A compartmental model to simulate temporal changes in soil structure under two cropping systems with annual mouldboard ploughing in a silt loam

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Received 7 October 1998; received in revised form 21 May 1999; accepted 1 December 1999

Abstract

A practical model of the soil structure dynamics in ploughed fields can be a powerful aid to farmers attempting to optimise their management practices. This paper describes a compartmental model that simulates the changes over several years in an indicator of the effects of cropping systems on soil structure. This indicator, the proportion of severely compacted clods in the ploughed layer, was measured in two plots at the INRA Experimental Centre at Grignon (Yvelines, France), where two cropping systems produced very different compaction conditions in a silt loam. The ploughed layer was considered to be a set of elementary compartments delimited by the wheel tracks and actions of tillage tools. The percentage of severely compacted clods in each elementary volume changed with time due to transfer between compartments during mouldboard ploughing, compaction and fragmentation. The proportion of severely compacted clods changed exponentially until it reached a plateau, after about 8 years. The equilibrium values of the indicator were very similar to those measured in the experimental plots. The model was very sensitive to the rate at which severely compacted clods were lost, probably because the vertical distribution of these clods in the soil profile was not taken into account in this compartmental model. The model in its present state can be used to compare the effects on soil structure of various technical changes. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Cropping system; Soil structure; Soil compaction; Soil fragmentation; Mouldboard ploughing; Compartmental model

1. Introduction

The structure of the soil in the ploughed layer of a cultivated field is influenced by external factors, both man-made (e.g., wheeling, tillage tools) or natural (e.g., climate, fauna, roots). These factors can cause compaction, fragmentation or even displacement of the soil (Boizard et al., 1994). The combined effects of these factors alter the characteristics of the soil which define its structure (Dexter, 1988; Stengel, 1990), particularly the spatial arrangement, size and shape of the soil particles, and consequently the pore space volume. A cropping system is characterised by the scheduling and nature of the cultivation operations

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used for successive crops. Each of these operations is defined (Manichon, 1988) by (1) the nature of the mechanical stress it applies to the soil, and by (2) the size and the spatial location of the soil volumes affected by this stress. Thus, the soil structure generally varies greatly, at a metric or decimetric scale, from one part of a cultivated field to another. The scheduling of successive operations also determines the conditions under which the stress occurs and thus the reaction of the soil. It also determines the intensity, and sometimes the nature, of the action of natural factors. It is difficult to forecast the overall effect of a cropping system on the evolution of the structure of the ploughed layer, for at least three reasons. First, most studies on the intrinsic properties of the material have been done in the laboratory, and their results are not readily transposable to the field (Kay et al., 1988). Second, many studies on changes in soil structure have examined only one of the processes involved. They are generally devoted to compaction (Ragahvan et al., 1990), and few have examined fragmentation and displacement. Third, available models describing the processes influencing soil structure use input and output variables that are in general not compatible. It is thus impossible to predict the effect of successive operations when they involve different mechanical processes.

Soil structure (in interaction with climate) influences crop yield, (Hadas et al., 1978; Tardieu and Manichon, 1987), soil biological activity (Sims, 1990), the transport of water and solutes (Jarvis et al., 1991; Gerke and Van Genuchten, 1993; Pikul and Zuzel, 1994; Curmi et al., 1996), emissions of nitrous oxide from the soil (Ball et al., 1997), and the risk of water erosion (Bresson and Boiffin, 1990). A model that could predict changes in soil structure at the field scale under the influence of management practices would thus be very useful for evaluating improvements in sustainable cropping systems.

This paper describes a compartmental model which concerns cropping systems including annual ploughing. It was established in a field trial designed in such a manner that the tool width and location of wheel tracks allowed a precise analysis of the effects of compaction, fragmentation and soil displacement on soil structure dynamics. We studied two plots where the cropping systems produced very different degrees of compaction conditions. Soil structure was first described using a morphological description of the ploughed layer. This method (Manichon, 1982, 1987) allows the zones and clods showing different compaction degrees in a soil profile to be identified visually and classified from macroscopic features. Then we evaluated an indicator of soil structure, the proportion (in mass) of severely compacted clods within the ploughed layer. The objectives of this study were (1) to describe the assumptions of the model, (2) to describe the model itself, and (3) to discuss its ability to simulate the changes in the indicator of soil structure over time.

