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Vanadium uptake and translocation in dominant plant species on an urban coastal brownfield site

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HIGHLIGHTS

- Factors that control plant V uptake and translocation are evaluated.
- Root uptake and translocation efficiency do not significantly vary with the species.
- Root V concentration increases with soil potentially leachable V content.
- Excessive V in the soil can inhibit plant root V absorption capacity.
- Vanadium translocation to plant aerial parts depends on individual plant response.

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ABSTRACT

This study, conducted at a brownfield site in New Jersey, USA, investigated factors controlling V uptake and translocation in naturally assembled plant species. Six dominant species were collected from 22 stations in the study area. We found that V concentration in the plants decreased in a sequence of root > leaf > stem. No significant differences were found among the six dominant plant species in terms of root V uptake efficiency (V BCF) and V root to shoot translocation (V TF). Although soil pH and TOC did not show significant impact on V accumulation in the roots, soil labile V content showed significant positive linear correlation ($p < 0.05$) with plant root V. Nonlinear regression analysis indicates that V translocation efficiency decreases with increasing concentration in the soil, implying that excessive V in the soil might inhibit its absorption by the plant roots. Leaf V concentration was constant in all the plant species regardless of the variation in soil V concentration. The study shows that the six dominant plant species on site had limited amount of V translocated to the aerial part of the plant.

1. Introduction

Urban brownfields are abandoned, idle or under-used commercial and industrial sites where on-site contamination has inhibited redevelopment due to potential environmental and social risks (Gallagher et al., 2008). In addition, soil metal contamination in urban brownfields has aroused great environmental and public health concerns (Albering et al., 1999; Qian et al., 2011; Luo et al., 2012). Remediation of the urban brownfield is becoming increasingly important in post-industrial landscapes. Compared to the traditional chemical/physical remediation approaches for metal-contaminated soils, phytoremediation/phytostabilization offers a cost-effective and environmental friendly solution (Ferro et al., 1999; Glass, 1999; Wu et al., 2010; Desouki and Feng, 2012). Previous studies indicate that there are several processes involved in metal uptake by plants from soils and metal translocation within the plants. These processes include uptake of bioavailable metals, metal chelation and compartmentation in roots, metal translocation from root to shoot, and metal chelation and compartmentation in leaves (Weis and Weis, 2004; Pilon-Smits, 2005; Colangelo and Guerinot, 2006; Wu et al., 2010; Qian et al., 2012). While soil metal bioavailability determines the potential uptake, soil pH, redox potential, and total organic matter content control the release of metal from different fractions of the soil metals (Driscoll et al., 1994; Evangelou, 1998; Pilon-Smits, 2005; Sposito, 2008; Violante et al., 2010). Plant uptake of bioavailable metal ions occurs at the interface between rhizosphere soil and root surface. Metals are then accumulated in the root or further translocated to the aerial tissue through vascular tissue (Pilon-Smits, 2005). It has been observed that high metal concentrations in the contaminated brownfield can have negative impact on

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metabolism of the plants (Larsson et al., 2013). When the concentrations of soil metals exceed the tolerance threshold, metabolism is impacted and the plant will likely be excluded from the vegetation assemblage (Gallagher et al., 2008). Many species however, can tolerate excessive amount of metals in the environment with strategies such as exclusion and detoxification/isolation (Baker, 1981; Ehlken and Kirchner, 2002; Remon et al., 2013). The tolerance strategy further determines metal concentrations in different tissue parts of a plant. As an excluder, a plant is capable of inhibiting the uptake of certain metals. In contrast, as an accumulator a plant is capable of detoxifying or isolating certain metals and accumulating high concentration of the metals in the aerial tissue (Ehlken and Kirchner, 2002; Pilon-Smits, 2005; Tangahu et al., 2011). Due to biological magnification, high metal concentrations in the aerial plant tissue can potentially result in both ecological and public health risks. It is therefore crucial to understand how soil properties and plant species impact metal assimilation when evaluating brownfield bioremediation, mitigation and restoration.

