



**HAL**  
open science

## Compensating for the export of nutrients and restoration of degraded soils

Arnaud A. Legout, Claudine Richter, Noémie Pousse, Gregory van Der Heijden, Jean-Louis Morel, François Charnet, Marie-Odile Simonnot, Jacques J. Ranger

► **To cite this version:**

Arnaud A. Legout, Claudine Richter, Noémie Pousse, Gregory van Der Heijden, Jean-Louis Morel, et al.. Compensating for the export of nutrients and restoration of degraded soils. 2014, pp.547-557. 10.4267/2042/56273 . hal-02800538

**HAL Id: hal-02800538**

**<https://hal.inrae.fr/hal-02800538v1>**

Submitted on 24 Nov 2021

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# COMPENSATING FOR THE EXPORT OF NUTRIENTS AND RESTORATION OF DEGRADED SOILS

## Report of the workshop 3

---

**ARNAUD LEGOUT – CLAUDINE RICHTER – NOÉMIE POUSSE – GREGORY VAN DER HEIJDEN – JEAN-LOUIS MOREL – FRANÇOIS CHARNET – MARIE-ODILE SIMONNOT – JACQUES RANGER**

---

*This paper is the English translation of: « Compensation des exportations minérales et remédiations aux dégradations des sols. Compte rendu de l'atelier 3 » – Revue forestière française, 4-2014. <http://documents.irevues.inist.fr/handle/2042/4752>.*

### CONTEXT

This workshop presented the current state of knowledge and discussed ecological engineering practices for soil rehabilitation and ways of preserving the services provided by soils, including the production of wood. The workshop considered three main subjects:

- Compaction of forest soils: prevention techniques and possible restoration methods.
- The increased export of forest biomass and compensation by liming.
- Recycling waste (sludge) and use of industrial wasteland.

To form a basis for discussion, each subject was introduced by a presentation of the problems and the solutions tested for restoring, preserving or even improving soil properties and functions. The effectiveness of these solutions was also described (solutions that had been found to be unsatisfactory, that had been found to work, that were being evaluated and those that required further research), as well as their cost and level of maturity, the evaluation of their impacts in the short, mid and long term and their indirect benefits.

This article summarizes the presentations and discussion that followed the presentations.

### COMPACTION OF FOREST SOILS, POSSIBLE PREVENTION AND RESTORATION TECHNIQUES

The increasing mechanization of forestry operations and the use of heavier machines with greater payload increase the mechanical stresses on forest soils.

## Feedback on the practices involved and risk factors

If the load exceeds the bearing capacity of the soil, it causes the restructuring of the soil matrix, in particular reducing porosity (ratio of pore volume to total volume of the soil), increasing soil bulk density and the soil bearing capacity up to the point where there is a balance between the stress and the deformation. Soils are, therefore, degraded to a greater extent when machines pass over them for the first time (thereafter, the soil becomes increasingly compacted and resistant to pressure). This is a valid reason for restricting the movement of machines to permanent tracks.

Soil structure changes caused by forest machines can limit the root development of trees (greater resistance to root penetration, creation of barriers which inhibit roots from spreading horizontally through the soil, reduction of water and air mobility), reducing the productivity and/or increasing the sensitivity of forest stands to various natural stressors (drought, wind, attacks by insects and disease). The reduction in water infiltration and drainage when the soil structure has been compacted can also lead, in heavy rainfall conditions, to an increased risk of erosion on slopes or increased risk of saturation in flat areas. Soil compaction can also affect biodiversity and the water and air purification functions performed by forest ecosystems.

Reference was made to the progressive increase in the size and weight of forestry machines which could compact the soil to a greater depth, making it very difficult, if not impossible, to restore. This would lead to the formation of a hardpan, well known in agriculture, the consequences of which would be far more damaging to forests where the size and longevity of trees are of a different order of magnitude. Action must, therefore, be taken as far upstream as possible to prevent damage, in particular by setting up a network of appropriate forestry tracks and carrying out practicability studies. New tracked vehicles (prototypes of German and Scandinavian machines), which reduce the pressure on the soil, are now being tested in state-owned forests (Augris, 2012). The return of smaller machines with wide tires to reduce the ground pressure was also mentioned, in particular in forest ecosystems that were highly sensitive to compaction.

