Fertility indicators in temperate forest soils: issues, approaches and prospects

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WHY DO WE ESTIMATE THE FERTILITY OF FOREST SOILS?

The fertility of a soil classically refers to an aptitude to produce plant biomass, under a given set of climatic and topographic conditions; it therefore contributes to an ecosystemic supply service (MEA, 2005). It is generally subdivided into three components – chemical, physical and biological – which are closely linked (Genot *et al.*, 2009). The chemical component describes the ability of the soil to supply the nutrients that are essential to the plant, in the appropriate forms, quantities and proportions; it is itself broken down into three components that target fertility in the short, medium and long term, respectively. It also considers the risks of toxicity linked to some elements, such as aluminium. The physical component takes into account the properties that influence the soil water regime (storage capacity and infiltration), as well as root prospection and biological activity (porosity, compactness, stoniness and aeration). Lastly, the biological component corresponds to the influence exerted by living organisms on the availability of mineral elements (through weathering, recycling or symbioses) and on the physical condition of the soil.

The fertility diagnosis encompasses highly diverse objectives associated with various spatio-temporal scales and users. Within the context of forest soils, fertility assessment aims at selecting objectives within the framework of a management plan (e.g. by giving priority to protection, conservation or production issues etc.), establishing sustainable forestry practices (rotation length/target diameter, release treatments, thinnings, regeneration cuttings), specifying harvesting scenarios (tree compartments, minimum upper-stem diameter, harvesting methods) or determining additional prevention/restoration measures (e.g. by liming). The diagnosis can also contribute to the selection of the target tree species, be used for the evaluation of site productivity, for the estimation of the change in fertility over time, for the determination of the sensitivity of the soil to disturbances of various kinds and for the evaluation of past management.

INDICATORS

In order to have a proper assessment of soil fertility and to adequately respond to the variety of objectives, it is useful to rely on indicators. In a general manner, indicators are substitutes that provide information in a simplified way on the functioning (Driving forces, Pressures, State, Impacts and/or Responses) of a complex system. While they can appear in a number of extremely diverse forms (Heink and Kowarik, 2010), all indicators should be:

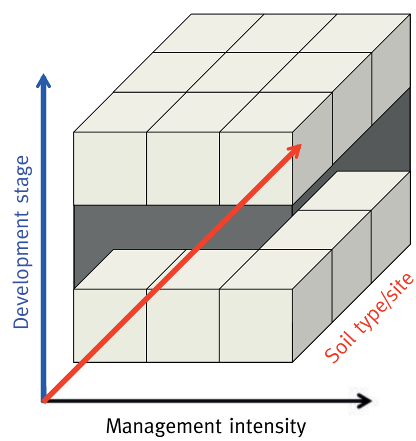
- robust;
- sensitive;
- repeatable;
- accurate, presenting among others a low background noise compared the signal sought for;
- efficient, *i.e.* it has a good ratio of purchase cost/information provided;
- able to be interpreted;
- stable over time, if the objective is to detect changes;
- based on reliable and easily accessible data sources;
- linked to a documented benchmark.

ASSESSING THE FERTILITY OF FOREST SOIL: THE SPECIFIC CHALLENGES

The characteristics of the trees, the specificities of the soils and the management methods play a major role in the way of assessing the fertility of forest soils and in the selection of the indicators to be implemented in order to estimate it (Burger and Kelting, 1999) (figure 1).

Figure 1 **IN A GIVEN CLIMATIC CONTEXT, THE FOREST SOIL FERTILITY INDICATORS DEPEND ON THE SOIL TYPE, THE INTENSITY OF THE MANAGEMENT AND THE STAND DEVELOPMENT STAGE**

(modified according to Burger and Kelting, 1999)



Specificities linked to trees

The longevity of trees, the way in which they manage mineral resources and their large size are all factors that make assessing the fertility of forest soils more complex.

Due to their long-lived habit, trees have a more or less pronounced footprint on the ecosystem, which makes it more difficult to isolate that part of the fertility that is intrinsic to soil. In the long and medium terms respectively, the reserve of nutrients in the system and the supply dynamics under the effects of element recycling and external flows (mainly atmospheric inputs and soil weathering) become major determining factors for fertility. Even though – considered on an annual scale – certain fluxes are low, their cumulated contribution over a rotation can prove to be substantial and can provide for a high rate of productivity for soils usually classified as being chemically poor. Lastly, during the course of stand development, the key processes involved in the nutrition of trees and the soil zones that are preferentially explored by the roots are likely to change, which can impact the selection of the most relevant indicators to be implemented according to stand age.

