From Forest Nursery Notes, Summer 2008

162. Soil construction: a step for ecological reclamation of derelict lands. Sere, G., Schwartz, C., Ouvrard, S., Sauvage, C., Renat, J.-C., and Morel, J. L. Journal of Soil Sediments 8(2):130-136. 2008.

Soils, Section 3: Remediation and management of contaminated or degraded lands

Research Article

Soil Construction: A Step for Ecological Reclamation of Derelict Lands

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DOI: http://dx.doi.org/10.1065/jss2008.03.277

Please cite this paper as: Séré G, Schwartz C, Ouvrard S, Sauvage C, Renat J-C, Morel JL (2008): Soil Construction: a Step for Ecological Reclamation of Derelict Lands. J Soils Sediments 8 (2) 130–136

Abstract

Goal, Scope and Background. Efficient and environmentally friendly technologies for soil reclamation require efforts to develop innovative processes. Alternative technologies to drastic techniques (containment, total removal of soil) are receiving increasing interest. They are based either on the use of ameliorants (*e.g.* lime, fertilizer, organic mulch) and more recently on the spreading of organic wastes (e.g. compost, sewage sludge). This paper presents a new process of soil construction using wastes and industrial by-products which are formulated and stacked in layers to build a new soil profile over *in situ* degraded substrates. Work was conducted to assess the feasibility of the ecological reclamation, focusing on the major functions of constructed Technosols.

Materials and Methods. Two large lysimetric plots (10 x 10 m) were built on a former coking plant, and two strategies of constructed soil profiles were compared: i) a control soil using thermally treated industrial soil available *in situ*, and ii) a constructed soil with a combination of thermally treated industrial soil mixed with exogenous materials such as green waste compost and paper mill sludge. Rainfall was measured periodically, drainage effluent was collected, and aliquots were sampled per plot. Plants were collected in 8 replicates for each plot.

Results. Water balance data showed that about 10% of the rain water percolated through the constructed soil profiles. Drainage effluent contained a low concentration of contaminants, below the French water drinking standards. Plants grew without any deficiency symptoms on both plots. Apart from the sowed plants, indigenous species developed on the constructed Technosols.

Discussion. The experimental set-up was representative of the real conditions for the implementation of such reclamation technologies. In spite of the significant concentrations of trace elements in the parent materials, the fluxes in the drainage effluent were very low because of the high pH. Significantly higher biomass values were recorded on the constructed soil than on the control, as well as a better development of indigenous plants.

Conclusions. The constructed soils are examples of Technosols as they are made exclusively of technogenic parent materials. Our results showed that they can behave like natural soils (water cycle, trace elements filtration, biomass production). The process of soil construction is not only an efficient way to reclaim derelict lands, but also a safe alternative for the recycling of wastes and by-products with a minimum use of unpolluted and fertile agricultural soil.

Recommendations. The restoration of soil functions, thanks to the soil construction process, must be considered as a primary step for the ecological reclamation of derelict lands. In this way, the pedo-engineering approach should be considered as an essential part of the global ecological engineering for the reclamation of derelict lands.

Perspectives. Two major outlooks appear: i) testing a larger variety of wastes and by-products as parent materials for different constructed soils, ii) generalize the results on constructed soils to the characterization of Technosols.

Keywords: Derelict land reclamation; mass balance; pedo-engineering; soil construction; soil functions; technogenic material; Technosols; trace elements

Goal, Scope and Background

Efficient and sustainable reclamation technologies are required to limit the depletion of natural resources, e.g. arable soil, and to propose new ways of waste recycling. Anthropogenic influence, especially by urban and industrial activities, leads to a deep alteration of soils and results in the disturbance of the whole ecosystems (Wali 1999). Sealing, soil contamination, handling of soil material, and the incorporation of technogenic materials[1] are the main causes of the degradation of soil functioning. Soils made of large amounts of technogenic materials are classified as Technosols (FAO 2006, Lehmann 2006, Rossiter, 2007). They are characterized by extreme values of bulk density (from less than 0.5 to more than 1.6 $kg \cdot dm^{-3}$), coarse textures, great horizontal as well as vertical heterogeneity (Morel et al. 2005, Lehmann & Stahr 2007). In extreme cases (e.g. mining, disposal areas) it has been suggested that they could not be considered as soils in either a pedological or a biological sense (Bradshaw 1983). A common characteristic of degraded soils is the lack of fertility inducing poor plant cover

