QUALITY OF FOREST SOILS FACING GLOBAL CHANGES

DOMINIQUE ARROUAYS – JACQUES RANGER

This paper is the English translation of: « La qualité des sols forestiers face aux changements globaux » – Revue forestière française*, 4-2014. http://documents.irevues.inist.fr/handle/2042/4752.*

INTRODUCTION

Positioned as an interface in the environment, soils constantly exchange flows with four major components of the environment: the biosphere, the atmosphere, the hydrosphere and the lithosphere. At the interface of the living world and of the mineral world, soils are characterised by their extraordinary complexity: they combine the three phases – solid, liquid and gas – they have a very large variability of organo-mineral associations from complex biological and physico-chemical processes, a level of micro-biodiversity that still remains largely unknown, highly diverse pedogeneses, etc.

In this way, soil has a variability that occurs from the scale of the nanometre to that of the planet, and levels of organisation that run from the molecule scale to the large biome scale. It is this immense variability that renders it necessary to have a spatial knowledge of soils, their functioning and behaviour, in order to be able to manage them locally in the most appropriate way.

BUT WHY SHOULD SOIL BE MANAGED?

Soil carries out ecosystem services that are highly numerous:

— it is the point of support to agricultural and forest production, the mooring point for root, and reservoir for water and for nutrients,

— it is the point of support for our landscapes and for the development of our infrastructures,

— it constitutes a record of human activity and is the home of a part of our archaeological heritage,

— it filters, immobilises or breaks down pollutants,

— it recycles organic wastes of all kinds,

— it is a central link in the regulation of greenhouse gases,

— it is home to a remarkable and abundant biodiversity, which represents substantial genetic and ecological potential,

— it is a source of materials (granulates, sands, brick, pottery clay, etc.),

— It regulates the surface water regime and the supply of groundwater.

Among these many services, some can clearly prove conflicting. The actions to be taken to protect soil and to maintain or improve some of its functions therefore depend at once on the services that are expected of it and on its intrinsic characteristics. As a result, these actions must also take place at the local level, as for example on the scale of a forest stand.

However, soil is also at the heart of great global issues such as food security, climate change, the development of renewable energy sources, the availability of good quality water and the preservation of biodiversity. This observation recently led to the emergence of the concept of "soil security" (McBratney *et al.*, 2014), the establishment of a worldwide partnership on soil that mobilises all member countries of the FAO (http://www.fao.org/globalsoilpartnership/), the establishment of a large programme for the constitution of a digital database on soils around the world (Arrouays *et al.*, 2014a et b), and the proclamation by the United Nations for the international year of soils in 2015.

These actions come from the awareness – relatively recent – that soil is a resource that is not generally renewable on a time scale that is compatible with the rates with which it is likely to be degraded. The soil is in a dynamic equilibrium with the environment factors, of which human pressure is an integral part. Human's actions can be decisive as regards the evolution of soil: as anthropological pressures are mainly increasing, threats to soil are becoming more and more of a preoccupation. Some of these threats are more serious for forest soils as they are mostly managed in an extensive way.

These main threats are listed below:

— erosion,
— decrease in organic matter content,
— sealing of soil under constructions or infrastructures,
— contamination, either local or diffuse,
— acidification,
— decrease in fertility or facing imbalance in the nutrient offer for plants,
— decrease in biodiversity,
— compaction.

These threats do not concern forest soils in an equal manner and in many cases the intensity of these threats differs between forest soil and agricultural soil.

WHAT ARE THE THREATS FACING FOREST SOIL?

The erosion of soil is a major problem in large parts of the world (in China in particular). In France, it is estimated that around 20% of the mainland territory is concerned by erosion that leads to a non-sustainable situation: in other words, the soil masses lost by erosion are greater than those formed by weathering and pedogenesis. The surface areas affected are mainly arable lands. However, in forest soil, erosion is generally not a major problem, as the soil is protected from the impact of rain by forest cover, understory vegetation, and the accumulation of debris and organic matter on its surface. However, it may occur in some situations of steep slope and for some practices (clear cutting and keeping the soil bare, excessive compaction), or – in particular in the Mediterranean region – following fires. In these cases, very negative consequences may be observed (gully erosion, removal of the soil surface layer that is the richest in nutrients, muddy flooding downstream, etc.).