To prevent damage to soil from traffic, forest managers can assess the sensitivity of the soils and stop certain machines from driving on excessively sensitive soils (permanently saturated, peat bog, etc) and/or when the soil humidity is too high (reduction in load bearing capacity) and/or if the pressure exerted by the machine is greater than the load bearing capacity of the ground. The PROSOL guide (Pischedda, 2009) sets out general recommendations, depending on the type of soil and its humidity, to ensure that traffic do not damage the physical quality of the soil. Decision-making software such as ProFor© (Munich University) has also been developed but the required data is not always easy to obtain for foresters in the field, such as the humidity of the soil at the time the machine was being used (Matthies *et al.*, 2006; Bénard, 2009).

Despite the best efforts of forest managers, it is sometimes difficult to prevent damage. The question then arises of restoring the physical quality of the soil to prevent malfunctioning of the ecosystem. There are various restoration techniques which are often based on agricultural practices. These can only be used in particular conditions (degree of soil humidity, etc.), their effectiveness varies and their cost that may be exorbitant for forest owners.

## Restoration of compacted soil

- *Natural restoration of soils*

Little research has been undertaken to understand the mechanisms and time required for the natural restoration of compacted soil because it requires a multidisciplinary approach to deal with

the broad range of soil properties, carried out on sites with well-determined initial conditions (soil, pressure applied, initial compaction) where the soil can be monitored in the mid or long term (Goutal, 2012).

Soil porosity is complex and often results from a number of different processes (biological, in particular root and soil fauna activity, and physical, in particular wetting/drying and freezing/thawing cycles) which take place on different temporal and spatial scales. Porosity is essential for all soil functions: plant production, purification of water and air, preservation of biodiversity. Consequently, when the soil structure is damaged by the passage of heavy machinery, it is important that all the processes which created the soil structure can combine to restore it. However, root and soil fauna activities are seriously damaged by compaction and can take several decades to return to their initial state and may still not succeed in recolonizing the densest parts of the soil (Capowiez *et al.*, 2009). The effectiveness of physical phenomena in restoring the soil structure may be reduced by changes in water and heat transfer in the compacted soils. For example, in acid forest soils where the activity of soil burrowers (in particular anecic worms) is reduced, the soil structure has been shown to be restored by physical phenomena alone (wetting/drying, freezing/thawing) 4 to 5 years after compaction, but water and air transfer, plant growth and biological activity do not return to the initial conditions (Bottinelli *et al.*, 2014). The soil structure is restored by natural processes quicker and more effectively at the soil surface than at depth where the temperature and humidity variations and insect activity are more limited.

The time required for soil to return to the functioning of an undisturbed soil after compaction varies from a few years to several decades, depending on the soil type, the climate and the initial compaction as well as on the parameters used for the studies. Experiments are underway to study rehabilitation assisted by physical, chemical and even biological solutions. An overview of the current state of knowledge is given below.

- *Physical soil restoration*

Physical restoration consists in using different soil working techniques and gives mediocre results despite the high costs. This is explained by the specific characteristics of forest soils (presence of stumps and residues, soils with a lot of persistent roots and rocks, often very acidic and/or hydromorphic, etc.).

Mechanical processes using a disk harrow or plow are too superficial to restore the physical quality of compacted forest soils. These methods do not decompact or completely drain the whole of the depth affected by heavy machinery and the problems related to deep compaction remain (poor root development, poor drainage, etc.).

A better option is deep subsoiling as this usually decompacts the whole of the compacted layer of soil. However, this is not appropriate in all cases. Digging localized holes for planting (decompaction for each plant), in soils with poor drainage (for example, flat land with no or very few large particles) will create a plant pot effect which will not benefit the stand. The planting holes must be interconnected by deep subsoiling to evacuate the water down the slope minimizing the disruption to the soil. In general, mechanical remediation of forest soils should avoid unnecessary disturbances which are often detrimental to soil functions, including its carbon fixing capacity.

