

Inferring the perennial biomass and phytoremediation potential of thirty-one woody species from large phytomanagement field trials

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ABSTRACT

Growing woody biomass on trace element-contaminated marginal lands is a promising phytomanagement strategy, provided that species combine high productivity with appropriate contaminant accumulation profiles. In this study, we evaluated the five-year field performance and phytomanagement potential of 31 woody species established at three French trace element-contaminated sites differing in soil properties and contamination histories: Thann, Carrières-sous-Poissy, and Leforest. Above- and belowground fresh biomasses were quantified, rhizospheric soil pH and CaCl₂-extractable elements were measured, and trace element concentrations were analysed in leaves, bark, and trunk tissues of two species common to all sites, *Salix aquatica* 'Grandis' and *Ostrya carpinifolia*. Strong interspecific and intersite variability in field biomass was observed. At Carrières-sous-Poissy, *Elaeagnus umbellata* and *Acer saccharinum* showed the highest fresh biomass, whereas *Salix alba* and *Alnus subcordata* performed best at Leforest, and *Ostrya carpinifolia* and *Salix alba* produced the highest fresh biomass at Thann. Shoot and root fresh biomasses were strongly correlated at each site. Soil pH showed only non-significant numerical trends among species, whereas selected CaCl₂-extractable elements differed between planted groups and site-specific controls. *Salix aquatica* 'Grandis' accumulated high Cd and Zn concentrations in leaves and bark, but its maximum mean foliar concentrations remained below the operational hyperaccumulation thresholds for both elements. *Ostrya carpinifolia* displayed comparatively low trace element concentrations. These results highlight the need for site-specific selection of woody species and identify complementary candidates for phytoextraction, biomonitoring, and phytostabilization in contaminated-land phytomanagement.

1. Introduction

Soil is a vital and one of the most important non-renewable natural resources, providing physical, chemical, and biological substrates and functions necessary to support life (Ciadamidaro et al., 2024). However, soils are increasingly threatened by pollution, generating a major risk to human health and to terrestrial and aquatic ecosystems. Population growth and associated industrial and developmental activities have intensified environmental pressures, leading to long-term soil degradation (Desalme et al., 2012; Bhatt et al., 2022). Due to their widespread use in industries and daily-life products, trace elements (TE) have entered soil and water environments and are now detected in all biological systems, such as microorganisms, plants, higher animals, and

humans, globally (Sunderland et al., 2019). As the human population continues to grow and consume more resources, pressure on land increases (Schröder et al., 2022; Ofori-Agyemang et al., 2024). The European Commission estimated up to three million contaminated sites in Europe, with around 250,000 sites requiring urgent remediation (Pérez, Eugenio, 2018). It is therefore necessary to find solutions inspired by and supported by nature that could offer environmental, social, and economic benefits while creating resilience (Triest et al., 2016).

Among nature-based solutions (NBS), phytomanagement is widely applied worldwide for the remediation of TE-contaminated soils, in which phytostabilization (Šimek et al., 2017; Burges et al., 2018) and phytoextraction (Sessitsch et al., 2013) are considered the most appropriate techniques (Clemente et al., 2015). Within this context,

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phytostabilization promotes TE stabilization by decreasing their bioavailability in soil. In the phytostabilization approach, TE-excluding plants are used and can be combined with soil amendments and/or microbial inoculants (assisted phytostabilization) (Mench et al., 2010; Kidd et al., 2015; Burges et al., 2017, 2018). Conversely, in the phytoextraction approach, TEs are accumulated into harvestable plant tissues (Gómez-Sagasti et al., 2021).

However, when TE contamination of a soil exceeds threshold values, land-use restrictions for food production are usually applied, but plant production for non-food purposes is desirable for economic and ecological reasons (Günthardt-Goerg et al., 2022). In this context, contaminated lands are considered an important source of land for growing energy crops (Gerwin et al., 2018). Indeed, cultivating industrial crops on marginal land unsuitable for food production is a viable alternative to minimize adverse effects, direct or indirect, on food security, land-based greenhouse gas emissions, and biodiversity loss. Within phytomanagement strategies, Lal and Pimentel (2007) proposed that bioenergy plantations could be established on contaminated sites, as well as on degraded or drastically disturbed soils. Therefore, restoration of degraded soils through the implementation of dedicated woody plantations for biofuel/biomass production would be a win-win strategy.

