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# CHEMICAL AND PHYSICAL PROPERTIES OF SOILS IN FRANCE: SPATIAL CONTEXT AND EVOLUTION

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**Summary:** France has a wide variety of soil types mainly due to the geological and climatic diversity of the land. Soil quality at a chemical and physical level is to some extent responsible for the differentiation of natural regions as they appear today and it has always determined the land use pattern particular to each region. Land layout, however, has evolved constantly, especially through the actions of man. During this half of the XXth century, the transformation of agricultural methods has been accompanied by large-scale land use development such as land reclamation and consolidation. Since the beginning of the XIXth century, the amount of land covered by forests has increased thanks to the reforestation of marginal zones. In cropped soil, fertilization has overcome problems of natural soil nutrient depletion, whereas in forestland acidification is on the increase and can lead to soil deficiences. Yet, the overapplication of fertilizers poses another problem as intensive indoor production runs the risk of contaminating the hydrographic network. Soil degradation is taking on new forms as arable crops in regions with little marked topography are subject to erosion. Particle movement and even phytosanitary products from cropped plots contaminate downstream water and coastal areas. High crop yields have modified the water cycle and drained soil water reserves. Supplementary irrigation is becoming commonplace even in northern areas. No one really knows what the long-term consequences for the soil and groundwater will be. The notion of soil quality has evolved, bringing about changes in land development and landscape differentiation. In the future, the question of soil quality should be a key element in any considerations on how the soil should be managed in a sustainable agriculture, which respects the environment.

**Key words:** Soil, quality, fertility, water, erosion, environment.

## Introduction

Soil quality was first defined as the capacity of the soil to provide a medium favourable to the development of the whole biomass, in particular plants. Nowadays, beyond the scope of agricultural production, the concept of quality includes our environment, i.e. the aesthetic value of landscapes, constraints related to land layout as well as protection of water quality.

This quality depends on several factors. Intrinsic factors of soil should be distinguished from external factors, in particular environmental and climatic factors. The soil is a physical support used for the repeated passage of animals and farm machines as well as a reservoir and a transit area for water and gas. The development of the whole biomass, in particular plants, depends on the soil capacity to allow the transport of gas and water from one place to another. From a chemical point of view, the soil is a source of ions essential for plants. The presence of ions in excess, whether they are useful or not, can cause toxicity phenomena.

This article aims at presenting a few ideas regarding the chemical and physical quality of soils as clearly as possible. We will not attempt to be exhaustive. We will focus on the diversity of soils at the regional scale and at the scale of much smaller areas. We will put an emphasis on the changes in the land use pattern, which have occurred recently. We will study how physical and chemical properties influenced agricultural practices and their consequences on soil quality.

## An organized soil patchwork whose development has evolved throughout history

### *A large diversity of soils at the scale of the country*

It is very difficult to present the variability of soils at the scale of a country such as France. The key of the soil map of France at the scale of 1:1,000,000, which was established by Dupuis (1996), reveals 46 soil units. This map gives only a very simplified representation of soil diversity, as can be observed in the field (Jamagne et al. 1995). This diversity is due to the high diversity of rocks on which soils developed. Examining soil maps at a larger scale, such as 1:100,000, and theirs keys show the diversity of soils at the scale of the country. The IGCS programme (Inventaire, Gestion et Conservation des Sols) developed by INRA and the Ministry of Agriculture which started a few years ago aims at systematically studying the whole territory at the scale of 1:250,000. The results of the studies already performed and of those currently performed were integrated into databases to be able to exploit them. Soil maps as well as thematic maps regarding the slope, water reserve, stoniness or acidity which were traditionally obtained from these soil maps, are now only the graphical expression of the knowledge of soils and their properties in a given territory at a given time and at a given scale (Arrouays et al. 1989; King et al. 1991, 1992; Girard et al. 1993; Bornand et al. 1994; Roque & Hardy 1997).

*A distribution of soils in close relationship with geology and topography*

The diversity and pattern of soil distribution is often better understood at the scale of the catchment. Fig. 1 shows a simple example of soil distribution at this scale as well as the land use pattern, as observed at the beginning of the 1960s. This example presents soils from the Perche area, at the edge of Beauce and Normandy and illustrates the different types of soil from the plateau down to the bottom of the valley. The difference in elevation can reach about 100 m. In this area where most soils outcropping on the surface are from the Lower Cretaceous period, each lithological unit is no thicker than a few tens of meters. The following main geological deposits are successively observed:

— Flint clays on the plateau and at the top of hills. They originate from the weathering of Senonian chalk during the Cenozoic era. Unlike chalk, the weathering material no longer contains carbonates. It is a clayey residue presenting a high stoniness;

— Sands of Perche from the Cenomanian period at the top of the slope;

— Chalky, marly and decarbonated clayey layers (green clays) from the lower Cenomanian period in the middle of the slope;

— The Jurassic is located below clays and marls and can outcrop in some basins.

The geological study of this region shows the role of the nature of the substratum in the resulting soil sequence (Isambert 1974). At the scale of the landscape, the following soil sequence is observed:

— Planosols with a depleted clay content on the surface at the top of hills. The clay content of the fine fraction (< 2 mm) often reaches more than 70 % in depth. The stoniness can exceed 50 %. Although located at the top of hills, these soils are poorly drained and present an excess of water in winter. They become rapidly dry in summer. Because they are stony, very clayey and contain very few chemicals, these soils are occupied by forests, which are now old enough to be used as timber.