On the other hand, the management of nutrients by trees is in particular based on the recycling of elements within the plant ("internal" recycling or translocation), between the plant and the soil ("external" recycling), and on the presence of mycorrhizae for the uptake of soil resources. Under these conditions, it may be complex to differentiate that part of fertility linked to the species traits, more or less expressed depending on the site, and that which relates to the recycling of elements or to the specific characteristics of the site; in other words, it can prove delicate to get "absolute" indicators of fertility, based on soil properties only.

Lastly, the large size of the trees and the resulting substantial exploration of the aerial and soil space leads to key questions such as: where should we measure? (Which compartments or which plant tissues? Which soil horizons?) ; do we need to integrate spatially or to target the measurements on key compartments and/or zones? ; how can we take into account the potential influence of deep layers, bearing in mind that this contribution can – for a given site – change not only as a function of stand age but also within a year?

Specificities linked to forest soils

One of the difficulties when characterising forest soils is their strong spatial heterogeneity, which is higher than that observed in agricultural soils. This higher lateral and vertical variability can be explained by the impact trees have on the soil, in particular through organic matter inputs, and by the low anthropisation of most forest soils. This heterogeneity makes it even more difficult to determine the fertility of forest soils and to follow their evolution.

Whilst – with the exception of podzolic and hydromorphic soils – which are more frequent under forest cover, the frequency of the various types of soil does not differ much between forest and agricultural land use, large differences have been noted for certain physico-chemical characteristics: globally, forest soils are characterised by a more pronounced acidity (lower pH), as well as by higher carbon content and C/N ratio values (Badeau *et al.*, 1999). Lastly, the difference in nutrient status between forest and agricultural soil can be explained by the selection of better soils for agriculture as well as by the practices that historically have tended to impoverish forest soils and to enrich agricultural soils (Koerner *et al.*, 1999).

Specificities linked to management

Although forest management covers a wide range of intensities, the degree of artificialisation is on average much lower under forests than under a system of annual crops or under meadows. For diverse reasons, the practices aimed at alleviating the inherent soil/site constraints such as hydromorphy, excess acidity and compactness are relatively unfrequent in forestry; similarly, the external factors that are likely to influence fertility, such as atmospheric inputs, are not controlled. As a result, intrinsic fertility proves to be a major factor in the assessment of fertility and in the selection of management objectives.

On the contrary, the development of mechanisation and the increased wood harvesting intensity for bio-energy may in some cases lead to swift and negative consequences for the chemical, physical and biological components of soil fertility. The possible impacts of these practices are particularly serious as natural restoration depends on biological activity which is lower in acid soils, and because remediation methods (e.g. fertilisation, liming, application of wood ash, decompaction, etc.)

are costly, often insufficient and sometimes cause adverse effects. In this respect, it is important for the indicators that are implemented to be able to evaluate the sensitivity of the soil to these practices and to quantify the evolutions under their effect.

WHAT APPROACHES SHOULD BE IMPLEMENTED?

In short, three types of approaches can be implemented, independently or in combination, in order to estimate the fertility of forest soils: an analytical approach, an approach based on the response of communities of organisms other than arborescent woody plants, and an approach based on the response of stands (table I); the last two involve bio-indication, since they rely on organisms for the diagnosis. These three approaches result in indicators that proved efficient for assessing the fertility of forest soils; at the same time, they may serve as a framework for the elaboration of new indicators (section "Prospects").

Table I **A simplified typology for the approaches currently implemented to estimate the fertility of forest soils. In practice, these approaches are organised according to a *continuum***

Approch	Principle
Analytical	Estimation of the (maximum) size of a reservoir of available resources (water, nutrients), and of its supply dynamics
Response of communities of organisms other than woody arborescents	Examination of the response of communities in terms: – of presence/absence, abundance – activity, measured according to a range of criteria/markers (e.g. morphology, chemistry, etc.)
Response of stands	Examination of stand response in terms of: – productivity – mineral nutrition (foliar concentrations)

Analytical approach

A first approach, referred to as analytical, consists in estimating the availability of resources (water, nutrients) considering (i) the size of the reservoirs, (ii) their supply dynamics and (iii) the plant's ability to mobilise these resources under the prevailing environmental conditions; it is mainly based on the physical and chemical properties of the soil, as well as on topographic and climatic descriptors.

