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Sustainable Management of Agricultural Soils

Coordinated by
Yves Coquet
Joël Michelin

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Contents

Introduction

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Toward the multifunctional usage of agricultural soils

Historically, the study of soils has been inseparable from that of agriculture. Backed by a utilitarian approach and the scientific renewal of the 18th century, its initial focus was on understanding the determining factors of agricultural soil fertility on the basis of its two founding disciplines: soil chemistry and agricultural hydraulics. The end of the 19th century saw the emergence of a naturalistic approach to soils with the birth of pedology. These two methods of soil study continued until the end of the 20th century, particularly in the teachings of the agricultural colleges in France. During the second half of the 20th century, the emergence of several environmental challenges brought to light the fact that soils have other functions as well as ensuring sufficient plant production. Today, soil is at the heart of new challenges, such as climate regulation, pollution control, water flow regulation, waste management and the maintenance of biodiversity. The broad-reaching nature of these issues has led soil science to evolve from a disciplinary approach divided into subdisciplines (soil chemistry, soil biology, pedology, etc.) to a truly trans-disciplinary approach, examining the interrelations between the different functions of the soil and drawing on other disciplines (ecology, economics, sociology, etc.). This evolution is reflected in an increased integration and globalization of knowledge regarding soils, supported by the use of systemic approaches and increasingly effective computer software.

In recent decades, training on soils in agricultural higher education programs have changed significantly, from an approach essentially centered on plant production capabilities (in agriculture and forestry) – heir to 19th century agricultural chemistry – to a multifunctional approach to soils. This paradigm shift owes a great deal to the work of ecologists, and in particular to the work carried out during the Millennium Ecosystem Assessment at the very beginning of the 21st century. Beyond the multifunctional approach of soils, this work has highlighted the many ecosystem services provided by soils, in addition to agricultural, forest and pasture production services. For the past 20 years, the evolution of soil-related training in higher education has followed this dynamic, particularly at AgroParisTech, France, with greater integration with other disciplines, more attention paid to functions other than ones related to agriculture and forestry production, and a more prominent role given to the assessment of ecosystem services provided by soils. The goal of this book is to illustrate this evolution, focusing on a limited number of themes.

Overview of the book

Chapter 1, addressing *soil tillage* and its impact on the structure of the soil, demonstrates the role played by plowing and the consequences of its elimination in the context of conservation agriculture. Chapter 2 focuses on the impacts of agricultural practices on soil *biodiversity* and the mechanisms for managing this biodiversity. Chapter 3 concerns the study of the *spatial variability* and the *mapping* of agricultural soils, with an update on the information available on soils in France and around the world, as well as examinations on the use of relatively recent tools such as drones. Chapter 4 is devoted to soil *erosion* in connection with agricultural activities and the techniques for remedying it through integrated watershed management. Chapter 5 presents the *legal aspects* of soil protection and agricultural land. Chapter 6 concerns the methods for *estimating the agronomic value* of soils, while Chapter 7 looks at the application of the notion of *ecosystem services* to soils. The last three chapters are devoted to specific types of soils: *Mediterranean agricultural soils* (Chapter 8), *tropical soils* (Chapter 9) and *urban agricultural soils* (Chapter 10). The chapters that comprise this work cover only a small part of the entirety of the topics relating to agricultural soil management. Rather, the goal is to demonstrate how some of these issues are now addressed within the framework of higher education as it is practiced today, and in particular at AgroParisTech and at Paris-Saclay University, where the majority of the contributors teach. We hope that these elements can be useful to all readers who wish to bring their knowledge up-to-date on the topics covered here, or simply to become familiar with them.

1

Tillage and Structure of Agricultural Soils

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1.1. What is tillage? Why should soils be "tilled"?

