RESEARCH ARTICLE

Tree-ring recorded variations of 10 heavy metal elements over the past 168 years in southeastern China

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Heavy metal pollution is a serious concern in the urban area of China. Understanding metal pollution history is crucial for setting up appropriate measures for pollution control. Herein, we report a record of concentrations of 10 heavy metals (Fe, Mn, Cu, Zn, Ni, Cr, Cd, Pb, Co, and Sr) in Pinus massoniana tree rings from Fuzhou City over the past 168 years, which represents the longest tree-ring chronology of heavy metals in China. The studied metals displayed contrasting distribution patterns. Among them, Mn and Sr showed the strongest migration trend with peak concentrations at the pith. Co, Cd, and Pb also showed distinctively high concentrations near the boundary between heartwood and sapwood. Ni, Cu, Cr, and Fe showed an increasing trend possibly due to migration toward bark caused by physiological activities and increasing tourism activities and traffic pollution. The other elements (Cr, Fe, and Zn) with low migration revealed the historical pollution possibly discharged by the Fuzhou Shipping Bureau and other anthropogenic activities. Strong correlations between Cu content and temperature were found, which provides an alternative tree-ring proxy for climate reconstruction. This study provides a long-term perspective of the joint impacts of physiological, environmental, and climatological factors on the concentrations of heavy metals in southeastern China.

Keywords: Tree ring, Heavy metal element, Pollution, Fuzhou

1. Introduction

With the acceleration of industrialization and urbanization, pollution caused by increasing concentration of heavy metal elements has become a serious concern in Anthropocene epoch, particularly for urban areas, due to heavy traffic, coal combustion, various industrial activities, and waste disposal (Craul, 1999; Buszewski et al., 2000; Rucandio et al., 2011; Parzych and Jonczak, 2013, 2014; Wang et al., 2020a). Heavy metals with molecular weights over 40 are difficult to be decomposed or removed, and even a low concentration of heavy metals in soil and vegetation can cause harmful effects to survival and health of plants, animals, and human beings (Tan, 2004; Liu et al., 2017, 2020a, 2020b, 2021). To effectively control contamination, it is prerequisite to comprehend the temporal evolution of heavy metal elements and their interactions with biospheres, atmosphere, hydrosphere, and soil (Yang et al., 2012; Liu et al., 2019a, 2019b, 2019c, 2020c; Wang et al., 2020b, 2020c; Wei et al., 2020). Unfortunately, routine monitoring for the heavy metal elements often has a short time span with strong industrial activities. Therefore, long-term proxy data are crucial to evaluate the anthropogenic pollution history of heavy metals. Among these proxy data, tree-ring proxy is widely used, since it is not only accurately dated and highly resolved but also widely distributed, which can provide the evolution of chemical components across both space and time (Wen et al., 2004; Xu, 2004).

A basic hypothesis of dendrochemistry is that the chemical composition of tree rings reflects the environmental chemical composition of the year when tree rings were formed (Watmough, 1999). It was widely accepted that the heavy metal elements tend to translocate after entering from phloem to xylem (Bondietti et al., 1989). Migrations of heavy metal elements in tree rings are influenced by both environmental conditions and tree physiological processes (Hagemeyer and Lohrie, 1995; Watmough and Hutchinson, 2002, 2003; Bindler et al., 2004; Monticelli et al., 2009). Knowledge on the element concentration in tree rings can not only provide information of forest health (e.g., Innes, 1993), soil chemistry (e.g., Augustin...
by P. massoniana and intermixed with other species such as Cunninghamia lanceolata and Castanopsis carlesii.

The tree-ring cores were collected from trees near a major road from the foot (elevation 119.43 m) to the top (elevation 525.79 m) of the mountain. Two to three cores were collected from each tree using 5-mm-diameter increment borer at the breast height of different orientations. The samples were mounted, air-dried, and polished with sandpaper until the cellular structure can be clearly identified. The cross-dated series were measured to a precision of 0.001 mm. Finally, we retained a total of 54 cross-dated tree-ring samples from 27 trees with a length of 168 years. Surface soil samples were collected from 10 plots under sampling trees using a stainless steel trowel and then were air-dried and stored in plastic bags prior to analysis.

2.2. Measurement of the heavy metal elements in tree rings and topsoil
The dated tree-ring cores were ultrasonically cleaned by Double deionized water (Milli-Q Millipore 18.2 resistivity) for 1 h in order to eliminate any surface contaminants introduced by coring or handling, which were dried afterwards. The annual rings of the cores were stripped with a thin stainless steel blade under a binocular microscope. The rings formed in the same calendar year were mixed together and stored in a sealed bag. A 0.05 g sample was immersed in 2 ml of HNO₃ and 2 ml of H₂O₂ in a PTFE vessel digesting at 150 °C for 18 h. The solutions were then diluted with 5% nitric acid to a final volume of 40 ml and were subsequently filtered using 0.45 μm syringe filters. For calibration, the standard material and a blank sample were digested simultaneously. Soil samples for chemical analysis were sieved and pestled in an agate mortar. Soil samples (0.04 g) were digested in 0.5 ml HNO₃ and 1.5 ml HF for 14 h at 150 °C. Add 0.25 ml HClO₄ after cooling, the mixture was dried on an electric hot plate until it turned into white ash. And 2 ml dd-H₂O and 1 ml HNO₃ were added to the white ash. After digested at 150 °C for 14 h, samples were diluted to 40 ml using dd-H₂O at final volume.