The decrease in organic matter content also does not concern forest soil to a great degree. In France it is estimated that soils under forest contain around one and a half times more organic carbon than agriculture land, and even more if the climate is cold (Meersmans *et al.*, 2012a and b). The risks of a loss of organic matter (and consequently of an associated flow of CO_2 into the atmosphere) are mainly attributable to drastic changes in use (deforestation) and to a possible effect of climate change (increase in mineralisation rate or C return by litterfall), and even to an excessive intensification of harvesting (whole tree vs stem-only harvesting). If we reason globally on the scale of France, the forest soil is currently a carbon sink, mainly due to the fact of the extension of both naturally regained surface areas and forest plantations.

The disappearance of the soil under constructions or infrastructures affects the surface area of a French département (6100 km^2) every 7 years. In the vast majority of cases, this involves agricultural soil (90% of artificialised surface area concerns agricultural soils). However, there are local situations where the pressure of urbanisation is such that some forest soils are artificialised. This mainly concerns coastal areas, as some mountain areas or mountain valleys where the constructible space is restricted by topography, or by the geotechnical characteristics of the subsoil, and some areas where the value of land assigned to uses other than forest is such that urban predominance develops to the detriment of the latter (for example, on the periphery of the Bordeaux agglomeration, where the Landes de Gascogne forest has become gradually urbanised while the areas of wine-producing AOC are better preserved).

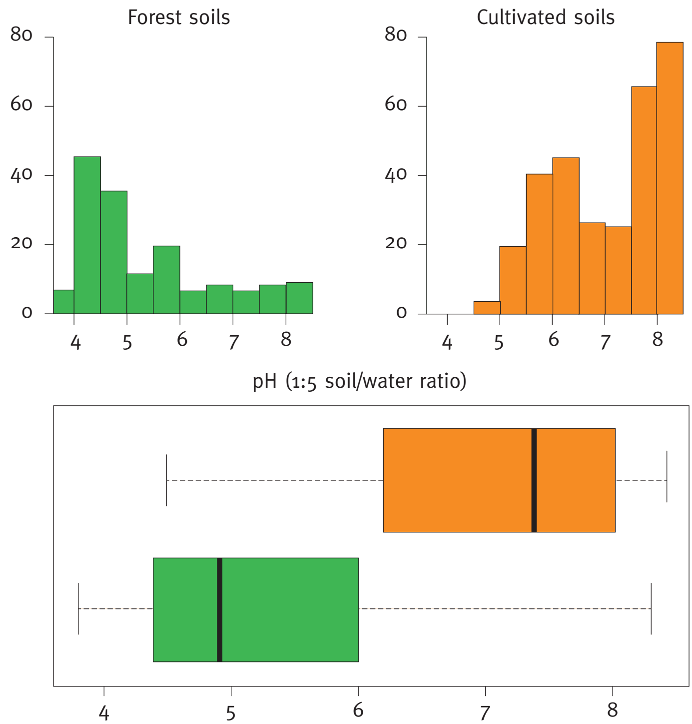
The preservation of forest soil in the sub-urban environment is favoured due to its function as a "green belt" and recreational space. It may however be affected by large linear developments (motorways, high speed train lines, etc.) when the avoidance of forests poses technical or economic difficulties.

As a rule, local or diffuse contamination affects forest soil less than agricultural soil due to the use of less inputs containing substances that are potentially toxic (pesticides in particular). However, the forest is not protected from generalised widespread contamination of long range atmospheric origin, or from nearby atmospheric emissions (Villanneau *et al.*, 2009, 2013). In this case, the forest soil may even be more affected due to the efficient canopy interception of these emissions washed down to the soil by rain. In addition, the acid character of a large number of forest soils accentuates the mobility of some elements that are potentially toxic.

Whilst these questions are quite well managed in agriculture by the practices of liming and fertilisation, **the acidification and maintenance of chemical fertility** represent major issues for forest soils, when the parent material does not contain enough weatherable alkaline reserves. The prospect of a possible increase in the rate of biomass harvesting in forest (dead wood, branches, tree crowns, sometimes stumps and roots), poses the question of the maintenance of a sufficient nutrient reserve in the soil. Risks of nutrient imbalance increases following inputs dominated by a single element (for example, atmospheric nitrogen deposits). The question of mitigation of forest soil acidity by liming and fertilisation therefore remains complete. Some drops in pH could lead to overpassing of thresholds in terms of the functioning and pedogenesis of some soils. Figure 1 (p. 18) is a good illustration of the contrast between the pH distribution of agricultural and forest soils. Under cultivation, we observe a bimodal distribution and relatively few highly acidic pHs. "Peaks" of high pH are mainly linked to a permanent "recharging" of cations that is mainly attributable to soil tillage or erosion on calcareous shallow soils. Concerning forest, the distribution reveals a lot of highly acidic pHs, and demonstrates that – with the exception of soil developed on highly calcareous materials, easily weatherable, and consequently efficiently buffered against pH variations, or those that are constantly renewed by erosion – the natural evolution of soils in our climates leads to a loss of cations and acidification.

