would only take two values: b1 for porosity facies showing the presence of tubular macropores, whatever their origin (root or fauna), and b2 when also observing fresh casts or chambers in the soil fragment, with individualised aggregates or older casts with poorly welded aggregates that could still be identified as coming from fauna (Fig. 3).

Implication for the soil structure assessment on the whole profile

In this morphological approach of soil structure, the different types of porosity of clods and aggregates are related by transformation processes in a conceptual model of soil structure dynamics (Roger-Estrade *et al.*, 2004). A representation of the assumptions made on the processes involved

is shown in Figure 4, where solid lines represent the processes taken into account in the initial description and dotted lines the processes added in the modified method. Severe compaction creates clods with a Δ structure, regardless of the initial structure (arrows denoted as '1'). Fine aggregates (FA) are created during secondary tillage by intense fragmentation (arrows '2'). Type Γ results from the effect of aggregation of fine soil elements (arrows '3'). Type Φ results from the effect of weathering on Δ clods (arrows '4'). In the new system, type P is added, resulting in the transformation of Δ zones by an alternation of wetting and drying cycles in poor drainage conditions on top of compacted volumes limiting water infiltration (arrows '5'). The added arrows also show the action of biological activity, modifying Δ, P and Φ porosity within each type (circular arrows '6') and gradually transforms them into fine aggregates (arrows 7).

4. Evaluation of improvements to the improved "profil cultural" method

4.1 Description of the five experiments

The modified method was tested in five experiments in France (Estrées-Mons, Lyon and Kerguehennec), Argentina (Parana) and Brazil (Londrina) to evaluate the method's contribution to determining soil structure in a wide range of soils, climates and cultural practices. The situations are very different in terms of climatic conditions: annual rainfall varies between 713 and 1651 mm and the average temperature between 11.1 and 21 °C (Table 1). Soils are known to have very different physical behaviours. The experiments were also chosen because the experimental treatments had been set up for several years (between three and 33 years) and it was of interest to evaluate the method's ability to assess the cumulative effects of these cropping and tillage systems. On the Estrées-Mons and Parana sites, the modified method was compared to the original method, while on the three other sites, two experimental treatments were selected to identify whether the developments made to the method led to a better diagnosis of the effect of tillage systems or type of fertilisation. Soil profiles were made in 2015 at each site, except at Estrées-Mons where it was

undertaken in 2014. The location and width of the profile were chosen to be representative of the plot, and the interpretation was undertaken qualitatively from the drawing based on the location and importance of each type of structure (Figs. 5, 6 and 7). A quantitative assessment completed the visual approach by calculating a ratio for each type of porosity as the percentage of the area to the total area of the topsoil or H5 horizon (when the H1 horizon was recently fragmented) (Table 2). As the method was very destructive and time consuming and the location of the profile was chosen to be representative of the plot, one profile was performed per plot. The percentage of areas with the presence of bioturbation within each type of structure was also calculated (Table 2).

4.2 Comparison of the original *versus* the modified "profil cultural" method

The first comparison was from the long-term experiment at Estrées-Mons in France (Boizard *et al.*, 2013).

The treatment MONS-RT-HC under RT has high compaction risk with the late harvesting of sugar beet and maize in autumn, during wet periods of the year (Table 2). Using the initial "profil cultural" method, the high level of compaction was revealed, since 80% of the H5 horizon had a CΔ or CΦ soil structure (Fig. 5c). More precisely, the analysis of the structural map of the profile showed that the intensity of compaction, measured by the thickness of the compacted volume under wheel tracks, varied between cultivation operations. The analysis also provided information on the age of the compaction: it can be assumed that the CΦ areas resulting from weathering of Δ zones are more aged than the CΔ areas.

The same observations could be made using the modified method (Fig. 5d). Using the improved method, an intense biological activity was observed throughout the CΓ areas, with the presence of tubular pores and casts. The modified method also allowed a differentiation to be made within the highly compacted areas according to earthworm activity: about 85% of (CΦ + CΔ) areas were colonised by earthworms that created macropores (Table 2); the zones with no macropores were located at the top of the horizon and probably resulted from more recent compaction performed after the earthworm action, destroying the biopores. The modified method also allowed a CP

structure to be identified at the top of the CΦ zones: it could be assumed that the platy soil structure resulted from reduced drainage during wet periods at the top of ancient CΔ volumes, which were then transformed into CΦ structure by weathering. In the cases where no CP structures were present above CΔb1 volumes, it could be assumed that recent compaction had destroyed the soil structure.

Furthermore, the new method gave a more precise analysis of the effect of soil structure on root growth. Indeed, with the initial method (Fig. 5c), it was assumed that all the CΔ volumes within the soil profile severely impeded rooting (about 50% of the volume of the horizon), while the CΓ and CΦ zones were favourable. The analysis was different with the modified method (Fig. 5d): roots could colonise the CΔb1 units as well as the CΦb1 ones. Therefore, the remaining unfavourable zones (CΔ and CP) represented less than 20% of the volume of the horizon. This observation was consistent with many results showing a similar yield in NT and CT treatments. Similarly, the modified method allowed a better prediction of the soil structure's effects on the water regime which was deemed to be more favourable with the new method, because the presence of macropores plays a major role in the restoration of infiltration rate following compaction.