Soil tillage likely dates back to the same time as sedentarization of human societies during the Neolithic age, as the need arose to transform the natural environment to allow for agricultural activities. The first stage of this settlement process consisted of clearing or deforesting a given location, often accompanied by the burning of vegetation – a process which still occurs today in the form of "slash-and-burn" practices. Thus, it is conceivable that a major concern for Neolithic farmers was to maintain the gains derived from slash-and-burn techniques, namely, a "clean" plot – a term still used today by many farmers, referring to a plot where no vegetation grows other than what has been planted for cultivation. This brings to light one of the primary functions of tillage: to fight against weeds.

After clearing comes the sowing of the crops, and then the second function of tillage: the burying of seeds. Historically, the plow was used primarily to sow seeds (Sewell 1919; Sigaut 1977). The first tools for soil tillage were made from wood, some of which featured very simple designs, such as the use of simple sticks for burying seeds or the well-known African daba. These appeared at the same time as agriculture: the first appearance of ox-drawn plows dates back to 3000 BCE in Egypt and Mesopotamia. The first iron tools date back to the Roman Empire (around 200 BCE). Over time, the plow was gradually improved by adding elements such as

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wheels and moldboards, until the advent of the tractor around the middle of the 19th century, which increased the farmer's capacity to work the soil tenfold.

Figure 1.1. *Image showing the tillage process in ancient Egypt at the tomb of Sennedjem, 13th century BCE, Deir el Medineh, Egypt (source: The Yorck Project (2002)). For a color version of this figure, see www.iste.co.uk/coquet/agricultural.zip*

In today's highly mechanized agriculture, tillage is no longer used to sow seeds in the ground. Instead, it is used to prepare the soil to facilitate the installation of the crop, burying the seeds directly in the prepared soil using such techniques being carried out by tools specially designed for sowing (seeders). The function of burying weeds continues, but also concerns the organic materials present on the surface of the soil, whether from the previous harvest – thus referred to as "crop residues", such as grain stubble if it is not exported in the form of straw – or exogenous inputs, such as manure, slurry, composts and other organic waste products. Tillage makes it possible to incorporate these organic materials by mixing them over the full breadth of the surface layer of the soil being tilled, and thus to increase the organic matter content of this layer.

Finally, the fourth and final function of tillage is to modify the soil structure. Through their mechanical action on the soil, soil tillage tools increase and/or modify soil porosity. This porosity allows for better rooting of the plants and a better infiltration and circulation of the water in the soil. Tillage is a very effective technique for increasing the porosity of the soil by fragmenting the soil into structural elements (i.e. clods and aggregates) of various sizes. When these structural elements are too large in relation to the size of the planted seeds, the farmer may have to carry out “surface techniques”, consisting of an additional tilling at a level shallower than the plowing. This creates a “finer” soil structure, consisting of smaller structural elements, of sizes suitable for the seeds that have been sown. This is referred to as a “seedbed”. The objective of these tilling operations is to obtain a good soil structure (“a good tilth” as referred to by Kuipers (1963)), which will allow for the optimal development of the crop.

Figure 1.2. *Mechanized plowing, Grignon plateau, 2002. Crop residues (corn) located on the surface of the soil are buried by tillage (photo credit: C. Coutadeur)*

1.2. Soil structure

Soil structure describes the way in which the different particles that constitute the solid phase of the soil are arranged in physical space. These particles, whether of a mineral or organic nature, can vary greatly in size, ranging in scales from micrometers or smaller (as in the case of clays) to decimeters (coarse, “block”-type elements). The porosity of the soil is the space located between the soil particles. The size of the porosity can also vary to a large extent. The soil particles are connected to each other through forces of various different kinds. In particular, the bonds between mineral particles and organic particles play an important role in the determination and stability of the soil structure. Only part of the soil structure is visible to the naked eye (visual resolution is around 0.1 mm). This is the soil structure that is described by soil scientists or agronomists based on observation pits.

