Ecological Engineering 94 (2016) 182–189

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Phytoextraction of Na^+ and Cl^- by *Atriplex halimus* L. and *Atriplex hortensis* L.: A promising solution for remediation of road runoff contaminated with deicing salts

Rémi Suaire[a,d], Ivana Durickovic[a,*], Lucie Framont-Terrasse[a], Jean-Yves Leblain[b], Anne-Claire De Rouck[b], Marie-Odile Simonnot[c,d]

[a] Cerema Dter Est, 71 rue de la Grande Haie, 54510 Tomblaine, France
[b] Cerema Dter Nord Picardie, 151 rue de Paris, 02100 Saint-Quentin, France
[c] CNRS, Laboratoire Réactions et Génie des Procédés, UMR 7274, 1 rue Grandville BP20451, 54001 Nancy Cedex, France
[d] Université de Lorraine, Laboratoire Réactions et Génie des Procédés, UMR 7274, 1 rue Grandville, 54001 Nancy Cedex, France

ARTICLE INFO

Article history:
Received 21 October 2015
Received in revised form 5 April 2016
Accepted 22 May 2016
Available online 9 June 2016

Keywords:
Phytoremediation
NaCl
Road runoff
Deicing salt
Halophytes

ABSTRACT

Two halophytes, *Atriplex halimus* and *Atriplex hortensis*, were selected to be tested for phytodesalination of road runoff. A 60 d pot experiment was conducted and germination, survival, growth, and bioaccumulation of NaCl and trace metals by both species were monitored in conditions simulating those encountered in road runoff treatment systems. NaCl concentration was controlled in the hydration solution and ranged from 0 to 2 g/L. Germination and survival of young seedlings were not affected by salinity increase in the tested range. Growth was enhanced by NaCl in the hydration solution for *A. halimus* whereas water content (WC) was significantly and negatively correlated with NaCl concentration. No significant effect of NaCl concentration in the hydration solution was recorded on either growth or WC for *A. hortensis*. Both *Atriplex* species accumulated Na^+ and other cations. Results for Na/K molar ratio indicated that *A. halimus* was not affected as much as *A. hortensis* in its homeostasis and nutritional capacities. These results show that both *Atriplex* species are able to germinate, grow and accumulate sodium when watered with hydration solutions polluted with NaCl. They are therefore good candidates for phytodesalination of road runoff polluted by deicing salts, and should be tested at the pilot scale.

1. Introduction

In order to maintain roads safe for traffic under winter conditions, 200,000–2,000,000 tons of deicing salts are spread on the French road network every year. In France, sodium chloride, (NaCl) represents more than 99% of deicing products (Setra, 2011). Sodium chloride spread on roads is then diluted by precipitation and transferred to the road runoff treatment network. Road runoff waters collected in this network are then transiently stored in retention ponds. One pond, located in the North East of France, has been studied for 3 years (Suaire et al., 2013). Sodium chloride concentrations at the inlet and outlet have been monitored. At the input, sodium concentrations range between 10 and 2900 mg/L, and chloride concentrations between 5 and 4000 mg/L. Almost all the sodium chloride entering the pond is flushed out during early summer and fall. In the output water, sodium concentration range from 10 to 1100 mg/L, and chloride concentrations from 5 to 500 mg/L. These results show that the high loads of dissolved NaCl present in road runoffs are only diluted by their residence time in the retention pond (Suaire et al., 2013). Moreover, only 35% of deicing salts spread on roads are collected in the runoff treatment systems (Pilloy and Tchittarath, 1983). The major part of added deicing salts are eventually released into the environment despite these treatment systems.

There is no regulation to limit the amounts of deicing salts spread on French roads (Setra, 2011). In addition, NaCl used as a deicing salt has recently been added to Canada's list of toxic substances (EnvironnementCanada, 2000), whereas in France it is not yet considered as a pollutant.

Deicing salt release into the environment has been directly correlated with the increase in sodium and chloride concentrations in different environmental compartments (water, soil and biota) (Baeckstroem et al., 2004; Pienitz et al., 2006). This increase has dramatic impacts, e.g. an increase in soil pH and salinity, loss of biodiversity, trace metal remobilization from soils and

* Corresponding author.
E-mail address: ivana.durickovic@cerema.fr (I. Durickovic).

http://dx.doi.org/10.1016/j.ecoleng.2016.05.055
0925-8574/

Table 1
Granulometric characteristics of the sand used for the phytoextraction assays.

Granulometry	Clay (<2 μm)	Fine silt (2/20 μm)	Coarse silt (20/50 μm)	Fine sand (50/200 μm)	Coarse sand (200/2000 μm)
Weight (g/kg)	9	2	2	586	401

sediments and trace metal bioavailability in waters (Kaushal et al., 2005; Ramakrishna and Viraraghavan, 2005; Rodrigues et al., 2010). Desalination of road runoff is thus necessary before release into the environment.

