Nanoscale measurement of trace element distributions in *Spartina alterniflora* root tissue during dormancy

Huan Feng, Yu Qian, J. Kirk Cochran, Qingzhi Zhu, Wen Hu, Hanfei Yan, Li Li, Xiaojing Huang, Yong S. Chu, Houjun Liu, Shinjae Yoo & Chang-Jun Liu

This paper reports a nanometer-scale investigation of trace element (As, Ca, Cr, Cu, Fe, Mn, Ni, S and Zn) distributions in the root system *Spartina alterniflora* during dormancy. The sample was collected on a salt marsh island in Jamaica Bay, New York, in April 2015 and the root was cross-sectioned with 10μm resolution. Synchrotron X-ray nanofluorescence was applied to map the trace element distributions in selected areas of the root epidermis and endodermis. The sampling resolution was 60 nm to increase the measurement accuracy and reduce the uncertainty. The results indicate that the elemental concentrations in the epidermis, outer endodermis and inner endodermis are significantly (p < 0.01) different. The root endodermis has relatively higher concentrations of these elements than the root epidermis. Furthermore, this high resolution measurement indicates that the elemental concentrations in the outer endodermis are significantly (p < 0.01) higher than those in the inner endodermis. These results suggest that the Casparian strip may play a role in governing the aplastic transport of these elements. Pearson correlation analysis on the average concentrations of each element in the selected areas shows that most of the elements are significantly (p < 0.05) correlated, which suggests that these elements may share the same transport pathways.

It has been reported that many plants acquire metals and other trace elements from the rhizosphere and regulate their uptake properties within the root system. Thus, investigation of transport mechanisms that control the mobility and storage of these elements in the roots is important. As a survival strategy exhibited by many plant species, dormancy is a period of arrested plant growth in plant physiology, enabling the plants to survive conditions such as winter cold periods or dry seasons. Many plant species exhibit dormancy and have a biological clock that tells them when to slow activity and prepare soft tissues for a period of freezing temperatures or water shortage. The concentrations and distributions of elements in the plant root during dormancy are therefore in a quasi-steady state. This provides an opportunity to investigate the concentrations and distributions of these elements in the root system and the relationships among them. For over a decade, the role of Fe plaque in controlling metal mobility in the rhizosphere has been an issue of debate. Investigation of the function of Fe plaque in metal transport processes can aid in understanding biogeochemical cycling of metals by plant roots, but traditional methods of measuring Fe plaque have technical limitations. For example, the traditional dithionite–citrate–bicarbonate (DCB) method that was used to extract Fe plaque in the root in previous studies, only extracts Fe plaque on the root surface. This method is thus limited in extracting Fe from the entire root tissues and in mapping the distribution of Fe in the root cross-section. Therefore, it is difficult to fully understand the function of Fe plaque inside the root, especially around the Casparian strip, without high resolution measurements.
High-resolution nanoscale mapping techniques, such as the secondary ion mass spectrometry (SIMS) and synchrotron X-ray microfluorescence (μXRF), are useful for characterizing trace element concentrations and distributions in plants. Moore et al.14 summarized the application of NanoSIMS technique for determination of elemental distributions in plants14. Although NanoSIMS has a distinct advantage over synchrotron X-ray techniques in being able to detect light elements, the technique is not effective in studying heavy metals (e.g., Cd, Mn and Zn) due to its low ion yield14. The synchrotron μXRF technique has the advantage of overcoming this drawback of NanoSIMS and other traditional methods (e.g., DCB method) and has been successfully applied to studying metal concentrations and distributions in plants with micrometer scale resolution15–23.