Figure 1.3. *Left: profile of forest soil (Luvic Cambisol, Grignon park – soil thickness: 1 m) (photo credit: L.M. Bresson). Right: types of soil structure (1: granular; 2: crumb; 3: angular blocky; 4: subangular blocky; 5: prismatic; 6: columnar; 7: wedgelike; 8: platy) (source: Baize and Jabiol 2011). For a color version of this figure, see www.iste.co.uk/coquet/agricultural.zip*

The structure of natural soils is the result of their pedogenesis (soil formation process), which involves mechanisms of rock weathering, in conjunction with the climate, the topography and the living organisms that are present. Through cultivation, the farmer modifies the natural structure of the soil (Or et al. 2021) and, above all, gives it a much more marked temporal dynamic. The search for an "optimal" soil structure for a given crop or a given cultivation system has led to the question of how to objectify this structure, particularly by seeking to "measure" this structure. This has been a problem for a long time, and to this day, a satisfactory answer has not been found.

1.2.1. *Porosity and bulk density*

As mentioned earlier, one of the objectives of plowing is to increase the porosity of the soil. This porosity, P (as a fraction of volume), corresponds to the volume of pores contained within a given volume of soil. When a plow is passed, it cuts and fragments the soil into clods (structural elements larger than 2 cm) and fine earth (structural elements of a size less than or equal to 2 cm). The result is a "fluffy" soil surface level, with a high roughness (Figure 1.2) and whose average surface level is slightly higher than the initial average surface level.

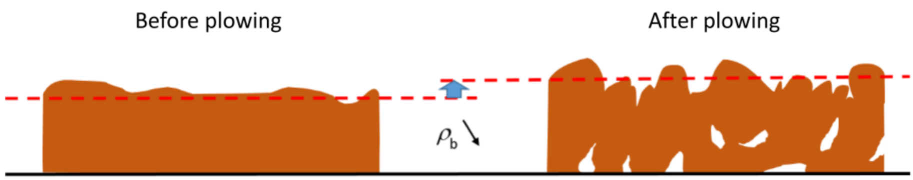

Figure 1.4. *Expansion effect of plowing on the soil surface layer. The average altitude of the soil surface (red dashed line) increases compared to the bottom of the plowed area (black solid line). The bulk density, ρ_b, of the plowed layer decreases. For a color version of this figure, see www.iste.co.uk/coquet/agricultural.zip*

The porosity of the surface layer is therefore increased by plowing. One indirect and very common way of measuring soil porosity consists of taking a known volume of soil (generally a cylinder) and measuring its dry mass (which is its mass after being dried in an oven at 105°C). The bulk density of the soil ρ_b (in kg.dm^{-3}) can therefore be obtained by:

$$\rho_b = \frac{M}{V},$$

where M is the dry mass of the soil sample and V, the volume of the sampling cylinder. If the density of the soil solid phase ρ_s is known, the porosity can then be calculated as:

$$P = 1 - \frac{\rho_b}{\rho_s}.$$

The density of the solid phase of a soil can be measured in the laboratory using a pycnometer, but for most soils, if they are not too organic, we can use the value of 2.65 kg.dm^{-3}, which is the same as that of quartz or calcite. Therefore, a soil with a bulk density of 1.5 kg.dm^{-3} will have a porosity of about 43%. When plowing a 25-cm thick soil layer with an initial bulk density of 1.5 kg.dm^{-3}, this results in a layer with a bulk density of 1.25 kg.dm^{-3}; the height of the average soil surface will increase by 5 cm and the porosity by 10 percentage points (increasing from approximately 43% to 53%). Similarly, any compaction of the soil, whether by mechanical devices or trampling by animals, may under certain conditions, cause a local lowering of the height of the soil surface and an increase in the bulk density of the soil.

In fact, bulk density has been and remains an effective measurement of soil structure. However, it is a very crude measurement that provides little information. Indeed, two soils of the same bulk density can have very different pore size distributions. The bulk density does not make it possible to determine whether the porosity consists of large or small pores (Gupta et al. 1989), nor does it offer any information about their level of connectivity, which plays a major role in the circulation of fluids in the soil.