Conventional desalination technologies (e.g. membrane processes) are too expensive and thus only applied to drinking water. Phytoremediation emerges as a promising technique for road runoff treatment and it can be defined as the use of plants and/or associated bacteria to reduce the concentration and the toxicity of an environmental pollutant (Greipsson, 2011; Mench et al., 2009; Morel et al., 2006). This general term includes different processes: phytostabilization, phytodegradation, phytovolatilization and phytoextraction. The last is based on the ability of some plants to extract pollutants from soil or water and concentrate them in their biomass (Greipsson, 2011). Phytodesalination can be defined as the phytoextraction of salts, it consists in using plants able to absorb sodium chloride. Actually, it is absorbed by two main pathways: (i) the salt dissolved in water is absorbed by the roots and may be translocated to the stems and leaves or (ii) salt particles are deposited onto the aerial parts by airborne drift (Trahan and Peterson, 2007).

Halophytes (plants growing on or surviving in saline conditions such as marine estuaries and salt marshes) are suitable for desalination. These plants have developed defense mechanisms against NaCl toxicity; some of them cannot survive in the absence of NaCl (Flowers and Colmer, 2008). These mechanisms include:

- selective ion accumulation or exclusion (Parida and Das, 2005);
- ion transfer control by limiting absorption by the roots and/or translocation to aerial parts (Parida and Das, 2005);
- ion compartmentalization in the plant (specific organs or tolerant structures in leaves) or in the cells (within vacuoles) (Zhu, 2003);
- intracellular compounds synthesis controlling Na^+ and Cl^- flux entering the plant cells (such as prolines or other proteins) (Parida and Das, 2005);
- photosynthetic adaptation in plants that are able to switch to Crassulacean Acid Metabolism (Koreeda et al., 2004).

Phytodesalination has been developed recently and has given promising results in different types of remediation programs such as agricultural soil reclamation (Rabhi et al., 2010; Ravindran et al., 2007) or wastewater desalination (Shelef et al., 2012). Furthermore, halophytes have been successfully tested for phytoremediation of soils polluted by trace metals and for phytodesalination (Manousaki and Kalogerakis, 2011). Their ability to tolerate high salinity levels and cope with severe drought and other environmental stresses make halophytes ideal candidates for phytodesalination of road runoff. Moreover, trace metals are well described road pollutants for which several halophytic species have been reported to possess tolerance and bioaccumulation abilities (Manousaki and Kalogerakis, 2011).

The aim of the research presented in this paper was to investigate the potential of two halophyte species, *Atriplex halimus* L. and *Atriplex hortensis* L., for road runoff desalination. These species are able to accumulate NaCl (Kachout et al., 2011; Lefèvre et al., 2009). Moreover, *A. halimus* is known for its metal accumulation abilities and water stress tolerance (Manousaki and Kalogerakis, 2009). Therefore, even though both species are well known salt tolerant species and *A. halimus* has already been suggested and tested for remediation of heavy metals, they both yet had to be tested for tolerance and accumulation under low salinity (representative of road runoff polluted by deicing salts). Moreover, the use of *A. hortensis* for remediation and both plants for remediation of road runoff is, to the best of our knowledge, a first contribution.

Pot experiments were carried out for 60 d to monitor germination rates, growth and survival of both *Atriplex* species, as well as phytoextraction of NaCl and trace metals (e.g. Cd, Cr, Cu, Ni, Pb and Zn, the main metallic road pollutants). Experimental conditions were controlled and a salinity gradient of the hydration solutions was chosen to represent the salinity previously measured at the retention pond outlet (Suaire et al., 2013). The influence of salinity on several components of fitness (germination, seedling survival and growth) was assessed during the assay, as well as bioaccumulation at the end of the trial. This experimental design allowed comparison of the two *Atriplex* species exposed to salinity reflecting what is encountered in runoff retention ponds.

2. Materials and methods

2.1. Seeds collection and conservation

Uncoated indigenous seeds of *A. hortensis* (Ducruttet™, France) and *A. halimus* (Alsagarden™, France) were stored at 4 °C in dry conditions until the beginning of the assay.

2.2. Sand culture

Sand was supplied by Castorama™ Company (France). Textural analyses were performed to measure the distribution of five size fractions (Table 1).

Agronomic parameters were measured by the Laboratoire d'Analyses des Sols (INRA, Arras, France).

pH was measured in water. Total carbonate was obtained from the emitted volume of CO_2 during sample acidification with HCl (NF ISO 10693).

Available organic carbon concentration was measured after extraction with a 0.01 mol/L $CaCl_2$ solution (according to the method developed by Laboratoire d'Analyses des Sols, INRA Arras, France).

Total nitrogen was obtained by dry combustion at 1000 °C (NF ISO 13878), $[P_2O_5]$ was obtained by the Olsen method (NF ISO 11263).

The analyses showed that this sand had a very low content of carbon, no carbonates, nitrate and phosphate (Table 2). Nutrients

Table 2
Main characteristics of the sand used for the phytoextraction assays.

Physico-chemical characteristics	
pH	5.99
$CaCO_3$ (g/kg)	<Detection limit
CEC (cmol+/kg)	0.391
Available organic carbon (μg/g)	16.5
Total N (g/kg)	<Detection limit
P_2O_5 (g/kg)	<Detection limit
Heavy metals extracted with a $CaCl_2$ solution at 0.01 mol/L	
Cd (μg/g)	0.0016
Cu (μg/g)	<Detection limit
Ni (μg/g)	<Detection limit
Zn (μg/g)	0.0126