Generally, a bulk chemistry approach gives information that averages over different components of the plants. Unlike conventional wet chemical analyses, the synchrotron-based techniques have demonstrated advantages in sample preparation and measurement. Synchrotron radiation measurement gives detailed views of the accumulation of metals and their chemistry on individual spots or within small areas in the plants including roots, stems, and leaves18–23. For example, a multilayer Laue lens (MLL)-based scanning hard-X-ray microscope24 has been developed at the Hard X-ray Nanoprobe (HXN) beamline at National Synchrotron Light Source II (NSLS-II). This beamline can provide an ultra-high spatial resolution measurement down to about 10 nm level for various scientific applications25–27. The unique feature of this high detection sensitivity and resolution measurement is to make each pixel size small enough to focus on a specific small area in the root tissue during the measurement. This feature can lead to a better understanding of the transport and distributions of the trace elements in the plants. Thus, synchrotron X-ray nanoprobe measurements can provide new insights into the mechanisms taking place in the plants during the course of metal uptake and transport at levels where interactions can be understood.

Here, we apply the synchrotron X-ray nanoprobe technique to investigate trace element distributions in the root tissue of the salt marsh cord grass, Spartina alterniflora, from Jamaica Bay, New York. The purpose of this study is to better understand the ecological function of the salt marsh ecosystems as habitats and nurseries for marine life.

Results
Concentrations and spatial distributions of trace elements in the root system. Examples of the distributions of As, Ca, Cr, Cu, Fe, Mn, Ni, S and Zn in each selected area in the epidermis (Areas S2493, S2496 and S2498) and the endodermis (Areas S2504, S2505, S2416 and S2418) are shown in Fig. 1 and Supplemental Information Figures S1–S6. Statistical analyses of the elemental concentrations in each selected area are summarized in Table 1. The nanometer scale high-resolution mapping indicates localized high concentration areas (“hot spots”) of these elements in the root tissue. For example, very high Fe concentration was found in several areas in both the epidermis and endodermis. Sulfur (S) showed a distribution pattern very similar to Fe in both epidermis and endodermis. The result suggests that Fe and S may form Fe-S compounds or precipitates and be deposited in the root tissue. The distribution pattern of Ca in the root epidermis is also very similar to that of Fe. Both Cr and Ni were found relatively evenly distributed in the epidermis and endodermis. Other elements (As, Cu, Mn and Zn) showed patchiness, with areas of high concentrations in both epidermis and endodermis (Figs 1 and S1–S6). The results suggest that the distributions of these elements in the root tissue are not uniform. In further data analysis, the seven areas were clustered according to their locations in the root, i.e., epidermis (S2493, S2496 and S2498), outer endodermis (S2504 and S2516), and inner endodermis (S2505 and S2518). As shown in Fig. 2, the median concentrations of As, Ca, Cr, Cu, Fe, Mn, Ni, S and Zn in the endodermis were generally higher than those in the epidermis although the concentrations of these elements in each selected area of the root epidermis and endodermis vary widely. Furthermore, the median concentrations of these trace elements in the outer endodermis are generally higher than those in the inner endodermis (Fig. 2). The results show a significant (p < 0.01) difference, based on a two-sample t-test, in the elemental concentrations between the inner endodermis and outer endodermis (Table 2).

Statistical analyses of trace elements in the root system and relationship with Fe. A one-way analysis of variables (ANOVA) was performed to examine the differences in concentrations among the epidermis, outer endodermis and inner endodermis. The results show statistically significant (p < 0.01) differences in the elemental concentrations among these layers (Table 3). Based on the mean concentration, which is an average of the concentrations in each selected area in the root tissue (Table 1), Pearson liner correlation analysis was performed to examine the relationship between the trace elements (As, Ca, Cr, Cu, Fe, Mn, Ni, S and Zn). The results show that most of these metals are significantly correlated at the 5% two-tailed significance level (Table 4). Hierarchical cluster analysis, which is also based the average concentration of each individual area in the root tissue (Table 1), shows that these elements (As, Ca, Cr, Cu, Fe, Mn, Ni, S and Zn) can be divided into three clusters, i.e., Cu, Ni and Cr; Mn, As and S; and Zn, Ca and Fe (Fig. 3).

Discussion
Wetland plants need essential nutrients for their growth. Commonly, they uptake and transport the nutrients from root epidermis to vascular bundle and then to stem and leaf5,26,28. Therefore, the root system is an active site for absorption of nutrients from the rhizosphere6–12. Trace elements such as Fe, Mn, Cu, Ni and Zn are essential micronutrients for plant growth, while As and Cr are not. Thus, transport and accumulations of these metals in the root tissues can be different4,5,33. Because non-essential elements, such as As and Cr, are not necessary for plant growth13,14, they are usually not actively taken up from rhizosphere and transported within the plant tissues.