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[1] "solid of liquid material created by humans as part of an industrial or artisanal manufacturing process and found in the soil" (FAO 2006)

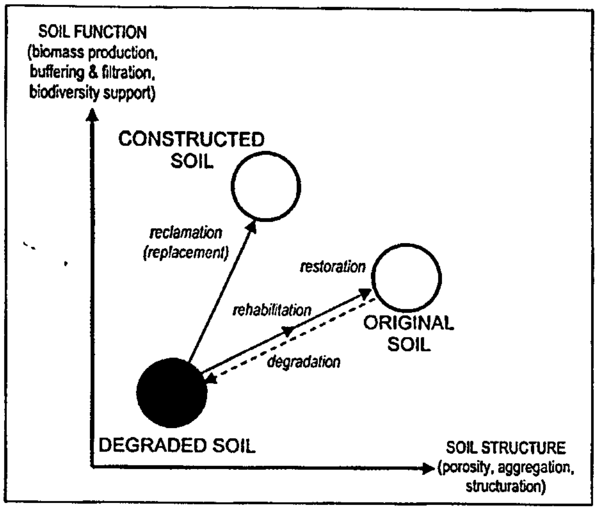


Fig. 1: The contrasting approaches to the restoration of soils on derelict lands, including soil construction (adapted from Bradshaw 1992)

(Vetterlein & Hüttl 1999). Various approaches of restoration, rehabilitation and reclamation are available in ecological engineering on degraded sites: i) restoration of the ecosystem involving the return to its original state ii) rehabilitation requiring only a partial return, iii) reclamation implying the end up in some new state where either structure or function of the ecosystem are different from the original state (Bradshaw 1997, Décamps 2002). By this means the approach of soil construction can be understood as reclamation in the scope of the ecological engineering (Fig. 1).

Many authors highlight the fact that the main precondition for ecosystem reclamation is the re-functioning of soil (Bradshaw 1997, Wali 1999, Šourková et al. 2005, Li 2006). Indeed, this is a preliminary step to the promotion of plant and animal development (Madejón et al. 2006). The soil has to be restored to its basic natural functions: i) basis for biomass production (to provide nutrients, air and water and to be a medium in which plant roots can penetrate), ii) filtering, buffering and transformation (to enable water cycle, nutrient storage and pollutant binding), iii) biological habitat and gene reserve (to provide habitats for numerous microorganisms and organisms). Furthermore, the reclamation of the soil is based on the reconstruction of its properties such as, for example, water holding and sorption capacity, nutrient content and availability, accumulation of organic matter (Šourková et al. 2005). Apart from massive techniques such as total removal, complete containment of soil or reconstitution of topsoil with natural arable earth, extensive *in situ* reclamation treatment technologies can be appropriate for brownfield lands (Dickinson 2000, Dick et al. 2006). The most common rehabilitation technologies, in the short term, involve the addition of ameliorants to soils such as lime, fertilizer, organic mulch, phosphates, zeolites, bentonite, gypsum coupled with physical treatments like drainage, scarifying or ripping (Bradshaw 1983, Vangronsveld et al. 1995a, Vangronsveld et al. 1995b, Li 2006). Over a long term, this is followed by the implantation of appropriate herbaceous and tree vegetation (Bradshaw 1983, Rawlinson et al. 2004). The use of amendments or natural topsoil presents significant disadvantages from economic – the technologies are too much expensive – and environmental – natural soils are non-renewable resources in the short-term – points of view. This is incompatible with the lack of funds devoted to these operations and contrary to the sustainability and environmentally friendly demand that should be the rule (Bradshaw 1997, Hüttl & Bradshaw 2000). Thus, the application of organic wastes to disturbed ecosystems has received increasing attention in many countries in recent decades. This is due not only to the potential effects of the addition of organic matter, but also to the increasing availability of cheap sources of wastes and by-products (e.g. sewage sludge, compost, industrial by-products) (Vetterlein & Hüttl 1999). Furthermore, this new way of waste recycling must be considered as an interesting alternative outlet to spreading or incineration. Thus, the use of organic residues as amendments for the reclamation of derelict lands has been largely studied (Bradshaw 1983, Metcalfe & Lavin 1991, Pulford 1991, Sopper 1991, Pichtel et al. 1994, Wilden et al. 1999, Castro et al. 2007). Recently, studies have been carried out on the use of industrial by-products such as fly ash and especially paper mill sludge (Pichtel et al. 1994, Tisch et al. 1999, Fierro et al. 1999, Fierro et al. 2000). The properties of paper mill sludge (e.g. high organic matter and carbonate contents) make it a valuable candidate for remediation practices (Boni et al. 2004). In most cases, the quantity of wastes applied is low, ranging from 50 to 200 t ha^{-1} dry matter and formed a thin layer < 15 cm at the surface of derelict soils. Some exceptions are noticed where the application of wastes reaches quantities up to 650 t ha^{-1} dry matter (Metcalfe & Lavin 1991).

