How monitoring networks contribute to the understanding and to the management of soil and forest ecosystems?

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INTRODUCTION

Environmental changes, atmospheric pollution and climate change in particular, have a strong impact on the functioning of ecosystems and consequently on the best adapted way in which to manage them. In spite of the many things we have learned from the research, a good deal of the complexity of our environment is still not very well understood; the models for forecasting impact often find it difficult to reproduce the phenomena observed, let alone anticipate them. What is more, environmental changes may lead to new conditions that call into question the validity of some of the knowledge that has been acquired up to now and on which predictions need to be able to lean, as is for example the case with knowledge on the sensitivity of forest trees to the climate (Lebourgeois and Mérian, 2011).

Faced with the complexity of the phenomena at stake, long-term monitoring networks have been put in place on a national and international scale, in order to observe the changes in progress on permanent observation sites. The aim is not only to be able to detect and quantify temporal trends in the functioning of ecosystems, but also to correlate them with external influence factors. These monitoring networks fit into a broader continuum of environmental observation systems (Ferretti *et al.*, 2013).

They take up a key position in the needs for the spread of knowledge between:

— research sites, highly instrumented with a view of understanding the functioning of forest ecosystems, but necessarily not numerous and which cannot represent the diversity of contexts;

— and the inventory or remote sensing data, aimed at highly dense spatial cover yet limited to simpler parameters or parameters that are highly inclusive and without necessarily having continuity in the long term.

In metropolitan France, three national monitoring networks are concerned with the change in soil and/or forest conditions. Here it is a matter of summarising their characteristics and complementarities and then presenting their main contributions in the response to the burning questions on soil.

Table I — **Summary of the characteristics of French surveillance networks monitoring soil and/or forest**

	Extension	National coordination	Objectives
RMQS : Soil quality monitoring network	Extensive monitoring on a grid of 16 km × 16 km (~2 200 plots, of which ~550 in the forest)	US1106 InfoSol Inra for the GIS Sol	Soil monitoring (forest + other land uses)
RSSDF : Systematic network for the monitoring of forest damage		Forest Health Department (Ministry of Agriculture)	Health monitoring of forest trees + Characterisation of soil and vegetation
RENECOFOR : Network for the long-term monitoring of forest ecosystems	Intensive monitoring (multi-domain) (102 plots)	ONF R&D Department	Monitoring of forest ecosystems (forest stand, ground vegetation, soil, etc.) in response to external factors (weathern atmospheric deposition, forest management, etc.)

PRESENTATION OF THE MONITORING NETWORKS CONCERNED IN FRANCE

Objectives, designs and complementarities in the approach to soil

Table I summarises the main characteristics of the three networks presented and their spatial spread is illustrated in figure 1 (p. 97).

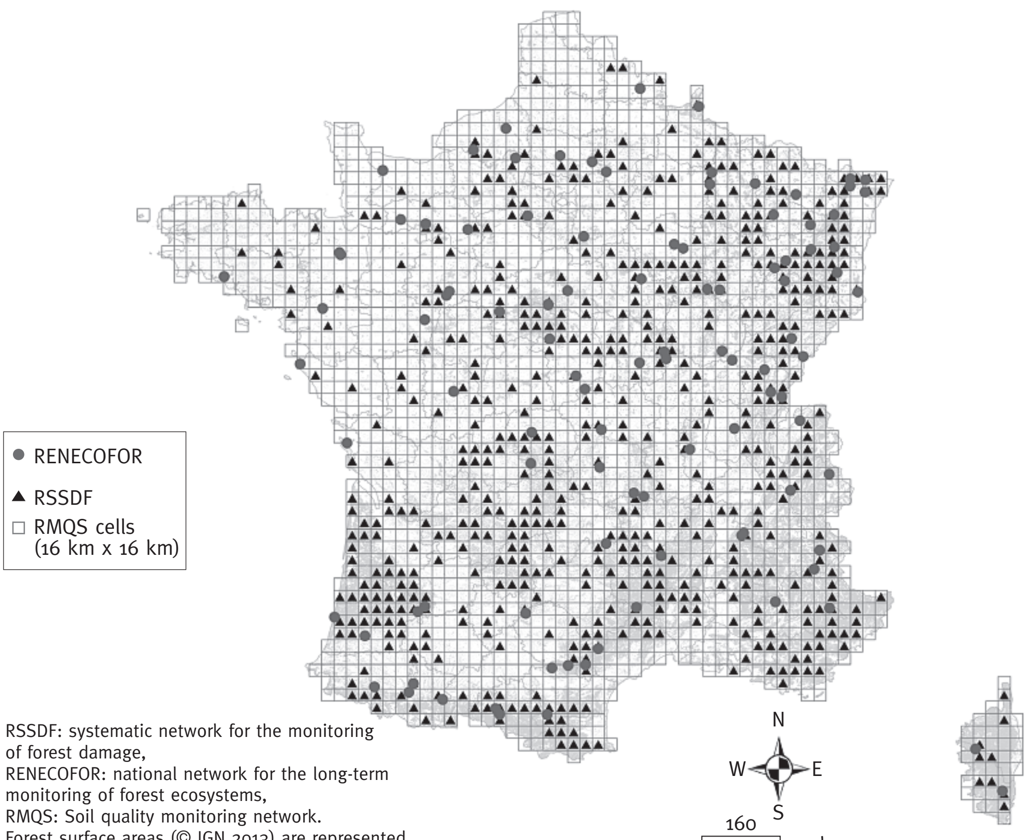
The systematic network for the monitoring of forest damage (RSSDF) and the RENECOFOR network were set up in 1989 and 1992 respectively as a response to the fears raised by “acid rain” concerning the future of forests (Barthod, 1994). They are the two French components of continuous monitoring of pan-European forests (*ICP Forests* programme) which has been developed under the aegis of the United Nations Convention on long-distance transboundary atmospheric pollution, in close consultation (period 1987-2006) with the European Commission:

— The RSSDF represents the extensive component of pan-European forest monitoring. It includes around 550 permanent plots spread over a systematic grid of 16 km x 16 km on which the health of forest trees is monitored annually. It has been subject to a first campaign to describe and analyse the soil in 1993-1995 (Badeau, 1998), without the initial goal of monitoring over time but only of ecological characterisation, with in particular a single sampling point per plot at the point of the description pit. A second campaign was funded by the European Union (Biosoil programme) in 2007-2008, according to a more demanding methodology that is more harmonised on the continental scale but not directly comparable to that used in 1993-1995 (Badeau *et al.*, 2009). In some other European countries which had produced their first inventory with a desire to reproduce it (and which had a better quality of sampling), this campaign had a scope that was a lot larger than in France.

— The RENECOFOR network represents the intensive component of pan-European forest monitoring (Ulrich, 1995). Made up of 102 permanent plots divided up between the main production forest contexts, it is aimed at monitoring the evolution of forest ecosystems through a large number of parameters (growth, phenology, nutrition and health of the forest trees; litterfall; soil fertility; ground vegetation species composition), whilst taking into account the environmental variations that they undergo (atmospheric pollution, meteorology, effects of cuttings and storms). Monitoring of the physico-chemical properties of soil has led to two campaigns in 1993-1995 and 2007-2012 according to methodologies that are strictly comparable and integrate 25 sampling points grouped into 5 composite samples for analysis for each plot (Ulrich *et al.*, 2009). Soil sampling is not

	European integration	Soil sampling campaigns	Spatial replicates by plot and by soil layer	Soil layers
	No	1st : 2000-2009 2nd in project : 2015-2026	25 points sampled using a corer, 1 composite analysed	Humus 0-30 cm 30-50 cm + 50-100 cm during the 2nd campain
	ICP Forests Level I	1st : 1993-1995 2nd : 2006-2007 Protocols that are not directly comparable	1 sampling point on the soil pit or 6 points sampled using a corer, 1 composite analysed	Humus 0-10 cm 10-20 cm 20-40 cm 40-80 cm
	ICP Forests Level II	1st : 1993-1995 2nd : 2007-2012	25 points sampled on mini trenches, 5 composites analysed	Humus 0-10 cm 10-20 cm 20-40 cm

FIGURE 1 **SPREAD IN METROPOLITAN FRANCE OF SURVEILLANCE NETWORKS MONITORING SOIL AND/OR FOREST IN RELATION TO THE SOIL**



RSSDF: systematic network for the monitoring of forest damage,
RENECOFOR: national network for the long-term monitoring of forest ecosystems,
RMQS: Soil quality monitoring network.
Forest surface areas (© IGN 2013) are represented in grey in the background

carried out using a corer but on mini trenches of depth up to 40 cm in such a way as to maximise the representativeness of the samples even in the most stony contexts. In addition, soil samples were taken from 40 cm to 1 m depth on the description pits and without any monitoring over time.