Iron is an example of a micronutrient element for plants, and as a consequence, should be actively taken up. Previous synchrotron X-ray measurement indicated that Fe could be present in the root tissue as Fe nanoparticles, dominated by Fe3+. More specifically, some prior studies reported that Fe accumulations did not occur to any extent within the outer epidermal wall or cortex of Spartina alterniflora roots15. The penetration depth of Fe into
the roots was only up to 15–17 μm, a depth approximating the thickness of an epidermal cell36. In contrast, however, other studies reported that Fe was found in the cells of the root rhizodermis, exodermis and endodermis, including the Casparian strip37. Our high resolution synchrotron nano-XRF measurements show that Fe not only deposits in the epidermis, but also has considerable deposition around the Casparian strip in the endodermis. Previous studies also suggested that Fe plaque could serve as a barrier preventing metals from entering plant roots37–39, while others suggested that Fe plaque should not be the main barrier 10. Our results show significant (p < 0.05) correlations between the metals (As, Ca, Cr, Mn and Zn) and Fe in both epidermal and endodermal root tissue (Fig. 4), suggesting that these trace elements are scavenged by Fe. In contrast, Cu and Ni show no significant (p > 0.05) correlations with Fe (Fig. 4), implying that scavenging by Fe is not a main barrier to these elements during their transport.

Early studies found that the rhizosphere is a favorable environment for microbial communities40–43. As a consequence of early diagenetic reactions in the salt marsh system, a sulfide phase may assist in explaining the observed metal transport and distributions. Bacterial sulfate reduction can result in elevated hydrogen sulfide concentrations in marsh peat pore water, causing the precipitation of metal sulfides (e.g., FeS). Indeed, the co-existence of Fe and S in the root tissue (Fig. 1) and the significant (p < 0.01) correlation between Fe and S (Fig. 5) suggest the possible presence of an Fe–S phase.

Iron-sulfur (Fe–S) clusters built of iron and acid-labile sulfide are ubiquitous/central prosthetic groups required to sustain fundamental life processes. These include photosynthesis, respiration and nitrogen fixation44.
The main function of Fe–S proteins is electron transfer through the redox cycling of Fe (Fe²⁺ or Fe³⁺). It has been reported that Fe–S cluster biosynthesis involves complex biochemical pathways, and the chemical properties of the Fe–S cluster enable the associated proteins to be involved in metabolic processes. Therefore, FeS and/or Fe-S clusters could be in part responsible for the strong correlations of these elements such as As, Ca, Cr, Mn, Ni and Zn with S (Fig. 6). Although Cu does not show a significant ($p < 0.05$) correlation with S (Fig. 6), it does show significant ($p < 0.05$) correlations with Mn (Table 4).

Indeed, the present study shows that all the elements (As, Ca, Cr, Cu, Fe, Ni, S and Zn) are significantly ($p < 0.05$) correlated with Mn (Table 4). Like Fe, Mn is an important essential micronutrient for wetland plants to create the organic compounds that make up plant tissue or drive growth processes. It is a structural component of the chloroplasts where photosynthesis occurs. Therefore, Mn is irreplaceable and necessary for plant growth and development.

Table 1. Statistical results of the concentrations of trace elements in each selected area in S. alterniflora root: median, mean, standard deviation and variation range. The concentration unit is in counts per second (cps). S2493, S2496 and S2498 are measured in the epidermis, and S2504, S2505, S2516 and S2518 are in the endodermis. (Abbreviation: $n =$ number of data points, min = minimum, max = maximum, and s.d. = standard deviation).

 aument de Fe–S proteínas es el paso de electrones a través de la redox cíclica de Fe (Fe²⁺ o Fe³⁺). Se ha reportado que la biosíntesis de los complejos Fe–S involucra vías bioquímicas complejas, y las propiedades químicas de los complejos Fe–S permiten que los proteínas asociadas estén involucradas en procesos metabólicos. Por lo tanto, FeS y/o Fe-S pueden ser parte responsable de las fuertes correlaciones de estos elementos como As, Ca, Cr, Mn, Ni y Zn con S (Fig. 6). Aunque Cu no muestra una correlación significativa ($p < 0.05$) con S (Fig. 6), sí muestra una correlación significativa ($p < 0.05$) con Mn (Tabla 4).