The second comparison was from Parana in Argentina in no-till and continuous soybean (PAR-NT-CS) for seven years. From the assessment using the initial method, 85% of the H5 horizon was identified as cΦ, resulting from compaction followed by cracking under the effect of climate. Some CΔ volumes were observed within the H5 horizon, probably resulting from more recent compaction (Fig. 6c). The modified method gave a more precise description of the structure, with the presence of a continuous platy soil structure in the upper part of the soil profile and a massive structure with the presence of vertical cracks and tubular macropores in the bottom part of the H5 horizon, (Fig. 6d and Table 2). It was also observed that part of the CΔ volumes exhibited macropores, due to root development (CΔb1). In this situation, the continuous platy soil structure over the entire width of the profile is an obstacle to rooting and water infiltration, favouring runoff, while the continuous CΦb1 soil structure below (with vertical cracks and macropores created by the roots of previous

crops) favours rooting. In the same experiment in Parana, PAR-NT-CS with the continuous soybean was compared to a crop succession under no-till: wheat/soybean-maize rotation (PAR-NT-R). Observation of the soil structure with the modified method showed that the platy soil structure in PAR-NT-R was 45% thinner and the mulch 50% thicker than in PAR-NT-C, while the two soil profiles were similar to the initial method. The modified method gave a more precise description of the structure, which was more consistent with the intensity of runoff and erosion and the observations of the root system, as shown by Sasal *et al.* (2016b submitted).

4.2 Application of the improved "profil cultural" method

The improved method was tested in three others sites. to identify whether the developments made to the method led to an improved soil structure assessment and thus a better diagnosis.

Comparison of organic and mineral fertilisation under no-till

At Kerguehennec in western France, mineral *versus* poultry manure fertilisation was compared for 15 years on a maize/winter wheat/rape/winter wheat crop rotation and phacelia (cover crop) in a Humic Cambisol (Table 1). The treatment with mineral fertilisation (KER-NT-M) exhibited a continuous soil structure in H5, that was highly porous (CΓb2), with biological porosity resulting from earthworm activity (Fig. 7). In contrast, compacted volumes were identified in KER-NT-P, with large cΔb1 volumes and platy soil structures (CP). Compaction resulted from the spreading of manure in wet conditions. In KER-NT-P, analysis of the CΔb1 units allowed not only an evaluation of the compaction due to manure spreading (which was already the case with the former method), but also (i) the study of the influence of earthworms on soil structure regeneration and (ii) the dynamics of platy soil structure development in the poorly drained zones of the profile. In KER-NT-M, the modified method did not improve the diagnosis of soil structure compared to the initial method.

Impact of different tillage systems

In Londrina in Brazil, no-till (LOND-NT) *versus* conventional tillage with disc ploughing (LOND-CTD) was compared for 33 years on a soybean/wheat crop rotation in an Oxisol. Compaction was observed in the two experimental treatments, with CΔ soil structure dominant in H5 (Fig. 7 and Table 2). In LOND-NT, the origin of the compaction in CΔb1 zones could be attributed to wheel tracks at harvesting. However, analysis of the other compacted volumes in LOND-NT and LOND-CTD did not allow a conclusion to be drawn between compaction by wheels or hard setting. The main difference between the two experimental treatments was the spatial arrangement of the soil structure. In LOND-CTD, a clear distinction between the different layers was observed in H5. From the bottom to the mulch at the surface, there was a severely compacted horizon without any trace of biological activity, then a compacted layer with biological pores, topped by a compacted layer with biopores and cracks due to weathering. The structure in LOND-NT appeared to be more homogenous with a high presence of biological pores and casts on the whole soil profile. In Londrina, the modified method allowed a more precise analysis of the effect of soil biota on structure, in interaction with the compaction process due to wheeling or climate (hard setting).

In Lyon in France, ploughed (LYON-CT) and no tilled (LYON-NT) systems were compared for three years on a winter wheat/maize/soybean crop rotation in a Fluvisol. In LYON-NT, a significant proportion of the H5 horizon was highly compacted due to repeated passages of wheels in moist conditions in 2013 and 2014. However, the significant presence of biological activity (b1) had the ability to reduce the effect of this compaction on rooting and water infiltration as well as climate (shrinkage had created a CrΔ zone in the centre of the H5 horizon). The climate also induced CP soil structure in this poorly drained soil profile, which was already visible after just three years of no-till. As in Londrina, a continuous mulch of residues mixed with a fragmentary and fine soil structure was observed on the soil surface under no-till.

In LYON-CT, the soil structure was more favourable in the ploughed horizon (H5), with dominant OΓ soil structure resulting from fragmentation by the tools. However an H6 horizon (25-40 cm depth) presented severe compaction, with only some earthworm galleries likely to ensure the

passage of roots and water. In the Lyon experiment, the modified method revealed that biological activity was fairly efficient at regenerating a compacted structure in the no till treatment, while it was not very efficient in the LYON-CT profile, for which the H6 horizon remained an obstacle for root growth and water infiltration.