Before deciding what measures should be taken, a survey should be undertaken to determine the major constraints, select appropriate tools and decide when to take action (humidity of the soil at the time of the work, etc.). The Alter (MGVF, 2012) and Pilote (MGVF, 2013) projects, targeted at plantations, were set up to evaluate and develop a range of mechanized solutions for soil preparation and weed control as an alternative to using herbicides.

Tracks also sometimes need to be repaired to make it easier to use them at a later stage. Leveling using scrapers is a standard practice if work has caused deep ruts. However, this is more a question of filling in ruts to improve the appearance of the tracks rather than of restoring the soil. The drainage capacity of tracks is still poor and vehicles are often unable to use them as the soil is too wet and will remain so for a large part of the year compared with parts of the forest that are not compacted.

- *Chemical restoration of soils*

Chemical restoration consists in applying amendments to the soil surface to improve certain properties or stimulate biological activities that will speed up restoration (applying flocculating cations, improving macrofauna and root development activity, etc). Results show that using dolomitic lime to stimulate restoration is only a short term measure (4-5 years) but has a significant effect on certain indicators such as growth (on-going INRA project). Longer term measurements are essential to understand the soil restructuring mechanisms using this technique, which requires medium and long term study.

- *Biological restoration by the trees*

Studies in Switzerland on deeply rutted skid trails in plots devastated by the 1999 storm showed that alder (*Alnus glutinosa*) could be used to restore the physical quality of compacted soils. The alders succeeded in rooting and growing in ruts and, 6-7 years after planting, there was a clear improvement in the physical properties (porosity, permeability to air) of the soils down to a depth of 30 cm. Furthermore, establishing a mat of vegetation, using plants that could colonize the trails rapidly, would increase the soil load bearing capacity and may provide a harvestable biomass between rotations.

### **Forest tracks: advantages and limitations**

One of the aims of tracks is to limit the compaction of soils within stands by restricting traffic to the tracks. The use of tracks has become standard practice, particularly in state-owned forests. Reservations about this practice were raised in the workshop, in particular because the use of tracks reduces the productive area and gives an impression of domesticated nature which degrades the social/recreational function of forests.

Although recommendations for setting up tracks have been formulated, there are still many questions about the practicability of tracks (When is it necessary to avoid driving on them? Is it up to the forest manager or the forest company to take the decision?). This question is of vital importance as the degradation of the tracks may lead to traffic moving off track, which is worse, and may eventually lead to the creation of new tracks, decreasing the productive area. Another concern raised concerned the possible impacts at the edge of the tracks, because, if compaction was limited to the track, the soil to the side might become hydromorphic. Research should be carried out in the future to improve our knowledge on this subject.

Solutions to limit degradation of tracks were discussed at the workshop, such as the improvement of the road network to reduce hauling/skid distances. However, this reduces the productive areas in forests and the costs of setting up such a network must also be included. Other solutions proposed were removing whole trees from the stands to limit successive passages by machinery or putting harvesting residues on the tracks to increase their load bearing capacity. Removing whole trees implies exporting all the harvest residues and this may degrade the level of mineralized nutrients in the soil (Cacot *et al.*, 2006; Landmann *et al.* this volume) in a large number of ecosystems. Putting harvesting residues on the tracks is currently widely used for mechanized conifer felling. This

technique limits the degradation of the track but concentrates the nutrients contained in the small branches and foliage on an unproductive area of the forest.

Natural restoration is a slow process, assisted restoration is expensive (cf. preceding paragraphs), and in both cases, it is probable that not all the initial soil functions will be restored. The problem can, however, be tackled from another angle, looking at the causes of degradation rather than the consequences. It is interesting to compare the cost of restoration with the cost of forestry management that limits soil compaction (cable logging, for example). This type of management is more expensive but, if it avoids costly restoration that would be required with traditional methods, then prevention is preferable to cure.