Vanadium (V) is a trace element ranking as the 22nd most abundant element in the earth's crust. Excessive amount of V in human body can increase the possibility of lung cancer occurrence. It can also cause nausea, mild diarrhea, and stomach cramps in human body (ATSDR, 2012). Naturally, V co-exists with minerals and fossil fuels in oxidation states of 3^+ and 5^+, yet naturally-occurring V enrichment is rarely found (ATSDR, 2012). It was reported that approximately 2.30×10^8 kg of V was annually introduced to the environment through human activities, of which 1.32×10^8 kg was deposited on the land and resulted in elevated soil V concentration (Hope, 1997). Fuel combustion is one of the most important anthropogenic V sources in the environment because V can be found in most of coal and crude oil products (Byerrum et al., 1974; Hope, 1994, 1997; Soldi et al., 1996; Chouparova et al., 2004; Nadal et al., 2004; Teng et al., 2011a). As a result, soil V concentration in the fuel combustion venues (i.e. areas close to oil refineries, fuel powered facilities, and heavy automobile traffic) is usually much higher than natural abundance (Soldi et al., 1996; Nadal et al., 2004; Al-Surrayai et al., 2009; Khan et al., 2011; Teng et al., 2011a). Vanadium flux from soil to land biota approximately ranges from 8.14×10^7 kg y^{-1} to 2.58×10^8 kg y^{-1} (Hope, 1997). In areas with high soil V concentration, assimilation of V by plants is considered as the major V flux from soil to biota because plants have the highest direct exposure to the soil (EPA, 2003). The role of soil properties and plant species in V assimilation in the plant has been studied and the results vary from case to case. Both soil pH and TOC have been shown to have a significant effect on V bioavailability in the soil (Połedniok and Buhl, 2003; Teng et al., 2011b; Agnieszka and Barbara, 2012). The accumulation of V in plant tissue also depends on plant species and soil V content. For example, V concentration in vegetable and grass tissues around a thermal power plant ranged from 2.95 ± 0.02 μg g^{-1} to 13.98 ± 0.11 μg g^{-1}, which has the potential to impact human health (Khan et al., 2011). Połedniok and Buhl (2003) found that V concentrations were 65 ± 20 μg g^{-1} and 22 ± 4 μg g^{-1} in the bush bean (*Phaseolus vulgaris* L.) root and aerial tissue, respectively, even though the extractable V concentration in the soil was 0.6 ± 0.05 μg g^{-1}. A study on plants growing in an industrial city in China revealed that V concentrations ranged from 2.6 μg g^{-1} to 42.8 μg g^{-1} in the leaf tissue of 36 plant samples and 88.2 μg g^{-1} to 868.4 μg g^{-1} in the soil, respectively (Teng et al., 2011b).

The interior section of the Liberty State Park contains a brownfield and is located in the densely populated city of Jersey City close to the borough of Manhattan, New York. Until its acquisition by the State of New Jersey in 1969, the site had been used for railroad transportation and coal storage for over a century. The historical coal combustion caused V enrichment in the soil, a condition typical of many post-industrial sites of from that era. A better understanding of the assimilation of V within the novel vegetative assemblages of such sites is critical to the assessment of the ecological risk associated with the use of phytostabilization as a mitigation strategy. In this study we explore V plant assimilation by characterizing the roles of soil properties, seasonal variations, and plant species in V root uptake and root to shoot translocation. We hypothesized, based on our previous work with other metals that V would be restricted primarily to the root system of the targeted species and that translocation to the aerial section of the plant would occur at significantly reduced concentrations.

2. Methodology

2.1. Study site

The Liberty State Park in northern New Jersey consists of approximately 5 km^2 (1156 acres) of protected land and water areas. It was originally a saltmarsh mud flat and shellfish bed under the water, which was later filled with municipal, commercial and industrial waste. By 1836 the Central Railroad of New Jersey (CRRNJ) began operations on the site. The site was used as the railroad center and freight yard for transportation and goods storage until the late 1960s when the New Jersey Department of Environmental Protection began to acquire the land, and transformed it into a public park. Our study site was an area of ~1 km^2 (251 acres) within the center of the Liberty State Park (Fig. 1). Due to the nature of the fill materials, the previous use as a coal storage facility, coal transport and incomplete combustion of fossil fuels, the freight yard was contaminated by various metals. The metals are unevenly distributed on this site and the concentrations of most metals are above the New Jersey Residential Soil Cleanup Criteria (NJDEP, 1999). Therefore, the study site has been isolated from public and left undeveloped since it was transferred to the New Jersey Division of Parks and Forestry in 1970 (Gallagher et al., 2008).

2.2. Sample collection

The first sampling campaign was conducted in June 2005 with twenty-two sampling sites selected based on the species dominance and vegetation assemblage patterns. Six dominant plant species growing on site, including three perennial herbaceous species (*Artemisia vulgaris* L., *Polygonum cuspidatum* Siebold & Zucc. and *Phragmites australis* (Cav.) Trin. ex Steud.) and three deciduous woody species (*Rhus copallinum* L., *Betula populifolia* Marshall and *Populus deltoides* W. Bartram ex Marshall), were chosen for this study. The dominant plant species at each sampling site were identified and triplicate root, stem and leaf samples of each were collected and stored in clean polypropylene containers. Soil samples around the plants from each of the 22 sampling sites were also collected in the area of the greatest root density. Detritus such as gravels and roots/leaves were removed from the soil samples before the soils were stored in labeled polypropylene containers and kept at 4 °C for further treatment and analysis. Soil pH was measured using a LaMotte field soil pH meter. A detailed description of the sampling procedures can be found in Gallagher et al. (2008).

The second sampling campaign was conducted in May and November 2011 and *P. australis* root tissue samples were collected in triplicates from two (Sites TP-1 and TP-25) out of 22 sampling sites based on the metal concentration levels in the soils determined by previous studies (Gallagher et al., 2008). *P. australis* roots were dug out of the ground with the soil around it and stored in clean Ziploc bags. Soil core samples (approximately10 cm in length) around the sampled plants were also collected. The core samples were capped on both ends of the core containers after the cores were recovered. Both plant and soil samples were temporarily stored in the coolers, transported to the laboratory and stored at 4 °C before the further treatment. During the sample treatment, bulk soils on the surface of root samples were initially removed by hand. The root samples were then rinsed with tap water. Finally, the clean root samples were rinsed with Milli-Q water and stored at 4 °C in a refrigerator. Soil core samples were sectioned in the