Quality control/assurance of the measurements includes: (1) the calendar years of heavy metal elements were determined by the cross-dating, which was checked by the COFECHA program (Homes, 1983) to ensure the accuracy of cross-dating; (2) in order to remove the insoluble residue on the experimental vessel, all the experimental PTFE was heated at 150 °C for 12 h, washed three times with ultrapure water, and soaked overnight; (3) all instruments were rinsed with pure alcohol after the treatment of each sample to avoid potential contamination of samples; (4) the reagents used in the digestion process are analytically pure reagents; (5) recoveries of standard plant and soil samples ranged from 93% to 102%; and (6) when performing elemental analysis, the correlation coefficient of the standard curve is controlled above 0.999, and a correction is performed when a certain sample amount is tested.

Concentrations of heavy metal elements of Fe, Mn, Cu, Zn, Ni, Cr, Cd, Pb, Co, and Sr were measured by the inductively coupled plasma mass spectrometry. In order
to reduce the matrix effect of the sample solution, internal standard elements of Rhodium and Rhenium, which are not contained in the solution and are close to the mass number of measured elements, were used as internal standard elements. The parallel test of relative standard deviation was lower than 5%, indicating that the machine runs smoothly. The calibration curve furnished good linear correlation coefficients (0.99982–0.99999) in our study.

2.3. Statistical analysis

Pearson correlations were calculated between different elements to detect their linkages and between elements and climatic variables (temperature and precipitation) during their common period from 1953 to 2016 to study the potential influence of climate. In addition, we calculated the autocorrelation as the correlation between consecutive years to represent the dependence of element contents in current year to the previous years. To alleviate the influence of trends on correlations, we additionally calculated the Pearson correlations for the first-order difference data. The first-order difference data were calculated as the residuals between consecutive years, which were normalized by their mean.

Apart from the Pearson correlation (Figure 2a and b), we employed an agreement measure of the year-to-year variation called Gleichläufigkeit coefficient (Eckstein and Bauch, 1969; Figure 2c) to evaluate the degrees of

**Figure 1.** Location and study region. (a) Location of the study region in China, locations of the (b) Fuzhou city and the Gu Mountain in the study region, and the (c) photos of the sampling site at the Gu Mountain. DOI: https://doi.org/10.1525/elementa.2020.20.00075.f1
agreement between elements on the high frequency domain. This statistic only examines whether the variations of two sequential values are matched or not but does not take into account the differences between the values. It is expressed as the percentage of cases of agreement (Allan Buras and Martin Wilmking, 2015), representing the degree of similarity within a number of time series on the high frequency domain (Schwein-gruber et al., 1993).

Principal component analysis (PCA; Richman, 2010) was used to identify the covariation patterns of elements. This method was widely applied to group different elements, which can be used to help assess the sources and absorption mechanisms of heavy metal elements in tree rings (Rodríguez-Catón et al., 2015; Marija et al., 2017). Hierarchical Cluster analysis was used to analyze the similarity of the concentrations of different elements in *P. massoniana* from 1848 to 2016 (Figure 3).

3. Results

### 3.1. Heavy metal elements in soil and tree rings

As shown in Table 1, six elements (Cr, Co, Ni, Cu, Zn, and As) in topsoil are lower than the allowable threshold concentrations of the national standards (GB15618–1995), except for Sr and Pb. A low concentration of most of the heavy metal elements standard suggests that pollution in Gushan area is not severe due to relatively low industrial activities compared with other low-lying areas. The content of Pb surpassed the first-level national soil standard (35 mg/kg) but still is much lower than the second-level national soil standards (250 mg/kg) set by the National Environmental Protection Agency. The ratios were calculated between element concentration in tree rings and soil as the absorption coefficient ($K_f = T/S$) (Table 1). Cr has the highest absorption coefficient ($K_f = 0.710$), followed by essential nutrients for plants such as Zn and Cu. The elements of the Ni, Co ($K_f = 0.023$) and Pb ($K_f = 0.018$) have the lowest absorption coefficient. There is no significant correlation between heavy metal elements and tree-ring width.
Table 1. Element concentrations (mg/kg) in topsoil. DOI: https://doi.org/10.1525/elementa.2020.20.00075.t1