1.2.2. *Soil structuring mechanisms*

Since natural soils have a structure, we will distinguish between natural mechanisms and anthropogenic mechanisms, all of which lead to changes in the soil structure. The natural mechanisms are linked to the action of the climate and that of living beings. These include the physical processes of freezing–thawing and shrinkage–swelling, as well as phenomena such as slaking and hardsetting. The processes that involve biological agents are aggregation and bioturbation (including root growth). Mechanisms of anthropogenic origin include tillage and settlement by agricultural machinery. Settlement can also occur due to the trampling of animals and can be therefore natural in origin. However, this phenomenon is often accentuated by human activity (by increasing the load of animals per hectare, or by the introduction of ungulates, as has occurred on the Australian continent).

1.2.2.1. *The freezing–thawing cycle*

Freeze–thaw cycles are a very effective way of changing the soil structure from large structural elements to smaller structural elements (crumbling). This is a phenomenon that is well known to farmers who, in regions where frost is significant, make use of it to refine the plowing they carry out at the beginning of winter on plots whose soil is particularly rich in clay. This allows energy to be saved for the preparation of the seedbed for spring crops.

The fragmentation that occurs in freeze–thaw cycles is due to the significant expansion of water in the soil when it freezes. This is incommensurable with the thermal expansion coefficients of the other constituents of the soil. When water shifts to a solid state, its volume increases by 9%, implying a linear expansion coefficient of around 3%, while by contrast this coefficient is around 10^{-6} m.m^{-1}.K^{-1} for the mineral constituents of the soil and 10^{-4} m.m^{-1}.K^{-1} for liquid water. Thus, the expansion of water when it freezes creates very significant stresses inside the pore space of the soil, and leads to ruptures within the structural elements, which then fragment into smaller elements.

The effectiveness of the freeze–thaw cycles decreases rapidly with depth, in parallel with changes in temperature. Their fragmentation effect hardly exceeds the depth of tillage in temperate climates. The freeze–thaw cycles play a prominent role in the fragmentation process, more than the seasonal changes in soil temperature (the depth at which water pipes are buried to prevent freezing is much greater than that of the soil fragmentation effect).

1.2.2.2. *Shrink–swell phenomena*

The other family of processes that have significant effects in modifying the soil structure are shrink–swell phenomena. When a soil dries out, its solid-phase particles may move closer to each other due to the effects of capillary forces, which become more and more intense when it is dried. This is known as soil "shrinkage". If the solid particles cannot move relative to each other (such as in the case of sandy soils), it is considered to be a "rigid" soil; otherwise, the soil is considered "deformable" (e.g. in the case of clay-rich Vertisol-type soils). Conversely, when the soil becomes moistened again, its volume may increase. This is referred to as the "swelling" of the soil.

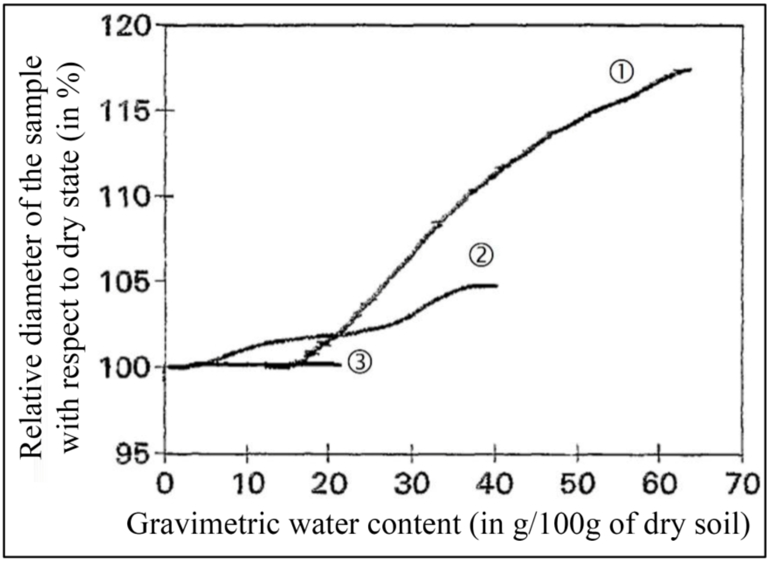

Figure 1.5. *Shrinkage curves of three soils (1: clay-rich soil – Vertisol; 2: loamy soil – Luvisol; 3: sandy soil – Ferralsol) (from Coquet 1996)*