• *Size of the reservoir*

The size of the reservoir and its level of filling correspond to the quantity of resources available in the functional rooting zone. As the quantity of available water greatly varies over the course of the year, the size of the "water" reservoir is normally evaluated taking into consideration its maximum filling level or Maximum Extractable Water Reserve (Jabiol *et al*., 2009a).

The estimation of the size of the reservoir most often involves two stages.

In a first stage, there is a need to define the zone that is prospected by the roots and to assess the root activity therein. This phase calls for an analysis of the potential constraints to the prospection and functioning of the root system, whether they be physical (porosity, compactness/induration, stoniness/cracking, aeration) or chemical (deficiencies, toxicities, antagonisms). For each component, the diagnosis mobilises a range of indicators that have largely been developed in reference works (e.g. Jabiol *et al*., 2009a; Baize and Jabiol, 2011). This may involve a number of different descriptors of the soil "profile" analysed in the field, through observations (e.g. morphology of the profile; forms of humus; traces of hydromorphy; nature, importance, depth of appearance and arrangement of coarse elements; etc.) or simple tests (e.g. use of a penetrometer to estimate compactness; use of an HCl test to detect the presence of carbonates in fine earth; etc.). These observations and tests may be supplemented by analyses of the physical and chemical properties of selected soil horizons in the laboratory (Gégout and Jabiol, 2001).

The estimation of the rooting zone using this approach includes a certain number of drawbacks. Among the most important, we should mention the differential sensitivity of species to certain constraints (Lebourgeois and Jabiol, 2002), the risk of confusion between current processes and fossil ones in the case of "morphological" indicators (Baize and Jabiol, 2011) and the difficulty in assessing the contribution of deep rooting to the acquisition of resources – which is nonetheless essential for the supply of water in summer for several species (Bréda *et al.*, 2002). Under these conditions, the direct observation of the root systems on deep pits is of the greatest interest (Jabiol *et al.*, 2009a).

In a second stage, it is a matter of evaluating the fraction of the total resources in the prospected zone that is present in a form that is "available" for uptake by trees.

It is commonly assumed that soil water is available for plants between the field capacity and the permanent wilting point (pF 4.2); the possibility is not however excluded that the trees would have access to the water retained at a higher tension (Bréda *et al.*, 1995). In practice, that fraction of water actually used by plants also depends on their drought tolerance strategy: we in particular distinguish between species with an isohydric behaviour (stomatal closure is early and the water actually available is at a lower level than the potential reservoir) and species with anisohydric behaviour (stomatal closure is late and the size of the reservoir can reach and even exceed the potential). These behaviours have major consequences for the assimilation of carbon by plants and for the risk of cavitation (Van der Molen *et al.*, 2011).

For the mineral elements, the stock of available elements represents the current fertility of the soil, by contrast to total reserves of mineral elements in their various forms, which determine the long-term fertility. The assessment of availability is nutrient dependent (Bonneau, 1995). For cations (K, Ca, Mg), more or less selective extraction methods lead to a pool referred to as "exchangeable". The estimation of bioavailable phosphorous is more complex, as this element is found in highly diverse forms, whose relative importance varies from one soil to the other; it is therefore necessary, in this case, to adapt the extraction method to the type of soil (Baize, 2000). Lastly, nitrogen availability cannot be properly estimated using this "reservoir" approach, as the stock present in available form is both proportionally very small and extremely transient; for this reason, it is evaluated by a mineralisation flux (net production of mineral nitrogen in the form $N\text{-}NH_4^+$ and $N\text{-}NO_3^-$) or by a nitrification flux (net production of $N\text{-}NO_3^-$) using incubations under controlled conditions.