| ID | Cr    | Co   | Ni   | Cu   | Zn   | As   | Sr   | Pb   |
|----|-------|------|------|------|------|------|------|------|
| GS01 | 30.912 | 4.142 | 11.345 | 7.734 | 54.190 | 4.647 | 28.478 | 35.333 |
| GS02 | 13.617 | 3.848 | 5.297 | 7.816 | 86.212 | 3.992 | 43.354 | 63.120 |
| GS03 | 16.468 | 4.631 | 6.591 | 6.268 | 58.690 | 3.765 | 35.745 | 42.791 |
| GS04 | 22.105 | 4.938 | 7.827 | 9.708 | 67.618 | 5.281 | 38.013 | 49.454 |
| GS05 | 18.330 | 4.028 | 7.150 | 9.194 | 63.442 | 4.948 | 38.595 | 46.325 |
| GS06 | 25.456 | 8.019 | 10.454 | 13.369 | 74.574 | 6.421 | 41.950 | 54.990 |
| GS07 | 26.757 | 6.242 | 10.904 | 14.437 | 78.942 | 7.012 | 41.950 | 54.990 |
| GS08 | 19.074 | 2.953 | 5.087 | 8.324 | 53.932 | 4.263 | 54.295 | 42.338 |
| GS09 | 23.167 | 3.388 | 7.883 | 10.136 | 70.903 | 5.291 | 36.236 | 41.697 |
| GS10 | 14.184 | 1.834 | 4.645 | 5.249 | 40.877 | 3.764 | 29.064 | 30.219 |
| Average | 21.007 | 4.402 | 7.718 | 9.224 | 64.938 | 4.938 | 37.597 | 47.096 |
| STD1a | 90 | 40 | 35 | 100 | 15 | 35 |
| STD2b | 41.3 | 7.41 | 13.5 | 21.6 | 82.7 | 5.78 | 34 | 34.9 |

\( K_f \) 0.710 0.023 0.125 0.190 0.333 0.047 0.018

\( a \) STD1 means the background values of the suburban soil in Fujian province.

\( b \) STD2 means the background values of the suburban soil in China. The environmental quality standard for soils is GB15618-1995.

\( c \) Co and Sr have no soil standard value in China at present.

Figure 3. Cluster analysis for variations of 10 element concentrations in the tree rings from 1848 to 2016. DOI: https://doi.org/10.1525/elementa.2020.20.00075.f3
3.2. Temporal variations of heavy metal elements and their correlations with climate

Heavy metal element concentration in our tree rings spans from 1848 to 2016. Trends of heavy metal elements of the Gu Mountain can be divided into four categories according to cluster analysis and PCA results (Figure 3). There is higher within-group correlations (Figure 2a, b) and Gleichläufigkeit score (Figure 2c) than between groups. We classify Mn and Sr as Type 1, which shows a steady declining trend (Figure 4a) ranging from 40.0 to 324.6 μg/g and 1.8 to 9.6 μg/g, respectively. Relative to Sr, Mn shows a slight upward trend from 1860 to 1876. Ni and Cu were classified as Type 2, which showed an increasing trend (Figure 4b) with a correlation of 0.55.

Different from a continuous upward trend for Cu, Ni shows stronger interdecadal variations such as a downward trend from 1880 to 1917. Concentrations of Co, Cd, and Pb, classified as Type 3, showed an increasing trend before 1940 but a lapsing trend afterwards, particularly for Pb (Figure 4c). Concentrations of Co and Cd then increase since 1864 and reach the peak during the 1920s–1940s. The correlations between Co and Cd, between Cd and Pb, and between Co and Pb are 0.73, 0.69, and 0.56, respectively. The remaining elements of Cr and Fe were classified as Type 4 with a correlation of 0.83, which display interdecadal fluctuations but no clear trend (Figure 4d). Mn, Sr, Co, Cd, and Pb with strong trends showed a stronger autocorrelation of a 3-year lag effect, whereas the rest elements (Ni, Cu, Cr, Fe, and Zn) have a weak autocorrelation (Table 2).

The heavy metal elements showed significant correlations with climate variables, except for Zn (Figure 5). In general, these elements have positive correlations with the temperature from August to November and the precipitation in October, and negative correlations with the relative humidity. Cr shows a significant correlation with precipitation in October (0.44) and is negatively correlated with relative humidity in August and September. The correlations between Fe, Ni, and Cu concentrations and relative humidity are more significant than the monthly temperature and precipitation. Ni shows significant negative correlations with relative humidity, particularly in August (−0.43). The correlations with climate are similar between Cu and Fe, which shows close correlations with the temperature in August–November and the relative humidity in July–September. The relationship between climate factors of the previous year and elements in tree rings show that the elements have no significant correlation with the precipitation of the previous year, but it still keeps the correlation with the temperature from May to August (Figure 6).
4. Discussion

4.1. Transportation of heavy metal elements from soils to tree rings

There are three ways for heavy metal elements to enter trees: (1) absorbed by root from soil moisture, (2) by leaves from air, and (3) direct deposition onto stem segments (Lepp, 1975). Previous studies have shown that most heavy metal elements were absorbed by roots (Watmough and Hutchinson, 2003). Absorption of different heavy metal elements varies for different tree species, soil types, and pH (Injuk et al., 1987; Vimmerstedt and McClenahen, 1995; Kirchner et al., 2008). The lowest absorption ratio for Co and Pb may be because that they are toxic to trees. Although the absorption ratio for Pb is low, its concentration is higher than national quality standard. This may be caused by the use of lead petrol from vehicles as the study sites are close to road (Lombardo et al., 2001).