2. Material and methods

2.1. Definition of the indicator of soil structure

Manichon (1982, 1987) proposed a method for describing the soil structure in cultivated layers that is based on the morphology of the soil elements created by tillage: fine soil and clods (diameter >2 cm). The method identifies three types of clods (Table 1) on the basis of their morphology, mainly the

<table>
<thead>
<tr>
<th>Type of internal clod structure</th>
<th>Morphology</th>
<th>Apparent structural porosity</th>
<th>Bulk density of air dried clods$^a$ (g cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δ</td>
<td>Smooth-breaking faces</td>
<td>Very low to zero</td>
<td>1.74–1.85</td>
</tr>
<tr>
<td>Φ</td>
<td>Near Δ, but with nascent cracks</td>
<td>Variable, crack type</td>
<td>1.67–1.80</td>
</tr>
<tr>
<td>Γ</td>
<td>Aggregates whose morphology varies. Structural porosity is visible. Very rough breaking faces</td>
<td>Variable (quantity and morphology) of various types (cracks, voids between the aggregates, tubular)</td>
<td>1.35–1.70</td>
</tr>
</tbody>
</table>

$^a$ Min–max values of the bulk density measured on three populations of clods (Δ, Γ and Φ) sampled in the tilled layer of the experimental plots at the INRA Experimental Center in Grignon (Manichon, 1982; Coulomb et al., 1990).
importance and characteristics of the apparent structural porosity. These three clod types and fine soil co-exist within the ploughed layer in proportions that depend on the cropping system (Manichon and Roger-Estrade, 1990; Coulomb et al., 1990). The composition of a given soil volume in the ploughed layer changes in response to the mechanical stresses applied, which may cause transformation from one state to another by fragmentation or compaction. The type and degree of change, in a given texture, depend on the initial state (structure and moisture content) of the soil volume and on the energy of the stress applied (Koolen, 1994). These processes are shown in Fig. 1.

The spatial variations in the structure of the whole ploughed layer are mainly due to the fact that the different soil volumes in this horizon are subjected to different mechanical stresses, depending on their location (depth and position relative to the wheel tracks). Thus climate (arrow 4 in Fig. 1) has its greatest effect near the soil surface. The fragmentation caused by tillage during seed bed preparation (arrow 2 in Fig. 1) is also greater in the upper part of the soil profile. On the other hand, climate has very little direct action on soil structure below the seed bed, in a temperate climate for a loamy soil. In the same way, the soil volumes which are severely compacted during wheeling are those located beneath the wheel tracks (Richard et al., 1999). When compaction is not severe (low axle load, low moisture content, zones located near the wheel tracks beside the rut), it creates \( \Gamma \) clods (arrow 3 in Fig. 1). Severe compaction (high moisture content, high load intensity, repeated passages over the same place) creates soil volumes having a \( \Delta \) internal structure, whatever the initial structure of the material (arrow 1 in Fig. 1). These compacted volumes are generally decimetre-sized. They are reduced by fragmentation during tillage (arrow 2 in Fig. 1), without altering their internal structure (Coulomb, 1992; Coulomb et al., 1993). Finally, the turnover and lateral displacement of the furrow slices cut by the plough also increases the spatial variation in the ploughed structure, mixing materials from different soil volumes (Kouwenhoven and Terpsta, 1972; Roger-Estrade, 1991), and bringing soil volumes which were at the bottom of the profile protected from the action of climate, to the surface (Hadas, 1997).

Thus, soil structure within the ploughed layer is, at a given moment, the result of a balance between compaction (creating \( \Delta \) clods), fragmentation (reducing them to fine soil or decreasing their size) and displacement during ploughing (mixing \( \Delta \) clods from different volumes). The proportion of \( \Delta \) clods within the ploughed layer is therefore an indicator of this balance. We have used it as an indicator of the effects of the cropping system on soil structure. The model describes the changes in this indicator, from one year to another.

