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Key words: trace elements, phytoextraction, *Salix*, combustion, dredged sediment landfill site

Abstract
Phytoextraction is an emerging technology to remediate soils and sediments contaminated with trace elements. In the particular case of dredged sediment landfill sites contaminated with metals, phytoextraction may contribute to the management scheme of sediments and to the revaluation of certain land-disposed contaminated sediments. In this study, rapidly growing trees (willows) were cultivated in short rotation coppice (SRC) on a metal contaminated dredged sediment landfill site to produce biomass for heat and financial return. Three willow clones were planted on 4.5 hectares of this disposal site to assess phytoextraction efficiency and biomass production. Two combustion assays were performed in a biomass boiler of 30 KW, the first one with *Salix* Zn and Cd enriched wood harvested from the SRC and the second one with *Salix* wood bought at a wood producer (control). Combustibles, ashes and gases were analyzed to study trace element behaviour during the combustion process. For phytoextraction efficiency, best results are obtained when exportation of both stems and leaves are carried out. The most optimistic scenario led to a reduction of the total Cd content of the sediment from 3.16 to 2 mg kg $^{-1}$ in 23 years. Due to boiling points, Cd and Zn were more found in fumes than in ashes. According to current regulation, *Salix* wood issued from phytoextraction should be used for non-domestic purpose, in industrial or collective boilers equipped with efficient filters.

Introduction
Phytoextraction is an emerging technology to remediate soils and sediments contaminated with trace elements (Vangronsveld et al., 2009). In the particular case of dredged sediment landfill sites contaminated with metals, phytoextraction may contribute to the management scheme of the sediments and to the revaluation of certain land-disposed contaminated sediments (Bert et al., 2009a). In this case, phytoextraction may be combined with bioenergy production to provide a benefit to the land owner and, at the same time, to guarantee pollutant impact control according to current regulation.
In the last years, different energy-recovery-techniques (incineration, combustion, gasification, pyrolysis, anaerobic digestion and pure plant oil production) using metal-accumulating bioenergy plants were investigated for this purpose (Keller et al., 2005; Van Ginneken et al., 2007, Stals et al., 2010).
The aim of this study is to assess phytoextraction efficiency of *Salix* on a metal contaminated dredged sediment landfill site and perform a combustion experiment with a *Salix* SRC sample to see the viability of the overall process, i.e. phytoextraction combined with reuse of metal enriched biomass.

Materials and Methods
In 1998, a short rotation coppice (SRC) of three willow clones (*Salix viminalis* “Tora” *Salix schwerinii x Salix viminalis* “Jorr” and “Björn”) was set up on 45,000 m² of a metal contaminated dredged sediment landfill site located in the North part of France. The SRC was harvested in 2001 to assess phytoextraction efficiency and biomass production. In 2006, trees were harvested and the crushed wood left on site.
In April 2010, based on a sediment characterization of the SRC area, samples of sediments and above ground parts of willows were taken in the most contaminated zone. Five samples of willows and associated sediments were taken for metal analysis.
Two combustion experiments were performed with two different *Salix* woods. One was harvested on the sediment disposal site (named “phytoextraction”) whereas the second was bought at a wood producer (named “control”). Woods were dried at 40 °C in a forced air oven until a moisture content of 15 %, thinned out the foliage of, ground and riddled (35 mm). In June 2010, combustion experiments were

carried out with a biomass boiler of 30 KW, built in a similar manner as higher boilers. Sixty three kilograms of “control” and 54 kg of “phytoextraction” were burnt. Combustibles, ashes and gases were analyzed to study trace element behaviour during the combustion process.

Results

Time needed to reduce Cd concentration in the upper 50 cm from 3.16 to 2 mg kg $^{-1}$ sediment should be 23 years. This result is obtained supposing a linear decrease of Cd content and with exportation of leaves and stems.

Cd and Zn concentrations in “control” and “phytoextraction” combustibles, ashes and gases are reported in Table 1. As expected, Cd and Zn concentrations in “phytoextraction” combustible are higher than in “control”. For “phytoextraction” and “control” combustibles, Cd and Zn are more found in the particle fraction of gases than in ashes. Indeed, in ashes, Cd represents less than 1% of Cd combustible content and Zn around 5% of Zn combustible content. In gases, Zn concentrations exceeded 100% mainly due to analysis uncertainties.

Table 1 Cd and Zn concentrations in combustibles (= fuels), ashes and gases.

		Concentrations in mg.kg $^{-1}$ of stems burnt	
		Control	Phytoextraction
Fuels	Cd	1.44	7.34
	Zn	38.01	284.6
Ashes	Cd	0.02	0.06
	Zn	1.54	15.03
Gases	Cd	0.96	6.33
	Zn	50.44	358.1

Discussion

For phytoextraction efficiency, best results are obtained when harvesting of both stems and leaves is supposed. This result is in accordance with those reported by Vangronsveld et al. (2009) on *Salix*.

Inside the boiler, temperature was about 1000°C. During the combustion assay, the boiling points of Cd (767 °C) and Zn (907 °C) were reached which explains that most Cd and Zn are found in fumes and not in ashes. This result confirms those found by Keller et al. (2005) on *Salix* and *Thlaspi* sp. and Bert et al. (2009b) on *Arabidopsis halleri* who performed incineration assays.

In the absence of metal emission limit values for boiler < 2 MW, trace elements in gas emissions were compared with emission limit values for 20 MW combustion plants. Cd and Zn exceeded these values for “phytoextraction”. As a consequence, gases issued from the combustion of *Salix* wood should be treated (e.g. efficient filters) to avoid air pollutant impact. In addition, such wood should be used for non domestic purpose, in industrial or collective boilers.

From the phytoextraction point of view, the best scenario will be to harvest *Salix* before leaves fall. Nevertheless, combustion of leaves and stems may increase metal concentrations in gases and modify combustion performances.

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