4.2. Radial migration of heavy metal elements

The mobility of elements across tree rings varies in different tree species at different biological traits such as different tree age, heartwood–sapwood patterns, under different regions of changing environmental conditions such as pollution sources, climate patterns, acid depositions, requiring such investigations for different trees in different regions (Smith and Shortle, 2003; Cui et al., 2013). Influences of physiological processes on element concentration vary depending on tree species and element (Brackhage et al., 1996). These physiological processes can cause biased element concentration in tree rings from the environment, such as a steady decline from pith to bark and a peak element concentration between the heartwood and sapwood (Liang and Huang, 1992).

The strong decline trends from pith to bark for Sr and Mn observed in this study were also found in Jeffrey pine (Pinus jeffreyi) from the Tahoe Basin, California, (Kirchner et al., 2008). The strong decline trend for Mn may be because that it is an essential element for metabolic processes of photosynthesis and respiration (Mariani et al., 2017). Continuous consumption of Mn in soil can contribute to the lapping trend in bioavailability in soil.

Table 2. The autocorrelation coefficients of the 10 elements. DOI: https://doi.org/10.1525/elementa.2020.20.00075.t2

| No. | Mn    | Sr    | Ni    | Cu    | Co    |
|-----|-------|-------|-------|-------|-------|
| 1   | 0.94** | 0.96** | 0.67** | 0.47** | 0.61** |
| 2   | 0.92** | 0.94** | 0.65** | 0.39** | 0.53** |
| 3   | 0.90** | 0.94** | 0.58** | 0.41** | 0.42** |

| No. | Cd   | Pb   | Cr   | Fe   | Zn   |
|-----|------|------|------|------|------|
| 1   | 0.89** | 0.94** | 0.39** | 0.35** | 0.16*  |
| 2   | 0.84** | 0.92** | 0.22** | 0.17*  | 0.23** |
| 3   | 0.81** | 0.90** | /      | /      | /      |

*Means significant correlation at 0.05 level. **Means significant correlation at 0.01 level.

Figure 5. Correlations between elements and (a) temperature, (b) precipitation, and (c) of the previous year. DOI: https://doi.org/10.1525/elementa.2020.20.00075.f5

Figure 6. Correlations between elements and (a) temperature of the previous year. The line means significant correlation at 0.05 level. DOI: https://doi.org/10.1525/elementa.2020.20.00075.f6
Accumulation of heavy metal elements at the heartwood-sapwood boundary from the 1920s to 1940s was also reported in previous studies (Donnelly et al., 1990; Xu, 2004)—for example, a peak concentration of Pb and Cd near the heartwood-sapwood boundary in *P. massoniana* (Xu, 2004) and *Ponderosa pines* (Cui et al., 2013) in Shenyang city. Watmough and Hutchinson (2002) found that the concentrations of Pb in Scots pine and *oak* peaked near the heartwood-sapwood boundary. These elements are often toxic elements, and trees can trigger a “detoxification mechanism” by transporting them from the active part, sapwood, to the inactive part, heartwood (Donnelly et al., 1990; Xu, 2004; Cui et al., 2013).

### 4.3. Pollution history recorded in heavy elements

Previous studies have proved ability of the tree rings of *P. massoniana* to record pollution history (Hou et al., 2002a, 2008b; Kuang et al., 2007). The increases in Cu and Ni generally agree with the enhancement of tourism and industrial activities and the known pollution history, specifically recorded undulations (Wang, 2005). Although Cr, Fe, and Zn (Type 4) have weakest migration across rings in our species, different species can have varying migration ability for Zn. For example, Zn can migrate across rings in *Pinus tabulaeformis* and *Toona sinensis* for 3 years, but there is no migration for Zn in *Firmiana simplex* (Liu et al., 2009a, 2009b). Since Cr, Fe, and Zn have the lowest migration ability, they can well reflect the environmental history (Kabata-Pendias, 2011). The peak concentration of Cr, Fe, and Zn that occurred from 1880 and 1900 may be associated with the heyday of iron ship construction from 1880 to 1907 of the Fuzhou Shipping Bureau including shipyards, iron foundries, and other enterprises, which is less than 4 km from our tree-ring site.

### 4.4. Climate–element relationships

Heavy metal concentration in tree rings can also be modulated by climate by affecting the pollution pathways (e.g., via leaf stomata) and physical processes (metabolism activities) of trees (Jónsdóttir et al., 2005; Sardans and Peñuelas, 2007; Sardans et al., 2008). This may explain the strong correlations (0.44, 0.39, and 0.44) between Cr, Fe, and Cu and the precipitation in October. There is no significant correlation between elements and precipitation in the previous year, which may indicate that the effect of precipitation on element absorption is more immediate. Actually, their correlations with climate are even higher than the correlations with tree-ring width and stable carbon isotopes in this area (Li et al., 2016). During wet conditions, these elements may be more soluble and easier to be absorbed by trees. In addition, some elements can easily enter leaves due to high stomatal conductance under wet conditions (Hagemeyer and Prasad, 1999; Fernández, 2013). On the other hand, a wet condition can cause stomata closure and plant cuticles to contract, inhibiting heavy metal elements from entering the leaves (Shahid et al., 2016). Tree-ring data have been widely used for climate reconstructions in arid and cold China, but they are less sensitive to hot and humid regions (Fang et al., 2017a, 2017b). The high correlations between heavy metal elements and climate suggest that they could be considered as alternative tree-ring proxy for reconstructing past climate in hot and humid regions.