### 2.2. Tillage and site characteristics

The INRA Experimental Centre at Grignon (Yvelines) is in the west part of the French Paris Basin. The soil is an Orthic Luvisol, according to the FAO classification, developed from a loess of the recent Würm, about 2 m below which is a calcareous rock. The ploughed layer (0–25 cm) of the two experimental plots contained an average of 235 g clay kg\(^{-1}\), 665 g silt kg\(^{-1}\), 93 g sand kg\(^{-1}\), 14 g organic matter kg\(^{-1}\), and 5 g CaCO\(_3\) kg\(^{-1}\). We selected two cropping systems. The first (CS1) had a cropping sequence in which sowing occurred only in autumn and harvesting only in summer: winter wheat (Triticum aestivum L.)
and winter rape (Brassica napus L.). The risk of compaction was low in this case. The second crop sequence (CS2) was maize (Zea mays L.)/winter wheat, so that one harvest took place in autumn every second year, when the soil in this region is often very wet, causing a greater risk of compaction than in the CS1 plot.

The experimental fields were divided into plots of 30 m × 17.5 m. These dimensions were adapted to the experimental equipment used for crop management. The tractor used for all cultivation operations had a distance between the centres of the two rear wheels of 1.75 m, and the rear tyres were 35 cm wide. The tools for seed bed preparation and seed drilling were also 1.75 m wide. Thus, the preparation and sowing tracks could be located so that each experimental plot was divided into 10 bands of one seed drill width. Each band was bordered by two wheel tracks (Fig. 2). In these experimental fields, each track was wheeled twice for each operation: the tractor rolled in the rut made at the preceding passage. Each wheel track was common to two adjacent bands. Therefore, a periodic pattern could be defined by one wheel track (the corresponding position in the soil profile was labelled L1) associated to the part of the band located between two wheel tracks (labelled L3). All passages were along these tracks once the plot was ploughed and until harvested. A positioning system also allowed the plots to be located at the same place every year, which caused the wheel tracks to be in the same place from one year to the next, with a precision of about 0.35 m. Wheel passages during harvesting (combine harvester, maize picker, trailers) were not restricted to the L1 position.

2.3. Soil structure observations

The soil structure in the ploughed layers of plots CS1 and CS2 was examined using two methods: (1) macroscopic observation of soil profiles, and (2) determination of the proportion of Δ clods. The soil profiles (whose width corresponded to that of one seed drill and depth was 0.6 m) were located perpendicular to the tillage direction and were examined while the plots bore winter wheat. The macroscopic structural features of the ploughed layer were mapped, using the method of Manichon (1982, 1987).

The proportion of compacted clods in the L3 compartment was measured on four profiles of each type. All the soil was removed from the L3 compartment, and separated into six samples, carefully positioned from left to right of this compartment. Air-dried soil was weighed and sieved to separate the fine soil from the clods larger than 2 cm. The Δ and Φ clods were separated from the G clods by bulk density. Preliminary observations of clods from the tilled layer of plots at the Grignon Experimental Centre (Manichon, 1982; Coulomb et al., 1993) had shown that air-dried Δ and Φ clods were best separated from the G clods by their greater bulk density. Preliminary observations of clods from the tilled layer of plots at the Grignon Experimental Centre (Manichon, 1982; Coulomb et al., 1993) had shown that air-dried Δ and Φ clods were best separated from the G clods by their greater bulk density.
1.67 g cm\(^{-3}\) (Table 1). Clods were sealed with paraffin and placed in a ZnCl\(_2\) solution whose density was this threshold value. As there was very few Φ clods, the fraction with a bulk density greater than 1.67 g cm\(^{-3}\) was defined as the Δ fraction. The Δ fraction was weighed. We computed the ratio of the mass of the Δ fraction to the total mass of soil for each sample. The mean of these six values gave the mean proportion of Δ clods in the L3 position. The soil from position L1 was also sampled to evaluate the proportion of Δ in this part of the profile.

2.4. Model structure

The ploughed layer is considered to be a set of elementary volumes (compartments) delimited by the action of the plough. The proportion of Δ clods in each elementary volume is similar to a concentration which changes time under the influence of the processes mentioned above. Each compartment is described by its Δ content at a specific date each year, chosen by convention just before harvesting. Three types of flow are responsible for the changes in the Δ content in a compartment: (1) the creation of Δ clods by compaction, (2) their transfer between compartments during ploughing due to lateral displacement of the furrow slice (as the direction of displacement is reversed from one year to the next, the reversibility of the transfer between compartments is not simultaneous: the direction of the lateral displacement during ploughing is reversed from one year to the next), and (3) the loss of Δ clods due to seed bed preparation and climate action.