The biodiversity in forest soil has highly contrasting characteristics, mainly linked to the richness in nutrient substrates and to the physico-chemical characteristics of the soil (Dequiedt *et al.*, 2011). In "rich" soils, with high contents in organic substrates, cations and fine mineral particles, the biodiversity can be remarkable. By contrast – in acid, sandy and quartz-rich soils – such as for example in the Landes de Gascogne – it can be reduced to the minimum. The systematic exportation of slashes can accentuate this decrease in biodiversity. The maintenance of soil biological activity is one of the key-conditions for the efficiency of nutrient cycles, as well as for the oxygenation of soil and its capacity to restore following compaction.

Figure 1 **DISTRIBUTION OF THE pH IN THE 0-30 cm LAYER OF AGRICULTURAL SOILS AND FOREST SOILS IN METROPOLITAN FRANCE**
Statistics taken from the Soil Quality Measurement Network



The compaction of forest soil is a relatively new problem linked to the development of mechanisation, a practice accentuated by the urgency of logging after the recent storms. The "natural" restoration of the soil structure implies either a capacity for regenerating its structure under the effect of the climate (for example as a result of the presence of swelling clay), or intense biological activity (for example via burrowing animals). Here too there is therefore an interaction with the relatively stable intrinsic characteristics of the soil (such as particle-size distribution) and others that change more rapidly, such as pH. Indeed, as seen above, biological activity is substantially reduced with soil acidity. In fact, the few works that exist in France show that in sensitive fine textured soils, such as those on the Lorraine plateau, the degradation can be very quick, a few months are sufficient to observe the effects of anoxia and hydromorphy on their morphology. Restoration is however very slow (only in the upper soil layer, 7 years after experimental compaction in the example of Lorraine) and poses the question of future damage, when heavy machinery will be used over non-restored soil (Pousse *et al.*, 2014): plough pan syndrome is a threat to forest soil, with predictable consequences for the sensitivity to stress of future stands.

THE "FUTURE" OF FOREST SOILS, THEIR EVOLUTION AND GLOBAL CHANGES

Due to tree longevity, silviculture must consider a strong adaptation of its practices to counteract the effects of climate change. Taking into account the uncertainties of these changes in the medium and long terms, and their consequences for the soil, the question is far from being an easy one. Beyond the immediate management of forest stands, one of the questions concerns the adaptation of tree species to these changes. Use of models also makes it possible to localise certain favourable areas, but remains subject to a very high degree of uncertainty (*e.g.* Loustau *et al.*, 2004). In addition, the majority of these predictions are made taking into consideration unchanged soil properties over time. But, it is well known that global changes are likely to have a rapid influence on a large number of them. For example, an increase in temperature may accelerate the mineralisation rate of soil organic matter; a higher frequency of storms may disturb the vertical structure of soil layers (this is already the case in the Landes de Gascogne), accelerate the mineralisation of their organic matter and lead to new compaction linked to the intensive use of heavy machinery for logging. An increase in extreme drought episodes may deeply change the soil structure with negative consequences on transfer properties and holding capacity, for water.

CONCLUSIONS

In theory, we have a large number of tools for the evaluation of the current condition of forest soil and the assessment of the management measures to be taken. These tools are however only able to be used if they are linked to reference points. These references have been acquired within the framework of a large number of programmes (Catalogues for forest stations, soil maps, Renecofor, BIOSOL, RMQS, Soere F-ore-T networks). However, they are not yet sufficiently complete and detailed to allow an application to a plot without a diagnosis that requires a local investigation. Forecasting and simulation tools do exist, but observation and monitoring remain indispensable, both for the validation of predictions and for the identification of new trends that have not yet been anticipated.

More generally, the chemical fertility of forest soils – which is one of the central questions of this thematic issue – essentially depends on flows, which are relatively weak and difficult to measure accurately, rather than on stock characteristics, which represent the dominant variables of the databases at global level. Only having state variables at these scales poses the problem of a reliable prediction of its dynamics.

Today – due to heightened anthropogenic pressure and global changes – the maintenance of the quality of forest soil has to come back to the forefront of our preoccupations. This is the subject of the 2013 REGEFOR Workshops and their proceedings, which are to be published in a thematic issue of the French Forestry Review.