When the soil has been degraded, the rules governing the allocation of the restoration costs are often not defined. Must the forestry company pay for the whole of the costs? Measures must be taken to clarify this issue and reach effective solutions. It will be much easier to achieve this by discussion rather than by accusing one party or another.

Given the mediocre results of natural and assisted restoration described above, emphasis should more than ever be placed on prevention.

## **INCREASED EXPORT OF BIOMASS AND COMPENSATION USING MINERAL AMENDMENTS**

Many questions related to the increasing demand for fuel wood were discussed in the workshop. In the fairly long term, in soils with a low level of mineralized nutrients, the export of biomass without compensation will lead to a reduction of soil chemical fertility and ecosystem functions (production, biodiversity, water quality). Forest managers must now find the right balance between the amount of biomass harvested and maintaining fertility. Decision-making tools are available such as the ADEME guide *Rational harvesting of forest residues* (Cacot *et al.*, 2006), that is currently being revised. This guide sets out the possibilities and conditions for increasing the exploitation of biomass depending on the soil fertility, with the aim of maintaining fertility.

When the chemical fertility in the ecosystem is significantly degraded, an amendment can be used to restore and generally improve functioning and ecosystem functions. This curative measure can also be applied as a preventive measure to maintain a given level of fertility. Given the increasing requirement for fuel wood, the question of rational application of amendments and fertilization will arise more and more frequently, but it is not limited to the production of fuel wood.

The increased use of fuel wood leads to the increased production of ash, combustion residues the chemical characteristics of which are those of an alkaline mineral amendment. The application of ash (as a neutralizer, fertilizer and amendment) in forests could compensate to some extent for the losses (in particular phosphorus and potassium) resulting from intense biomass exploitation, counteract the acidification of the soil and stimulate biological activity. At the moment, French regulations do not allow ash applications in forests but it would be worth assessing its usefulness (practices abroad, social acceptability, fate and impact of ash on the ecosystem, etc.) and determining when and how ash could be used in French forests (Deleuze *et al.*, 2012). There was not enough time during these workshops to discuss the application of ash in forests.

### **Are the effects of amendment beneficial and sustainable?**

Current practice consists in applying lime/dolomite/magnesite in various forms to the surface of the soil, together with phosphorus and/or potassium if necessary, to avoid nutrient imbalances. This is

intended to maintain or restore the level of nutrients in a forest soil and generally improve ecosystem functioning in the long term.

The longest amendment trials show that, after 40 years, most of the amendments added are still present and active in the soil-plant system. The general improvement recorded results from the fact that, in forests, the biogeochemical cycles are very effective at conserving nutrients which are actively recycled by the plants, minimizing the losses. Amendment has been shown to improve the chemical, physical and biological fertility of the soils, improve the health of the trees, increase their resistance to bad weather, improve the physical, chemical and biological quality of the surface water, etc. (Renaud *et al.*, 2009). Using amendments for restoration purposes usually enables the return to a “normal” production rate, an important aspect when deciding to use this method.

Given the current demand for increased production of fuel wood, it should be noted that chemical remediation is an integral part of a rational policy of exporting harvesting residues. Amending a chemically poor soil to restore its fertility should not encourage forestry companies to overexploit biomass.

## **ADAPTING FORESTRY PRACTICES TO THE ECOSYSTEM CAPACITIES**

Forest managers can, in theory, manipulate a number of different parameters to ensure the sustainability of the production capacity of forest ecosystems. However, in reality, the nutrient loss linked to the export of biomass is the easiest parameter to control the nutrient balance in the short term (atmospheric deposits, inputs from weathering, losses through drainage, losses from the export of biomass). General recommendations for maintaining productivity and sustaining the ecosystem were raised and discussed at the workshop (Ranger *et al.*, 2011):

- Selection of the right species: selecting the best species for the stand is one means of maximizing the sustainability of the ecosystem functions, protecting the stand from a large number of stressors.