To optimize land restoration processes, crops must exhibit enhanced stress tolerance and high water- and nutrient-use efficiency. Within the framework of phytomanagement, such crops should deliver ecosystem services and support diversified and integrated biomass utilization, while contributing to increased plant species diversity. Future biomass crops should be capable of withstanding harsh environmental conditions, including soil contamination, while simultaneously maintaining resilience through improvements in soil fertility and biodiversity. These requirements are often best met by perennial biomass cropping systems, such as miscanthus, fast-growing tree species, and wild plant mixtures.

Woody species constitute the largest proportion of plant biomass in native forests and shrublands, with an estimated three trillion trees worldwide (Crowther et al., 2015). These long-lived organisms play essential roles in ecological functioning, including biogeochemical cycles, climate regulation, soil conservation, and habitat provision (Bonan, 2016; Trumbore et al., 2015). They are also major primary producers in terrestrial food webs and provide renewable energy and raw materials (Gómez-Sagasti et al., 2021). Their potential is linked to high biomass productivity, extensive root systems, tolerance to TEs, and a strong capacity for TE accumulation in plant tissues (Migeon et al., 2009; Pulford and Watson, 2003). Several woody species have been investigated for these purposes, including poplar and willow, birch (*Betula pendula*), oak (*Quercus robur*), ash (*Fraxinus excelsior*), and maple (*Acer pseudoplatanus*). These species exhibit distinct physiological responses and adaptation strategies under TE-contaminated conditions (Evangelou et al., 2012; Mertens et al., 2007).

The previous two-year screening primarily assessed tree survival, height growth, stem and leaf element concentrations, and broad accumulating versus non-accumulating profiles (Ciadamidaro et al., 2019). However, it did not quantify whole-tree aboveground and belowground biomass after longer-term establishment, evaluate the distribution of elements between bark and trunk, or examine whether five years of woody cover were associated with changes in rhizospheric soil pH and CaCl_2 -extractable elements. The present study addresses these gaps by assessing 31 woody species after five years under field conditions. Specifically, our objectives were to (i) compare site-specific aboveground and belowground fresh biomass as indicators of field establishment, (ii) quantify pH and CaCl_2 -extractable element patterns in soils associated with the different woody species, and (iii) compare tissue-specific Cd and Zn accumulation and translocation in *Salix aquatica* 'Grandis' and *Ostrya carpinifolia*, two contrasting taxa present at all three sites. We expected species rankings and accumulation profiles to differ among sites because of contrasting soil properties and contamination histories.

2. Materials and methods

2.1. Site description and planting scheme

The experiment was carried out at three TE-contaminated sites in France, chosen for their different origins of contamination. Each experimental site covered approximately 1 ha (Ciadamidaro et al., 2019; Pfendler et al., 2024). The sites were located at Thann (47°47'48.4"N, 7°08'20.8"E), Carrières-sous-Poissy (48°57'39.7"N, 2°02'09.6"E), and Leforest (50°25'40.5"N, 3°02'40.5"E). A total of 38 woody species (Table S1) were initially planted on an industrial red-gypsum landfill at Thann, an agricultural soil historically contaminated by wastewater at Carrières-sous-Poissy, or an agricultural soil contaminated by atmospheric deposition at Leforest. At Thann, 18 species were planted across eight plots, for a total of 4752 trees (33 individuals per species per plot). At Carrières-sous-Poissy and Leforest, 16 species were planted across eight plots, for a total of 3968 trees at each site (31 individuals per species per plot). Planting was performed in November 2013 at Carrières-sous-Poissy and in April 2014 at Leforest and Thann. Species selection was adapted to site properties, geographic context, and local restrictions. A summary of the experimental design and of the soil characteristics is provided in Table S8.

For the present five-year assessment, 31 of the initial 38 woody species were retained because several taxa had very poor survival or growth. Four of the eight plots at each site were used for destructive sampling. Overall, 14, 14, and 15 species were investigated at Carrières-sous-Poissy, Leforest, and Thann, respectively. Three taxa were common to all sites (*Salix aquatica* 'Grandis', *Pterocarya stenoptera*, and *Ostrya carpinifolia*), six occurred at two sites (*Platanus orientalis*, *Populus* 'Oxford', *Quercus cerris*, *Quercus pedunculata*, *Quercus petraea*, and *Salix alba*), and the remaining taxa were site-specific, as detailed in Table S1.