5. Discussion

Benefits of the improved method for enhanced understanding of the impacts of cropping systems

The results obtained from the comparison of the initial and modified method at Estrées-Mons and Parana showed that the modified method allowed a more precise characterisation of the effects of natural processes on soil structure dynamics, and thus a better prediction of its consequences on plant growth and hydric properties. The application of the improved method in the other three sites highlighted differences in soil structure between the treatments, irrespective of the experiment. Both the initial and the modified method revealed changes in soil structure over time due to compaction, but the modified method enabled differences in soil structure altered by natural processes to be observed more precisely. Bioturbation was higher in no-till treatments (compared to conventional tillage systems) and could be zero in the deep horizons of conventional systems, which is consistent with many studies (Tebrügge and Düring, 1999; Jossi *et al.,* 2011; Crittenden *et al.*, 2015). Similarly, the ability to distinguish between the platy soil structure and other types of cracking improved the interpretation of the consequences of soil structure: although they are porous, root growth and infiltration are impeded in such structures.

Added value of the changes for users

Consultants and advisors primarily use the "profil cultural" method to make diagnoses in field conditions and help farmers make decisions. The issues involved may differ, such as the choice of equipment to limit soil compaction, as in Kerguehennec, or the effect of tillage system on plant development, as in Londrina and Lyon. The modified method resulted in a more accurate diagnosis. An example of its use can be taken from a recent study conducted on a potato crop in an area of intensive agriculture in northern France. Using the modified method, Tomis *et al. (*2013)

showed that the rooting depth of the potato crop in deeply compacted soils was dependent on the presence of macropores: rooting is limited to 30-40 cm in the absence of macropores and can reach 80 cm in the presence of vertical macropores created by anecic earthworms. This example shows that the diagnosis of the effect of this soil structure on rooting could be more severe if the presence of biopores is not taken into account. Furthermore, this method offers a framework to study the effects of natural agents on the regeneration of degraded structures in field conditions. The comparison of zones with different ages of the compaction event allows an appreciation of the speed and intensity of this natural regeneration process. Sasal *et al.* (2016b, submitted) also highlight the need to properly describe the features related to the action of natural processes for a better diagnosis of the runoff and erosion risks. In the context of the research, there are several objectives in using the "profil cultural" method, for instance to identify the spatial variability of soil structure in order to improve the sampling strategy for the study of soil properties or soil-root relationships (Neves *et al.*, 2003), to acquire a better understanding of soil structure dynamics (Sasal *et al.*, 2012; Boizard *et al.*, 2013) or to study soil biota (Vian *et al.*, 2009). This is particularly important in the context of tillage systems taking agroecology into consideration, where biological activity plays an important role.

Issues

Nevertheless several issues emerged that require further research. Knowledge about bioturbation is fragmentary: although the activity of earthworms is well known from numerous studies, less is known about the action of other species. This is the case with intense biological activity, particularly in the tropics where many species of different sizes are involved and little is known about their effect on structure. With regard to the action of earthworms, Capowiez *et al. (*2012) have shown that soil structural porosity and associated properties remain very low in compacted zones for several years, despite the significant and rapid contribution of earthworms to the infiltration rate by creating macropores. However these results are partial and there is a need for more research to understand how porosity and physical and hydraulic properties are altered by different types of species and bioturbation.

Another point about the implementation of the "profil cultural" method is that in this study its implementation was observed by experts who have many years' experience. Thirteen users of the method were surveyed about the changes introduced in France and Argentina. All the experts considered that these amendments were necessary and would be useful in improving their diagnosis in the field by integrating the role of roots and soil fauna in soil functioning. However several of them suggested that it would be difficult to implement this method in no-till since a level of expertise is required to evaluate the different criteria and would necessitate training in using the improved method correctly. Consideration should be given to organising training sessions and publishing a step-by-step guide for users. Interest was also expressed in a guide incorporating several methods and taking the soil and subsoil into account, as proposed by Batey *et al.* (2015).

6. Conclusions

Improvements to the "profil cultural" method were proposed from a collective approach and the method tested in five experimental situations in 2014 and 2015. The results demonstrated the modified method's ability to highlight differences in soil structure, make assumptions about their origin, whether they were caused by cultural operations, tillage systems soil or crop sequences, and predict consequences on the crop and the environment. This modified method should enable consultants and advisors to make more accurate diagnoses and allow scientists to give greater consideration to natural processes in field research.

Acknowledgments

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Tables

Table 1.   Main characteristic of topsoil on the experimental sites.