Created in 2000, the Soil Quality monitoring network (RMQS) is dedicated to evaluate and to monitor the quality of French soils. It includes 2200 permanent plots spread out according to the same extensive grid of 16 km x 16 km as the RSSDF but stretched to all types of soil use (not only forests but also cultures, prairies, natural or urban environments) and also the overseas territories. In the forest context, the plots of the RMQS have been installed in the immediate proximity of the plots of the RSSDF. Without being quantified, the spatial variability within each plot of the RMQS is integrated over 25 sampling points. Soil sampling is carried out at several soil depths using a corer down to 50 cm. A soil pit is also dug on each site for soil description and additional sampling.

Up until now, the RMQS network has been the object of a single measuring campaign between 2000 and 2009; the next campaign is planned from 2015 to 2026. By contrast to forest networks, and although soil monitoring networks exist in other European countries, the RMQS appears like a national system. Its harmonisation with other European countries is struggling to get off the ground, due to the absence of a framework directive on soil protection that would make said harmonisation mandatory, and despite the fact that such perspectives have been clearly identified in the conclusions of the European project Envasso (Morvan *et al.*, 2008).

Measurements carried out on soil

All plots in the three monitoring networks have been subject both to soil descriptions and analyses of their physico-chemical properties.

The soil descriptions, produced on soil pits and per horizon, rely on highly complete morphological criteria that are standardised within each network. In addition to their editing in the database, the results for soil description for the RENECOFOR network have in particular formed the subject of an exhaustive report illustrated by profile photographs (Brêthes *et al.*, 1997).

Physico-chemical analyses are detailed per layer of systematic depth for mineral soil so that their compatibility can be ensured between the plots of a single network. The systematic layers considered are the same for the two forest networks on a pan-European scale; those of the RMQS network are different and meet the needs for integration and comparison of the various land use categories (agricultural soil, forest soil, meadow soil, etc.). With regard to the parameters analysed, the two forest networks are mainly aimed at evaluating soil fertility (measurements of organic carbon, total nitrogen, pH, exchangeable elements, bulk density, particle size distribution) according to methods that are for the most part identical and harmonised on the pan-European scale. In keeping with its own objectives, the RMQS network is measuring fertility according to more universal analysis methods to deal with the various land uses encountered on this network. The RMQS also considers other parameters for soil quality such as biodiversity (micro-organisms, soil fauna, pathogens) and the in-depth characterisation of organic components (particular organic matter, spectral measurements in near and mid infra-red, black carbon). Lastly, the purpose of this network is to evaluate and monitor levels of soil contamination in the long term through analysis of the mineral contaminants (trace elements) and organic contaminants (PAHs, PCBs, dioxins, pesticides, etc.). The majority of chemical analyses of soil from the three networks have been carried out by the Soil Analysis Laboratory (LAS) of INRA in Arras, which is considered as the leading European laboratory according to its performances in inter-laboratory ring-tests as part of the *ICP Forests* programme. Within the framework of the European Biosoil programme cited above, it should be noted that all participating countries must transmit to the LAS an aliquot part of 10% of their soil samples in order to check the quality of their chemical analyses.

Joint quality requirements linked to monitoring objectives

Monitoring calls for quality requirements to ensure the actual comparability of the observations between plots and in the long term. The three networks considered here have a certain number of characteristics in common.

— They are based on permanent plots designed to house all monitoring activities and to minimise the artefact risks linked in particular to destructive sampling.

— The protocols used are described precisely and updated according to incremented versions whilst paying especial attention to the continuity of measures.

— Operators are trained for each monitoring activity, and changes in operator are reduced as far as possible for a more homogeneous application of the monitoring protocols.

— Uncertainties with regard to measurements are quantified as often as possible and are compared with the amplitude of the variations observed. The chemical analysis laboratories that contribute to the networks of the pan-European programme *ICP Forests* are subject to regular inter-laboratory ring-tests on the base of samples taken under the usual monitoring conditions.

— All soil and vegetation samples are dried and archived, with a view to being able to repeat the chemical analyses.

— The collected data are saved into databases that are structured, validated and documented, in keeping with the monitoring protocols.