2.2. Soil chemical analyses

Initial physicochemical characterization was performed in 2013, before tree planting, on bulk topsoil collected from the 0–20 cm layer. The complete baseline characterization is reported by Ciadamidaro et al. (2019), and the main properties are summarized in Table S8. Briefly, the soils were sandy loam at Thann (pH 7.4), sandy at Carrières-sous-Poissy (pH 7.2), and silty loam at Leforest (pH 6.5). The principal contaminants were Pb (311 and 195 mg kg⁻¹), Cd (6.0 and 3.7 mg kg⁻¹), and Zn (685 and 250 mg kg⁻¹) at Leforest and Carrières-sous-Poissy, respectively. At Thann, the substrate contained high concentrations of Fe (28, 267 mg kg⁻¹), S (85,712 mg kg⁻¹), and Mn (1472 mg kg⁻¹). Organic status and additional physical and chemical properties were not remeasured during the 2018 sampling campaign and should therefore be interpreted from the baseline characterization.

In 2018, three trees per species were randomly selected in each of four plots at each site, giving 12 biological replicates per species and site, depending on tree availability. The selected trees were uprooted using a mechanical shovel. Immediately after uprooting, each root system was shaken to remove loosely adhering soil, and approximately 0.5–2 L of the soil remaining attached to the roots (i.e., rhizospheric soil), depending on root-system size, was collected in plastic bags and stored at 4°C. The same individuals were subsequently used for aboveground and belowground biomass measurements (raw data are presented in Table S9). In total, 516 planted-soil samples were collected (14 species × 3 trees × 4 plots at Carrières-sous-Poissy and Leforest; 15 species × 3 trees × 4 plots at Thann). Trees were planted in rows, and impermeable plastic sheeting was used both to control weeds and to create vegetation-free areas. Control samples were taken from sheeted, unplanted zones. Soil samples were collected at the same depth from these covered areas, preventing root growth and ensuring that the sampled soil was not influenced by surrounding root systems. Three sampling points were collected per plot, resulting in 12 samples per site, with identical storage and processing procedures.

Soil samples were dried to constant mass at 40°C in a forced-air oven and ground in an agate mortar (Retsch RM100). The readily extractable elemental fraction was assessed by 0.01 M CaCl₂ extraction at a soil-to-solution ratio of 1:10 (Houba et al., 1996), followed by inductively coupled plasma atomic emission spectrometry (ICP-AES; Thermo Fisher Scientific, Pittsburgh, USA). Because CaCl₂ extraction targets a relatively small and readily exchangeable fraction, the term “CaCl₂-extractable” is used throughout rather than “total bioavailable.” Soil pH was measured in 1 mol L⁻¹ KCl extracts (1:2.5, m/v) after stirring for 1 h (Hesse, 1971), using a CRISON micropH meter (Barcelona, Spain).

2.3. Biomass measurement and chemical analysis

After soil sampling, aboveground biomass (trunk and branches) and belowground biomass (roots) of each uprooted tree were separated and weighed in the field. Approximately 1200 trees were harvested across the three sites, representing a total plant volume equivalent to approximately three fully loaded trucks. Oven-drying the complete biomass of every individual under standardized conditions was therefore not technically feasible, and biomass was recorded as fresh weight using the same procedure for all individuals. Consequently, these values should be interpreted as comparative field fresh biomass rather than dry-matter yield. For chemical analyses, *Salix aquatica* ‘Grandis’ and *Ostrya carpinifolia* were selected because previous results indicated contrasting accumulation profiles (Ciadamidaro et al., 2019). Leaf, trunk, and bark subsamples were washed with tap water followed by two distilled-water baths, oven-dried at 70°C to constant mass, and ground. Three grams of powder were ashed at 500°C and digested with 7 mL HNO₃ (68%) and 2 mL H₂O₂ (30%) to a final volume of 50 mL. Element concentrations were measured by ICP-AES (Thermo Fisher iCAP 6500, Courtaboeuf, France) and expressed as mg kg⁻¹ dry weight. For Cd and Zn, translocation factors were calculated from site- and species-specific mean concentrations as $TF_{\text{leaf/trunk}} = C_{\text{leaf}}/C_{\text{trunk}}$ and $TF_{\text{leaf/bark}} = C_{\text{leaf}}/C_{\text{bark}}$. The bioconcentration factor (BCF) was calculated by dividing the stem or bark content (mg kg⁻¹ DW) of an element by the soil extractable content (mg kg⁻¹ DW) of that element.