— The soils at the top of slopes are filter and sandy brunisols partly saturated in calcium, which are deep and

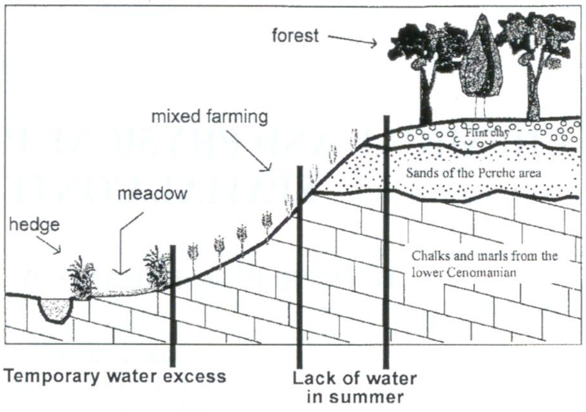


**Fig. 1.** Schematic spatial distribution of soils in the landscape and their use at the beginning of the 60s in the Perche area (adapted from Isambert 1984).

usually well exposed (east to south-east). Local archives indicate that these soils have been cultivated for several centuries. These soils were originally acidic and have consequently been fertilised, at least since the 19th century, as shown by the presence of numerous marl pits, either as open quarries at the edge of plots or as underground quarries in the middle of plots.

— Soils developed on chalky material and marl are brunisols, soils saturated in calcium or soils containing calcium carbonate. These soils have a loamy to loamy-clayey surface and are thus quite light and are usually located in benches. They were often used for fodder root and tuber crops, cereals and grain legumes, such as sainfoin. This calcium-rich plant played a major role in horse feeding.

Up to the 60s, highly organized clayey soils (vertic brunisols) developed on green clays too hard to cultivate as well as hydromorphic soils in the bottom of valleys temporarily or permanently subjected to excess water were used as pastures.

The land use pattern that we have described above clearly reveals the main factors, which have determined land development in the past. The soils with few physical constraints (low slope, sufficient water reserve, easy tillage, a high calcium content, chalky amendments) were used for crops. The soils which were too hard to cultivate or with an excess of water were used as pastures and usually located in the bottom of valleys. The soils where the physical and chemical constraints were the highest were kept as forests. In this region of bocage landscape, plots were surrounded by hedges and the field pattern followed the soil distribution relatively well at the landscape scale. Moreover, the small size of plots restricted the possible transfer of particles by runoff over short distances.

Soil distribution and the land use pattern as described above cannot be considered as general in France. It illustrates how an agricultural system based on mixed crop-livestock farming in Western France can be adapted to environmental constraints in a given region and at a given time.

Adapting the agricultural system to the environment sometimes led to the specialization of farming activity. This gave birth to the so-called "terroirs", the most famous example being vineyards. In a study in the Anjou region, Morlat & Asselin (1992) showed the role of the substratum, the soil type as well as the components of the landscape in the notion of "terroir". In the Champagne region, for example, the favourite substratum is chalk with south-south-east exposed sloping soils (Pomerol 1990; Ballif et al. 1995). Similar observations can be made in other regions of France (Alsace, Burgundy, Médoc, Côte du Rhône, etc.).

### A permanent evolution of the land-use pattern

As mentioned by Boulaine (1996), the land-use pattern has constantly evolved throughout history. It is known that, since the Neolithic new stone age and the beginning of forest clearing, the population of France has increased from a few tens of thousands of inhabitants to about ten million of people in the Middle Ages and up to 60 million nowadays. Deforestation of the most easily tilled land enabled farming activity to start and demography consequently evolved. Deforestation was then performed in areas considered as being more marginal because they were more difficult to cultivate. This was made possible via technological breakthroughs, such as animal draught with an ox and later with a horse, new soil tillage tools, the implementation of crop rotation systems, plant acclimatization and breeding, increasingly sophisticated recycling and fertilization techniques as well as development operations to compensate for excess water (drainage) or lack of water (irrigation).

The land-use pattern evolved most over the last 50 years. To summarize, we can say that fertilization techniques and development operations have removed some constraints while introducing new ones. Farms and even regions have become specialized. For more information, the reader is advised to read the Grand Atlas de la France Rurale (de Monza 1989). This collective work reviews the evolution of pasture, crop and forest areas, the various livestock farming types and the structure of farms over the last few years in France.

The most important change occurred in the 50s with the appearance of the tractor which replaced animal draught. This immediately led to an increase in the dairy herd. This phenomenon was increased due to the forage revolution. Many natural pastures were ploughed and replaced by an alternation of crops and temporary pastures. Grain and fodder maize for ensilage was also introduced at that time in the northern part of France.