Experimental site	Objective of the long term experiment	Location	References	Soil type	Clay g g^{-1}	Silt g g^{-1}	Sand g g^{-1}	C %	pH	Annual rainfall (mm)	Average annual air temperature (ºC)	Crop at the time of assessment	Duration of the experiment (year)	Date of assessment	Soil water content at the time of assessing (g g-1)	Operators
France - Estrées Mons	Influence of compaction risk and soil tillage system on soil structure dynamics	50°N, 3°E, 85 m elevation	Boizard et al., 2013	Haplic luvisol	0.19	0.76	0.05	0.9	7.6 H_2O	713	11.1	winter wheat (*Triticum aestivum*)	16	April 2014	22	Hubert Boizard and Denis Piron
Argentina – Parana	Effect of crop sequence on soil structure dynamics under no tillage	31°S, 60°W, 95 m elevation	Gregorutti et al., 2014 Novelli et al., 2013	Aquic Argiudoll	0.27	0.67	0.06	1.5	6.9 H_2O	1030	18	Soybean residues (*Glycine max*)	7	June 2015	23.7	Carolina Sasal and Juan José De Battista
France - Kerguehennec	Influence of soil tillage systems with different types of fertilisation on soil functioning	47°N 2°W 112 m elevation	Piron et al., 2012	Humic Cambisol	0.16	0.43	0.41	2.1	6.4 H_2O	957	11.6	Phacelia (*Phacelia tanacetifolia*)	15	October 2015	16	Hubert Boizard, Denis Piron and Djilali Heddadj
Brazil - Londrina	Comparison of no till and plough tillage systems on a soybean-wheat crop rotation	23°S, 51°W, 585 m elevation	No scientific publication	Rhodic Eutrudox	0.83	0.11	0.06	1.5	5.2 $CaCl_2$	1651	21	Wheat (*Triticum aestivum)*	33	July 2015	~Field capacity	Ricardo Ralisch, Carolina Sasal, Julio Franchini and Fátima Guimarães
France – Lyon	Comparison of no till and plough tillage systems on maize-soybean-winter wheat crop rotation	45°N, 4°E 204 m elevation	No scientific publication	Fluvisol	0.11	0.59	0.30	0.88	7.1 H_2O	860	11.4	Crop residues / bare soil	3	March 2015	21.7	Joséphine Peigné and Jean-François Vian

Table 2. Quantitative assessment of soil structure in the five experiments. The percentage of each type of porosity was calculated as the area of the type of porosity to the total area of the observed horizons using the improved method. The figures in brackets give the percentage of areas with presence of bioturbation within each type of structure

Site	Rotation	Experimental treatment	Description of the treatment	%Γ	%Δ	%Φ	%P
F - Estrées Mons	Sugar beet/winter wheat/maize/winter wheat *(Beta vulgaris L/ Triticum aestivum/ Zea mays L./ Triticum aestivum)*	MONS-RT-HC	Rotation having high compaction risk in reduced tillage (< 6 cm depth)	20 (100)	48 (80)	27 (100)	5 (100)
A-Parana	Continuous soybean *(Glycine max L.)*	PAR-NT- CS	No till with continuous soybean	8 (0)	14 (20)	41 (100)	37 (0)
	Maïs/blé-soybean *(Zea mays L.- Triticum aestivum/Glycine max L.)*	PAR-NT-R	No till with crop rotation	16 (100)	14(0)	46 (100)	24 (0)
F-Kerguehennec	Maize/winter wheat /rape /winter wheat and phacelia (cover crop)	KER-NT-M	No till with mineral fertilisation	94 (100)	6 (100)		
	(Zea mays L./ Triticum aestivum/ Brassica napus L./ Triticum aestivum and Phacelia tanacetifolia)	KER-NT-P	No till with poultry manure	73 (100)	19 (100)		8 (0)
B-Londrina	Soybean/wheat *Glycine max L./ Triticum aestivus*	LOND-NT	No-till	17 (100)	80 (100)		3 (0)
		LOND-CTD	Conventional tillage with disc ploughing	19 (100)	81 (52)		
F-Lyon	winter wheat/maize/soybean *(Triticum aestivum/ Zea mays L./ Glycine max L.)*	LYON-NT	No-till	17 (100)	68 (58)		15 (0)
		LYON-CT	Conventional tillage with mouldboard ploughing	44 (100)	56 (52)		

Figures

Figure 1. Principle of the stratification of the observation face of a soil pit from an example in plough tillage system. Vertical partition: H1 to H4 = secondary tillage operations, H5= primary tilled horizon not affected by secondary tillage, H6 and H7 = older tilled horizons when ploughing was deeper and P1= pedological layer, called H8 if it is affected by tillage (subsoiling)H1 = secondary tillage; H5 primary tilled horizon not affected by secondary tillage; H6 = older tilled horizons and P1 = pedological horizon. Lateral partition: L1 part of the profile located under the wheel tracks of field operation(s) done after secondary tillage, L2 part of the profile located under the wheel tracks that is not visible on the soil surface, generally created during secondary tillage and L3 part unaffected by the wheels since the last ploughing. Morphological units (U1, U2…) have a homogeneous soil structure.

Figure 2a.   Morphological aspect of the three types of porosity in the initial method. The samples were observed in a silty loam at Estrées-Mons (Northern France)

Figure 2b.   Morphological aspect of the type of porosity P, which supplemented the three original types. The sample was also observed in the silty loam at Estrées-Mons (Northern France)

Figure 3. The biological indicator illustrated for both b1 and b2 and for different types of porosity with the improved method

Figure 4. Changes in structural porosity over time. FA is fine aggregates. The initial model is shown by solid lines. The amendments proposed in the modified model are shown by dotted lines

Figure 5.   Cultural profiles observed on a 240 cm-wide profile in Estrées-Mons: picture of the profile (4a); zoom on some structural states (4b); drawing using the initial method (4c); drawing using the modified method (4d). Structural state are: (■) CΔ; (▦) CΦ); (■) CΓ; (▤) CP and bioturbation is indicated on each unit

Figure 6. Cultural profiles observed on a 160 cm-wide profile in Parana: picture of the profile (4a); zoom on some structural states (4b); drawing using the initial method (4c); drawing using the modified method (4d). Structural state are: (■) CΔ; (▦) CΦ); (▦) OΓ; (▤) CP and bioturbation is indicated on each unit