2.4. Statistical analysis

All statistical analyses were performed using R version 4.2.2 (R Core Team, 2022). For comparisons involving more than two groups, Kruskal–Wallis tests were followed, when appropriate, by Dunn’s pairwise tests with Holm adjustment for multiple comparisons. Compact letter displays in the figures were derived from the Holm-adjusted Dunn p-values, and groups sharing at least one letter were considered not significantly different at $\alpha = 0.05$. For the targeted comparisons of each planted group against the site-specific unplanted control reported in Table 1, Welch’s *t*-tests were used and p-values were adjusted by the Benjamini–Hochberg false-discovery-rate procedure within each site $\times$ element family. Pearson correlations were used to assess relationships between aboveground and belowground fresh biomass. Statistical significance was set at adjusted $p < 0.05$.

3. Results and discussion

3.1. Perennial biomass production at the three experimental sites

Aboveground and belowground perennial biomasses were quantified for 31 woody species across three phytoremediation sites, with 14 species evaluated at Leforest and Carrières-sous-Poissy and 15 species at Thann (Table S1). Considerable interspecific and intersite variability was observed (Fig. 1).

At Carrières-sous-Poissy, *E. umbellata* and *A. saccharinum* exhibited the highest productivity, producing 11.1 and 8.5 times more total biomass than *S. aquatica* ‘Grandis’, respectively. At Leforest, *S. alba* and *A. subcordata* were the most productive species, with biomass values

Table 1

Pairwise comparisons of CaCl₂-extractable element concentrations in planted soils versus the site-specific unplanted control (CON). Abbreviations are provided in Table S1. For each site and element, planted groups were compared with CON using Welch’s *t*-tests, and p-values were adjusted using the Benjamini–Hochberg false-discovery-rate procedure within each site $\times$ element family. Stars indicate adjusted p-values: $p < 0.05$ (*), $p < 0.01$ (**), and $p < 0.001$ (***).

Carrières-sous-Poissy		Leforest		Thann	
Tree	Statistics	Tree	Statistics	Tree	Statistics
EUM	Zn*, Ni*	ALS	Mn*, P**, S*	ABU	K*
FOR	Zn**, Ni*	OCA	Mn**, P**, S**	AGI	K**
FOX	Zn**, Ni**	PLO	Mn**, P**, S*	PTS	K**
HRH	Ni*	POX	Mn**, P*, S*	UPA	K**
OCA	Zn*, Ni**	PTS	Mn*, P**, S**	ZSE	K**
POX	Zn*, Ni**	QCE	Mn*, P**, S**		
PTS	Zn**, Ni*	QPD	Mn*, S**		
QCE	Zn**, Ni**	QPT	Mn*, P**, S**		
QPD	Zn**, Ni**	SAC	Mn*, P**, S*		
QPT	Zn**, Ni**	SAL	Mn*, P*		
SAQ	Zn*, Ni**	SAQ	P**, S**		
SVU	Zn*, Ni*	SCA	Mn*, P**, S**		
SJO	Mn*, P*, S*	SFR	P*, S**		
SVU	Mn*, P*, S*				

17.9 and 19.3 times higher than *Q. petraea*. At Thann, *O. carpinifolia* and *S. alba* produced 16.3 and 11.1 times more biomass than *C. sinensis*. Overall, Leforest showed the highest mean biomass production, followed by Carrières-sous-Poissy, whereas Thann exhibited the lowest productivity (Fig. 1).

Marked variability was observed within families. For example, *Salix caprea* produced approximately ten times less fresh biomass than *Salix alba* at Leforest, whereas *Quercus acutissima* produced 2.8 times more fresh biomass than *Quercus rysophylla* at Thann. These contrasts describe species-specific field performance but do not identify the physiological mechanisms responsible for them. Although Betulaceae and Salicaceae are frequently represented in phytoremediation studies, some taxa included here, such as *Hippophae rhamnoides* and *Ostrya carpinifolia*, have rarely been evaluated in this context. *Ostrya carpinifolia* showed particularly high fresh biomass at Thann, supporting its consideration as a candidate for revegetating harsh industrial substrates; the mechanisms underlying this performance were not measured in the present study.