Figure 1.5 shows the linear shrinkage curve of three types of soil: a Vertisol (from New Caledonia), a Luvisol (from Grignon, France) and a Ferralsol (from Senegal). These shrinkage curves were obtained by measuring the variation in diameter of a cylindrical soil sample while it was dried. The Vertisol, which contains swelling clays, has a linear shrinkage coefficient on the order of 17%, the Luvisol has a coefficient on the order of 5%, while the Ferralsol can be considered to be a rigid soil (linear shrinkage coefficient of <0.2%). When it dries, a Vertisol presents dramatic cracks, which close when it is re-humidified. Considerable pressure forces can appear along the faces of these closed cracks, generating slickensides that are typical of Vertisols (see item 7 in Figure 1.3). The magnitude of the shrink–swell phenomenon is much lower for loamy soils (such as Luvisols), but can nevertheless give rise to blocky or prismatic structures (3–5 in Figure 1.3). Since the changes in water content may affect great soil depths (particularly under forests), the shrink–swell changes concern the entire profile of the soil, unlike the freeze–thaw changes.

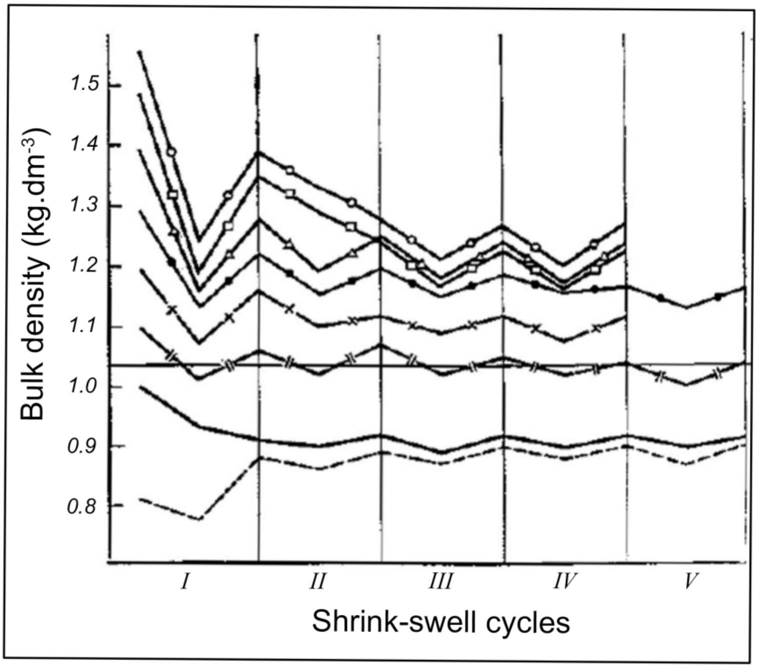

Figure 1.6. *Changes in bulk density of the tilled horizon of a remolded loamy soil during shrink–swell cycles for different initial bulk densities (as given by Kuznetsova and Danilova 1988)*

1.2.2.3. *Slaking and hardsetting*

In some particular cases, the moistening of a soil can lead not to swelling, but rather to a reduction in the soil's porosity, and therefore its apparent volume. This reduction is particularly striking in the case of the "hardsetting" of the soil. This hardsetting phenomenon is well known in the case of irrigation of salty clay soils. The abundance of sodium on the exchangeable complex of clays combined with the dilution occurring due to irrigation water leads to the dispersion of clay particles and a total loss of the soil structure. This phenomenon can also be observed to a lesser extent in the case of predominantly loamy soils (Bresson and Moran 2004) or even sandy soils (Lamotte et al. 1997) under specific conditions. The result of this hardsetting is a soil without any macrostructure, appearing as a continuous volume, which is difficult for water to penetrate.