Fig. 2 shows the current land-use pattern in the Perche region. The soils which were devoted to pastures are now cultivated. Permanent pastures have often been ploughed and the soils at the bottom of valleys have been drained. In

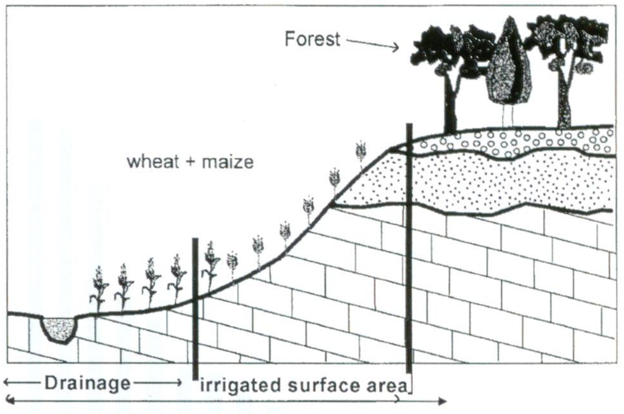


**Fig. 2.** Schematic spatial distribution of soils in the landscape and their current use in the Perche area (adapted from Isambert 1984).

order to increase the field pattern, hedges and banks were removed at the periphery of plots. The mean cereal yield increased from 20 quintals per year in 1950 to about 70 quintals and more in 1996. Given the high yields required, especially for cereals, the amount of water necessary for maintaining a regular and optimal cropping level was no longer sufficient. Drained soils were also irrigated in years deficient in water.

It should also be noted that the specialization of agriculture led to an increase in the cereal surface areas and new crops, such as protein-rich peas, rapeseed and sunflower. On the other hand, cattle farming was replaced or supplemented with housed rearing units (pigs, poultry). Changes in the landscape are related to agricultural practices and are mainly due to mechanization and land reorganization. In particular, land consolidation induces an increase in plot size and removes numerous linear elements, which participated in landscape structuring.

In marginal areas, i.e. at high altitude with steep slopes, the reforestation of abandoned land entirely changed the landscape. In France, the transformation of agriculture and rural emigration led to a global increase in the surface areas covered by forests (Fig. 3). This increase is not recent as it started at the beginning of the 19th century, i.e. since the beginning of rural emigration. In less than two centuries, the forest area has increased from 10 % to 25 % of the territory with a considerable increase in the volume of exploitable wood and the number of forest species, especially conifers.

In lowland, new areas where only forests previously grew, were put into crops, such as in the Champagne region and, to a lesser extent, in the chalky plateaux in the east of the Paris Basin (Ballif et al. 1995). Eliminating the constraints resulting from fertilization via the supply of soluble phosphates has enabled the development of intensive farming.

It should be mentioned that the irreversible process of urbanization and land development has constantly modified the landscapes (roads and motorways, housing estates, high-tension lines, airports). Urban areas are often

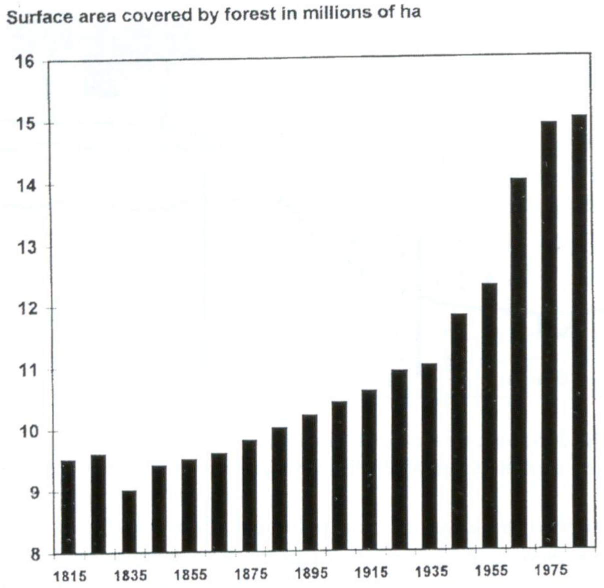


**Fig. 3.** Global evolution of soils under forests since the early 19th century. Surface area covered by forest in millions of hectares.

located on the best land of the country (about 5 %) and modify the land-use pattern (Thinon et al. 1996).

## Improving the management and the development of land use

The previous paragraphs show that the evolution of agriculture has intensified over the last 50 years. A land-use pattern based on mixed crop-livestock farming was maintained in lowland areas during the 19th century and up to the middle of the 20th century. In the second half of the century, mechanization, major development operations, such as drainage and land consolidation, and fertilization improvement seriously changed the initial potentiality of soils. The terroirs producing highly appreciated crops, such as wine and fruit, have kept their identity despite the context of internationalization which favours the uniformization of products. The notion of terroir should be better used in the future to obtain products of high quality with typical characteristics while better preserving the environment.

## The chemical quality of soils

### *Soil heritage*

It should be mentioned that the soil acts as an open chemical system. This means that a large part of the soil chemical elements can either be exported by crops or eliminated from the soil by the water. Atmospheric inputs as well agricultural practices can contribute to improving the soil from a chemical point of view. It is necessary to take into account the natural reserves of the soil when considering the balance of elements. In temperate regions, the soil progressively loses a part of its stock in bases, especially alkaline metals (K, Na) and alkaline earth metals (Ca, Mg) due to natural processes only. For more details, see Duchaufour (1995) and Robert (1996). This progressive loss first concerns soil carbonates and then the cations fixed on the surface of clays. The soil consequently becomes acidic. When acidity is high enough, the soil mineral constituents can be partially dissolved and free aluminium can be present in the soil and water. Well-known deficiency and toxicity phenomena are then observed.