2.4.1. Definition of the compartments

One position L1 and one position L3 were assumed to describe the basic pattern characteristic of these experimental plots (Fig. 2). The L1 position contained one compartment and L3 contained four compartments. These five compartments all had the same width (35 cm), corresponding to the wheel track width in L1 and the width of the furrow slices cut by the plough in L3. As we could only consider a finite number of compartments, we added a loop to the model. We assumed that the compartments on one side of the pattern received soil from the compartments at the other side of the adjacent identical pattern during ploughing. Every year ploughing caused redistribution of the soil between compartments by lateral displacement. We assumed that the coincidence between the limits of the compartments and those of the furrow slices was perfect. Thus, position L1 (the first compartment) corresponded to a single furrow slice cut every year.

2.4.2. Creation of Δ clods

In the CS1 plot, creation only occurred in the first compartment, as this was the only one which was wheeled enough after ploughing to be compacted (soil structure was not degraded during harvest as it occurred in dry condition in summer). We assumed that this compartment was entirely compacted every year (Δ content = 100%), whatever the soil moisture content during cultivation, because of the repeated passages during the crop cycle. In the CS2 plot, compaction also occurred in compartments of the L3 position, during the maize harvest in autumn. This operation was performed with a one row maize picker, attached to the same tractor that was used for the other field operations. There was thus one wheel track on each maize inter-row and each track was wheeled twice (once by the left-side wheels, once by the right-side ones at the next passage, except for the first and the last passages in the plot). As the inter-row spacing was 80 cm, there were two maize rows in each band. The tractor rolled over the L1 position to harvest one row, and over the L3 position to harvest the next row. The trailer passages used the ruts of the tractor carrying the maize picker. The repeated passages, the generally high soil water content during maize harvest and the weight of the maize picker (ca. 1 Mg), led to a severe compaction under the wheel tracks at the L3 position. This was taken into account in the model by compacting one compartment of the L3 position every second year; its Δ content was set at 100%. As the locations of the passages were not recorded, the number of the compacted compartment in L3 was randomly chosen from among the four of them.

2.4.3. Transfer coefficients

We assumed that the transfer coefficients remained unchanged from one year to another (no change in the plough characteristics). Assuming that the Δ clods were uniformly distributed within the furrow slices, we considered the proportion of Δ clods leaving a given compartment during ploughing to be equal to
the proportion of soil leaving this same compartment. There is only one model in the literature describing the turnover and lateral displacement of furrows during ploughing (Bousfield, 1880). This has been used by several authors (Nichols and Reed, 1934; Söhne, 1959; Feuerlin, 1966; Hénin et al., 1969). The above model assumes that the furrow slice is turned upside down and remains rigid during this movement. When this movement is projected on a plane perpendicular to the direction of motion of the plough, it consists of a double revolution around two centres (D and C’ in Fig. 3). The inclination of the furrow is given by the sine of the angle α between the furrow border and the plough pan, equal to the ratio \( P/L \), where \( P \) is the ploughing depth and \( L \) is the ploughing width. The soil from compartment \( i \) cannot be projected further than compartment \( i + 2 \) (Fig. 3). So, all the soil from one compartment is redistributed within the two adjacent compartments. The transfer coefficients are then equal to the proportion of soil belonging to compartment \( i \) projected to compartment \( i + 2 \) (noted \( c \)) and \( i + 1 \) (noted \( 1 - c \)). The value of \( c \) was estimated by a geometrical analysis of the furrow section \((A'B'C'D')\) in Fig. 3. Proportion of soil transferred from compartment \( i \) to compartment \( i + 2 \) was assimilated to the proportion of the surface of the furrow section corresponding to the area \((EA'B'F)\) in Fig. 3. The remaining part of the furrow section, \( 1 - c \), was assimilated to the proportion of the surface of the furrow section corresponding to the area \((EFC'D')\). The ploughing width and depth at the Grignon Experimental Centre were 35 and 25 cm, respectively. The corresponding value of \( c \) is 24.4%.