The limitations of these approaches are mainly the risks associated to the spreading of organic wastes: the transfer of pollutants (trace elements in particular) and their toxicity to organisms (Calace et al. 2005, Battaglia et al. 2007). Moreover, the efficiency of the technology using organic wastes is frequently discussed with regard to the sustainability of the reclamation (Villar et al. 1998, Vetterlein & Hüttl 1999, Nemati et al. 2000, Bacholle et al. 2006). This paper reports a process developed for soil construction based on the combination of wastes and industrial by-products to reclaim derelict lands. A field experiment was set up to assess the functioning of the constructed Technosol, focusing on two main functions: biomass production and buffering and filtration.

1 Material and Methods

1.1 Parent materials

Three different wastes and by-products were used: i) a green waste compost (GWC) mainly composed of urban tree and grass cuttings, licensed under NF U 44-051 standard; ii) a paper mill sludge (PS) which is a by-product of the paper industry, referenced in European Waste List (EWL) as "de-inking sludges from paper recycling"; iii) a thermally treated industrial soil (TIS) excavated from a former coking plant site initially heavily polluted with PAHs, referenced in EWL as "solid wastes from soil remediation containing dangerous substances".

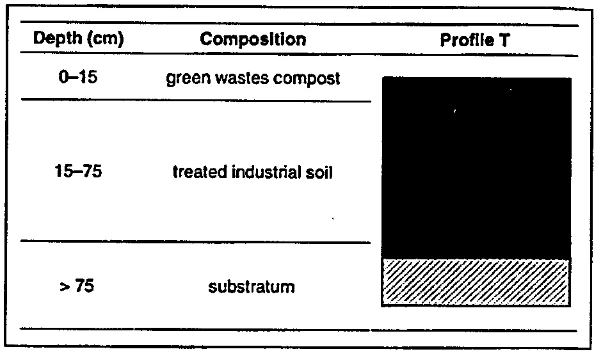
Table 1: Agronomic properties of the parent materials

	pH	Organic matter (g kg^{-1})	C/N	CEC^{d} (cmol kg^{-1})	P_{Olsen} (g kg^{-1})	$CaCO_3$ (g kg^{-1})
GWC^{a}	8.6	376	20	42.3	0.67	115
PS^{b}	7.9	251	27	4.6	0.01	478
TIS^{c}	9.0	94	97	6.7	0.05	245

[a] green waste compost
[b] paper sludge
[c] treated industrial soil
[d] Cation Exchange Capacity

Materials were analysed for agronomic parameters (Table 1). Methods used were the same as for natural soils: pH_{water} (ratio soil/solution = 1/5) (NF ISO 10390), organic matter and organic carbon (oxidation by heating at 900°C under O_2 flow), total nitrogen (Kjeldahl mineralisation– NF ISO 11261), total calcium carbonate (reaction with HCl and measurement of the volume of carbon dioxide evolution with a Scheibler device – NF ISO 10693), cation exchange capacity (exchanged ammonium ions – NF ISO 11260), P_{Olsen} ($NaHCO_3$ extraction and then proportioning of phosphorus complexes by spectrometric methods – NF ISO 11263) (AFNOR, 2004). Analyses were carried out by the certified laboratory of the French agronomic research institute (Laboratoire d'Analyse des Sols, INRA, Arras). Quality controls for soils, sludges and effluent samples were assessed by the French Committee of Accreditation (COFRAC).