### 5. Conclusions

This study provides the longest series of 10 heavy metal elements in tree rings of the past 168 years collected from Gu Mountain of Fuzhou areas in southeastern China. Heavy metal elements in tree rings are jointly modulated by environmental pollution, migrations across rings, and climate change. The 10 elements were classified into four types with Type 1 (Mn and Sr) showing strongest migration effect from the bark to peak, leading to a lapping trend from pith to bark. Type 2 (Co, Cd, and Pb) has moderately strong migration ability to shift these elements to the boundary between heartwood and sapwood. The other two types show limited migration, and Type 3 (Ni and Cu) seems to indicate an intensified pollution caused by tourism development and increased transportation. The high concentration of Cr and Fe in Type 4 between 1880 and 1900 coincides with the pollution associated with the heyday of iron ship construction in Fujian Shipping Bureau. We also found Cu and Fe showed strong correlations with the relative humidity in July–September. This suggests the modulation of climate on heavy metal in tree rings and the potential for using the heavy metal elements for climate reconstruction in regions where other tree-ring proxies have little climate sensitivity.

### Data accessibility statement

The following data sets were generated for this study:

- Time series of four groups for the element concentration from 1848 to 2016 revealed in tree rings.

These data are uploaded as online supporting information as part of this article.

### Supplemental files

The supplemental files for this article can be found as follows:

- Data S1. Raw data. Xlsx.

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Competing interests
The authors have no conflict of interest to declare.

Author contributions
- Contributed to conception and design: CSY, FKY, CXL.
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- Contributed to analysis and interpretation of data: CSY, FKY, DZP, CXL.
- Drafted and/or revised the article: all authors.
- Approved the submitted version for publication: all authors.