The estimation of the size of the reservoir requires the measurement of dry bulk density, i.e. soil mass (fine earth < 2 mm) per unit of volume. Whereas this parameter has long been considered as the physical soil property that is the easiest to measure, special care has to be taken (Lee *et al.*, 2009; Goutal *et al.*, 2012), in particular in order to take into account the water status of the soil at the time of sampling. The deep cracks of some bedrocks and the presence of coarse components also serve to make the problem more complex. The latter are not always inert (water and/or nutrients reservoirs that can be used by the roots). This complexity often leads to a simplification of the approach. For mineral nutrition, it is thus a common practice to base oneself on concentrations (and not stocks) in exchangeable elements of the soil horizon (or of the soil layer) considered as representative of the overall functioning (e.g. Lambert *et al.*, 1990).

- *Supply dynamics*

The supply of the reservoir calls for an estimation of the system inputs and outputs (water, mineral elements), as well as of internal recycling (mineral elements).

ANALYTICAL APPROACH (INITIATIVE) APPLIED TO THE ESTIMATION OF THE HYDRIC LEVEL OF A STATION (RESORT)

Figure 2a **THE MAXIMUM EXTRACTABLE WATER RESERVE (MAXIM. EWR) IS ESTIMATED BY CONSIDERING THE DEPTH PROSPECTED BY THE ROOTS AND THE MAXIMUM QUANTITY OF WATER AVAILABLE IN THE ROOTED HORIZONS.**

This may be calculated if we know the bulk density of the fine earth (bulk dens.), the volume percentage of coarse components and the texture of the soil for the various horizons concerned. The volume of this reservoir fluctuates over time under the effect of inputs (fraction of atmospheric precipitation reaching the soil surface, run-off, capillary rise) and outputs (evaporation at the soil surface, plant transpiration, run-off, deep drainage). On a pluri-annual scale, these effects may be estimated by climatic and topographic indicators. Figure 2b shows an example of qualitative topographic indicators.

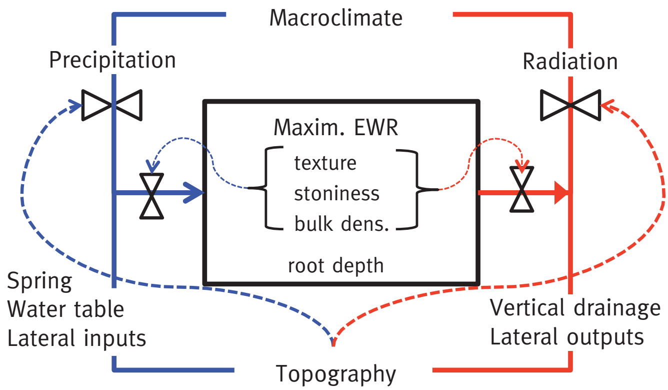
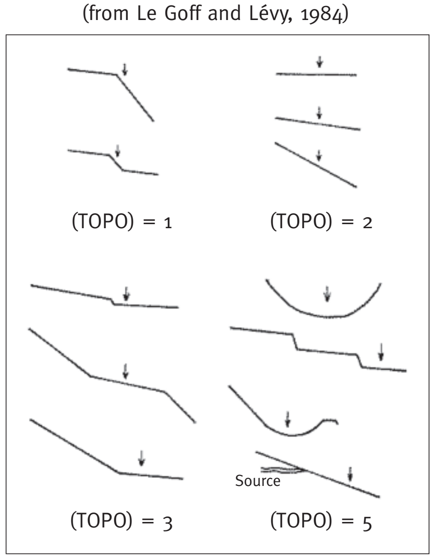


Figure 2b **TOPOGRAPHIC (TOPO) INDICATOR CHARACTERISING THE BALANCE BETWEEN INPUTS AND OUTPUTS OF WATER FOR LATERAL FLUXES**

(from Le Goff and Lévy, 1984)



In the case of water supply, the "average" dynamics of the reservoir associated to the inputs and outputs may be approached by combining topographic and climatic factors with the help of simple qualitative indicators (*e.g.* Le Goff and Lévy, 1984) or more complex and spatialised indicators (e.g. Lebourgeois and Piedallu, 2005; Richard *et al.*, 2013). On a finer time scale, follow-up of the intra-annual dynamics is founded on the parameterisation of water balance models (Granier *et al.*, 1995).