A precise indicator of the soil chemical evolution consists in measuring the cation saturation rate (Ca, Mg, Na and K) in relation to the total exchange capacity of the soil (T). T expresses the maximal amount of cations fixed at the surface of clays and organic matter. The base saturation rate S/T provides precise indications on the state of acidification of the soil.

Different situations can thus be identified in France where acidifying conditions prevail (about 60 %). Pédro & Scherrer (1974) distinguish:

— soils with aluminium subjected to intense acidification. This corresponds to outcrops of filter rocks favourable to the leaching of cations and siliceous rocks, i.e. poor in weatherable minerals susceptible to supply basic cations to the soil stock. This includes sands, sandstones and granitic areas;

— desaturated soils where acidification remains moderate, such as the loamy deposits of the Paris Basin et Aquitaine Basin;

— soils saturated by an excess of calcium on marls and soft calcareous rocks and an excess of calcium and magnesium on dolomitic rocks;

— recent deposits on seashores and tidal marshes which can be influenced by the sea (presence of sodium) and alluvial areas depend on the surrounding geological outcrops.

## Improving fertility via fertilization

The soil chemical reserve depends on the type of material on which the soil developed. It also depends on the age of the soil as well as outputs from plants. Plants take up the elements necessary for their vital functions, i.e. first nitrogen, then phosphorus and potassium as well as calcium, iron, sulphur, magnesium and trace elements. Although the soil is an open system which tends to lose a part of its elements, agriculture is the main cause for soil chemical impoverishment.

Boulaine (1995a,b, 1996) recalls that agricultural production units have always been chemically deficient because plant uptake was much higher than the supply originating from rock weathering in the absence of fertilization. In the 19th century, the soils were so poor in fertilising elements that they only fed 20 million inhabitants despite the progress made by agronomists and geneticists.

To remedy this degradation, amendment and fertilization practices were introduced. Calcareous amendments were made as early as Roman times provided that quarries were located close to the sites to be amended. Organic amendments as well as nitrogen-fixing legumes were also used. Soil fertilization was generalized with the introduction of phosphates, potash from Alsace and the industrial synthesis of nitrogen fertilizers. The current consumption of fertilizing elements shows differences in fertilization between regions. Supplies are high in intensive farming areas since, on average, they consist in 100 kg/ha/year of potassium ($K_2O$) and phosphorus ($P_2O_5$) and sometimes 200 kg nitrogen (N) in industrial crop areas (source FNIE-SCEES). Inversely, in regions where there are predominantly permanent pastures (Massif Central, Vosges, Alps), the level of fertilization is often lower than 20 kg/ha/year of $K_2O$ and $P_2O_5$ on average. The use of calcareous amendments and fertilizing elements has increased similarly (source CELAC). Forests have not been fertilized up to now, except the Landes forest and land which has reverted to forestry.

Soil analyses made in all the regions of France showed that, in cash crop regions, current inputs are usually higher than outputs. Situations are, however, very different (Schwartz et al. 1996). Reducing or even completely stopping $K_2O$ and $P_2O_5$ fertilization and calcareous amendments can only be made with a precise monitoring of fertility, based, in particular, on soil analyses. Completely stopping fertilization prevents compensating for losses and this could jeopardise the favourable chemical status of numerous soils, especially at the level of their pH and their ion saturation level in intensive farming systems with high yields.

Nitrogen plays a different role in comparison to other fertilizing elements. Nitrogen fertilization has only slightly increased the nitrogen stock in the soil because the nitrogen supplied and not taken up by plants is rapidly drained out of soils. In cash crop areas, overapplication of fertilizers has led to the leaching of nitric nitrogen. Due to the slow infiltration of nitrates to the water table, the high pollution levels currently observed may be the consequence of nitrogen overfertilization over the last decades.

## Trend towards fertility loss and consequences

A poor chemical content and soil acidification can be observed in soils which have never been amended, such as extensive grazings and forests as well as cultivated soils (Cheverry 1995). Acidification leads to low contents in exchangeable earth alkaline cations and high aluminium contents. Plants, in particular cultivated plants, consequently suffer from Ca and Mg deficiencies or aluminium toxicity, except some very frugal species. This acidification phenomenon was much studied in the Vosges forests by INRA and CNRS teams of Nancy and Strasbourg, respectively.

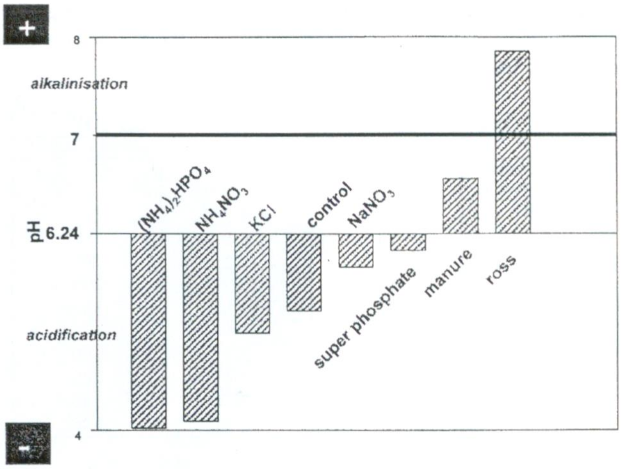


**Fig. 4.** Effect of fertilisation practices and amendments on soil acidity in the experiment in Versailles (France) involving 42 plots.