- Appropriate management of felling: practicing progressive transitions between forest rotations and preserving as much plant cover as possible on the ground (herbaceous layer, well established regeneration) during these transitions.

- Harvesting trees at a sufficiently advanced age: the initial stages in the life of permanent stands are less efficient in terms of mineral resource use to produce biomass (dominant young tissue, limited internal recycling within the plant, significant allocation of resources to the crown, etc).

- Rationalize harvesting and treatment of residues (Cacot *et al.*, 2006): harvest residues (branches, foliage, needles) are very rich in nutrients which, when exported, constitute a loss for the ecosystem.

- Spread residues from thinning or coppicing uniformly over the whole of the stand to avoid concentrating the nutrients returned to the soil in limited areas (as in the case of swathing, for example). Avoid scraping which causes a significant reduction in fertility if the humus and/or A horizon are transferred to the swath. Shredding residues can spread fertility more effectively but plowing into the soil may affect the soil functions (disruption of the structure, porosity, functional diversity, etc.).

- Rationalize the harvesting method to limit the physical degradation of the soil.

- Preferably use manageable combinations of species to main active functional biodiversity in the ecosystem. Given the problems of managing mixed stands (different growth speeds of very different species, etc.), it is preferable to use practices that have been tested.

## **MAKING USE OF SEWAGE SLUDGE AND INDUSTRIAL WASTELAND**

These two subjects are quite far-off from current forest practices but are interesting as a means of finding solutions for producing more biomass, either by establishing agro-forestry systems on wasteland or by considering sludge, not as waste, but as a source of nutrients to sustain the production of biomass using selected types of tree or shrub.

### **Recycling waste for intensive wood production**

Spreading sludge in forests is usually not permitted, but may be authorized for certain R&D projects (Carnus and Charnet, 2003), whereas 50 to 60% of the 1 million metric tons of sewage dry matter produced in France every year is spread on agricultural fields. The question of making use of sludge in coppices of trees that regrow from stumps such as the *Salix* and *Populus* genera of the Salicaceae family as well as *Robinia* and some others depending on the conditions, is not new (old experiments by AFOCEL, AILE program in the mid 1990s: AILE, 2007; Charnet, 2006).

The usefulness of this practice, which is still limited mainly to the north west of France (especially Brittany), is obvious considering the increase in demand for fuel wood with the development of large collective heating units and the abandonment of agricultural land. This removes from the agricultural production system the less fertile land which should in general be amended to sustain high, regular production of wood and fiber crops which require relatively large amounts of nutrients. In these conditions, adding residues appears to be an alternative to adding mineral fertilizers, both from the economic point of view (substitution for expensive fertilizers) and from the general ecological point of view (recycling waste with controlled impact). The use of such amendments should, however, be subject to quantitative regulatory thresholds for trace metals and nitrogen (using the COMIFER nitrogen application guide).

The ERESFOR project was started in 1999 by the Comité National Boues et Forêts, funded by the ADEME and the Ministry of Agriculture to study forest soils. It set up a network of 25 trials to study the effects of using sludge in short or very short rotation coppices. This network, inactive since 2007, identified the critical technical problems related to this practice such as the variability of the effects on growth, the calculation of physiologically balanced doses and scheduling the amendment with respect to harvesting. The main results obtained were described in the workshop but long term monitoring would be very useful.

Other research, such as the SYLVABIOM project (ANR Bioénergies 2008 programme), specifically dedicated to sustainable planting of trees for the production of biomass for energy should provide new answers to the use of sludge in short or very short rotation coppices but there are still many questions that need to be answered.

### **Exploiting industrial wasteland for the production of biomass**

Industrial wasteland is a major source of land. If these areas are not required for housing or setting up new industries, they can be used in other ways. The production of biomass for industrial use is a means of exploiting degraded soils and developing a range of ecosystem services from abandoned sites. The cost of rehabilitation/decontamination would then be covered by the profits from the associated industrial projects. Industrial wasteland is, therefore, a source of compensation and establishing forest cover helps give value to degraded areas. Large areas are concerned: Lorraine alone has more than 10,000 ha of industrial, urban, mining, military and railway wasteland. Some are highly contaminated, such as the 354 industrial sites included in the 5,500 polluted sites identified in France (BASOL, 2013).