Figure 1.7. *Cross-section of the surface of a loamy soil with a slaked crust (photo credit: C. Roth). For a color version of this figure, see www.iste.co.uk/coquet/agricultural.zip*

Slaking also causes the soil structure to disappear, but over a very limited depth of soil (up to a few millimeters), at the surface of the soil, under the effects of rain. This phenomenon is characteristic of loamy soils with a low clay content (<15%) and organic matter content. In the phenomenon of slaking, several mechanisms can play a role. These include the physical impact of raindrops when they fall on the surface of the soil, the bursting of the aggregates when the water suddenly penetrates them under the effects of capillary forces where air is unable to escape freely from the aggregates (dead-end pores), and the dispersion of clay particles.

In the case of slaking as well as in the case of hardsetting, the tillage of the soil must be accompanied by other corrective actions (such as the addition of organic matter to combat slaking or calcium, in the form of carbonates or sulfates, to avoid hardsetting) if it is desired for the soil to "recover" an adequate structure that will be relatively stable over time.

1.2.2.4. *Aggregation and bioturbation*

Living beings play a decisive role in the structuring of soils. Aggregation refers to the phenomenon in which the soil attains a structure that is visible to the naked eye, where it is possible to distinguish "aggregates", or structural elements, that vary in size (from a few tens of micrometers to a few millimeters), within which organic matter is closely bound to the mineral matter. The bonds between clay minerals and organic molecules, in particular those secreted by soil microorganisms, are particularly important in determining soil aggregation. For its part, bioturbation refers to the mixing effect of the solid phase of the soil resulting from the activities of the soil fauna, particularly earthworms.

In practice, it is difficult to distinguish aggregation and bioturbation effects, as the two phenomena frequently occur simultaneously, particularly near the surface of soils. Apart from castings from earthworms, particularly those left on the surface of the soils by anecic worms, bioturbation effects are rather visible in soil micromorphology, that is, through observing thin soil slides with a microscope, which allows for the identification of "papules" (bioturbation remains) within the soil (Sauzet et al. 2016). Vegetation also plays a very important role in the structuring of the soils, both through the mechanical actions due to the growth of the roots in the soil, as well as by stimulating the microbial processes by the contribution of organic materials by the roots (exudates or root decomposition).

1.2.2.5. *Compaction*

With the development of mechanized agriculture, the machines used for field work (tractors, combines, trailers for harvesting, etc.) have continuously improved, with the machines gaining in size and weight. This has given rise to an increase in the risk of soil compaction (or settlement), or even effects seen in the subsoil (in the agronomic sense, meaning the soil layer located under the tilled layer). Some authors consider that the increase in soil compaction may be one of the explanations for the stagnation in the yields observed in Europe since the end of the 1990s (Keller et al. 2019).

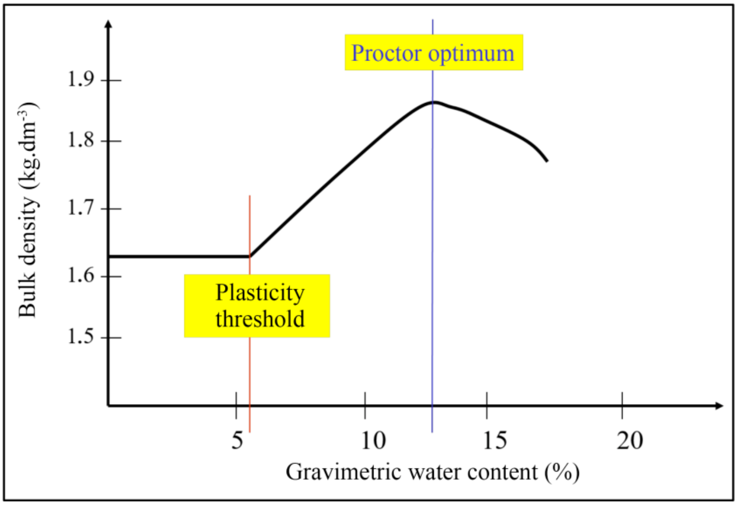

Figure 1.8. *Soil compaction curve as determined by the Proctor test (according to D. Tessier)*

Soil compaction depends on the mechanical stresses applied to it (pressure, shear), as well as on its own mechanical characteristics (shear strength and deformation capacity), which are in turn dependent on the properties and the state of the soils at the time when they are subjected to the stresses. In general, a sandy soil is much less sensitive to compaction than a loamy or clay-rich soil (O'Sullivan and Ball 1993; Unger and Kaspar 1994).