De hecho, el estudio actual muestra que todos los elementos (As, Ca, Cr, Cu, Fe, Ni, S y Zn) están significativamente ($p < 0.05$) correlacionados con Mn (Tabla 4). Como Fe, Mn es un nutriente esencial importante para plantas de humedal que crean los compuestos orgánicos que componen la materia vegetal o impulsan procesos de crecimiento. Es un componente estructural de las cloroplastos donde ocurre la fotosíntesis. Por lo tanto, Mn es irremplazable y necesario para el crecimiento y desarrollo vegetal.

| Scan # | Statistics | As | Ca | Cr | Cu | Fe | Mn | Ni | S | Zn |
|-------|------------|----|----|----|----|----|----|----|----|----|
| S2493 | n 10201    |    |    |    |    |    |    |    |    |    |
| S2493 | min 0.000  |    |    |    |    |    |    |    |    |    |
| S2493 | max 17.4   |    |    |    |    |    |    |    |    |    |
| S2493 | median 0.05|    |    |    |    |    |    |    |    |    |
| S2493 | s.d. 1.15  |    |    |    |    |    |    |    |    |    |
| S2496 | n 10201    |    |    |    |    |    |    |    |    |    |
| S2496 | min 0.000  |    |    |    |    |    |    |    |    |    |
| S2496 | max 17.4   |    |    |    |    |    |    |    |    |    |
| S2496 | median 0.05|    |    |    |    |    |    |    |    |    |
| S2496 | s.d. 1.15  |    |    |    |    |    |    |    |    |    |
| S2498 | n 10201    |    |    |    |    |    |    |    |    |    |
| S2498 | min 0.000  |    |    |    |    |    |    |    |    |    |
| S2498 | max 17.4   |    |    |    |    |    |    |    |    |    |
| S2498 | median 0.05|    |    |    |    |    |    |    |    |    |
| S2498 | s.d. 1.15  |    |    |    |    |    |    |    |    |    |
| S2504 | n 10201    |    |    |    |    |    |    |    |    |    |
| S2504 | min 0.000  |    |    |    |    |    |    |    |    |    |
| S2504 | max 17.4   |    |    |    |    |    |    |    |    |    |
| S2504 | median 0.05|    |    |    |    |    |    |    |    |    |
| S2504 | s.d. 1.15  |    |    |    |    |    |    |    |    |    |
| S2505 | n 10201    |    |    |    |    |    |    |    |    |    |
| S2505 | min 0.000  |    |    |    |    |    |    |    |    |    |
| S2505 | max 17.4   |    |    |    |    |    |    |    |    |    |
| S2505 | median 0.05|    |    |    |    |    |    |    |    |    |
| S2505 | s.d. 1.15  |    |    |    |    |    |    |    |    |    |
| S2506 | n 10201    |    |    |    |    |    |    |    |    |    |
| S2506 | min 0.000  |    |    |    |    |    |    |    |    |    |
| S2506 | max 17.4   |    |    |    |    |    |    |    |    |    |
| S2506 | median 0.05|    |    |    |    |    |    |    |    |    |
| S2506 | s.d. 1.15  |    |    |    |    |    |    |    |    |    |
| S2507 | n 10201    |    |    |    |    |    |    |    |    |    |
| S2507 | min 0.000  |    |    |    |    |    |    |    |    |    |
| S2507 | max 17.4   |    |    |    |    |    |    |    |    |    |
| S2507 | median 0.05|    |    |    |    |    |    |    |    |    |
| S2507 | s.d. 1.15  |    |    |    |    |    |    |    |    |    |
| S2518 | n 10201    |    |    |    |    |    |    |    |    |    |
| S2518 | min 0.000  |    |    |    |    |    |    |    |    |    |
| S2518 | max 17.4   |    |    |    |    |    |    |    |    |    |
| S2518 | median 0.05|    |    |    |    |    |    |    |    |    |
| S2518 | s.d. 1.15  |    |    |    |    |    |    |    |    |    |