Figure 7. Drawing of the cultural profiles observed with the modified method in Kerguehennec, Lyon and Londrina. Structural states are: (■) CΔ; (▦) CΦ); (■) CΓ; (▤) CP; (▦) OΓ and bioturbation is indicated on each unit
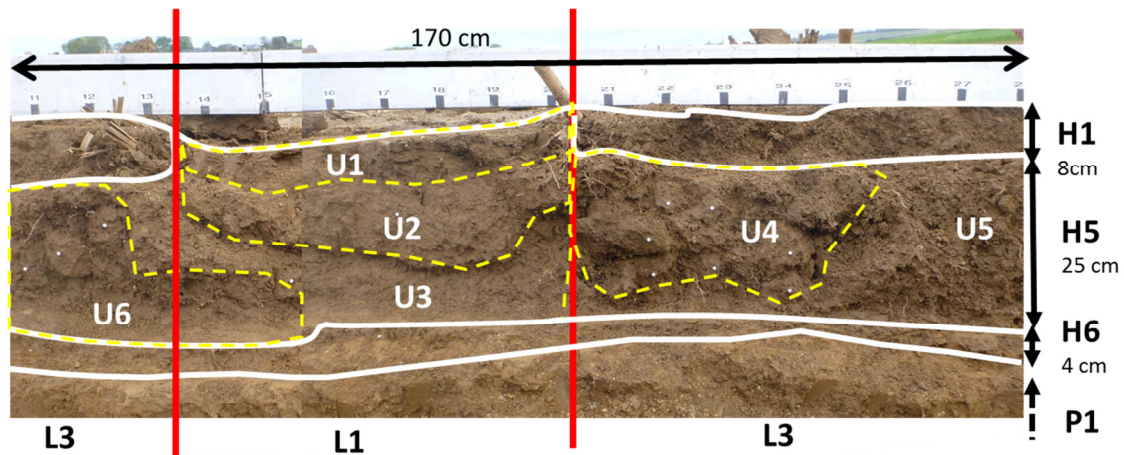
Photo : Vincent Tomis

Figure 1. Principle of the stratification of the observation face of a soil pit from an example in plough tillage system. Vertical partition: H1 to H4 = secondary tillage operations, H5= primary tilled horizon not affected by secondary tillage, H6 and H7 = older tilled horizons when ploughing was deeper and P1= pedological layer, called H8 if it is affected by tillage (subsoiling). Lateral partition: L1 part of the profile located under the wheel tracks of field operation(s) done after secondary tillage, L2 part of the profile located under the wheel tracks that is not visible on the soil surface, generally created during secondary tillage and L3 part unaffected by the wheels since the last ploughing. Morphological units (U1, U2…) have a homogeneous soil structure.

Δ as delta		No visible macropores Aspect of the breaking surface smooth High cohesion
Γ as gamma		High structural porosity with visible aggregates Rough surface
. **Φ as phi**		Resulting of Δ, type Φ is composed of fragments with sharp edges, separated by flat cracks oriented in all spatial directions

Figure 2a.   Morphological aspect of the three types of porosity in the initial method. The samples were observed in a silty loam at Estrées-Mons (Northern France)

P as platy		Resulting of Δ, type P is characterised by a network of horizontally-oriented cracks.

Figure 2b.   Morphological aspect of the type of porosity P, which supplements the three original types. The sample was observed in a silty loam at Estrées-Mons (Northern France)

		b1 : presence of macropores ~ 5 cm
		b2 : presence of macropores and casts in Δ or Φ types of porosity
		b2 : presence of macropores and casts in Γ type of porosity