Vegetation can develop spontaneously on abandoned sites and lead to the development of particular ecosystems such as a natural cover of plants resistant to heavy metals or forest ecosystems. This has occurred in the decanting basins used by the metal working industry, where the soils are technosols formed from 100% industrial waste with a very low metal bioavailability which allows a large number of species to settle and develop (Schwartz *et al.*, 2001). On the old Pompey steel works site (Meurthe-et-Moselle), a hundred species were counted including 18 trees (including birch, pedunculated oak and hornbeam) and about 70 herbaceous plants.

It is possible to consider using these sites for the production of biomass for industrial use. However, there are a number of problems in using soils whose functions are often highly degraded (compaction, extreme pH, sulfates, trace metals or persistent organic pollutants). In addition to treatments to reduce the effect of contamination, the functions of the soils need to be restored using soil construction processes based on urban and industrial waste (Séré *et al.*, 2010).

The feasibility of producing biomass on industrial wasteland has been tested in various projects such as PHYTOPOP and LORVER. LORVER set out to restore soil functions and create new agro-systems or agro-forest ecosystems on abandoned industrial wasteland providing satisfactory productivity. The trees/plants were selected for use as fuel (for example poplars), the production of fiber (hemp, nettles, etc.) and metal extraction (for example using hyperaccumulators). Such plants help to deal with pollutants and reduce the impacts associated with soil contamination.

The need to preserve land resources has led to consider all land available. Industrial wasteland is a new source of ecosystem services. The decisions to create new ecosystems and to manage these areas, however, requires new knowledge about the functioning of these specific agro-forest ecosystems (ecology, ecotoxicology, fate of contaminants, etc) and appropriate soil engineering for exploiting the resource.

### **Has the concept of the multifunctional forest reached a turning point?**

A fundamental concept of French forestry policy is managing forests to provide a wide range of functions. Forests must fulfill the main functions assigned by society: the production of wood (construction, wood industry, fuel, etc), protection of ecological functions (protection of biodiversity, quality of landscapes), provision of environmental services (quality of water and air), social and cultural services and protection against natural risks.

Given the current increasing demand for the production of fuel wood, the French concept of multifunctional forests has perhaps reached a turning point. The production and export of biomass must be limited to the capacities of the ecosystems to ensure that the production is sustainable. Exceeding this capacity could jeopardize many of the other functions. As already mentioned, the use of amendments is a possible alternative that would maintain a required level of fertility and productivity but this may be incompatible with maintaining the other functions. Given a certain conflict between the function of conservation and the function of production, the question of the specialization of forest ecosystems was raised at the workshop. This debate is not new: it comes to the fore whenever there is an energy crisis.

Should intensive production of biomass be concentrated in a certain number of forest ecosystems dedicated to the production of wood (or fiber) which would no longer fulfill all the functions described above? Would this specialization make it easier to provide all the other functions using forests with a high heritage value? The concept of multifunctional forests must be considered at

various scales and include various sustainability factors: demand for eco-materials, quality of soils and water, waste management, etc. Exploiting residues and using industrial wasteland to produce biomass must also be included in these considerations.