Shoot and root fresh biomasses were strongly correlated at each site (Pearson’s $r = 0.88\text{--}0.91$, $p < 0.001$; Fig. 2a), and significant correlations were also observed for 13 individual species ($r = 0.81\text{--}0.99$, $p < 0.05$; Fig. 2b). At Leforest, several *Alnus*, *Salix*, and *Populus* taxa showed comparatively high shoot-to-root fresh-weight ratios. Because water content was not measured, these ratios should not be interpreted as dry-matter allocation coefficients.

The biomass values obtained for *S. aquatica* ‘Grandis’ and *O. carpinifolia*, two species planted at the three sites, showed considerable variation between sites. For example, total *S. aquatica* ‘Grandis’ biomass at Carrières-sous-Poissy was 6.3 and 5.6 times lower than at Leforest and Thann, respectively, whereas *O. carpinifolia* biomass at Carrières-sous-Poissy and Thann was 3.0 and 4.0 times higher than at Leforest. In contrast, *P. stenoptera* exhibited similar perennial biomass across the three sites, although its overall productivity remained low, indicating poor adaptability relative to other woody species.

Additional species were planted at two sites. *Populus* ‘Oxford’ grew better at Leforest compared with Carrières-sous-Poissy, whereas the reverse was observed for the three *Quercus* species *Q. cerris*, *Q. petraea*, and *Q. pedunculata*. *Populus orientalis* and *S. alba* grew 3.2 as much at Leforest as at Thann. These data reflect tolerance to site-specific soil conditions. Although other studies demonstrated that climate is the main driver of tree growth and therefore forest productivity (Toledo et al., 2011), our results are in agreement with Bončina et al. (2023), which suggests that soil quality is a powerful driver of tree productivity (Soong et al., 2020).