EDTA extractable chromium (Cr), copper (Cu), nickel (Ni), lead (Pb) and zinc (Zn) were determined by ICP-OES spectrometer (NF ISO 11047) and methanol extractable PAH concentrations were analysed by HPLC analysis (NF ISO 13877) (Table 2). The metal and PAH concentrations measured in the parent materials (see Table 2) were below the European thresholds for pollutants (Directive n°86-278) with the exception of Pb and Zn in the treated industrial soil matrix.

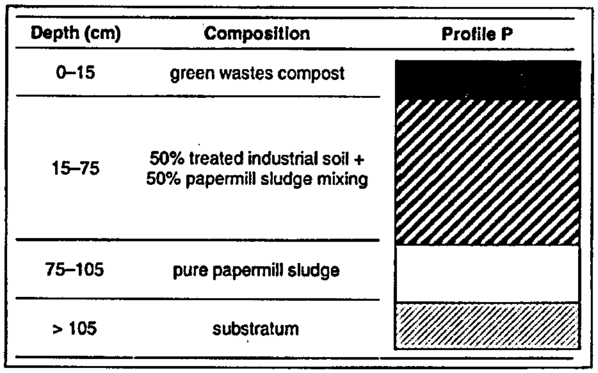


Depth (cm)	Composition	Profile T
0–15	green wastes compost	■
15–75	treated industrial soil	■
> 75	substratum	▨

Fig. 2: Description of constructed soil: profile T

1.2 Constructed soil formulation and experimental set-up

A field experiment was set up on the experimental site of the French Scientific Interest Group – Industrial Wasteland (GISFI) (http://www.gisfi.prd.fr), Homécourt, North-Eastern France, in December 2003. The climate is continental with a mean rainfall of 760 mm year^{-1} and a mean temperature of 10°C (extreme values: –21.6°C to 37.6°C). Two ditches were dug (surface: 10 m x 10 m; depth: 1.5 m); their bottom was covered with a geomembrane barrier. Both plots were equipped with a drainage network (polyvinyl chloride plastic pipe) connected to stainless steal tanks to collect drainage effluent. Then, they were filled with layers of wastes and by-products to build two different soil profiles. From bottom to top, profile T was filled, with i) a 60 cm layer of thermally treated industrial soil, and ii) a 15 cm-upper layer of green waste compost (Fig. 2). From bottom to top, profile P was filled with i) a 30 cm layer of pure paper mill sludge, ii) a 60 cm layer of treated soil and paper mill sludge mixture (1:1 volumetric ratio), and iii) a 15 cm layer of green wastes compost (Fig. 3).



Depth (cm)	Composition	Profile P
0–15	green wastes compost	■
15–75	50% treated industrial soil + 50% papermill sludge mixing	▨
75–105	pure papermill sludge	□
> 105	substratum	▨

Fig. 3: Description of constructed soil: profile P

Table 2: Pollutants content in the parent materials

	Total PAH concentrations (mg kg^{-1})					Total metal concentrations (mg kg^{-1})			
	BaA	CHRY	BaP	FLT	NAP	Cd	Cu	Pb	Zn
GWC^{a}	0.34	0.76	0.34	0.91	< 0.20	< 0.5	60.4	64.1	287.5
PS^{b}	0.17	0.61	< 0.10	< 0.10	< 0.20	< 0.5	47.8	10.1	41.1
TIS^{c}	3.07	3.54	2.03	7.82	0.81	0.9	37.7	496.2	759.8

[a] green waste compost
[b] paper sludge
[c] treated industrial soil
BaA: benzo(a)anthracene; CHRY: chrysene; BaP: benzo(a)pyrene; FLT: fluoranthene; NAP: naphtalene