**Arnaud LEGOUT – Grégory VAN DER HEIJDEN –  
Jacques RANGER**  
INRA Centre de Nancy-Lorraine  
Unité Biogéochimie des écosystèmes forestiers  
F-54280 CHAMPENOUX  
(legout@nancy.inra.fr)  
(gregory.vanderheijden@nancy.inra.fr)  
(ranger@nancy.inra.fr)

**Claudine RICHTER**  
OFFICE NATIONAL DES FORÊTS  
Département Recherche et Développement  
Boulevard de Constance  
F-77300 FONTAINEBLEAU  
(claudine.richter@onf.fr)

**Noémie POUSSE**  
OFFICE NATIONAL DES FORÊTS  
Département Recherche et Développement  
Pôle Recherche et Développement de Nancy  
11 rue de l'Île-de-Corse  
F-54000 NANCY  
(noemie.pousse@onf.fr)

**Jean-Louis MOREL**  
Université de Lorraine/INRA  
GISFI – UMR 1120 Laboratoire Sols et Environnement  
2 avenue de la Forêt de Haye – TSA 40602  
F-54518 VANDŒUVRE-LÈS-NANCY CEDEX  
(Jean-Louis.Morel@univ-lorraine.fr)

**François CHARNET**  
CNPFF-IDF  
Antenne d'Orléans  
13 avenue des Droits de l'Homme  
F-45921 ORLÉANS CEDEX 9  
(francois.charnet@cnpff.fr)

**Marie-Odile SIMONNOT**  
Université de Lorraine/CNRS  
GISFI – UMR 7274  
Laboratoire Réactions et Génie des Procédés  
ENSIC  
1 rue Grandville – BP 20451  
F-54001 NANCY CEDEX  
(marie-odile.simonnot@univ-lorraine.fr)

## REFERENCES

- AILE. — Le Taillis à très courtes rotations de Saule : de la production d'énergie renouvelable à la valorisation d'effluents prétraités. [Coppicing willow with very short rotations: from the production of renewable energy to recycling treated sewage] Programme LIFE-Environnement WilWater 2004-2007. — Rennes : AILE, 2007. — 4 p.
- AUGRIS (S.). — Des chantiers tests ONF pour trouver les outils de récolte adaptés aux petits bois. — *Le Journal de la Mécanisation forestière*, janvier-février 2012, pp. 27-29.
- Basol, 2013. — [En ligne] : <http://basol.developpement-durable.gouv.fr>
- BÉNARD (V.). — Profor©, logiciel d'estimation de la praticabilité des cloisonnements : premiers essais en Haute-Marne [Profor©, software for estimating the passability of forest tracks: first tests in Haute Marne]. — *Rendez-vous Techniques*, n° 23-24, printemps 2009, pp. 14-23.
- BOTTINELLI (N.), HALLAIRE (V.), GOUTAL (N.), BONNAUD (P.), RANGER (J.). — Impact of heavy traffic on soil macroporosity of two silty forest soils: Initial effects and short term recovery. — *Geoderma*, n° 217-218, 2014, pp. 10-47.
- CACOT (E.), EISNER (N.), CHARNET (F.), LÉON (P.), RANTIEN (C.), RANGER (J.). — La Récolte raisonnée des rémanents en forêt [Rational harvesting of forest residues]. — Angers : ADEME Éditions, 2006. — 36 p.
- CAPOWIEZ (Y.), CADOUX (S.), BOUCHAND (P.), ROGER-ESTRADE (J.), RICHARD (G.), BOIZARD (H.). — Experimental evidence for the role of earthworms in compacted soil regeneration on field observations and results from a semi-field experiment. — *Soil Biology and Biochemistry*, 41, 2009, pp. 711-717.