Acidification along with drought is involved in the decline of the Vosges forest (Landmann & Bonneau 1995).

Soil acidification is increased by acidic atmospheric deposits, called acid rain, which increase the losses in earth alkaline cations and aluminium solubilization. In the worst cases, the ionic aluminium solubilized in the soil appears in the streams leading to the death of salmonids (Probst et al. 1990).

Aluminium toxicity is also an endemic phenomenon in acidic tropical soils. In all cases, only planned amendment practices make it possible to obtain higher pH levels and thus to remedy this soil degradation process. Restoring soil chemical fertility is crucial in hyperacidified forest soils. Foresters assert that this complex ecological environment must be restored (Bonneau 1996).

An example of soil recalcification is obtained by comparing the current situations of fertilized cultivated soils with forest soils which have never been fertilized or amended. Table 1 shows the example of soils from the Perche area, in particular sand soils, that is soils with very low initial base reserves. These results were obtained from typical profiles of the Châteaudun soil map, i.e. forest and cultivated soils (Isambert 1974). The soil chemical statuses are completely different since the forest soil has a pH close to 4 and its saturation level in basic cations can drop down to 10 % of the exchange capacity. The pH of cultivated soils is close to neutrality and its saturation rate reaches 100 % due to amendment and fertilization practices.

This example illustrates the role played by fertilization in the protection of soil quality. This is in agreement with other long-term studies on the fertilization and amendment of soils, such as the study involving the 42 plots of Versailles. In 1928, through the impetus given by Demolon, Burgevin and Hénin set up a long-term fertilization experiment at the National Institute for Agricultural Research in Versailles. Each year, the same manure or amendment is supplied to the same plot (SNST 1978). The results spectacularly illustrate the positive or negative effect of certain fertilization

**Table 1:** Variations of the pH and saturation rate (Na, K, Mg, Ca) in sandy soils and soils developed on gaize in the Perche area (according to Isambert 1974).

| FOREST SOIL | | CULTIVATED SOIL | |
|---|---|---|---|
| pH | Saturation rate % | pH | Saturation rate % |
| Soils on sands from the Perche area | | | |
| 3.8 | 14 | 6.8 | 91 |
| 4.2 | 14 | 7.2 | 99 |
| 4.2 | 14 | 6.9 | 100 |
| 3.9 | 42 | 7.1 | 100 |
| Soils on gaize | | | |
| 4.5 | 36 | 7.7 | 100 |
| 4.1 | 49 | 7.6 | 100 |
| 5.3 | 86 | 7.4 | 100 |
| 4.6 | 85 | 6.8 | 100 |

practices in the long term. The soil was initially quasi-saturated in ions and was representative of leached-out soils developed from loess in Northern France. The effects of treatments can be summarized as follows:

— an increase in pH and the cation saturation rate (manure, carbonates, quick lime, dephosphorating ross) is observed,

— a spectacular acidification can sometimes occur. After 60 years, the saturation rate can be similar to that of a forest with a substrate very poor in bases (ammonium sulphate, ammonium nitrate),

— the control plot which received neither amendment nor fertilizer was notably acidified.

In addition to the evolution of the chemical quality, major modifications in the physical properties were observed. For example, the plots which received sodium nitrate, potassium chloride and sylvinite (KCl + NaCl) completely lost their initial grumous structure. The appearance of a surface crust as well as temporary waterlogging phenomena as early as the first rainfall after soil tillage were observed. The change in the soil cation status had consequences on the chemical status and induced major changes in physical properties.

## The chemical content of the soil must be better managed

Cultivated soils are used much more than before from a chemical as well as a biological point of view (element recycling). The long-term monitoring of the soil chemical status is thus necessary. The Observatoire de la Qualité des Sols monitors a few sites but this should be done more widely.

Maintaining the chemical quality of soils in the long term requires adapting the fertilization and amendment practices to the use of the soil. Situations are very different and of varying gravity depending on the type of soil. The problem of overapplication of fertilizers is raised, in particular due to the input of slurry and manure from soilless rearing units. Up to what limit can elements accumulate in the upper part of soils? The risks of washing down into the drainage network and the eutrophization of rivers are high (Cheverry 1995). The elements necessary for the plant, such as potassium and phosphorus, are the most concerned. Nitrogen, which is related to the management of organic matter, should also be mentioned (Balesdent). The metal elements used as additives in foodstuff, such as zinc and copper, are also involved. Inversely, in soils with low reserves, organic supplies are not enough to compensate for losses. Considering soil management in the medium term, completely stopping amendments could call into question one of the main agronomic principles of the last 50 years, i.e. the partial restoration of the soil chemical fertility.

## Physical quality of soils

### *An environment favourable to biological activity*

Soil physical quality is closely related to its structure, i.e. the way mineral and organic constituents are organized. Indeed, water, solutes and gas circulate or are stored and living organisms develop in the different types of voids resulting from this organization.

At a microscopic scale, the structure depends on the organization of elementary particles. At a more macroscopic scale, several levels of organization can be observed, from millimetric aggregates resulting from the assemblage of elementary particles to decimetric or even metric aggregates (Stengel 1990; Tessier 1994).