Volumes of rain and drainage effluent were measured periodically. All the drainage effluent coming from one plot was collected and homogenised in the tank. Representative aliquots were sampled and analysed. Water samples were collected after rainfalls. Drainage effluent samples were filtrated at 0.45 µm and acidified with 5% HNO_3 then analysed for Cr, Cu, Ni, Pb, Zn by absorption spectrophotometry (ICP-OES VARIAN). The surface was left unplanted during 1.5 year and after that period rye grass (*Lolium perenne* L. var. Tove) and alfalfa (*Medicago sativa* var. Europe) were sown (seed densities of respectively 240 kg ha^{-1} and 200 kg ha^{-1}) on both plots. No fertilisation was applied and there was one application of a total herbicide (glyphosate, 24 L ha^{-1} in May 2004) and two manual weedings (July 2004 and October 2004). Pits were dug each year in May 2004, May 2005 and May 2006. Root profiles were described in May 2006. In June 2006, the vegetation was sampled on 8 quadrates (0.5 x 0.5 m) by plot (10% of the total surface), in order to measure the biomass production.

2 Results

2.1 Water balance

The water balance described by rainfall and drainage effluent collected showed that the drain network worked properly and the soil profiles were filtrating media (Fig. 4). For both profiles, three hydrologic phases were identified. Whereas both profiles behave similar in phases i) and ii), in phase iii) their behaviour became different: i) during the first 400 L m^{-2} of rainfall (equivalent to 6 months), the soil system is under stabilization and no logical pattern linking rainfall and drained volumes could be identified, ii) from 400 to 1300–1500 L m^{-2}, within 12 months, a steady throughflow occurred corresponding to 10–11% of the rainfall, i.e. 160 L m^{-2}; iii) after that period, whereas the behaviour of water in profile T remained constant (Fig. 4.a), a significantly lower proportion of rainfall went through the entire profile P; from 1300 L m^{-2} (06/2005) till the end of the experiment, the draining velocity decreased in a drastic way and drained volumes represented only 1.5 % of the rainfall (Fig. 4.b).

2.2 Trace element fluxes in drainage effluent

The Zn and Ni breakthrough curves are presented (Fig. 5). They illustrated the extreme observed behaviours of heavy metals fluxes (Cd/Pb/Zn on the one hand and Ni/Cr on the other hand). The evolution of the concentration of Zn in the drainage effluent from profile T and profile P were similar with frequent and random variations around an average value close to that of rain water (60.1 µg L^{-1}) (Fig. 5.a). These variations were not related to climatic conditions. The concentrations of Ni in the drainage effluent of profile P were significantly higher (5–20 µg L^{-1}) than in the drainage effluent from profile T (0–5 µg L^{-1}) and the rain water (0.6 µg L^{-1}) (Fig. 5.b). The major peaks of concentration in the drainage effluent from profile P (72 µg L^{-1} and 165 µg L^{-1}) were observed during two heavy rainfalls at the end of the summer 2004 and the spring 2005. The concentrations of trace elements in the drainage effluent were below the French drinking water standards.

The overall mass balance on the time period shows that within these two years, respectively 0.6% of the Zn and 0.2% of the Ni present in the parent materials have been mobilized and carried away from the profile T, whereas 0.7% of the Zn and 3.1% of the Ni have been drained from the profile P.

2.3 Vegetation development

During the first 1.5 year of the experiment, there was a spontaneous development of vegetation such as *Chenopodium album*, *Taraxacum officinale* and *Cirsium vulgare*. One year after the sowing of alfalfa and rye-grass, the biomass production and the root profiles on profile T and profile P showed that plants had grown on both plots. Some differences were recorded on the diversity and dry biomass pro-