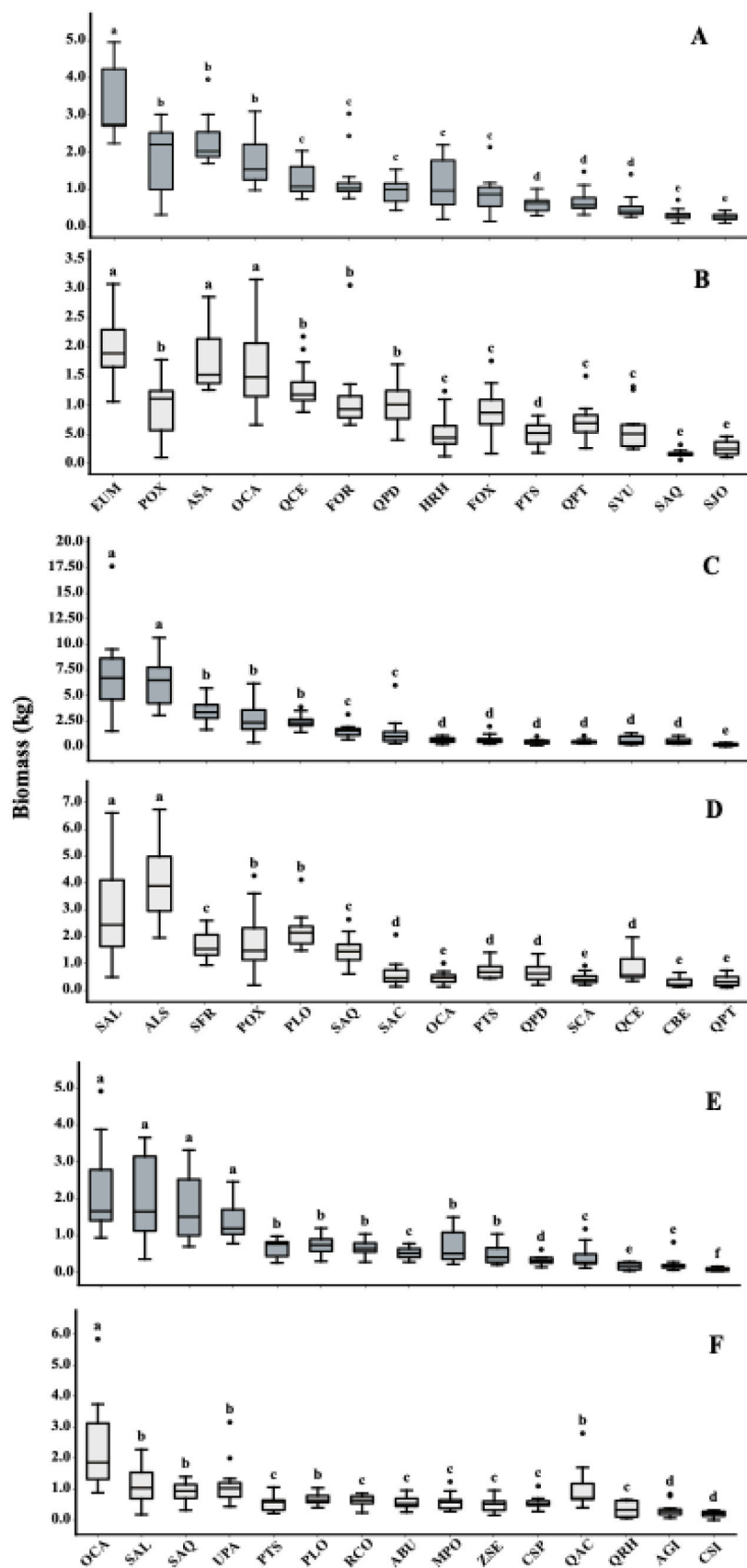


Fig. 1. Mean perennial aboveground (A, C, E; trunk and branches) and belowground (B, D, F; roots) fresh biomasses (g FW) for woody species planted at Carrières-sous-Poissy (A, B), Leforest (C, D), and Thann (E, F). Abbreviations are provided in [Table S1](#). Multi-group comparisons were performed using Kruskal–Wallis tests followed by Dunn’s tests with Holm adjustment. Compact letters are based on adjusted p-values; groups sharing at least one letter are not significantly different at $\alpha = 0.05$.

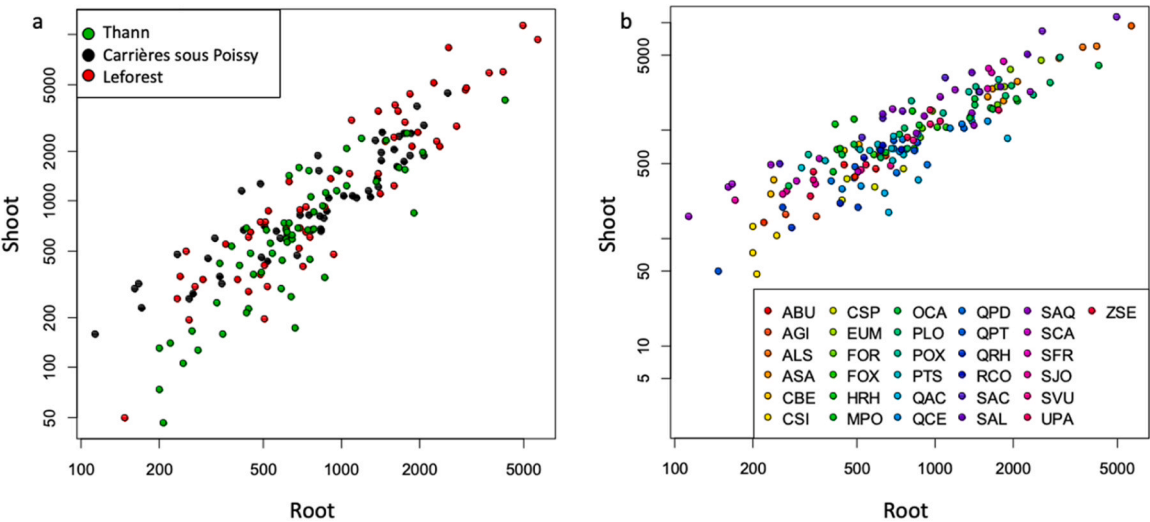


Fig. 2. Scatter plots representing the relationships between the aboveground (x-axis) and belowground (y-axis) biomass of the 31 tree species grown at the three sites. Sites (a) or species (b) are differentiated by different colors.