For the supply of mineral elements, the supply dynamics represents the medium-term fertility. The main external fluxes to be considered are atmospheric inputs and soil weathering. The first can be evaluated with the help of atmospheric deposition models (Croisé *et al.*, 2005). In spite of its potential importance for fertility, the estimation of element inputs from weathering remains extremely complex and is associated with a high degree of uncertainty (Turpault *et al.*, 1999). It can be based as a first approach on simple indicators such as the nature of the rocks, the nature of the parent material or substrate, the lithology, and the texture and/or mineralogy (Jabiol *et al.*, 2009a). In general, the weathering flux is related to the cationic composition of the exchange complex; it is always very low in poor soils. Recycling of mineral elements represents another supply component to be taken into account for the nutrient supply of trees. In general, the physico-chemical parameters, used in a purely analytical approach, have proven to be quite poorly performing for the estimation of these fluxes; they are then associated with – or even replaced by – bioindicators such as those considered in the following section. In addition, the most appropriate indicator may vary depending on the element. In this way, the recycling of calcium seems to be tightly related to the form of humus (Jabiol *et al.*, 2009a). For this element, species also play an essential role: for example, average annual recycling by above-ground litterfall on the experimental site of Breuil-Chenue (Morvan), varies between 6 and 22 kg ha^{-1} for the groups fir-pine and Douglas-oak, respectively; the group beech-spruce has intermediate values of 12 kg ha^{-1} (Moukoumi, 2006). For nitrogen, the form of humus and the C/N ratio of the hemi-organic horizon, in combination with other variables such as pH, have proven to be relevant indicators in some situations (Seynave *et al.*, 2004). Another possibility consists in measuring specific nitrogen pools, that are more directly linked to mineralisation (Ros *et al.*, 2009). An analysis of vegetation has proven quite effective in estimating soil nitrification (figure 3, p. 112) but was unable to predict nitrogen mineralisation (Andrianarisoa *et al.*, 2009). For nitrogen, the species also play a major role in mineralisation fluxes by modulating the forms of mineral nitrogen produced (Zeller *et al.*, 2007).

Response of the communities of organisms other than that of arborescent woody plants

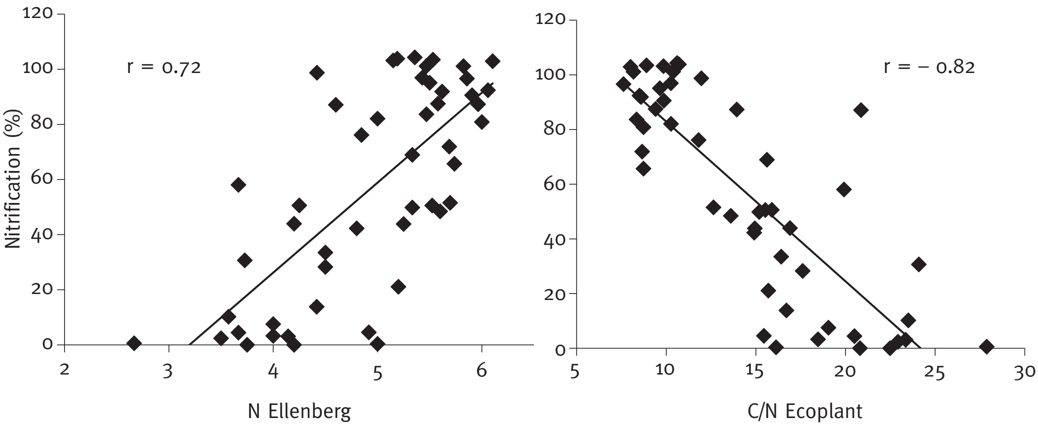
A second approach rests on the quantification of the response of communities made up of organisms other than that of woody arborescents, in terms of presence/absence, abundance and/or activity. The latter can be traced from morphological and/or physico-chemical descriptors.