2.4.4. Loss of \( \Delta \) clods

The \( \Delta \) clods were only lost from the surface layer of the ploughed horizon during seed bed preparation and under the influence of climate (fragmentation due to swelling and shrinkage). The \( \Delta \) clods in this layer were fragmented and gradually transformed to fine soil. So the \( \Delta \) content was zero in the seed bed just before harvest. With Coulomb et al. (1993), we assumed that there was no loss of \( \Delta \) clods during ploughing. We also assumed that the loss of \( \Delta \) clods from one compartment was proportional to the total \( \Delta \) content of the compartment at that time. As \( \Delta \) clods were assumed to be uniformly distributed throughout the compartments, the rate of loss was assumed to be equal to the proportion of soil in the seed bed layer. This coefficient (noted \( r \)) was the same for all the compartments in L3, and was estimated to be the ratio between the seed bed depth and the total depth of the ploughed

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**Fig. 3.** Model of the furrow movement during ploughing. The figure shows a section of the furrow in a plane perpendicular to the direction of motion of the plough. Vertical bars are the limits of the compartments \( i, i + 1, i + 2 \). \( A', B', C' \) and \( D' \) are the positions of the points \( A, B, C \) and \( D \) respectively, after ploughing. The transfer coefficient \( (c) \) was assimilated to the proportion of the furrow projected from compartment \( i \) to compartment \( i + 2 \) (i.e., the ratio of the surface of area \((EA'B'F)\), dark grey) to the total surface of the furrow section \((A'B'C'D')\).
had a very low structural porosity. There was no difference between the two seed beds, which were entirely composed of fine soil. However, soil structure in the part of the profile below the seed bed and outside the wheel tracks (L3) appeared to be different in CS1 and CS2. The CS1 plot showed wide variations in the spatial distribution of the compacted clods, which were more frequent near the L1 compartment of the left part of the map, and rarer in the centre of the profile. The CS2 plot had a greater proportion of compacted clods over the whole profile, and these clods were more regularly distributed within the L3 compartment, although they were slightly more frequent in the part of the L3 compartment near the left wheel track. The size distributions were also different: the clods were, on average, bigger in CS2.

Table 2 shows the measured $D$ contents in the L1 and L3 positions of the four profiles investigated in each plot. The $D$ content was near 100% in L1 of both CS1 and CS2 plots. This is coherent with the observations of the profiles, which showed that soil structure was massive under the wheeled part of the plots. In L3, $D$ content appeared to be about twice as great in CS2 as in CS1. The proportion was significantly higher in the sub-sample taken near the L1 compartment (No. 1) than in the other compartments of the L3 position. Thus, the two cropping systems resulted in different soil structures in the ploughed layer, which were perceptible not only from a morphological description of the structure of the ploughed layer (Fig. 5), but also by measuring the proportion of $D$ clods in the L3 position of the profile. This result validates the choice of the indicator of soil structure.

3.2. Simulations

3.2.1. CS1 plot

The initial conditions in CS1 and CS2 were fixed with a $D$ content of zero in the four compartments of the position L3. The results of the simulation are shown in Fig. 6. The change with time in the $D$ content in position L3 (mean of the four compartments) was an 8-year initial phase, in which change was exponential, followed by a plateau, when the system was in steady state (Fig. 6a). The simulated content at equilibrium was 36%. This value is very close to the measured value of 33% (Table 2). Thus, the $D$ clods represented, at equilibrium, about one third of the total mass of soil

layer. The average seed bed depth in Grignon was 5 cm and the ploughing depth was 25 cm. So, $r$ was calculated as follows:

$$r = \frac{5}{25} = 0.20.$$ 

Fig. 4 shows the model adapted to the CS1 plot in a diagram form. The associated mathematical model is given in Appendix A.

3. Results

3.1. Proportion of $D$ clods

Fig. 5 shows the maps of the CS1 and CS2 plots, summarising the data over several years. Both systems had massive structures under the wheel tracks, and the corresponding compartment of the soil profile (L1)
in the L3 position. The increase in the $D$ content occurred while there was no compaction in the L3 position and was thus only due to lateral transfer during ploughing. The alternating direction of lateral displacement from one year to the next during ploughing and the fact that the parameters were constant throughout the simulation, rapidly brought the system to a steady state. Other simulations, not presented in Table 2:

### Table 2
Proportion of compacted clods ($D$ internal structure) in the wheeled (L1, 1 sample) and the no-wheeled (L3, 6 samples) positions measured in the four profiles of the CS1 plot (above) and the CS2 plot (below)

<table>
<thead>
<tr>
<th>Profile</th>
<th>L1 position</th>
<th>L3 position</th>
<th>Mean of the six samples in the L3 position</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td><strong>CS1 plot</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>97&lt;sup&gt;a&lt;/sup&gt;</td>
<td>40</td>
<td>11</td>
</tr>
<tr>
<td>II</td>
<td>93</td>
<td>62</td>
<td>19</td>
</tr>
<tr>
<td>III</td>
<td>95</td>
<td>56</td>
<td>40</td>
</tr>
<tr>
<td>IV</td>
<td>98</td>
<td>59</td>
<td>30</td>
</tr>
<tr>
<td>Mean</td>
<td>96&lt;sup&gt;a&lt;/sup&gt;</td>
<td>54&lt;sup&gt;b&lt;/sup&gt;</td>
<td>25c</td>
</tr>
<tr>
<td><strong>CS2 plot</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>94</td>
<td>62</td>
<td>64</td>
</tr>
<tr>
<td>II</td>
<td>98</td>
<td>69</td>
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<td>III</td>
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<tr>
<td>IV</td>
<td>99</td>
<td>59</td>
<td>65</td>
</tr>
<tr>
<td>Mean</td>
<td>96&lt;sup&gt;a&lt;/sup&gt;</td>
<td>67b</td>
<td>65b</td>
</tr>
</tbody>
</table>

<sup>a</sup> Values are in percentages (g g<sup>−1</sup>).

<sup>b</sup> The same letter in a same column or a same line indicates that the mean, in this line or column, are not different at the 10% level (analysis of variance performed after log-transformation of the variables).
here, have shown that the equilibrium content did not depend on the initial D content. If a perturbation was introduced in the simulation (by adding compaction to a compartment of L3) while the system was in steady state, the simulated value of the indicator deviated from the initial trajectory, then returned to the equilibrium value after some years of simulation under the initial conditions. The steady state is stable (Jacquez, 1985; Pavé, 1994). The model allowed us to simulate the differences between compartments within the L3 position (Fig. 6b). The equilibrium values for the compartments were rather different. Those near the L1 position had higher values than those at the other end of the pattern. This is consistent with the observations of soil profiles shown in Fig. 5. This difference can be attributed to the lateral displacement of the furrow slice during ploughing. When the system was in a steady state, the alternating directions of displacement produced great symmetry between the compartments of L3 from one year to the next, with the highest content in the second compartment when displacement was to the right and in the fifth when the furrow slice was displaced to the left.

3.2.2. CS2 plots

The changes in the D content in the four compartments of L3 are shown in Fig. 7a, for three random examples. The general shape of the curve was similar to that for the CS1 plots, but the mean value at
equilibrium was higher, and the Δ content oscillated around this average value after a period of 8 years. The mean content was around 61%. As the value in Table 2 for the CS2 plots was measured when the crop was wheat (i.e., after a maize harvest), they should be compared to the mean values of the odd years in the simulation, when the system is in a steady state. This value is 66.5%.

The steady state of the system appeared to be dynamically stable (Pavé, 1994), oscillating more or less regularly around an equilibrium value that was significantly higher than that for the CS1 plots. The Δ content obtained in the 22nd year of simulation in each of the four compartments of L3 is shown in Fig. 7b. The differences between compartments were less marked than those in the simulation of the CS1 plots, which is consistent with the observations of soil profiles shown in Fig. 5.

4. Discussion

The formalisation of the mathematical model led us to make some simplifying assumptions concerning the dynamics of soil structure in the ploughed layer. A first group of assumptions was related to the input and output of Δ clods, a second group to the transfers between compartments of the ploughed layer. The first group of assumptions were (1) the creation of 100% Δ in the first compartment every year and in one of the four compartments of L3 once in every 2 years in the CS2 plots, (2) no creation of Δ clods when harvesting takes place in summer, and (3) the loss of all the Δ clods in the seed bed.