The concentration unit is in counts per second (cps). S2493, S2496 and S2498 are measured in the epidermis, and S2504, S2505, S2516 and S2518 are in the endodermis. (Abbreviation: $n =$ number of data points, min = minimum, max = maximum, and s.d. = standard deviation).
Figure 2. Box plot of As, Ca, Cr, Cu, Fe, Mn, Ni, S and Zn concentrations and variations in the root epidermis and the outer and inner endodermis around the Casparian strip. The results indicate that these elements in outer endodermis have relatively higher concentrations than that in the other layers, suggesting that the Casparian strip plays a role in the elemental transport in the root system.

| Element | Tissue component  | Number of data | Mean  | Standard deviation | p-value |
|---------|-------------------|----------------|-------|--------------------|---------|
| As      | Inner endodermis  | 20402          | 2.79  | 2.23               | 0.000   |
|         | Outer endodermis  | 19834          | 5.25  | 3.01               |         |
| Ca      | Inner endodermis  | 20402          | 9.24  | 9.44               | 0.000   |
|         | Outer endodermis  | 19834          | 20.43 | 19.82              |         |
| Cr      | Inner endodermis  | 20402          | 6.93  | 3.12               | 0.000   |
|         | Outer endodermis  | 19834          | 10.65 | 3.86               |         |
| Cu      | Inner endodermis  | 20402          | 75.0  | 26.3               | 0.000   |
|         | Outer endodermis  | 19834          | 92.4  | 12.3               |         |
| Fe      | Inner endodermis  | 20402          | 213   | 123                | 0.000   |
|         | Outer endodermis  | 19834          | 475   | 244                |         |
| Mn      | Inner endodermis  | 20402          | 8.24  | 3.42               | 0.000   |
|         | Outer endodermis  | 19834          | 13.77 | 4.95               |         |
| Ni      | Inner endodermis  | 20402          | 7.62  | 3.55               | 0.000   |
|         | Outer endodermis  | 19834          | 10.36 | 3.96               |         |
| S       | Inner endodermis  | 20402          | 4.77  | 3.10               | 0.000   |
|         | Outer endodermis  | 19834          | 9.74  | 5.69               |         |
| Zn      | Inner endodermis  | 20402          | 12.7  | 5.1                | 0.000   |
|         | Outer endodermis  | 19834          | 25.1  | 7.7                |         |

Table 2. Results of two-sample t-test compare concentration differences between inner endodermis and outer endodermis for the indicated metals.
Manganese (Mn) can be present in wetland plants as Mn oxides or Fe-Mn plaque (Fe-Mn oxides), which can scavenge other metals by adsorption or co-precipitation during transport.

To further examine the close relationships among the elements (As, Ca, Cr, Cu, Fe, Mn, Ni, S and Zn) in the root tissue (i.e., epidermis and endodermis), hierarchical cluster analysis was performed on the data. As shown in Fig. 3, there are three main clusters, i.e., Cu, Ni and Cr; Mn, As and S; and Zn, Ca and Fe. Elements in the same cluster correlate with each other better than with the elements in other clusters, and thus may have the same transport mechanisms or share similar transporting agents. Although the investigation of the exact mechanisms is beyond the scope of this study, the results indicate that the transport of the measured trace elements within the plant tissues are via different pathways or transport proteins. Some elements may share the same transport pathway or be part of a similar transport protein in the root46,47. As well, expression of uptake and transport of these elements by the root may be different.