The soil water status at the time the stresses are applied is an essential factor in the compaction. A dry clay soil will be insensitive to compaction, while it will be much more sensitive if it is wet. In geotechnics, where a civil engineer seeks to obtain soils that are as stable as possible (and therefore as compacted as possible), the Proctor test makes it possible to define the optimal water content, which will enable the maximum bulk density to be achieved during compaction (Figure 1.8). This is exactly what farmers seek to avoid when they work their fields with agricultural machinery.

Soil compaction can also occur due to trampling by some of the heavier animals. Cattle and equine animals can generate stress levels of several hundred kPa under their hooves, stresses which are equivalent to (or greater than) those exerted by the heaviest machines in mechanized agriculture.

1.2.2.6. *Soil tillage*

The phenomena of slaking, hardsetting and above all compaction lead to a decrease in soil porosity and to a change in soil structure, which can pose a problem for farmers. When a slaked top layer is dry, this can form an impenetrable obstacle for sprouting plants, and thus prevent crops from emerging. For its part, soil compaction can seriously limit the rooting of the crop (Unger and Kaspar 1994). In order to recover a structural state of the soil surface layer that is favorable to the development of crops, farmers carry out tillage, which can be done in several stages using different tools.

The deepest type of tillage (with the exception of subsoiling) is plowing (Figure 1.2). This type of plowing has various objectives (see section 1.1), including that of recreating porosity inside the soil (Figure 1.4). In Europe, plowing is generally carried out using a moldboard plow (Figure 1.2), which makes it possible to cut a strip of soil and rotate it from 130° to 160°. By contrast, plowing in North America is carried out using a disc plow, which is less efficient than the moldboard plow in rotating the soil, but more efficient in mixing it. Currently, the depth of plowing in Europe is on the order of 20–25 cm, but in the past, it was possible for significantly deeper plowing to be carried out (of up to 35 cm or more). A fairly deep tillage can be carried out using tined tools, such as cultivators, which are used in particular for post-harvest stubble removal of grain straw. Rotary cultivators make it possible to obtain a more homogeneous relief of the soil surface than a cultivator with fixed tines.

Figure 1.9. *Tillage tools: (a) front cultivator; (b) rotary harrow; (c) subsoiler (photo credits: Pottinger, Quivogne). For a color version of this figure, see www.iste.co.uk/coquet/agricultural.zip*

In general, the soil structure created by plowing is not suitable for seeding a crop immediately after plowing. As indicated previously (section 1.2.2), the freeze–thaw and wet–dry cycles can contribute significantly to the fragmentation of large structural elements (clods) created by plowing and to a "finer" structure being obtained (that is to say, one consisting of smaller structural elements). An alternative (or complementary) solution to the effects of the climate consists of carrying out a "resumption" of the plowing using another tool that works at a shallower depth, which will make it possible to obtain a finer and above all more homogeneous structure. Various different tools, such as pulverisers (or "cover-crops") or harrows (fixed, alternating, or rotating), make it possible to effectively fragment the upper part of the plowed layer. This surface tillage of the soil can be completed using a roller, which will "recompact" the soil surface and thus promote better contact between the soil and the seeds that have been planted. The degree of fragmentation and settlement of the seedbed will depend on the size of the seed; for instance, a corn seedling will not need a seedbed as thin as a rapeseed seedling.