Willows and poplars are widely used in phytomanagement because many taxa combine rapid juvenile growth, extensive root systems, high transpiration, and resprouting ability (Pulford and Watson, 2003; Isebrands and Richardson, 2014). *Populus* ‘Oxford’ and *Salix aquatica* ‘Grandis’ have also been reported to accumulate trace elements under contaminated conditions (Marmioli et al., 2011; Ciadamidaro et al.,

2019; Chalot et al., 2020). In the present study, however, their biomass production varied markedly among sites, highlighting the importance of local soil and environmental conditions in determining field performance. The high productivity of *Alnus subcordata* at Leforest may similarly be related to the ecological traits commonly associated with nitrogen-fixing *Alnus* species. Other woody taxa, including *Betula*,

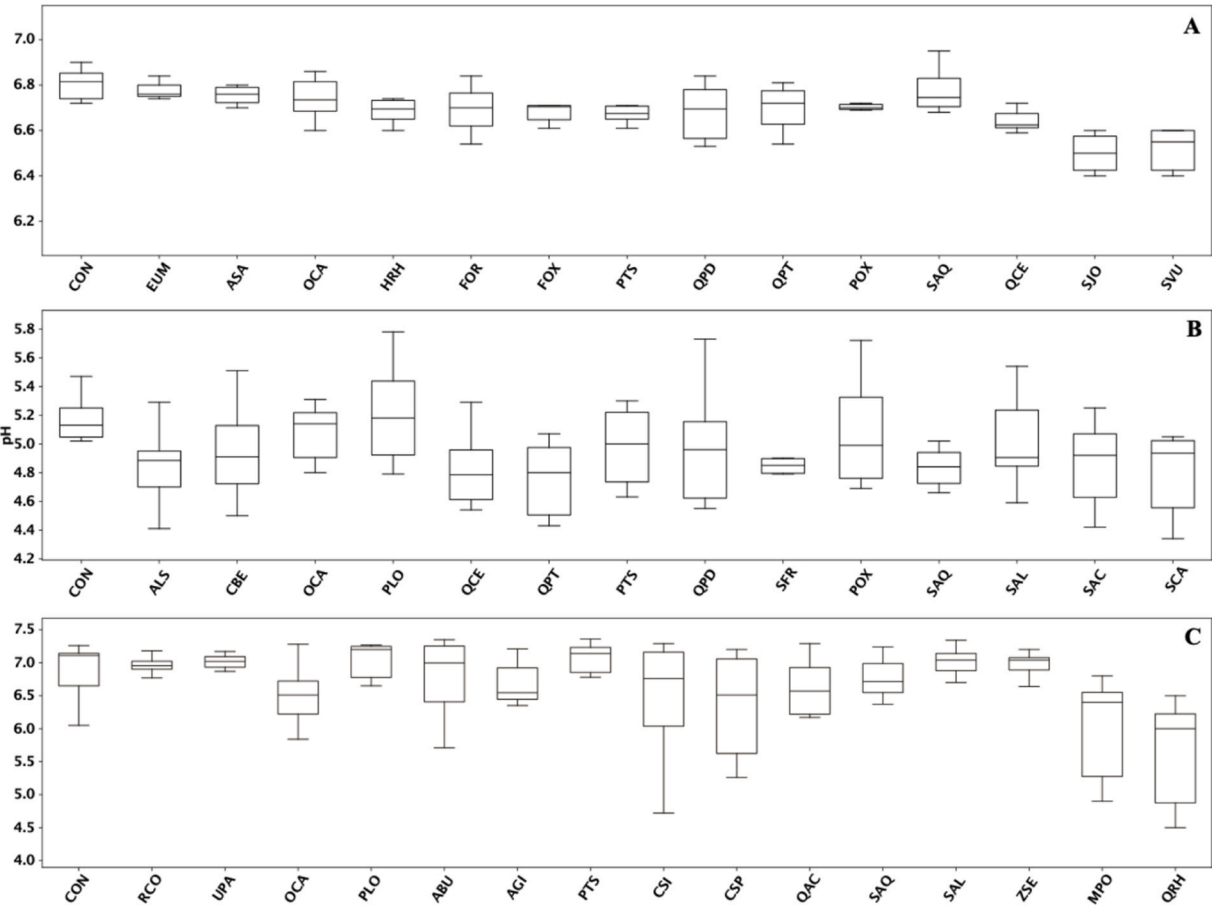


Fig. 3. Mean soil pH values for planted groups and unplanted controls at Carrières-sous-Poissy (A), Leforest (B), and Thann (C). Abbreviations are provided in Table S1. No statistically significant differences among planted groups and the unplanted control were detected at any of the three sites; the displayed differences are descriptive trends only.

Quercus, and *Acer*, have been reported to exhibit contrasting strategies of element exclusion, root retention, and transfer to aboveground tissues (Rosselli et al., 2003; Mertens et al., 2007; Evangelou et al., 2012), which may contribute to the species- and site-specific patterns observed here.