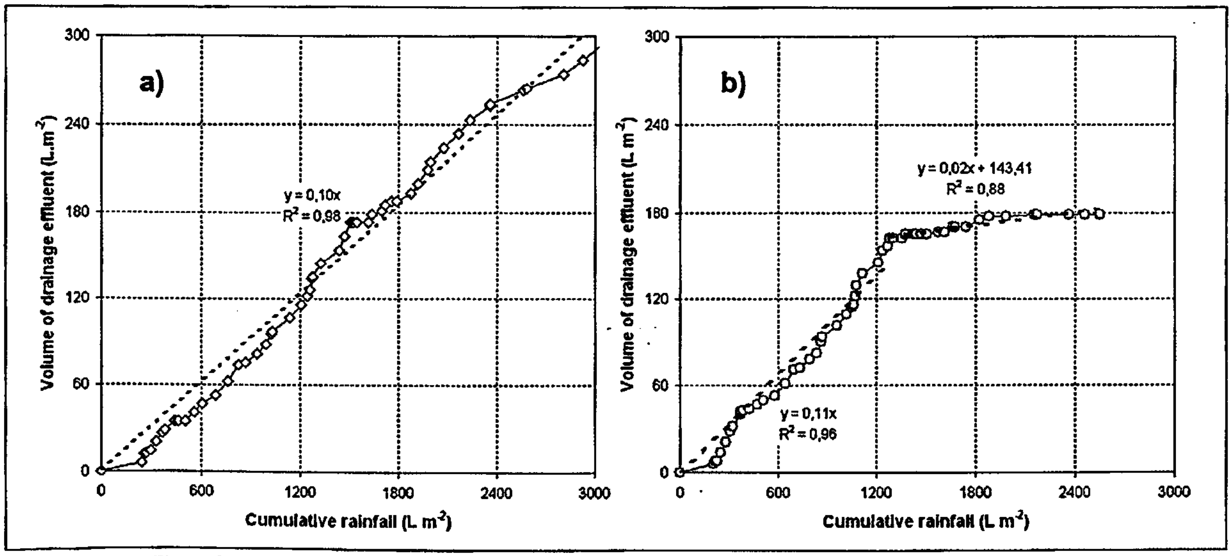


Fig. 4: Cumulative volumes of drainage effluent from a) profile T, b) profile P as a function of rainfall during 3 years

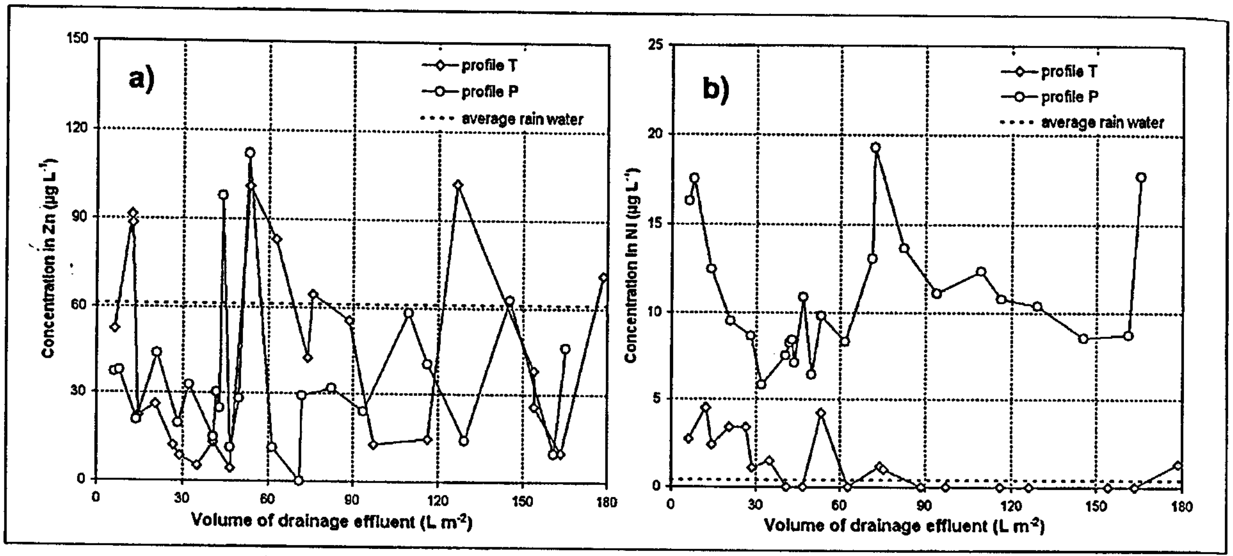


Fig. 5: Evolution of the concentrations of a) Zn; b) Ni in rain water and drainage effluent