References
Aimin, H, Shaolin, P, Guoyi, Z. 2002a. Tree-ring chemical changes and possible impacts of acid precipitation in Dinghushan, South China. Acta Ecologica Sinica 22(9): 1552–1559.
Aimin, H, Shaolin, P, Guoyi, Z. 2002b. Concentrations and correlation of eight important elements in the annual rings of Pinus massoniana in Dinghushan, Guangdong. Chinese Journal of Ecology 21(1): 6–9.
Augustin, S, Stephanowitz, H, Wolff, B, Schroeder, J, Hoffmann, E. 2005. Manganese in tree rings of Norway spruce as an indicator for soil chemical changes in the past. European Journal of Forest Research 124(4): 313–318.
Baes, CF, Mclaughlin, SB. 1984. Trace elements in tree rings: Evidence of recent and historical air pollution. Science 224(4648): 494–497.
Bindler, R, Renberg, I, Klaminder, J, Emteryd, O. 2004. Tree rings as Pb pollution archives? A comparison of 206Pb/207Pb isotope ratios in pine and other environmental media. Science of the Total Environment 319(1): 173–183.
Bondietti, EA, Baes III, CF, Mclaughlin, SB. 1989. Radial trends in cation ratios in tree rings as indicators of the impact of atmospheric deposition on forests. Canadian Journal of Forest Research 19(5): 586–594.
Brackhage, C, Hagemeyer, J, Breckle, SW, Greszta, J. 1996. Radial distribution patterns of Cd and Zn in stems of Scots pine (Pinus sylvestris L.) trees analyzed 12 years after a contamination event. Water Air and Soil Pollution 90(3): 417–428.
Buras, A, Wilming, M. 2015. Correcting the calculation of Gleichläufigkeit. Dendrochronologia 34: 29–30.
Buszewski, B, Jastrzębska, A, Kowalkowski, T, Górnabinkul, A. 2000. Monitoring of selected heavy metals uptake by plants and soils in the area of Toruń, Poland. Polish Journal of Environmental Studies 9(6): 511–515.
Chen, J. 2001. Classification and distribution of mountainous soils in Fujian province based on Chinese soil taxonomy. Journal of Mountain Science 19: 1–8.
Chen, XL, Li, ZZ, Jin, JH, Liu, JH, Wu, MR, Zhong, JL. 2011. Soil pH value, organic matter and magnetic susceptibility in different urban function zones of Fuzhou city. Bulletin of Soil and Water Conservation 31(5): 180–185.
Chun, L, Hui-Yi, H. 1992. Tree-ring element analysis of Korean pine (Pinus koraiensis Sieb. et Zucc.) and Mongolian oak (Quercus mongolica Fisch. ex Turcz.) from Changbai Mountain, north-east China. Trees Structure & Function 6(2): 10315521559.108.
Clair, St, Samuel, B, Sharpe, WE, Lynch, JP. 2008. Key interactions between nutrient limitation and climatic factors in temperate forests: A synthesis of the sugar maple literature. Canadian Journal of Forest Research 38(3): 401–414.
Craul, PJ. 1999. Urban soils: Applications and practices. Hoboken, NJ: John Wiley & Sons.
Cui, M, He, X, Davi, N, Chen, Z, Zhang, X, Peng, J, Chen, W. 2013. Evidence of century-scale environmental changes: tree ring in tree-ring from Fuling Mausoleum Shenyang, China. Dendrochronologia 31(1): 1–8.
Donnelly, JR, Shane, JB, Schaberg, PG. 1990. Lead mobility within the xylem of red spruce seedlings: implications for the development of pollution histories. Journal of Environmental Quality 19(2): 268–271.
Eckstein, D, Bauch, J. 1969. Beitrag zur rationalisierung eines dendrochronologischen verfahrens und zur analyse seiner aussagesicherheit. Forstwissenschaftliches Centralblatt 88(1): 230–250.
Fernández, V, Brown, PH. 2013. From plant surface to plant metabolism: the uncertain fate of foliar-applied nutrients. Frontiers in Plant Science 4: 289.
Hagemeyer, J, Prasad, MN. 1999. Heavy metal stress in plants: From molecules to ecosystems. Berlin, Germany: Springer Verlag.
Hagemeyer, J, Lohrie, K. 1995. Distribution of Cd and Zn in annular xylem rings of young spruce trees [Picea abies (L.) Karst.] grown in contaminated soil. Trees 9(4): 195–199.
Hevia, A, Sánchez-Salgueiro, R, Camarero, JJ, Buras, A, Sangüesa-Barreda, G, Galván, JD, Gutiérrez, E. 2018. Towards a better understanding of long-term wood-chemistry variations in old-growth forests: A case study on ancient Pinus uncinata trees from the Pyrenees. Science of the Total Environment 625(2018): 220–232.
Innes, JL. 1993. Forest health: Its assessment and status. London, UK: CAB International.
Nabais, C, Freitas, H, Hagemeyer, J. 1999. Dendroanalysis: A tool for biomonitoring environmental pollution? Science of the Total Environment 232: 33–37.
Fang, K, Cook, E, Guo, Z, Chen, D, Ou, T, Zhao, Y. 2017a. Synchronous multi-decadal climate variability of the whole Pacific areas revealed in tree rings since 1567. Environmental Research Letters 13(2): 024016. DOI: http://dx.doi.org/10.1088/1748-9326/aa9f74.
Fang, K, Guo, Z, Chen, D, Linderholm, HW, Li, J, Zhou, F, Guo, G, Dong, Z, Li, Y. 2017b. Drought variation of western Chinese Loess Plateau since 1568 and its linkages with droughts in western North America.
Kuan, YW, Zhou, GY, Wen, DZ, Chen, SW, Li, XG. 2007.
Kuang, Y, Zhou, G, Wen, D. 2008. Environmental biology.
Liu, Y, Wang, WP, Bao, TY, Yang, ZY, Liu, N
Lepp, NW. 1975. The potential of tree-ring analysis for monitoring heavy metal pollution patterns. Environ-
Kuang, Y, Zhou, G, Wen, D. 2008. Environmental bioindication of sulphur in tree rings of Masson pine (Pinus massoniana) in the Pearl River Delta, South China. Journal of Tropical and Subtropical Botany 15(5): 383–389.
Kuan, YW, Zhou, GY, Wen, DZ, Chen, SW, Li, XG. 2007. Historical changes in heavy metals in tree-rings of Masson pine (Pinus massoniana) in the Pearl River Delta, South China. Journal of Tropical and Subtropical Botany 15(5): 383–389.
Kuang, Y, Zhou, G, Wen, D. 2008. Environmental bioindication of sulphur in tree rings of Masson pine (Pinus massoniana) in the Pearl River Delta of China. Journal of Beijing Forestry University 30(2): 1227.
Lageard, JGA, Howell, JA, Rothwell, JJ, Drew, IB. 2008. The utility of Pinus sylvestris L. in dendrochrono-
Lepp, NW. 1975. The potential of tree-ring analysis for monitoring heavy metal pollution patterns. Environ-
Liu, Y, Wang, WP, Bao, TY, Yang, ZY, Liu, N. 2009b. Content variations of heavy metals recorded by tree rings from a displaced steel works in the eastern Xi’an city. Asian Journal of Ecotoxicology 4(3): 382–391.
Li, Y, Fang, K, Cao, C, Li, D, Zhou, F, Dong, Z, Zhang, Y, Gan, Z. 2016. A tree-ring chronology spanning 210 years in the coastal area of southeastern China, and its relationship with climate change[J]. Climate Research 67(2): 209–220.
Liu, J, Luo, XW, Wang, J, Xiao, TF, Chen, DY, Sheng, GD, Yin ML, Lippold, H, Wang, CL, Chen, YH. 2017. Thallium contamination in arable soils and vegetables around a steel plant: A newly-found significant source of Tl pollution in South China. Environmental Pollution 224: 445–453
Liu, J, Luo, X, Sun, Y, Tsang, DCW, Li, N, Yin, M, Wang, J, Lippold, H, Chen, Y, Sheng, G. 2019b. Thallium pollution in China and removal technologies for waters: A review. Environment International 126: 771–790.
Liu, J, Yin, ML, Xiao, TF, Zhang, C, Tsang, D, Bao, Z, Zhou, YT, Chen, YH, Luo, XW, Yuan, WH, Wang, J. 2020a. Thallium isotopic fractionation in industrial process of pyrite smelting and environmental implications. Journal of Hazardous Materials 384: 121378.
Liu, J, Ren, J, Zhou, Y, Tsang, DC, Lin, J, Yuan, W, Wang, J, Yin, M, Wu, Y, Xiao, T, Chen, Y. 2020b. Effects and mechanisms of mineral amendment on thallium mobility in highly contaminated soils. Journal of Environmental Management 262: 110251.
Liu, J, Wei, X, Zhou Y, Tsang, D, Bao, Z, Yin, M, Lippold, H, Yuan W, Wang, J, Feng, Y, Chen, D. 2020c. Thallium contamination, health risk assessment and source apportionment in common vegetables. Science of the Total Environment 703: 135547.
Liu, J, Ren, S, Cao, J, Tsang, D, Beiyuan, J, Peng, Y, Fang, F, She, J, Yin, M, Shen, N, Wang J. 2021. Highly efficient removal of thallium in wastewater by MnFe2O4-biochar composite. Journal of Hazardous Materials 401: 123311.
Lombardo, M, Melati, RM, Orecchio, S. 2001. Assessment of the quality of the air in the city of Palermo through chemical and cell analyses on Pinus needle. Atmospheric Environment 35(36): 6435–6445.
Marija, P, Dragana, P, Olga, K, Snežana, J, Dragan, C, Pavle, P, Miroslava, M. 2017. Evaluation of urban contamination with trace elements in city parks in Serbia using pine (Pinus nigra Arnold) needles, bark and urban topsoil. International Journal of Environmental Research 11(5): 625–639.
Mihaljević, M, Ettrler, V, Šebek, O, Slacek, O, Kríbek, B, Kyncl, T, Majer, V, Veselovsky, F. 2011. Lead isotopic and metallic pollution record in tree rings from the Copperbelt Mining–Smelting Area, Zambia. Water Air & Soil Pollution 216(1–4): 657–668.
Monticelli, D, Iorio, AD, Ciceri, E, Castelletti, A, Dossi, C. 2009. Tree ring microanalysis by LA–ICP–MS for environmental monitoring: validation or refutation? Two case histories.” Microchimica Acta 164(1–2): 139–148.
Parzych, A, Jonczak, J. 2013. Content of heavy metals in needles of Scots pine in selected pine (Pinus sylves-
Parzych, A, Jonczak, J. 2014. Pine needles (Pinus sylves-
Patrick, GJ, Farmer, JG. 2006. A stable lead isotopic investigation of the use of sycamore tree rings as a historical biomonitor of environmental lead contamination. Science of the Total Environment 362(1–3): 278–291.
Pearson, CL, Manning, SW, Coleman, ML, Jarvis, KE. 2005. Can tree-ring chemistry reveal absolute dates for past volcanic eruptions? *Journal of Archaeological Science* 32(8): 1265–1274.