Table 3. Summary of one-way analysis of variance (ANOVA) test results. According to the root areas analyzed, data are grouped into the root epidermis, inner endodermis and outer endodermis. There are significant differences in metal concentrations among these different root tissue layers.

| Source | Type III SS | Degree of freedom | Mean squares | F-ratio | p-value |
|--------|-------------|-------------------|--------------|----------|---------|
| As     | 99890       | 2                 | 49945        | 7191     | 0.000   |
| Error  | 510072      | 73436             | 6.95         | 11387    | 0.000   |
| Ca     | 3214924     | 2                 | 1607462      | 11064    | 0.000   |
| Error  | 10366966    | 73436             | 141          | 1.000    |         |
| Cr     | 280137      | 2                 | 140068       | 329      | 0.000   |
| Error  | 928670      | 73436             | 12.7         | 1.000    |         |
| Cu     | 5914697     | 2                 | 2957349      | 4329     | 0.000   |
| Error  | 50166621    | 73436             | 683          | 1.000    |         |
| Fe     | 1263000000  | 2                 | 631700000    | 18599    | 0.000   |
| Error  | 2494000000  | 73436             | 33965        | 1.000    |         |
| Mn     | 594723      | 2                 | 297362       | 16878    | 0.000   |
| Error  | 1293809     | 73436             | 17.6         | 1.000    |         |
| Ni     | 115348      | 2                 | 57674        | 3909     | 0.000   |
| Error  | 1083412     | 73436             | 14.8         | 1.000    |         |
| S      | 516332      | 2                 | 258166       | 12720    | 0.000   |
| Error  | 1490425     | 73436             | 20.3         | 1.000    |         |
| Zn     | 3009492     | 2                 | 1504746      | 43488    | 0.000   |
| Error  | 2540970     | 73436             | 34.6         | 1.000    |         |

Figure 3. Results of the hierarchical clustering analysis showing the relevant associations among the elements measured. Three clusters are evident: 1) Cu, Ni, Cr; 2) Mn, As and S; and 3) Zn, Ca and Fe. The joining algorithm is the Ward minimum variance method and the distance metrics are based on the Pearson correlation coefficient.

Reproduction. Manganese (Mn) can be present in wetland plants as Mn oxides or Fe-Mn plaque (Fe-Mn oxides), which can scavenge other metals by adsorption or co-precipitation during transport.
Conclusions

This investigation applies synchrotron nano-XRF technique to studying trace element concentrations and distributions in *Spartina alterniflora* root system with a resolution of nanometers. High concentrations of trace elements (As, Ca, Cr, Cu, Fe, Mn, Ni, S and Zn) were found in localized areas in the root epidermis and endodermis. Despite the fact that metal concentrations vary widely in the root tissue, statistical analysis indicates that the outer endodermis has relatively higher concentrations of these elements than the epidermis and inner endodermis. The results imply that the Casparian strip may play a role in elemental transport. Significant ($p < 0.01$) correlation between Fe and S suggest the formation of an Fe-S precipitate or Fe-S cluster in the root tissue. As well, significant ($p < 0.01$) correlations of As, Ca, Cr, Mn, Zn and (Ni) with Fe and S in the epidermis and the endodermis suggest scavenging by Fe plaque, sulfide precipitation and/or Fe-S cluster complexation play an important (perhaps combined) role in metal transport in the root tissue. Linear regression analysis shows that As, Ca, Cr, Cu, Fe, Ni,
S and Zn are significantly ($p < 0.05$) correlated with Mn, suggesting that the divalent metal (e.g., $\text{Mn}^{2+}$) may be also responsible for the metal transport.

### Materials and Methods

#### Sample collection and preparation.
Field work for the sample collection was conducted in April 2015 in Elders Point East marsh in Jamaica Bay, Long Island, New York. Elders Point East was heavily degraded and was restored in 2006–2007 by the US Army Corps of Engineers. The restoration involved the emplacement of dredged sand to elevate the marsh surface and the planting of 700,000 salt marsh cord grass ($S. \text{alterniflora}$) in the low marsh and salt hay ($S. \text{patens}$) in the high marsh zones. A sample of $S. \text{alterniflora}$ was collected with the associated peat at a site ($40°38′10.208″ \text{N}, 73°50′44.59″ \text{W}$) using stainless steel spades, placed into large plastic containers and then transported to Stony Brook University for further treatment. Soils were carefully removed from the roots by hand and the trace residual soils on the roots were carefully rinsed off with small amounts ($<20 \text{ml}$) of deionized water.