- *Vegetation*

Plants have long been used as bio-indicators of environmental conditions (Cajander, 1926; Duchaufour, 1948). One of the oldest approaches is based on the use of ecological or socio-ecological groups, i.e. groups of species with comparable affinities for certain environmental conditions, with the aim to estimating the position of sites along gradients of water and nutrients (ecograms). In this framework, the assessment of fertility is carried out by assigning each species from a site to an ecological group, and then by weighting the various groups as a function of the number of species that they contain in order to determine a level of acidity or soil water content (Rameau *et al.*, 1989). To refine the diagnosis, the size of the various groups present in a vegetation *relevé* is sometimes weighted by their relative coverage and the relevance of their indicator character. The implementation of vegetation databases containing several thousand plots with both vegetation inventories and soil laboratory analyses now makes it possible to formally calculate indicator values for a large number of ecological variables. The EcoPlant database has thus made it possible to

Figure 3 RELATIONSHIP BETWEEN THE AVAILABILITY OF NITROGEN BIO-INDICATED BY THE VEGETATION, AND THE POTENTIAL NITRIFICATION VALUES (NET NITROGEN PRODUCTION IN THE FORM OF NITRATES, AS A PERCENTAGE OF NET TOTAL PRODUCTION OF MINERAL NITROGEN) MEASURED IN 49 BEECH SITES IN NORTH-EAST FRANCE (ANDRIANARISOA *et al.*, 2009).

On the left, nitrogen availability is bio-indicated according to Ellenberg's value system, on the right according to that of Ecoplant. The correlations between the bio-indicated values and the potential mineralisation (total production of mineral nitrogen) measured on the same sites are null (data not shown).



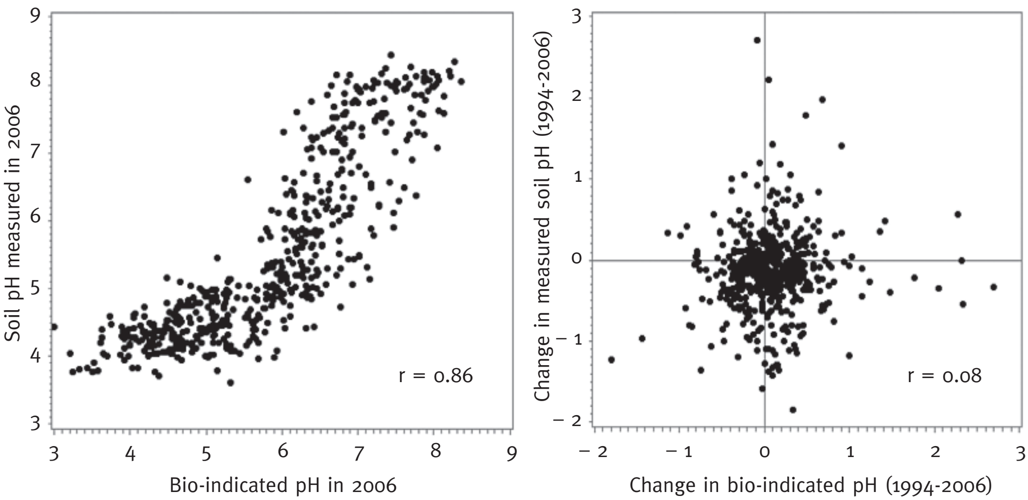
calculate indicator values for over 500 species that are commonplace in France for the soil pH, the C/N ratio and the base saturation (Gégout, 2006). As a result, it becomes possible to predict for a site the value of these variables by calculating the mean of the indicator values for all species present on this site (Ellenberg *et al.*, 1992). The EcoPlant indicator values used in conjunction with the tens of thousands of spatialised vegetation *relevés*, carried out by the National Forest Inventory, have been used to map out certain soil parameters such as the surface pH of forest soil on a national, regional or intra-regional scale (Gégout *et al.*, 2008). As shown by the comparison between prediction models of the site index, the ability of vegetation to estimate stand fertility compares quite well to that of purely physical factors (Bergès *et al.*, 2006). In practice, the flora can be used alone or in combination with other types of indicator to estimate the fertility of forest soils; it has a special interest when it makes it possible to use it instead of methods that are much more cumbersome to implement and/or much more expensive. Its use to predict soil fertility calls for certain precautions in order to minimise the disturbing influence of factors such as light intensity, silviculture, dominant species and stand dynamics. From the point of view of monitoring of fertility over time, the vegetation has largely been used to emphasise the effect of atmospheric nitrogen deposition and to a lesser extent that of acid deposition on soil (Thimonier *et al.*, 1994; Riofrio *et al.*, 2012). The large number of sites with ground vegetation inventories as well as the availability of long-term (> 50 years) records of vegetation data constitute a main advantage of this approach. It does however seem relevant to further test to what extent the changes in the values bio-indicated by the vegetation match the evolutions resulting from direct measurements of the targeted physico-chemical parameters. With regard to pH, the rare results obtained so far are proving disappointing (Rabastens, 2009; figure 4, p. 113).