Dominique ARROUAYS
INRA Centre Val de Loire
Unité InfoSol, US 1106
2163 avenue de la Pomme de Pin
CS 40001 Ardon
F-45075 ORLÉANS CEDEX 2
(Dominique.Arrouays@orleans.inra.fr)

Jacques RANGER
INRA Centre de Nancy-Lorraine
Unité Biogéochimie des écosystèmes forestiers
F-54280 CHAMPENOUX
(ranger@nancy.inra.fr)

REFERENCES

ARROUAYS (D.), GRUNDY (M.G.), HARTEMINK (A.E.), HEMPEL (J.W.), HEUVELINK (G.B.M.), HONG (S.Y.), LAGACHERIE (P.), LELYK (G.), MCBRATNEY (A.B.), MCKENZIE (N.J.), MENDONÇA-SANTOS (M.D.), MINASNY (B.), MONTANARELLA (L.), ODEH (I.O.A.), SANCHEZ (P.A.), THOMPSON (J.A.), ZHANG (G.L.) — GlobalSoilMap: towards a fine-resolution global grid of soil properties. — *Advances in Agronomy*, 125, 2014a, pp. 93-134.

ARROUAYS (D.), MCKENZIE (N.J.), HEMPEL (J.), RICHER DE FORGES (A.C.), MCBRATNEY (A.B.), eds. — GlobalSoilMap. Basis of the global spatial soil information system. — CRC Press, Taylor & Francis, 2014b. — 478 p.

DEQUIEDT (S.), SABY (N.P.A.), LELIEVRE (M.), JOLIVET (C.) THIOULOUSE (J.), TOUTAIN (B.), ARROUAYS (D.), BISPO (A.), LEMANCEAU (P.), RANJARD (L.). — Biogeographical Patterns of Soil Molecular Microbial Biomass as Influenced by Soil Characteristics and Management. — *Global Ecology and Biogeography*, 20, 2011, pp. 641-652.

LOUSTAU (D.), BOSC (A.), COLIN (A.), DAVI (H.), FRANÇOIS (C.), DUFRÊNE (E.), DÉQUÉ (M.), CLOPPET (E.), ARROUAYS (D.), LE BAS (C.), SABY (N.), PIGNARD (G.), HAMZA (N.), GRANIER (A.), VIOVY (N.), OGÉE (J.), DELAGE (J.). — Modelling the climate change effects on the potential production of French plains forests at the sub regional level. — *Tree Physiology,* 25, 2005, pp. 813-823.

McBRATNEY (A.B.), FIELD (D.J.), KOCH (A.). — The dimensions of soil security. — *Geoderma,* 213, 2014, pp. 203-213.

MEERSMANS (J.), MARTIN (M.P.), DE RIDDER (F.), LACARCE (E.), WETTERLIND (J.), DE BAETS (S.), LE BAS (C.), JOLIVET (C.C.), BOULONNE (L.), LEHMANN (S.), SABY (N.P.A.), BISPO (A.), ARROUAYS (D.). — A novel soil organic C model using climate, soil type and management data at the national scale (France). — *Agronomy for Sustainable Development*, 32, 2012a, pp. 873-888.

MEERSMANS (J.), MARTIN (M.P.), LACARCE (E.), DE BAETS (S.), JOLIVET (C.), BOULONNE (L.), LEHMANN (S.), SABY (N.P.A.), BISPO (A.), ARROUAYS (D.). — A high resolution map of the French soil organic carbon. — *Agronomy for Sustainable Development*, 32, 2012b, pp. 841-851.

POUSSE (N.), BOCK (J.), RANGER (J.). — Impacts de la circulation d'un porteur forestier sur deux sols sensibles au tassement et dynamique de restauration naturelle. — *Rendez-Vous techniques*, n° 43, 2014, pp. 33-39.

VILLANNEAU (E.), SABY (N.P.A.), ARROUAYS (D.), JOLIVET (C.C.), BOULONNE (L.), CARIA (G.), BARRIUSO (E.), BISPO (A.), BRIAND (O.). — Spatial distribution of lindane in topsoil of northern France. — *Chemosphere*, 77, 2009, pp. 1249-1255.

VILLANNEAU (E.J.), SABY (N.P.A.), ORTON (T.G.), JOLIVET (C.C.), BOULONNE (L.), CARIA (G.), BARRIUSO (E.), BISPO (A.), BRIAND (O.), ARROUAYS (D.). — First evidence of large-scale PAH trends in French soils. — *Environmental Chemistry Letters*, vol. 11, n° 1, 2013, pp. 99-104.