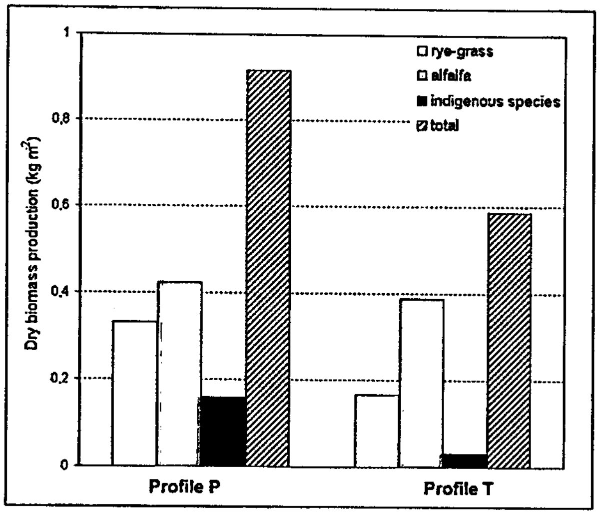


Fig. 6: Biomass production on the profile T and profile P

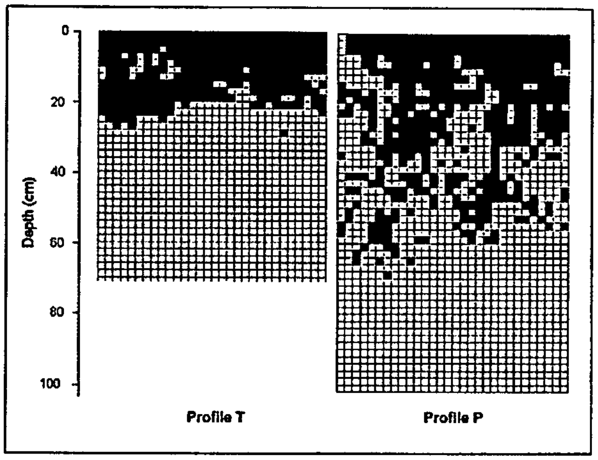


Fig. 7: Root profile on the profile T and profile P

duction (Fig. 6). There was a significantly higher rye-grass production on profile P (0.33 kg m^{-2}), than on profile T (0.17 kg m^{-2}), and the total biomass production was also greater on profile P (0.92 kg m^{-2}), compared to profile T (0.59 kg m^{-2}). On the other hand, the alfalfa production was similar on both plots (0.39 to 0.42 kg m^{-2}). No statistical differences have been observed for the indigenous species because of a very high variability, but a higher diversity of species as well as a higher biomass production was recorded in profile P.

There was also a significant difference in root exploration of the two profiles (Fig. 7). The penetration of roots in profile T was limited to 25 cm, i.e. the first horizon (compost) and the upper part of the second horizon (treated industrial soil). Roots penetrated deeper in profile P (70 cm), occupying a large portion of the first two horizons (compost and paper mill sludge/treated soil mixing). The surface explored by the roots in the first 70 cm was also larger in profile P (47%) than in profile T (28%).

3 Discussion

The constructed Technosols were studied through the characterization of their functioning (i.e. water and trace element cycles and biomass production) for three years with an *in situ* set-up of lysimetric plots.

This method was chosen to be representative of the reality of the *in situ* implementation of reclamation technologies. The large surface of the plots (100 m^2) ensures the representativity of the results and justifies the absence of replicates. But, only some aspects have been investigated: i) the volumes and quality of the drainage effluent as well as the vegetation development have been studied during only 3 years so that it gave a view only of the early functioning of the newly constructed Technosols profiles; ii) plant biomass productions were measured in the last year of the experiment so that no temporal evolution could be presented; iii) only some trace elements have been studied because of their significant concentrations in the parent materials, unlike the low concentrations of organic pollutants.