Pearson, CL, Manning, SW, Coleman, ML, Jarvis, KE. 2006. A dendrochemical study of *Pinus sylvestris* from Siljansfors Experimental Forest, central Sweden. *Applied Geochemistry* 21(10): 1681–1691.

Pearson, CL, Dale, DS, Brewer, PW, Kuniholm, PL, Lipton, J, Manning, SW. 2009a. Dendrochemical analysis of a tree-ring growth anomaly associated with the Late Bronze Age eruption of Thera. *Journal of Archaeological Science* 36: 1206–1214.

Pearson, CL, Dale, DS, Brewer, PW, Salzer, MW, Lipton, J, Manning, SW. 2009b. Dendrochemistry of White Mountain bristlecone pines: an investigation via synchrotron radiation scanning X-ray fluorescence microscopy. *Journal of Geophysical Research: Biogeosciences* 114(G1): 1206–1214.

Richman, MB. 2010. Rotation of principal components: a reply. *International Journal of Climatology* 7(5): 511–520.

Rodríguez-Catón, M, Villalba, R, Srur, AM, Luckman, B. 2015. Long-term trends in radial growth associated with Nothofagus pumilio forest decline in Patagonia: Integrating local-into regional-scale patterns. *Forest Ecology & Management* 339(339): 44–56.

Rucandio, MI, Petit-Dominguez, MD, García-Giménez, R. 2011. Biomonitoring of chemical elements in an urban environment using arboreal and bush plant species. *Environmental Science & Pollution Research* 51(1): 51–63.

Schweingruber, FH, Briffa, KR, Nagler, P. 1993. A tree-ring densitometric transect from Alaska to Labrador. *International Journal of Biometeorology* 37(3): 151–169.

Shahid, M, Dumat, C, Khalid, S, Schreck, E, Xiong, T, Niazi, NK. 2016. Foliar heavy metal uptake, toxicity and detoxification in plants: A comparison of foliar and root metal uptake. *Journal of Hazardous Materials* 325: 36–58.