Figure 3. The biological criterion illustrated for both b1 and b2 and for different types of porosity with the improved method
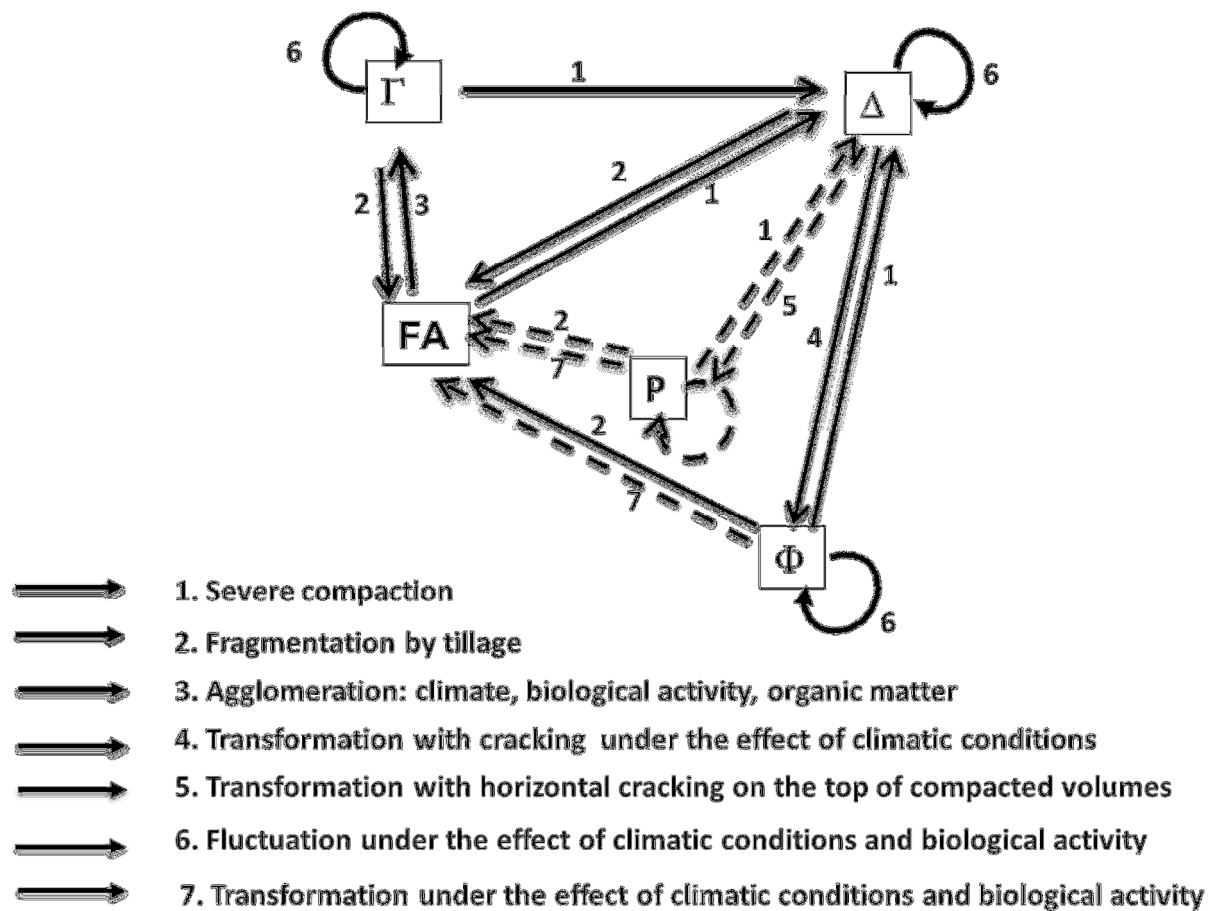
Figure 4. Changes in structural porosity over time; FA is fine aggregates; the initial model is represented by solid lines. The amendments proposed in the modified model are represented by dotted lines
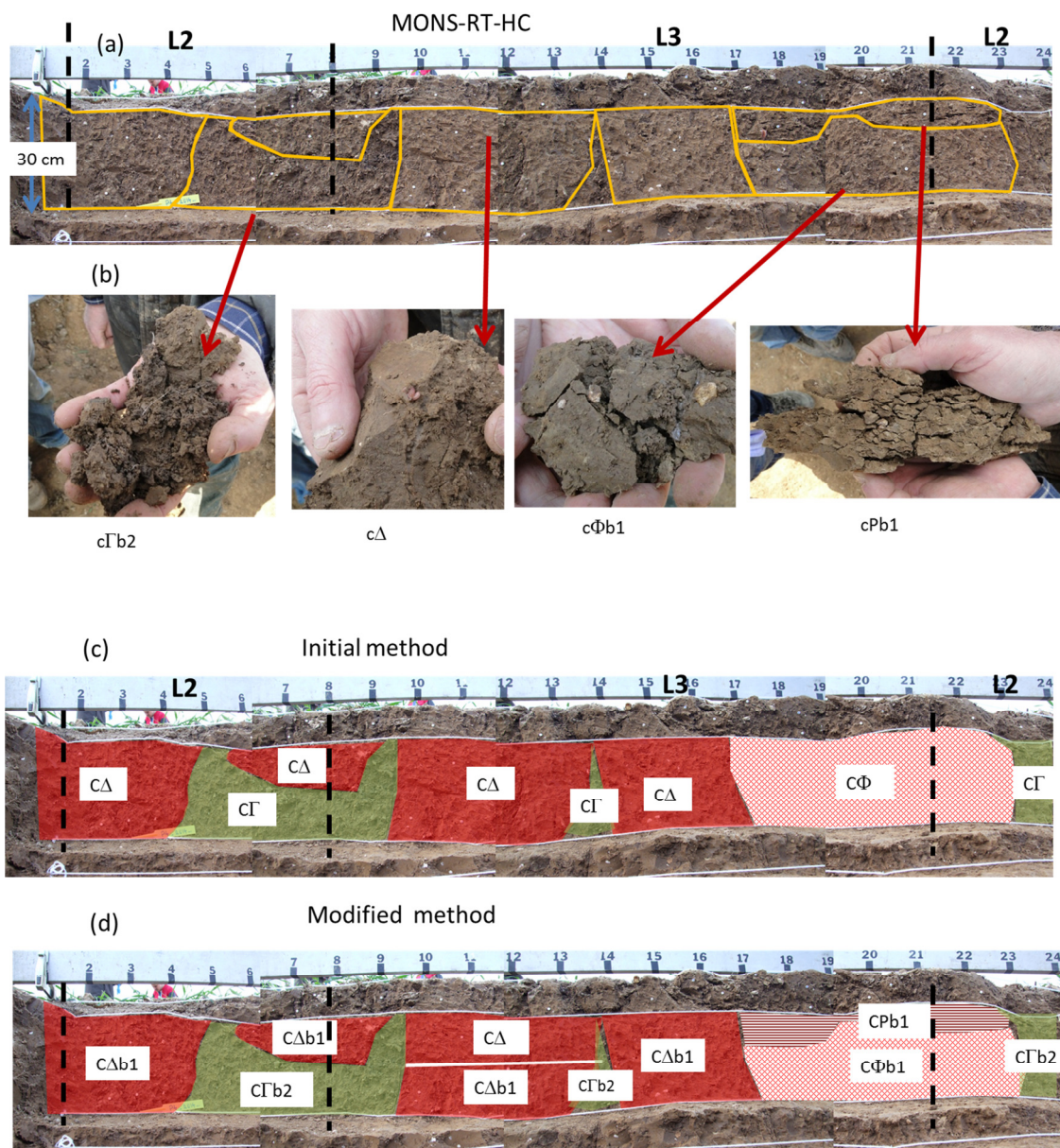
Figure 5. Cultural profiles observed on a 240 cm-wide profile in Estrées-Mons: picture of the profile (4a); zoom on some structural states (4b); drawing using the initial method (4c); drawing using the modified method (4d). Structural states are : (■) CΔ; (▦) CΦ); (■) CΓ; (▤) CP and bioturbation is indicated on each unit
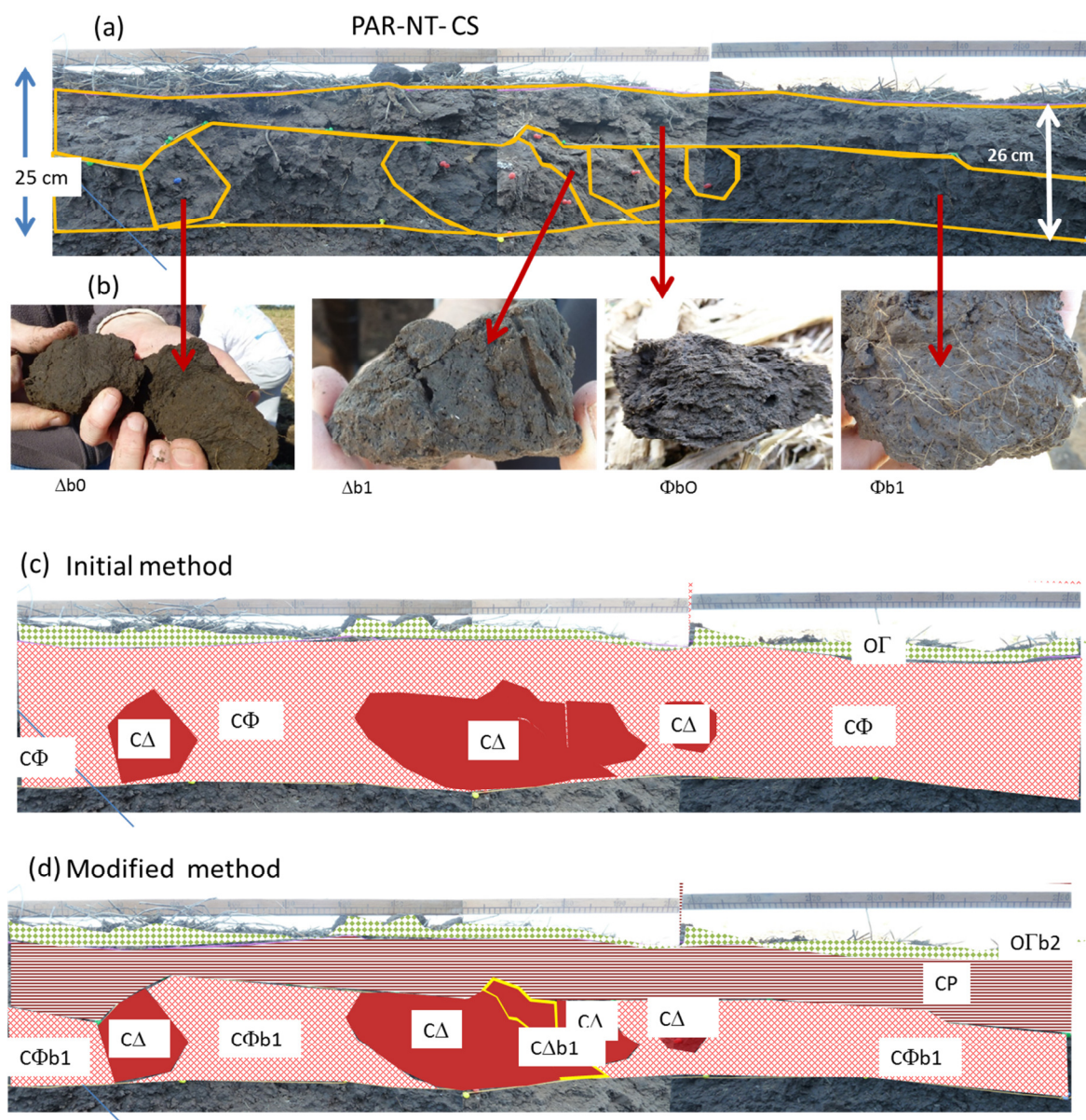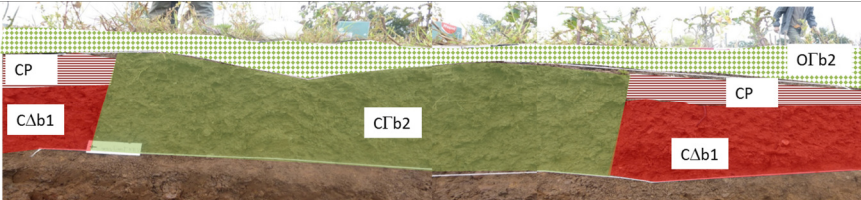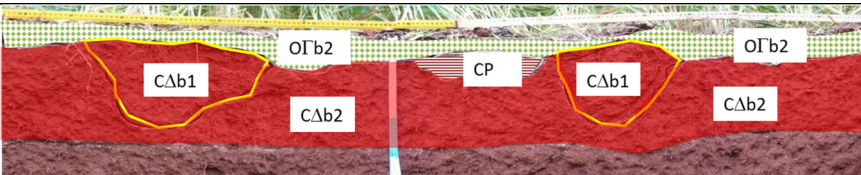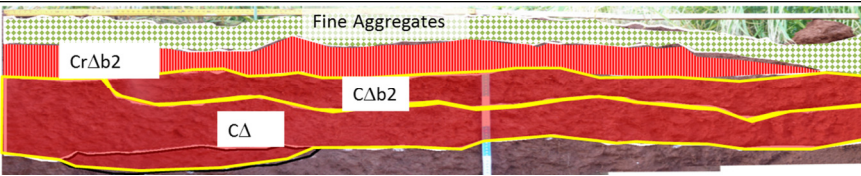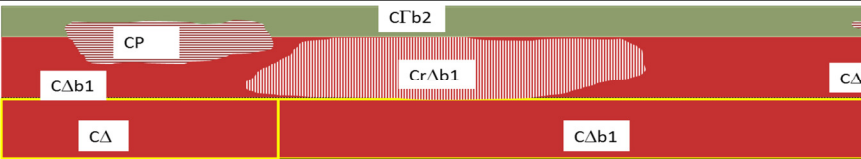
Figure 6. Cultural profiles observed on a 160 cm-wide profile in Parana: picture of the profile (4a); zoom on some structural states (4b); drawing using the initial method (4c); drawing using the modified method (4d). Structural states are: (■) CΔ; (▦) CΦ); (▦) OΓ; (▭) CP and bioturbation is indicated on each unit