• *Forms of humus*

Just as is the case for vegetation, forms of humus (Jabiol *et al.*, 2007a; Jabiol *et al.*, 2009b) integrate a whole of environment factors. They can therefore be used – within certain limits – to estimate the

FIGURE 4 **USE OF THE VEGETATION TO QUANTIFY THE CHANGES OF FERTILITY OF THE FOREST GROUNDS**

On the left: relationship between the measured *vs* vegetation bio-indicated pH of the top soil in 2006 within the BioSoil network (545 sites).
On the right: relationship between the changes in measured *vs* bio-indicated pH between 1994 and 2006 on the same sites (Rabastens, 2009).



fertility of forest soils. Whilst their integrating character can represent an advantage by synthesising groups of parameters, interpretation in terms of processes can prove highly complex and has frequently been the subject of over-generalisations (Nicolas *et al*., 2006). These are mostly linked to the fact that the nature and relative importance of the factors involved in humus build-up can differ depending on the spatial and time scale considered. In this way, at the country scale, the form of humus essentially reflects the site factors (Jabiol *et al*., 2007b; Ponge *et al*., 2011); at the plot or group of trees level, the effect of stand or of sylvofacies and their time dynamics may be primordial, and shift the biological functioning towards a moder or a mull (Bernier and Ponge, 1994; Aubert *et al*. 2005). Moreover, the relationship between the form of humus and nutrient availability may be misleading; in this way, Paré and Bernier (1989) have shown that the availability of phosphorous in sugar maple – estimated by foliar concentration – was higher in stands developed on mor than on mull.

• *Soil organisms*

More recently, the interest in using soil organisms as soil quality bioindicators has been investigated, in particular through the research programme entitled “Soil quality bioindicators” funded by ADEME (French Environment and Energy Management Agency) between 2004 and 2012 (Bispo *et al*., 2009). One major issue is to bio-indicate the key functions or processes of soil fertility that are poorly taken into account or even entirely overlooked by other indicators. This calls for parameters that measure the abundance, the diversity of communities or certain activities. As an example, we can mention key organisms associated with the recycling of organic matter and the supply of nutrients for plants, organisms affecting aeration and/or the physical properties of the soil, enzymatic activities or genes that reflect the capacity to degrade organic matter or that are involved in the nitrogen cycle (Uroz *et al*., 2014 – this volume –). Although this programme was not initially designed to specifically deal with forest soils, table II (p. 114) presents, by way of comparison with the other sites investigated, whether agricultural or contaminated, the most promising indicators for forest soils. As the measurements become easier to deal with – largely due to the development of molecular approaches – the biological characterisations of the soil are in full expansion and it should soon be possible to establish the first benchmarks, as well as to link the composition and activity of communities to the functioning of forest soils, in particular by using functional traits (Pey *et al.*, 2014).

Table II **Candidate biological indicators for the monitoring of forest soil fertility (ADEME programme "soil quality bioindicators")**

Family	Parameters	Functions
Micro-organisms	– Bacterial and fungal biomass – Diversity of communities(1) – Enzymatic activities(2)	Cycles of elements and in particular carbon
Fauna	– Functional diversity of nematodes	Regulation of bacterial and fungal populations
	– Diversity of collembola and mites(1) – Biological Soil Quality Index (based on total macrofauna)	Regulation of bacterial and fungal populations Fragmentation and degradation of organic matter

(1) For this group of indicators, only the taxonomic diversities have been analysed within the framework of the programme; the possibility of using traits and functional groups is currently under investigation.

