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New parameters for a better evaluation of vegetative bioremediation, leaching, and phytodesalination

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ABSTRACT

Vegetative bioremediation of calcareous sodic and saline-sodic soils is a biological approach for soil desalination by plants. It is based on three main processes: (*i*) sodium release from cation exchange sites, (*ii*) its leaching, and/or (*iii*) phytodesalination (Na^+ uptake by plant roots and its accumulation in shoots). Leaching needs sufficient rainfall and/or adequate irrigation. Thus, under non-leaching conditions, phytodesalination is the only existing process in terms of sodium removal. Several works tried to evaluate these processes; used plants were grown in field, in lysimeters, or in non-perforated pots. The evaluation of vegetative bioremediation, leaching, and phytodesalination was mainly based on plant analyses (including biomass production, sodium accumulation, test culture, and co-culture) and soil analyses (porosity, salinity, sodicity…). Nevertheless, used parameters are not enough to ensure comparisons between results found in different investigations. The present study introduces new parameters like phytodesalination efficiency, yield, and rate as well as vegetative bioremediation and leaching yields and rates. Our study is also illustrated by an estimation of all parameters for several previously-published data from our own works and those of other authors. Obtained results showed usefulness of these parameters and some of them can be extended to heavy metal phytoexraction.

1. Introduction

Salt-affected soils constitute a concern for at least 75 countries and it is expected that every day, about 2000 ha of irrigated land is degraded by salts (Qadir et al., 2014). According to Richards (1954), salt-affected soils can be divided into three groups: saline, sodic, and saline sodic soils. Their classification was based on two main concepts: salinity and sodicity that represent unique and distinct descriptions of all impacts of soluble salts (including NaCl) on soils (van de Graaff and Patterson, 2001). Salinity is a function of all electrolytes and is measured by electrical conductivity (EC), whereas sodicity stands for the proportion of sodium in the whole cations and is measured by the Exchangeable Sodium Percentage (ESP) or by the Sodium Adsorption Ratio (SAR) (van de Graaff and Patterson, 2001; Shahid, 2002). Several hydraulic, physical, and chemical methods were developed for the reclamation of these soils (Shahid, 2002). The biological approach include organic manure, crop rotation, salt-tolerant crops (Shahid, 2002), and vegetative bioremediation (Qadir and Oster, 2004).

Vegetative bioremediation is an emerging issue that was shown to be an efficient tool of reclamation for calcareous sodic and saline-sodic soils. It is based on the use of a plant to remove salt from the arable layer. This biological approach is a function of four factors: (i) an increase in partial pressure of CO_2 in the soil through root respiration and microorganism activities, (ii) a release of protons, especially in the case of N_2-fixing Legumes as associated with rhizobia, (iii) an increase in soil porosity by root expansion, and (iv) an accumulation of sodium ions in plant shoots (See Qadir and Oster, 2004). These 4 factors are responsible for 3 main sub-processes that constitute the whole process of vegetative bioremediation (Fig. 1):

Adsorbed sodium release: it depends on the two first factors that favor $CaCO_3$ dissolution and make easier the substitution of Na^+ cations by Ca^{2+} ones in the cation exchange sites. This increases sodium concentration in the soil solution.
Released sodium leaching: the third factor allows sodium leaching since it ameliorates soil physical properties. The latter were shown to be affected by sodicity (Srivastava et al. 2014).
Phytodesalination: a fraction of released sodium is absorbed by plant roots and accumulated in its aerial organs.

According to Qadir and Oster (2004), vegetative bioremediation is tributary of adequate rainfall and/or appropriate irrigation that allow Na^+ leaching. For this reason, they neglected phytodesalination

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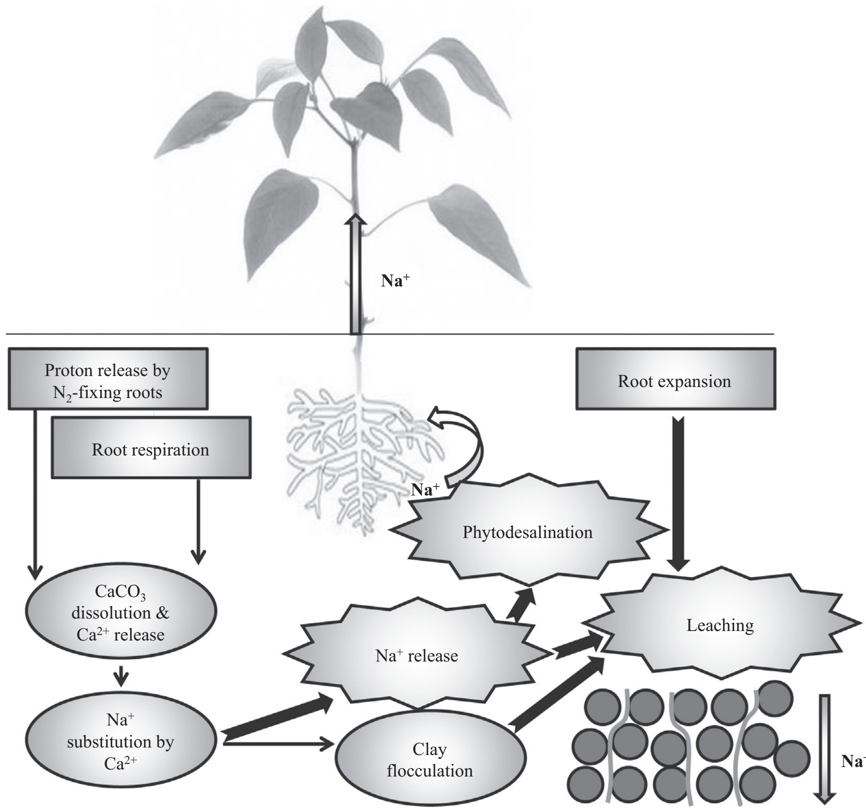