Sheppard, PR, Ort, MH, Anderson, KC, Elson, MD, Vázquez-Selem, L, Clemens, AW, Little, NC, Spekanik, RJ. 2008. Multiple dendrochronological signals indicate the eruption of Paricutin volcano, Michoacán, Mexico. *Tree Ring Research* 64: 97–108.

Sheppard, PR, Ort, MH, Anderson, KC, Clyne, MA, May, EM. 2009. Multiple dendrochronological responses to the eruption of Cinder cone, Lassen Volcanic National Park, California. *Dendrochronologia* 27: 213–221.

Smith, KT, Balouet, JC, Oudijk, G. 2008. Elemental scanning of an increment core using EDXRF: from fundamental research to environmental forensics applications. *Dendrochronologia* 26: 157–163.

Smith, KT, Shortle, WC. 2003. Dendrochemistry of base cations in red spruce: the fallacy of the passive recorder. *Eos, Transactions of the American Geophysical Union* 84(46) Fall Meeting Supplement. Abstract B12F-04. Available at https://ui.adsabs.harvard.edu/abs/2003AGUFM.B12F.045/abstract.

Sardans, J, Peñuelas, J. 2007. Drought changes phosphorus and potassium accumulation patterns in an evergreen Mediterranean forest. *Functional Ecology* 21: 191–201.

Sardans, J, Peñuelas, J, Estiarte, M. 2008. Warming and drought change trace element bioaccumulation patterns in a Mediterranean shrubland. *Chemosphere* 70: 874–885.

Tan, JA. 2004. Earth environment and health (in Chinese). Beijing, China: Chemical Industry Press. Available at http://eduzt.gicp.net:808/ReadBook.aspx?p=MzEzODUzMzwlDE3&bkid=3138531&Euid=Z18k13cknaLqNdvea2MA==.

Wang, YP, Xu, CX, Wang, SM. 2005. Correlation between chemical element contents in tree rings and those in soils near tree roots in the southern suburbs of Beijing, China. *Geological Bulletin of China* 24(10–11): 952–956.

Wang, J, Jiang, Y, Sun, J, She, J, Yin, M, Fang, F, Xiao, T, Song, G, Liu, J. 2020a. Geochemical transfer of cadmium in river sediments near a lead-zinc smelter. *Ecotoxicology and Environmental Safety* 196: 110529.

Wang, J, Zhou, Y, Dong, X, Yin, M, Tsang, D, Song, G, Liu, J. 2020b. Temporal sedimentary record of thallium pollution in an urban lake: An emerging thallium pollution source from copper metallurgy. *Chemosphere* 242: 125172.

Wang, J, She, J, Zhou, Y, Tsang, D, Beiyuan, J, Xiao, T, Dong, X, Chen, Y, Liu, J, Yin, M, Wang, L. 2020c. Microbial insights into the biogeochemical features of thallium occurrence: a case study from polluted river sediments. *Science of the Total Environment* 739: 139957.

Watmough, SA. 1999. Monitoring historical changes in soil and atmospheric trace metal levels by dendrochemical analysis. *Environmental Pollution* 106(3): 391–403.

Watmough, SA, Hutchinson, TC. 2002. Historical changes in lead concentrations in tree-rings of sycamore, oak and Scots pine in north-west England. *Science of the Total Environment* 293(1–3): 85–96.

Watmough, SA, Hutchinson, TC. 2003. Uptake of 207Pb and 111Cd through bark of mature sugar maple, white ash and white pine: a field experiment. *Environmental Pollution* 121(1): 39–48.

Wei, X, Zhou, Y, Jiang, Y, Tsang, D, Zhang, C, Liu, J, Zhou, Y, Yin, M, Wang, J, Shen, N, Xiao, T, Chen, Y. 2020. Health risks of metal(loids) in maize (Zea mays L.) in an artisanal zinc smelting zone and source fingerprinting by lead isotope. *Science of the Total Environment* 742: 140321.

Wen, DQ, Kuang, YW, Zhou, GY, Yu, C. 2004. Progress on the Applications of tree-ring analysis in environmental monitoring (in Chinese). *Guangxi Science* 11(2): 134–142.
Witt, GB, English, NB, Balanzategui, D, Hua, Q, Gadd, P, Heijnis, H, Bird, MI. 2017. The climate reconstruction potential of Acacia cambagei (gidgee) for semi-arid regions of Australia using stable isotopes and elemental abundances. *Journal of Arid Environments* **136**: 19–27.

Xu, H. 2004. Progress on dendrochemistry for monitoring heavy metal pollution in environment (in Chinese). *Earth Environmental* **32**(3–4): 1–6

Yang, YK, Wang, WK, Deng, HZ, Sun, H. 2012. Study on the relation of Environmental change with Element Contents of S and Pb in Tree Rings. *Science Technology and Engineering* **12**(028): 7309–7313.

Zhang, C, Huang, B, Piper, JD, Luo, R. 2008. Biomonitoring of atmospheric particulate matter using magnetic properties of Salix matsudana tree ring cores. *Science of the Total Environment* **393**(1): 177–190.

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