- CARNUS (J.-M.), CHARNET (F.). — Des boues en forêt ? [Applying sludge in forests]— *Forêt-Entreprise*, n° 150, 2003, pp. 55-60.
- CHARNET (F.). — Valorisation des boues biologiques en taillis à très courtes rotations de Saule. Expérimentation sur la commune de Pleyber-Christ (Finistère) [Applying biological sludge to willow coppices with very short rotations]. Convention ADEME. — Orléans : IDF, 2006. — 35 p.
- DELEUZE (C.), MICHENEAU (C.), RICHTER (C.), BOULANGER (V.), GARDETTE (Y.-M.), BRÊTHES (A.), GIBAUD (G.), AUGUSTO (L.), DUPONT (C.), GAUTRY (J.-Y.), FRAYSSE (J.-Y.), RANTIEN (C.). — Le Retour des cendres de bois en forêt : opportunités et limites [The return of using wood ash in forests: advantages and limitations]. — *Rendez-Vous Techniques*, n° 35, hiver 2012, pp. 16-28.
- GOUTAL (N.). — Modifications et restauration de propriétés physiques et chimiques de deux sols forestiers soumis au passage d'un engin d'exploitation [Modifications and restoration of physical and chemical properties in two forest soils subject to the passage of forestry machines]. — Nancy: AgroParisTech, 2012. — 223 p. (Thèse) [En ligne]: <http://pastel.archives-ouvertes.fr/pastel-00737884>.
- MATTHIES (D.), ZIESAK (M.), KREMER (J.). — Le logiciel Profor©, un outil de prévention pour juger de la praticabilité des sols lors de l'exploitation forestière [Profor©, a prevention tool to assess the passability of the ground during forestry operations]. — *Rendez-Vous Techniques*, n° 14, automne 2006, pp. 3-8.
- MGVF. — [En ligne]: <http://www6.nancy.inra.fr/mission-gestion-vegetation-foret/Projets-en-cours/projet-ALTER>. — 2012.
- MGVF. — [En ligne]: <http://www6.nancy.inra.fr/mission-gestion-vegetation-foret/Projets-en-cours/projet-PILOTE>. — 2013.
- PISCHEDDA (D.). — Pour une exploitation forestière respectueuse des sols et de la forêt « PROSOL » — Guide pratique [PROSOL guide to forestry management to protect soils and forests]. — FCBA, ONF, 2009. — 110 p.
- RANGER (J.), AUGUSTO (L.), BERTHELOT (A.), BOUCHON (J.), CACOT (E.), DAMBRINE (E.), GAVALAND (A.), LACLAU (J.-P.), LEGOUT (A.), NICOLAS (M.), NYS (C.), PONETTE (Q.), OTTORINI (J.-M.), SAINT-ANDRÉ (L.). — Sylviculture et protection des sols [Forestry practices and protection of soils]. — *Revue forestière française*, vol. LXIII, n° 2, 2011, pp. 245-264.
- RENAUD (J.-P.), PICARD (J.-F.), RICHTER (C.), LEGOUT (A.), NYS (C.). — Amendements calco-magnésiens et fonctionnement écologique : bilan des expériences conduites dans l'Est de la France (massif vosgien et Ardennes) [Dolomitic lime amendments and ecological functioning: report on experiments in Eastern France (Vosges and Ardennes)]. — *Revue forestière française*, vol. LXI, n° 3 spécial "Amendements des sols forestiers", 2009, pp. 283-300.
- SCHWARTZ (C.), FLORENTIN (L.), CHARPENTIER (D.), MUZIKA (S.), MOREL (J.-L.). — Le Pédologue en milieu industriels et urbains. I. Sols d'une friche industrielle [Pedology in industrial and urban environments. 1. Soils in industrial wastelands]. — *Étude et Gestion des Sols*, 8, 2001, pp. 135-148.
- SÉRÉ (G.), SCHWARTZ (C.), OUVRARD (S.), RENAT (J.-C.), WATTEAU (F.), VILLEMIN (G.), MOREL (J.-L.). — Early pedogenic evolution of constructed Technosols. — *Journal of Soils and Sediments*, 10, 2010, pp. 1246-1254.

---

**COMPENSATING FOR THE EXPORT OF NUTRIENTS AND RESTORATION OF DEGRADED SOILS. Report of the workshop 3 [Abstract]**

French forests are currently under increasing pressure from nutritional, forest management and climatic factors that may affect the sustainability of forest ecosystems and degrade the chemical, physical and biological components of the soil. This workshop presented the current state of knowledge and discussed how soils may be degraded and how soil degradation may be remediated and restored. It also provided an opportunity for discussing various approaches to ensure sustainable forest production by using different types of input (liming/ ash, sludge, etc.) or by producing biomass on industrial wastelands.

---