Fig. 1. Schematic representation of vegetative bioremediation process and its sub-processes: Na^+ release, leaching, and phytodesalination.

fraction when discussing the whole removed sodium quantity from the soil. On the contrary, some other authors (Zahran and Abdel Wahid, 1982; Helalia et al., 1990; Zhao, 1991; Zhao et al. 2001, 2005; Graifenberg et al., 2003; Tester and Davenport, 2003; Kushiev et al., 2005; Ravindran et al., 2007; Rabhi et al., 2009, 2010a, 2010b; Jlassi et al., 2013) found that appropriate plants can accumulate high Na^+ quantities within their shoots, which gives importance to the phytodesalination sub-process. Actually, arid and semi-arid regions are the most suffering areas from salinity/sodicity problems and are characterized by a marked scarcity of good quality irrigation water (Munns and Tester, 2008). Hence, to deal with vegetative bioremediation, it is necessary to have sufficient bioclimatic data as well as information related to irrigation water availability and quality.

Several works were performed to evaluate the capacity of some plants to enhance sodium leaching with the aim to decrease soil salinity/sodicity (Qadir and Oster, 2004). Two major culture types were considered: in lysimeters and in field. A lysimeter is a specific pot equipped with a system to collect water on the bottom used to calculate evapotranspiration through the amounts of received and leached water. Its use in leaching experiments allows leachate collection for quantification and further analyses. For field leaching experiments, a drainage system is installed to collect drained water. In both lysimeter and field investigations, authors used a variety of plants and specific parameters. In general, species with high biomass production together with the ability to withstand moderate soil salinity/sodicity and periodic inundation were shown to be efficient in sodium leaching from their root zone (Qadir and Oster, 2004). Several plants were tested for their capacity to enhance Na^+ leaching such as *Leptochloa fusca* (L.) Kunth. (Qadir et al., 1996), *Medicago sativa* L., *Sesbania aculeata* L. (Ahmad et al., 1990), *Oryza sativa* L. (Iwasaki, 1987), and *Glycyrrhiza glabra* (Kushiev et al., 2005).

In the same way, a variety of investigations were realized to estimate the role of phytodesalination in decreasing soil salinity/sodicity. These works were based on the aptitude of some plants to accumulate salts within their shoots. The tested plants were in general salt-accumulating halophytes such as *Suaeda salsa* (Zhao, 1991), *Salsola soda*, *Portulaca oleracea* (Graifenberg et al., 2003), *Suaeda maritima*, *Clerodendron inerme*, *Ipomoea pes-caprae*, *Heliotropium curassavicum*, *Excoecaria agallocha* (Ravindran et al., 2007), *Sesuvium portulacastrum* (Ravindran et al., 2007, Rabhi et al., 2009 and 2010a), *Arthrocnemum indicum* (or *Tecticornia indica*), and *Suaeda fruticosa* (Rabhi et al. 2009, 2010b). They were grown either in pots under non-leaching conditions or in field. To work under non-leaching conditions, authors usually use either non-perforated pots or non-excessive irrigations (not exceeding 50% of the field capacity of the soil).

In literature, we did not find enough parameters allowing comparisons between plants from different studies although some authors mentioned percentages of salt removal (Qadir and Oster, 2004; Rabhi et al., 2009; Rabhi et al., 2010a, 2010b). The only parameter that was defined and used was phytodesalination capacity (Rabhi et al., 2010a, 2010b). In the present work, we introduce some new useful parameters that make easier comparative studies between plants used in vegetative bioremediation, taking into account the relationships between sodium leaching and phytodesalination on the one side and plant and soil statuses on the other side.

2. Methods

2.1. Phytodesalination capacity (C_{PH})

It measures the quantity of sodium accumulated in shoots of a plant species or more than a species in a "vegetative bioremediation" culture per hectare (Rabhi et al., 2010a). In other words, C_{PH} quantifies sodium accumulated in shoots of a given area in a given moment. Hence, it can vary with time following the variations in