Concerning the creation of Δ clods, the extension of this model to farm conditions must better take into account the compaction process. The repetition of the passages at the same place in Grignon insured maximum compaction in L1 and L3. Noteworthy is the fact that these traffic rules are specific to the Experimental Centre at Grignon. They were adopted because the small size of the experimental plots and to prevent an uncontrolled extension of the compacted zones. We need a more precise modelling of compaction in cultivated fields before we can extend the model to situations where the wheel passages are not so strictly located. The present model allows integration of this new information. It will also be necessary to have accurate data on the water content in the plot and its spatial variation (particularly as a function of depth) before we can extend the model to farm situations. This factor is most important for field compaction with a specific machinery (Guérit, 1990). We also considered Δ clods to be only created in soil volumes located just beneath the tyres. This is consistent with the data of Richard et al. (1999) for a similar soil type, showing that zones of maximal compaction (with a Δ internal structure) are located under the ruts.

Concerning the loss of Δ clods, we performed a sensitivity analysis of the rate of loss of Δ clods (parameter r). The value of this parameter was changed from 16 to 24% (corresponding, for a ploughing depth of 25 cm, to a depth of 4–16 cm during seedbed preparation). The equilibrium Δ content of the L3 position is shown in Fig. 8, as a function of the r value. The equilibrium value dropped as the loss rate increased: the Δ content was divided by three when the secondary tillage depth was increased from 4 to 16 cm. This high sensitivity is probably due to the fact that destruction of the Δ clods was overestimated when the rate of loss was uniformly applied to all the Δ of the compartments. Actually, Δ clods located under the seed bed are protected from fragmentation. The model would probably be less sensitive to the loss rate if the vertical position of the Δ clods were taken into account.

![Fig. 8. Sensitivity of the model to the loss rate: proportion of compacted clods in the L3 position at equilibrium as a function of the annual rate of loss of the compacted clods (parameter r of the model). The conditions for the simulations are those of the CS1 plot.](image-url)
The second group of assumptions concerns: (1) the way the turnover of the furrow slice was modelled (particularly the fact that we assume that the furrow remains rigid during this movement), (2) the coincidence between the limits of the compartments and the passage of the plough, and (3) the uniform distribution of the Δ clods in the compartments (leading to the assumption of transfer from one compartment to another proportional to the existing stock of Δ clods). A more realistic model of the plough action (randomising the location of the plough passage, or introducing changes in the furrow shape) would change the values of the transfer coefficients and the form of the transfer matrix. Simulations, not presented here, made with different transfer matrices have shown that the equilibrium values for the Δ content in the position L3 were not very sensitive to the form of this matrix. But the distribution of the Δ clods between compartments was greatly effected. We also tested the sensitivity of the model to the value of the transfer coefficient (parameter $c$). This parameter depends on the ploughing width and depth. The $c$ values obtained when the ploughing width was increased from 30 to 50 cm and the ploughing depth from 25 to 50 cm, ranged from 7 to 29% (Fig. 9). Equilibrium values of the Δ content of the L3 position obtained when $c$ was increased in this way, increased slightly from 27 to 37%.

5. Conclusions

The similarities between the experimental values and the simulations confirm that the indicator selected is suitable for assessing the cumulative effects of cropping systems on soil structure in the ploughed layer. This similarity also reinforces the validity of the main assumption, that the interaction between the soil conditions and the cultivation operations (location of passages, depth of tool action, etc) determines the changes in soil structure in the ploughed layer. It is thus necessary to take into account all the cultivation operations (and not only soil tillage) for modelling changes in soil structure of the ploughed layer. Our results for instance outlined the importance of the effects of late harvesting on soil structure.

These results indicate that this method of modelling the changes in soil structure at the soil profile level and taking into account the successive cultivation operations of a cropping system is valid. The model in its present state can be used to compare the effects on soil structure of technical changes, such as working width. But some aspects of the model must be improved. The great sensitivity to the depth of secondary tillage must be reduced. The main cause of this sensitivity is that we have not taken into account the spatial distribution of the Δ clods within the ploughed layer, where Δ clods are lost only from the upper part of this horizon. The sensitivity would be reduced if we could eliminate the Δ clods only in the upper part of ploughed. This calls for a different method of simulation, on which we are presently working.

Secondly, the indicator is only based on evaluation of the overall proportion of Δ clods in the ploughed layer. This is not sufficient to assess the effects of soil structure on the rooting system. We also need to know the size distribution of the compacted clods in the ploughed layer (Tardieu and Manichon, 1987). This requires simulating the changes in the clods size by assessing fragmentation more accurately.