Certain tools, such as the cultivator (rotary harrow), are designed to remedy slaking when it appears. This is a superficial tillage (2–3 cm) that seeks to fragment the slaked crust and recreate the circulation of fluids at the surface of the soil. This tillage can also allow sprouts to rise if the slaked crust has formed immediately after seeding.

The last major category of tillage tools has the explicit objective of counteracting soil compaction. This category includes decompactors, which plow the soil to the tillage depth and can be used to decompact the soil after a harvest carried out in bad conditions (wet soil), which has led to soil compaction, and subsoilers, deeper tools, whose objective is to decompact the soil under the plowed layer.

As this section makes clear, there are a wide variety of tillage tools, which have only briefly been touched upon here. These tools are typical of highly capitalistic agriculture, since all such tools have a high cost and require large amounts of energy to be used. They are one of the factors that explain the tremendous productivity gains made by agriculture during the 19th and 20th centuries.

1.2.3. *A method for characterizing the structure of cultivated soils: the "*Profil cultural*"*

We have seen that soil structure can be quantified in a rudimentary fashion by measuring the soil's bulk density (section 1.2.1). This measurement is generally carried out on a volume of soil that barely exceeds 1 dm^3 and cannot account for the spatial and temporal variability of the structure of cultivated soils without multiplying the measurements over time and in space (Strudley et al. 2008). The original idea that the agronomist Hubert Manichon had for studying the structure of cultivated soils while preparing his thesis (Manichon 1982) was to observe the soil, using the methods of a soil scientist, but focusing on the effects of the different tools used during crop succession (Manichon 1987). The observation was carried out from a pit that was excavated perpendicular to the direction of movement of agricultural machinery on the plot, wide enough to include, at a minimum, the greatest working width of the machinery and a depth greater than the maximum depth of the soil to be tilled.

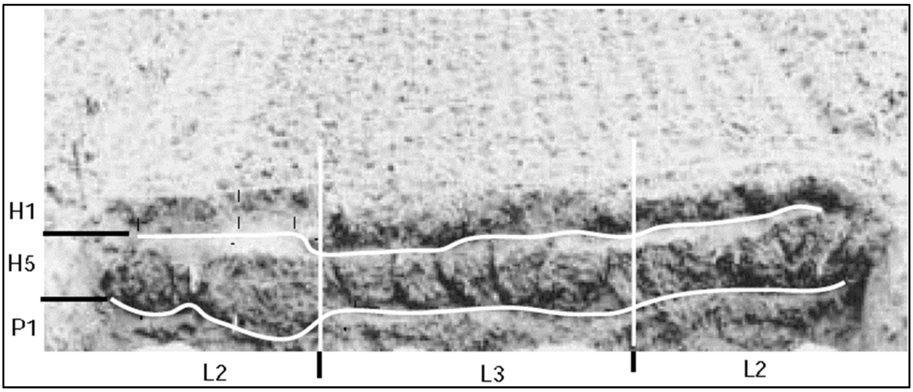

Figure 1.10. *Crop profile of a plot where corn has been sown (Grignon, France). H1: seedbed; H5: plowed layer not taken up by surface tillage; P1: soil under the tillage. L2: Path of the wheels of the tractor pulling the harrow for the creation of the seedbed; L3: area not affected by the wheel paths (as given by Desbourdes-Coutadeur 2002)*

A compartmentalization of the soil profile is first carried out, taking into consideration a vertical compartmentalization according to the depths of the different tillage tools. We may distinguish certain elements such as (given in order from the surface) the seedbed, the plowed layer not modified by superficial tillage, the plow pan, and the soil that is not tilled. Additionally, it also considers a lateral compartmentalization on the basis of the location of the paths of machines' wheels, which can generate soil compaction. The soil structure within each compartment is then described according to a purely morphological approach. The large structural elements (clods) are described geometrically and according to their "internal state". A state noted as "Γ" is distinguished, representing a soil with a macroporosity clearly visible to the naked eye, as well as a condition noted as "Δ", corresponding to a compacted soil without macroporosity, and a state as "Φ", corresponding to a