A part of the soil structure results from the conditions of soil formation and evolution in the long term. In cultivated soils, the action of man is the main factor of evolution (tillage, seedbeds, passage of machines, etc.) (Boiffin et al. 1990; Coulomb et al. 1990). The action of man leads directly (agricultural practices) and indirectly (action of the plant) to the evolution of the structure. With time, this evolution can lead to a degradation or a regeneration (Guérif 1990). The stability of the structure subjected to various damaging agents, such as rain, wind and compaction by machines and animals, is a major point in soil physical quality. Clayey soils are usually the most stable while loamy soils are far less stable (Hénin et al. 1969). The presence of binding agents and cement between soil particles, such as organic matter, and the implementation of adapted agricultural practices (soil tillage, plant canopy) make it possible to increase the stability of the structure (Balesdent). Soil chemical quality also has an influence on the structural stability. The presence of monovalent ions (Na) on the exchange complex has a strong negative influence.

In the following paragraph we will successively review two major aspects of the physical quality of soils, i.e. relations with water, in particular their capacity to retain the water available for plants, and the stability of the structure at the surface of soils. If the stability is too low, runoff phenomena can be observed during rainfall, which has

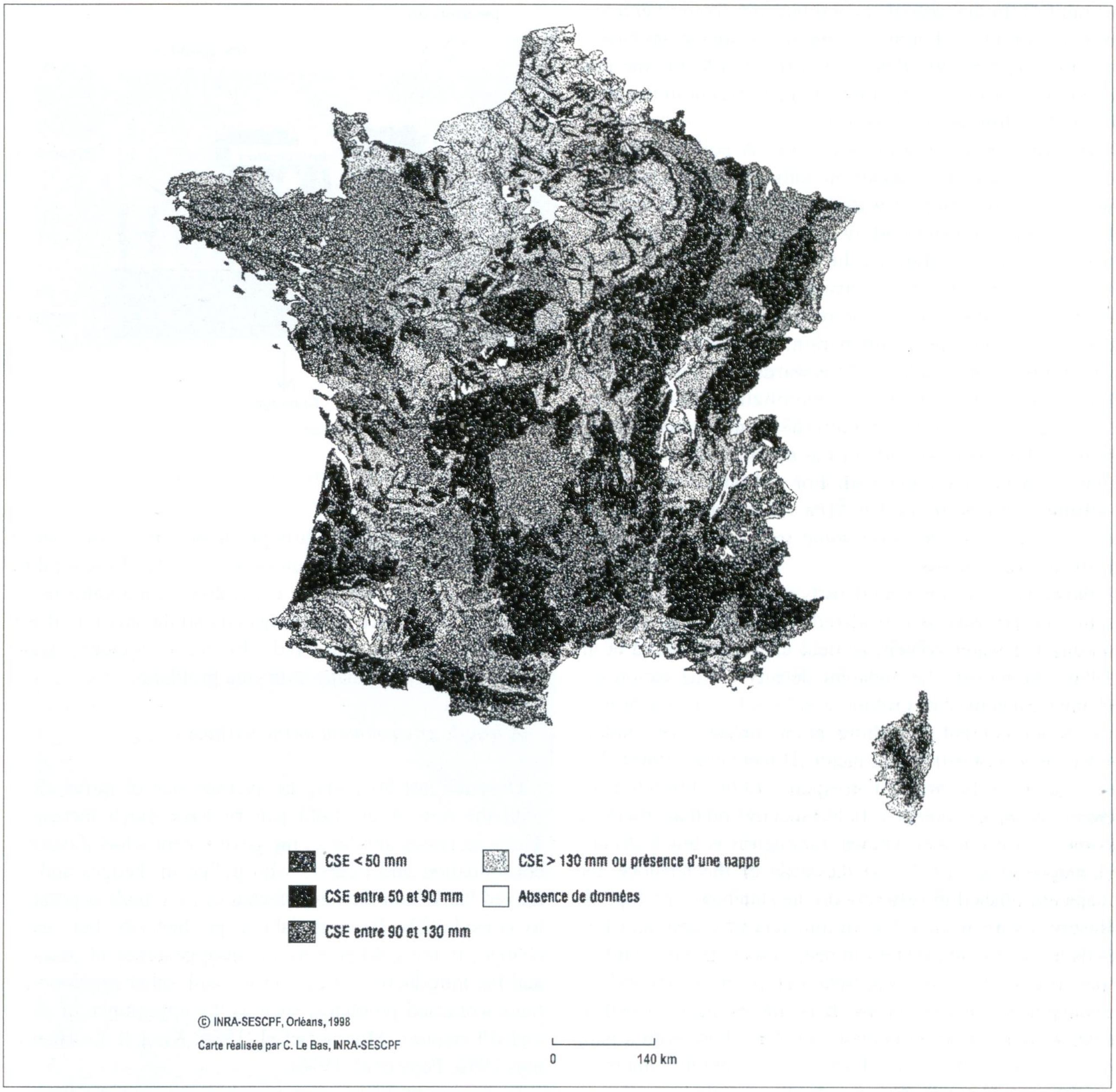


**Fig. 5.** Water storage capacity (WSC) of soils (according to King et al. 1995).

consequences on the transport of earth material and associated products, such as fertilizers and pesticides.