The sample was further treated at Brookhaven National Laboratory. A sample of fresh root with a diameter of ~1 mm was selected for synchrotron nanofluorescence (nano-XRF) measurement. The root was suspended in an optimal-cutting-temperature (OCT) compound (Surgipath Medical Industries, Surgipath, Canada), which is used to embed tissue samples prior to frozen sectioning on a microtome-cryostat and does not infiltrate the specimen. The sample was rapidly cooled to $−20 \degree \text{C}$, and once the OCT compound solidified, a cryotome (Cryostat CM1950, Leica Microsystems) was used to cut a $10 \mu\text{m}$ thin section. The thin section of the root sample was mounted on a silicon nitride membrane window (Noracda Inc., Edmonton, Canada), with an area of $1 \text{mm} \times 0.5 \text{mm}$ for sample placement. The sample was then fixed on an aluminum holder for synchrotron nano-XRF analysis. Between the preparation of the thin section and the synchrotron nano-XRF analysis, the mounted sample was kept in a desiccator at the Hard X-ray Nanoprobe (HXN) Beamline at the National Synchrotron Light Source II (NSLS-II) of the Brookhaven National Laboratory (Upton, NY).

#### Synchrotron X-ray nanofluorescence (nano-XRF) measurement.
Concentrations and distributions of the trace elements in $S. \text{alterniflora}$ root were investigated at the Hard X-ray Nanoprobe (HXN) Beamline
at NSLS-II. The HXN beamline provides a scanning X-ray microscopy capability with multimodality imaging including fluorescence and differential phase contrast at a 15 nm spatial resolution. In this study, the nano-XRF measurement was carried out at 12 keV using a HXN X-ray microscope equipped with a pair of multilayer Laue lenses. Seven small areas with a dimension of approximately $6 \mu m \times 6 \mu m$ were selected in the root epidermis and endodermis around the Casparian strip (Fig. 7). Specifically, three areas (S2493, S2496 and S2498) were in the epidermis, two areas (Areas S2505 and S2418) were in the outer endodermis and two areas (Areas S2504 and S2416) were in the inner endodermis (Fig. 7). In order to examine the function of Casparian strip in the elemental transport, there were some overlaps in the areas chosen in the outer and inner endodermis.

Fluorescence imaging scans, via continuous fly-scan, were performed with a sampling resolution of 60 nm per pixel and dwell time of either 0.15 or 0.25 second per pixel, depending on the signal strength. The fitting of the X-ray fluorescence data was accomplished using PyXRF, an X-ray fluorescence analysis package developed at the NSLS-II.

Figure 6. Results of Pearson linear regression analyses of As, Ca, Cr, Mn, Ni and Zn with S in the Spartina alterniflora root. The significance levels of the correlation are indicated by $p$ values. All the elements except Cu show significant correlation with S at the 95% confidence level. The relationships suggest that S may precipitate or cluster other elements during the transport in the root system.
Data analysis. Extraction of the data matrix was made possible by Matlab (MathWorks) and the data matrix of each element was then converted to a linear dataset for further analysis. Statistical analysis was performed using Systat (Systat Software, Inc.). In hierarchical cluster analysis, the joining algorithm used to amalgamate clusters was Ward’s method, which assesses the relationship between each cluster by calculating the total sum of squared deviations from the mean of a cluster, and the metric for measuring distance for the raw and standardized data was the Pearson correlation coefficient.

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**Author Contributions**

H.F., Y.Q., J.K.C. and Q.Z. designed the study, participated in the field work, and conceived the experiment. H.F., W.H., H.Y., L.L., X.H. and Y.S.C. conducted the synchrotron nano-XRF measurement and processed the data. H.F., H.L. and S.Y. performed the statistical data analysis. H.F., Y.Q. and C.J.L. prepared the thin section of the root sample for the experiment. All authors reviewed the manuscript.

**Additional Information**

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