Name of the experimental treatment	Horizon and depth (cm)	Profile structure maps	
KER-NT-M No till with mineral fertilisation 200 cm width	H0: 0-10 H5: 10-27		H0: fragmented soil structure with high presence of biological macropores and casts H5: soil structure is continuous (CΓb2: 95%) with the presence of a significant structural porosity, mainly due to earthworms activity (macropores and casts)
KER-NT-P No till with poultry manure 200 cm width	H0: 0-10 H5: 10-27		H0: lumpy soil structure with high presence of biological macropores and casts H5: 40% of the horizon were highly compacted (CΔb1 and CP) with platy soil structure located at the top of the CΔb1 zones and presence of some biological pores in CΔb1 zones: 60% of areas has a continuous soil structure and high structural porosity (CΓb2)
LOND-NT No-till 200 cm width	HO: 2 to 5 H5: 5-30		H0: continuous mulch of residues mixed with fragmentary soil structure and presence of bioturbation H5: soil structure is continuous and massive with high presence of macropores and casts (CΔb2: 74%). Presence of some compacted volumes with few biopores (CΔb1) underneath the mulch and corresponding to wheel tracks
LOND-CTD Conventional tillage with disc ploughing 200 cm width	H1: 0-10 H5: 10-40		H1: a fragmentary layer composed of fine aggregates H5: H5 layer is highly compacted especially at the bottom (CΔ: 48%). At the top, current regeneration (CΔb2 and CrΔb2: 52%) under the effect of climate and biological activity with presence of macropores and some vertical cracks just at the top
LYON-NT No-till 300 cm width	H0: 0-3 H5: 3-25 H8: 25-35		H0: very loose soil structure due to crop residues and biological activity on the surface. H5: high compaction with a continuous soil structure. Presence of a platy soil structure at the top of a CΔ zone and highly compacted area perforated by earthworm channels in the bottom part of H5 H8: high compaction is observed with a discontinuous presence of earthworm macropores (CΔb0 and CΔb1)

| LYON-CT Conventional tillage with mouldboard ploughing 300 cm width | H5: 0-25 | | H5: co existence of two types of structure: (1) many fragmented areas with presence of crop residues (OΓb2: 70%) and (2) zones where compacted clods are dominant (BΔb1: 30%) due to poor fragmentation by ploughing in a highly compacted soil. |
| | H6: 25-40 | | H6: highly compacted area inherited from the ancient tilled horizons (plough pan and deep compaction after subsoiling) with little presence of earthworm galleries (CΔ: 70% and CΔb1:30%) in this horizon. |

Figure 7. Drawing of the cultural profiles observed with the modified method in Kerguehennec, Lyon and Londrina. Structural states are: (■) *CΔ;* (▨)
CΦ); (■) *CΓ;* (▬) *CP;* (▨) *OΓ and bioturbation is indicated on each unit*