SUMMARY OF CURRENT CONTRIBUTIONS OF THE MONITORING NETWORKS ON SOIL

Contribution 1: new soil quality inventories

The establishment of monitoring networks has firstly contributed new inventories according to homogeneous methodologies on a large scale for a large number of ecosystem parameters, in particular on soil quality. The results of the campaigns carried out within the RSSDF and the RENECOFOR network have helped to document the state of chemical fertility of forest soil on the national scale (Ponette et *al.*, 1997; Badeau, 1998; Badeau *et al.*, 1999). On the European scale, the Biosoil programme has made it possible to resume with substantial improvements the state of knowledge of forest soil condition for a total of over 5,000 permanent plots of the programme ICP Forests (De Vos and Cools, 2011). As regards the RMQS network, its first campaign (2000-2009) has made it possible to establish reference values for a large number of parameters measured in French soil (Arrouays *et al.*, 2011; Gis Sol, 2011), and in particular to evaluate the extension of a large number of soil contaminants (Saby *et al.*, 2011; Villanneau *et al.*, 2013). It has also contributed to improve the evaluation of stocks of soil organic carbon in metropolitan territory and to associate uncertainty values to this quantification (Martin *et al.*, 2011; Meersmans *et al.*, 2012). Lastly, the diversity of the situations taken into account by the RMQS has offered the possibility to make a new comparison of soil quality in France according to land use categories, whilst taking into account not only chemical fertility (pH, basic saturation rate, organic carbon, etc.) but also other parameters such as the quantity of microbial DNA (Dequietd *et al.*, 2011).

Contribution 2: the first results of monitoring over time are encouraging

The recent performance between 2007 and 2012 of the second soil analysis campaign on the 102 plots of the RENECOFOR network offers the first opportunities to detect the evolutions of their properties on a national scale according to a methodology comparable to the initial measures carried out between 1993 and 1995. A first analysis of these data was carried out as of 2013 with the support of the Ministry of Agriculture and aimed at detecting changes in organic carbon stocks measured in forest soil and humus (Jonard *et al.*, 2013). It was in particular a matter of checking the hypothesis that was made in international commitments for the reduction of greenhouse gas emissions, according to which forest soil and humus could not be a source of net carbon emissions. The results uncover some substantial changes over a period of fifteen years. On the scale of all sites and considering the sum of humus and mineral soil layers of up to 40 cm in depth, organic carbon stocks significantly increase according to an average amplitude of +0.34 t C ha^{-1} $year^{-1}$. What is more, the replication of analyses in 5 clusters per plot makes it possible to quantify spatial variability and to distinguish significant changes over time for 25% to 55% of the plots according to the layers, the majority in the sense of an increase but some also in the sense of a decrease in organic carbon stock. The significant changes are more numerous in the layers nearest the surface, and the lowest significantly detected change corresponds to an amplitude equal to 8.4% of the initial stock. In addition to their value on the specific matter of organic carbon stocks, these first results are encouraging for future analyses of changes in chemical fertility parameters (total nitrogen, pH, exchangeable elements and base saturation, extractable phosphorous).

Contribution 3: monitoring of the reaction of forests linked to soil properties

In addition to its continuity over time, the value of the intensive monitoring carried out on the RENECOFOR network lies in the possibility of connecting between them the changes observed in different compartments of the forest ecosystem. In this case, measurements of the chemical properties of soil carried out on plots of the network provide elements that are essential in the understanding of the balance of nutrients within forest ecosystems. Concerning tree nutrition, the reduction in foliar contents of phosphorous uncovered on the network between 1993 and 2005 seems more accentuated on acid soils than on eutrophic soils (Croisé and Jonard, 2008). The recent repetition of soil analyses offers a new perspective for comparison of the trend observed on the foliar phosphorous with a possible change in the phosphorous that is extractable from the soil. As a result of the fall in atmospheric acidifying deposition, it will also be worthwhile to compare any possible changes in the rate of soil saturation with the contrasted changes observed in the chemistry of soil solutions on 17 sites (Nicolas *et al.*, 2008). Lastly, beyond searching for correlations between the changes observed in various compartments of the ecosystem, the monitoring data are useful in order to check the validity of current knowledge on ecosystem functioning processes. The data of the RENECOFOR network is in particular used to validate the outputs of the nutrient cycling models used to simulate the effect of various scenarios of atmospheric deposition, harvesting intensity and climate change (Van der Heijden *et al.*, 2011; Jonard *et al.*, 2012).