Appendix A.

The following equations correspond to the diagram shown in Fig. 4, for the compartment 3. Let us consider $x'_3$ to be the Δ content in this compartment in year $t$, just before harvest. $x'_3$ is the percentage of the...
total soil in this compartment whose internal structure is \( \Delta \). If ploughing has displaced the soil to the right in year \( t \), we have:

\[
x^t_3 = 0 \cdot x^t_3 - 1 + c x^t_3 - 1 \text{(all the soil in the third compartment has left this compartment)} + x^t_3 - 1 \text{(proportion of the volume of the first compartment projected into the third one)} + (1 - c) x^t_3 - 1 \text{(proportion of the volume of the second compartment projected into the third one)}.
\]

Some of the \( \Delta \) clods disappear during seed bed preparation and under the influence of climate during the crop cycle:

\[
x^t_3 = [0 \cdot x^t_3 - 1 + c x^t_3 - 1 + (1 - c) x^t_3 - 1] (1 - r) \text{;} \quad (r \text{ being the rate of loss}).
\]

Thus, at the end of the crop cycle:

\[
x^t_3 = [c x^t_1 - 1 + (1 - c) x^t_2 - 1] (1 - r).
\]

We proceed in the same way for compartments 2, 4 and 5. The first compartment is special: this compartment has a given \( \Delta \) content (from compartments 4 and 5) after ploughing; the successive wheel passages increase this content to 100% during cultivation after ploughing. This simplifies the equation for this compartment. Its \( \Delta \) content is assumed to be constant at 1.

For the five compartments we have:

\[
\begin{align*}
x^t_1 &= 1, \\
x^t_2 &= (1 - c) x^t_1 - 1 + c x^t_3 - 1 (1 - r), \\
x^t_3 &= (c x^t_1 - 1 + (1 - c) x^t_2 - 1) (1 - r), \\
x^t_4 &= (c x^t_2 - 1 + (1 - c) x^t_3 - 1) (1 - r), \\
x^t_5 &= (c x^t_3 - 1 + (1 - c) x^t_4 - 1) (1 - r),
\end{align*}
\]

Using matrix notations, these equations become

\[
X' = (1 - r) M X^{-1} + U',
\]

with

\[
\begin{bmatrix}
x^t_1 \\
x^t_2 \\
x^t_3 \\
x^t_4 \\
x^t_5
\end{bmatrix}
= (1 - r)
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 \\
1 - c & 0 & 0 & 0 & c \\
c & 1 - c & 0 & 0 & 0 \\
0 & c & 1 - c & 0 & 0 \\
0 & 0 & c & 1 - c & 0
\end{bmatrix}
\begin{bmatrix}
x^t_1 - 1 \\
x^t_2 - 1 \\
x^t_3 - 1 \\
x^t_4 - 1 \\
x^t_5 - 1
\end{bmatrix}
+ \begin{bmatrix}
0 \\
0 \\
0 \\
0 \\
0
\end{bmatrix}
\]

The matrix \( M \) is the transfer matrix: each element of this matrix \( f_{ij} \) (where \( i \) indicates the line and \( j \) the column) is the transfer rate from compartment \( j \) to compartment \( i \). The coefficients on the diagonal are zero, because no soil from one compartment remains in it after ploughing. Coefficients on the first line are also zero because transfers towards the first compartment have been neglected, and the \( \Delta \) content in this compartment is set at 1. The reasoning is the same when ploughing throws the soil to the left; we have in this case:

\[
X' = (1 - r) M' X' - 1 + U',
\]

with

\[
\begin{bmatrix}
x^t_1 \\
x^t_2 \\
x^t_3 \\
x^t_4 \\
x^t_5
\end{bmatrix}
= (1 - r)
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 - c & c & 0 \\
0 & c & 0 & 0 & 0 \\
1 - c & c & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
x^t_1 - 1 \\
x^t_2 - 1 \\
x^t_3 - 1 \\
x^t_4 - 1 \\
x^t_5 - 1
\end{bmatrix}
+ \begin{bmatrix}
0 \\
0 \\
0 \\
0 \\
0
\end{bmatrix}
\]

References