*An essential role in the water cycle*

Water has to pass through the soil to supply groundwater tables. The soil is also the environment from where plants can draw the water and the ions necessary for their development. The water that is really available for plants depends on the energy with which it is retained. The soil is a porous environment, in which water is bound by capillarity. The solidity of the bond increases with decreasing sizes of voids. The amount of water retained depends on the size of the water reservoir, i.e. the porosity and the depth of the soil. The extension of the root system of plants and the demand determined by the climate (evapotranspiration) are also major factors that should be taken into account for studying the availability of water for the development of plants (Fig. 5).

When the rain reaches the soil surface, a part is intercepted by plants and may be directly evaporated into the atmosphere. In extreme cases, in conifer forests for example, less than 65 % of rainfall reaches the soil (Granier et al. 1995). Interception is usually lower in crops (< 10 %). The proportion of water that reaches the soil can either percolate if soil permeability is high enough or runoff over the surface. The distribution between percolation and runoff depends both on the soil structure and the type of rainfall. In the case of several tens mm/hour over a few minutes or tens of minutes, runoff is almost inevitable whereas with drizzle (less than a few mm/hour) the percolation speed is usually high enough, except in the presence of highly developed crusts.

In summer, soils tend to dry up. A soil usually becomes recharged in water in autumn and spring, i.e. when the proportion of water evaporated at the soil surface or evapotranspirated by plants is lowest in comparison to a given rainfall height. In winter, the water content at field capacity is usually reached, that is the maximum water that can be retained by the soil. In the case of winters deficient in rain, the field capacity is sometimes not reached. Afterwards, in spring, plant transpiration participates in mobilizing the water reserve. The soil can dry up until the plant reaches wilting point, which corresponds to the maximal suction that a plant can exert on the soil. For cultivated plants, the wilting point is about 1.6 MPa. This limit can be exceeded in forests because some trees are well adapted for high water stress.

Nowadays, the apparent density of the soil, which represents soil porosity, is considered as a good factor for estimating the water content at field capacity (Bruand et al. 1996). Moreover, the apparent density or the cation exchange capacity can provide a satisfactory estimation of the water content at wilting point, unlike size grading which is a poor estimating factor (Bruand et al. 1988). The soil water reserve which corresponds to the difference between the water content at field capacity and that at wilting point, is still not well known although it is much studied (Jamagne et al. 1977). At the scale of the territory, the maps established mostly rely on the statements of experts. Reserves vary from a few millimeters in coarse and thin soils to more than 300 mm in deep soils with medium texture (Fig. 6). These soils present high potentialities and are mainly used for cash crops. It is interesting to note that soils with a low water content are often those with a poor chemical content (soils developed on granite material, sandstone and sand). This is why these soils have always been used for forests.

Intensification of farming has consequences on the physical properties of the soil. The amount of water necessary for producing a given mass of dry matter ranges from 300 to 900 g of water for 1 g of dry matter, with about 500 g for wheat (Chamayou & Legros 1989). The passage from a 10 quintal yield per hectare in the Middle Ages to a 20 quintal yield at the beginning of the century and about 100 quintals today indicates that the water reserve is much more used nowadays. The consequences of this increase are not well known. The action of drought has been evidenced in our forests, especially in soils with a low water reserve in the Vosges region. Tree decline is partly due to the successive severe droughts in the 80s and 90s.

An insufficient water reserve led to the establishment of irrigation. This has increased the surface areas cultivated

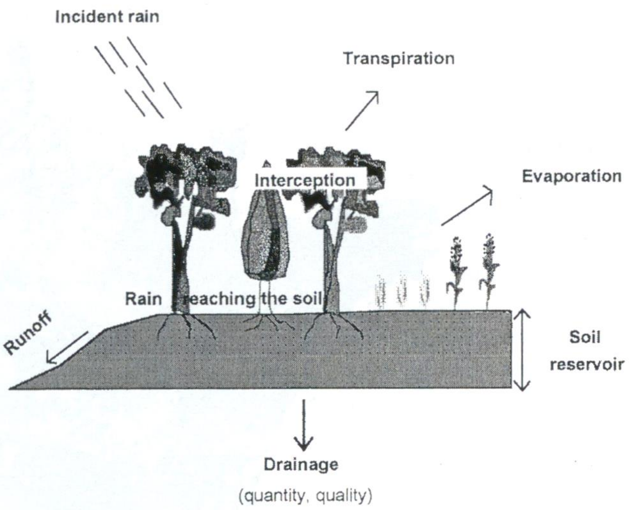


**Fig. 6.** Schematic water cycle in soils with a plant cover.

with maize, a plant which is profitable under satisfactory conditions but which consumes much water. In several regions where cash crops are cultivated, a simultaneous increase in the surface areas irrigated and the amount of water supplied was observed. In these regions, water management raises many worrying problems.

### *A fragile environment at the surface*

Over the last 50 years, the average size of farms along with the size of the field pattern have much increased. These increases are due to the government which favoured consolidation and farmers who pulled up hedges and removed banks and ditches. Mechanization made it possible to considerably increase labour productivity but major changes in the field pattern, the disappearance of pastures and the introduction of new crops with other rotation systems worsened problems, such as the appearance of sheet and rill erosion (Monnier et al. 1986; King & Le Bissonnais 1992; Papy et al. 1996).