Contribution 4: provision of indicators for the guiding of public policies

The monitoring networks also respond to a need for support to public policies. Within the framework of the United Nations convention on long-distance trans-boundary atmospheric pollution, it is in particular a matter of following changes in acidification and eutrophication constraints brought about by atmospheric deposition with regard to the forest soil's capacity to cope with them. In this way, each year the data of the RENECOFOR network help to guide the estimation of exceedance of critical loads for acidification and eutrophication, indicators according to which the European objectives for the reduction of atmospheric emissions are discussed within the framework of the Gothenburg protocol (Posch *et al.*, 2012). The soil properties data from the RSSDF and the RENECOFOR network are also used for the sustainable management indicators of forests, which are published every 5 years on the national and pan-European scale. Within the framework of international commitments with a view to the reduction of greenhouse gas emissions, the data from the first campaign of the RMQS network serve as a national benchmark in the evaluation of organic carbon stocks in soil per type of occupation (forest, meadows, annual crops, perennial crops) and in estimating their evolution as a function of the changes in land use.

Moreover, the data acquired by the RMQS on the contamination of French soil with trace elements have made it possible to support the implementation of the public policies established within the framework of the management of polluted sites and soils. Indicators for anomaly detection thresholds have been placed at the disposal of soil depollution professionals (DREAL – decentralised services of the State in the region, consultancies, consultants, municipalities, etc.), with a view to facilitating the implementation of the process of Environment Condition Interpretation (ECI) and site management plans. Measurements of persistent organic pollutants (herbicides, furans, polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), organochlorine pesticides (OCPs), serve as benchmarks and feed the Pesticide Residue Observatory. All data on contaminants are used by INERIS in the construction of diagnostics tools within the framework of the subject of environmental inequalities and environmental black spots, which is largely taken up as a major pillar of the next National Health and Environment Plan (PNSE3).

Lastly, the data of the RMQS allow the Observation and Statistics Department (SOeS) of the Ministry of Ecology to establish indicators on the soil, which are necessary in order to feed its tools for the provision of information on the Internet (Géoïdd interactive cartography, Report on the condition of soils in France, publications, etc.), as well as to submit reports on the soil to the European authorities (European Commission, European Environment Agency, Eurostat, OECD).

Contribution 5: support to research

Finally, the monitoring networks offer support and methodological reference points to research and development:

— The monitoring results gathered in the structured databases are made available on request.

— The archived soil study samples may also be made available on request. The provision of samples for research even represents one of the main objectives that motivated the establishment of the soil archive associated to the RMQS network.

— The sites are able to play host to a number of complementary measures or can be used as experimental indicators, provided that this work does not disturb the monitoring activities.

— The methods, described and tried and tested, are also available.

CONCLUSIONS AND PERSPECTIVES

With barely 20 years having passed, the monitoring networks are still very young in view of the speed of change of their objects of study – soils and forests. Monitoring of soil quality in particular is only just beginning to contribute results for change over time. Despite this, the monitoring networks have already proven themselves in terms of multiple and original contributions to knowledge of soils and forests, strongly linked to research. What is more, it is a question of systems that are pioneering in their domain and which are revealing in a new way the spatial and temporal availability of a large number of parameters and which have accumulated a full-fledged area of separate know-how in the observation of the environment.

In future, the possibilities for the use of monitoring results will increase as the series of data acquired get longer. We can anticipate that the expectations will become greater and diversify due to the environmental changes and the changes in forest management methods. In this way, some parameters – such as soil compaction – may represent new monitoring issues.

However, the continuity of monitoring networks is never fully guaranteed and calls for constantly renewed political support. A particular element of fragility concerns the taking into account of this specific mission within the various public establishments that carry out these activities, i.e. ONF, INRA and IGN, in more or less strong internal changes in a highly tense economic context.

The absence of a legal framework – and in particular of a European directive on soil – accentuates this vulnerability. Here we would like to emphasise the full importance of what has been achieved and the compelling need to continue this mission of performing soil and forest monitoring.

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HOW MONITORING NETWORKS CONTRIBUTE TO THE UNDERSTANDING AND TO THE MANAGEMENT OF SOIL AND FOREST ECOSYSTEMS? (Abstract)

Faced with the uncertainties linked to environmental change, the monitoring networks are an essential source of data in order to anticipate changes in ecosystems. In France, three national networks are concerned with the change in the soil and/or forest in relation to the soil. Initially designed to monitor the effect of atmospheric pollution on the health of forests, the systematic network for the monitoring of forest damage (RSSDF) and the RENECOFOR network correspond to the two extensive and intensive components of pan-European forest monitoring (ICP Forests). Created more recently, the RMQS specifically monitors soil quality by extending the grid for forest monitoring to other land uses (crops, meadows, natural or urban environments). Pioneering and recent initiatives regarding the speed of change of soils and forests, these networks have nonetheless already generated a large number of original results and have shown their potential to meet expectations that are becoming increasingly diversified.