(2) Among the enzymatic activities tested, those related to the carbon cycle (cellulase, laccases, β-glucosidase, xylanase), nitrogen cycle (urease), phosphorous cycle (acid and alkaline phosphatases) and sulphur cycle (arylsulfatase) have been highly discriminatory, as have been the more global activities (e.g. carbon mineralisation, hydrolysis of fluorescein diacetate, dehydrogenase).

Response of stands

The third approach quantifies fertility by analysing the response of the stands themselves, in terms of foliar nutrient concentrations, or of productivity.

The diagnosis based on foliar analysis relies on the hypothesis according to which foliar nutrient concentrations – as well as some ratios between elements – is the reflection of the nutritional status of the tree. The principle of "point" assessment is relatively simple as it consists in confronting the measured concentrations to threshold values established from controlled experiments (Bonneau, 1995). Foliar analysis can also be used as a long-term nutrition monitoring tool; this has made it possible to point out a general trend towards decreasing phosphorus availability (Duquesnay *et al.*, 2000; Jonard *et al.*, 2009). Even though the recommended sampling is aimed at limiting the confounding sources of variability – in particular by targeting the period of sampling and the part of the tree – the interpretation of the results need to consider the possible impact of residual variation sources such as those linked to the climate or fructifications.

The site index, i.e. the dominant height achieved by a monospecific even-aged stand at a given reference age, is undoubtedly the most familiar indicator to foresters. The statistical relations between this index and a range of different environmental variables are frequently used in order to better understand the site-specific parameters that determine the productivity of stands for the species and study zone under consideration (e.g. Seynave *et al.*, 2004; Bergès *et al.*, 2005). This procedure in particular supposes that fertility does not change over time, i.e. that it depends neither on the date of stand establishment (no "external" influence, linked for example to climate change), nor on stand age, or that these effects may be taken into account by adequate procedures (e.g. Bontemps *et al.*, 2007 for the consideration of the "date" effect). In addition, use of the method implies the presence of a stand, which must moreover meet specific features in terms of structure – evenaged – and species composition – pure – which limits its scope.

PROSPECTS

In spite of the substantial progress that has been made in the assessment of forest soil fertility over the past ten years, several paths for improvement can be identified.

A first issue concerns the evaluation of the match between "species" and "site". Tailoring the soil fertility indicators to one given species (or group of species) or to some climate context needs to look for an appropriate aggregation level, which makes it possible to individualise the main components involved (typically: climate, soil water budget, nutrient availability). At the same time, it must be ensured that the following takes place: (i) ranking of factors by importance (for a given species and genotype, productivity at regional and supra-regional level is determined firstly by climatic factors, which in turn may affect water supply, the decomposition of organic matter and consequently also mineral nutrition, the length of the vegetation period etc.); (ii) minimising redundancies (redundancy can be said to occur when the factors considered in an indicator partly express the same information); and (iii) consideration of the possible interactions (we speak of interaction if the effect of a factor depends on one or more other factors).

A second area of progress concerns the assessment of mineral fertility in soils with low chemical fertility, where the contribution of element fluxes – in particular those linked to recycling – is essential (Legout *et al.*, 2014 – this volume –). One possible path could consist in combining physico-chemical indicators and bioindicators, whilst taking care to ensure their mutual independence.

Lastly, a third prospective approach concerns the development of indicators that are sensitive enough to be able to measure modifications in the fertility of forest soils or to anticipate the possible evolution under the effect of forestry practices or global changes. Given the spatial heterogeneity that is often very high in forest soils, the challenge not only consists in identifying the appropriate parameters, but also in optimising the sampling strategy in such a way as to ensure their representativeness.

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FERTILITY INDICATORS IN TEMPERATE FOREST SOILS: ISSUES, APPROACHES AND PROSPECTS (Abstract)

The specifics of forest ecosystems require a strategy of soil fertility assessment distinct from that commonly used in agro-ecosystems. Existing indicators fall into three main approaches. The first is to estimate the availability of resources (water, minerals) considering the size of the pools and the dynamics of supply. A second is based on the quantification of the response of communities of organisms other than arboreal plants in terms of presence/absence, abundance and/or activity. The third assesses fertility by analyzing the response of the forest stand/tree itself, in terms of productivity or foliar nutrient contents. For each approach, a series of indicators are presented, stating: their principles and indications, how to acquire them, their interests and limits, their links with other indicators and few prospects for improvement.