In erosion problems, it is necessary to consider the elementary watershed, which can be defined as an isolated territory from a hydraulic point of view and which leads to a single outlet. Runoff occurs when infiltrability at the soil surface is lower than rain intensity. Soils mainly composed of loam present the highest erosion risks due to their sensitivity to soil capping which increases with decreasing organic matter level. The degradation of the soil surface is more rapid when agricultural practices reduce the size of soil aggregates and the soil is bare (Boiffin & Sebillotte 1976). Seedbeds often constitute potentially trickling surfaces. The slope, the geometry and the nature of the flow network of the water running off in the watershed also play a role.

In the case of intense rainfall, the surface can be degraded when it is not completely closed (Fig. 7). Under the impact of drops, soil particles can be suspended. Runoff can

**Fig. 7.** An example of sheet erosion in the pays de Caux area (Picture Y. Le Bissonnais).

**Fig. 8.** An example of rill erosion in the pays de Caux area (Picture Y. Le Bissonnais).

wash away the finest particles. This is sheet erosion (King & Le Bissonnais 1992; Gallien et al. 1995). It is usually admitted that, in the most fragile soils, i.e. those of the loamy type, with low organic matter contents (< 1.5 %) a cumulated rainfall of 60 to 100 mm is enough for a seedbed at the fragmentary state to reach the ultimate stage of degradation, i.e. the formation of a sedimentary crust at the surface (Le Bissonnais & Le Souder 1995; Bresson & Boiffin 1990). At this stage, soil infiltrability becomes very low (from 1 mm/hour to a few mm/hour) and the smallest rain event can cause runoff. If the soil surface contains few clods and is covered by plants, runoff water is only slightly loaded. Water speed can be high in the lines where runoff concentrates and create furrows and small ravines which are specifically localised in the landscape (rill and gully erosion — Ludwig et al. 1996), (Fig. 8).

Studying the erosion and runoff processes shows that they are very complex. They involve the amount of water, the slope, the length of the water trajectory as well as the soil state at the beginning of the rain event (Monnier et al. 1986; Le Bissonnais et al. 1990). The initial state depends on the previous successive rain events leading to the evolution of the surface soil structure. Globally understanding the phenomena requires taking into account the succession of rain events during the growth cycle (Boiffin & Sebillotte 1976; King & Le Bissonnais 1992).

Erosion has multiple consequences. For the farmer, this means that seedlings can be submerged and plants can suffer from losses, which is detrimental to crop yield. Regarding soil quality, this means the disappearance of arable land and in particular fine soil fractions which play a major role in soil quality (clays and organic matter). Erosion thus contributes to the irreversible loss of soils. The emphasis is currently laid on the consequences of erosion at the environmental level: flooding and silting of rain sampling networks, submersion of roads, disastrous spates.

Implications at a more general level are numerous. The part of the soil washed away is the most superficial and the finest. It thus contains mineral nutrients (phosphorus, potassium, nitrogen) and associated chemicals controlling plant pests and diseases (herbicides and pesticides) (Lecomte et al. 1997). Most of these chemicals, except nitrates, are fixed on solid particles, thus contributing to the pollution of rivers and shores. Erosion and its consequences are thus not limited to agricultural systems.

*For an agro-environmental management of soils*

While fertilization has made it possible to solve problems resulting from the increasing inadequacy between the soil chemical capacity and the requirements of a cultivated plant, removing physical constraints has made it possible to reach high intensification levels in farming. In this article, we did not study drainage and irrigation, although it would have been of interest. In particular, drainage can lead to an increase or a decrease in runoff and erosion, depending on the situation and the scale of observation. We have shown that the current agricultural systems are located in transformed landscapes. Farming intensification has modified the terrestrial water cycle. Although not well known, some effects, such as erosion and its consequences at the environmental level, especially spate and water pollution phenomena, can already be detected (Papy & Douyer 1991; Lecomte et al. 1997).

Other effects have been studied less but their long-term consequences deserve attention. The change in physical properties of soils in the long term following severe desiccation and the use of heavy and powerful machines should be mentioned. Ground water recharge and quality will probably raise major problems in the future, because soil water reserves are under increasing demand, which affects the global water resources from a qualitative as well as a quantitative point of view.

## Conclusions

Soil diversity in France is so high that soil management in relation to environmental problems cannot have a single answer. Controlling fertilization and amendment practices is an essential condition for maintaining soil quality in the long term. It involves monitoring soil chemical quality in order to adapt supplies. The problem of overfertilization at the regional scale, in particular due to industrial farming, as well as the improvement of fertility in forest and pasture soils must not be overlooked.

Over the last 50 years, the landscape has been transformed due to major development operations, such as drainage and land consolidation. The initial potentiality of soils has been improved but this evolution presents drawbacks. In numerous regions with loam soils which are known to have a structural fragility, the increase in the field pattern and agriculture specialization causing the disappearance of pastures has led to a new type of erosion in these lowland regions with moderate relief and climate. The impact on the environment does not only affect the plot, but a much wider area too, since the river pattern can be affected. Solutions cannot only be found in agricultural practices but at a more global level, in the management of watersheds. Localized resowing of sensitive areas, such as waterways, thalwegs, plot margins and river edges, the diversification of crops, and the development of sensitive areas to preserve soils and decrease pollution are the solutions currently suggested but they are not all satisfactory in the long term.

INRA research work in this area aimed at understanding the mechanisms and the phenomena causing the evolution of soil properties. It describes the processes involved, diagnosis tools and the current elements available for assessing risks. Nevertheless, the inventory of soils and properties at the territory scale is still partial.

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