The water balance results showed that water percolated and evaporated in profiles T and P. The concentration of trace elements in the drainage effluent from profile T and profile P was low. To a large extent, this fact can be related to the high pH values (> 7.9) of the parent materials that lead to a low metal solubility and especially to the high buffering capacity for H^+ of paper sludge (Battaglia et al. 2007). However, noticeable concentrations of metals were sporadically recorded possibly as a result of a co-transport with soluble organic matter (Hering & Morel 1988, Sauvé et al. 2000). Even if the properties of the soils in the lysimetric plots were close to real *in situ* conditions, the leaching of elements and the drainage were modified by the presence of a drainage network and a geo-textile barrier. Hence, the water flux and leaching of metals were probably overestimated. The constructed Technosols allowed plant growth, and plant development was not modified by the technogenic origin of the parent materials. This means that the water holding capacity and the nutrient supply were sufficient as no deficiency was observed and the vegetation cover presented deep root penetration and increasing plant density with time.

This project compared a classical earthwork reclamation practice (profile T) and a new process of soil construction using wastes and by-products (profile P). The parent materials used in the two soil profiles exhibited differences in parameters such as porosity, permeability, water holding capacity or chemical composition. As a result, differences were observed in the water balance monitoring and the leaching of the elements between the two options. For example, the presence of paper mill sludge in profile P conferred a higher water buffering capacity than in profile T, especially during the dry period. As a consequence, plant response was also higher in profile P than in profile T, for both quantitative and qualitative characteristics. Plant diversity was higher in profile P than in profile T; indigenous species progressively installed on the soils and replaced the initially sowed plants (rye-grass and alfalfa). The constructed soil containing paper mill sludge (profile P) allowed a faster ecological restoration, as the plant cover evolved quickly from a two-species cultivated system to a more diverse plant ecosystem.

4 Conclusions

Our work demonstrates that a Technosol made only of technogenic parent materials can behave like natural soils. Indeed, our study showed that the two soils were filtrating media for water that they acted as a filter for trace elements, they were sources of nutrients and sowed and indigenous plants grew on them. The results obtained on *in situ* lysimetric plots showed that the ecological restoration was initiated. The use of wastes and by-products is an alternative technology to reclaim derelict lands. The process of soil construction is the expression of a pedo-engineering approach that is based on the reasoned combination and implementation of technogenic parent materials to build a functional organo-mineral soil pedon (Séré et al. 2007). This work provides the basis to develop an innovative and environmentally friendly technology. Indeed, the soil construction is not only an efficient way to reclaim derelict lands without using natural arable earth, but also an appropriate alternative for the valorisation of wastes and by-products.

5 Recommendations

Soil construction based on the recycling of wastes and by-products has to be preferred to the use of natural soil material. This is a way to reduce the consumption of soil resources. The early stages of the reclamation process of the ecosystem are crucial and this work demonstrates that putting attention on the soil before any other components of the derelict ecosystem is a primary factor for success of the restoration. The formulation of the technogenic materials constitutive of constructed soils has to be adapted to future land use. The soil construction process depends on the expected soil functions. For example if plant growth is required, the physical and chemical fertility of the constructed soil is the main target. The selection of the wastes and by-products, their mixing and position in the soil profile have to provide optimised growth conditions. No decision making tools being available at this time, an agronomical characterisation of the parent materials and a pilot scale approach are needed to orientate soil construction.

6 Perspectives

There are many perspectives of work in this new field of pedo-engineering. First of all, it seems necessary to complete the ecological assessment of soil construction, further indicators are needed, especially on the biological activity (Chambers & Wade 1992). A longer period of monitoring is required to study the evolution of constructed soils as well as the evidence of the ecological reclamation. Then, to develop this approach, some others wastes and by-products that could be used as parent materials should be tested in different kind of constructed soil profiles. A major objective would be to succeed in choosing the technogenic parent materials depending on local available targets and on the future land use of the reclaimed site.

Acknowledgement. This project is supported by the GISFI programme and was founded by the Etat Français, Région Lorraine, Agence de l'Environnement et de la Maîtrise de l'Energie (ADEME), Etablissement Public Foncier de Lorraine (EPFL) and Arcelor Real Estate. The authors wish to thank Stéphane Colin, Alain Rakoto and Marc Weiler for their precious technical help.

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Received: February 27th, 2007
Accepted: March 1st, 2008
OnlineFirst: March 2nd, 2008