Tree taxa differ in architecture, tissue water content, rooting

strategy, and requirements for soil structure, pH, nutrients, and water. Root development is also strongly influenced by site-specific texture, drainage, and stoniness. Consequently, the fresh biomass comparisons reported here are intended to rank comparative field establishment within each site, not to estimate intrinsic dry-matter productivity or biomass-conversion yield across taxonomically diverse species. The

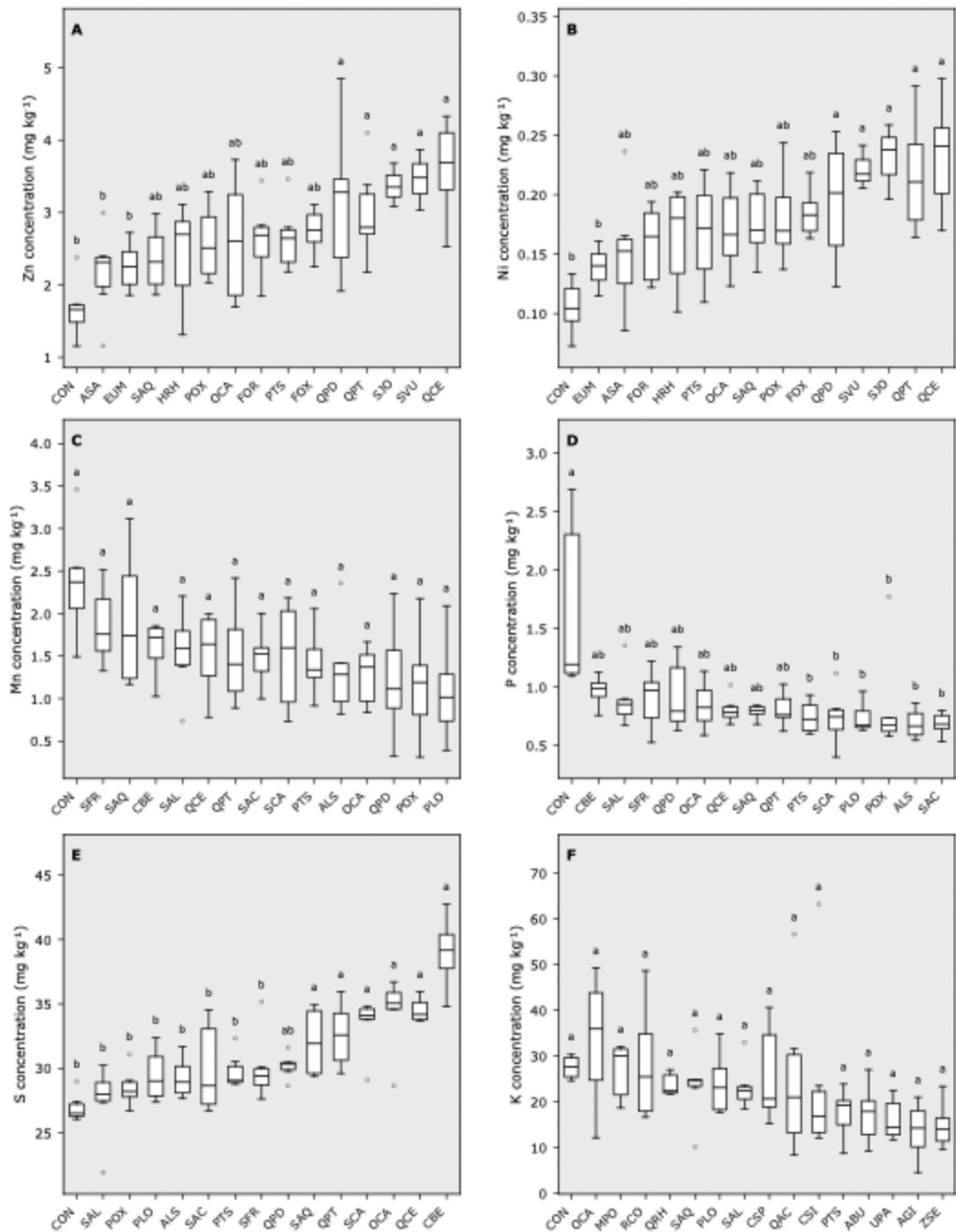


Fig. 4. Mean CaCl₂-extractable element concentrations (mg kg⁻¹ DW) in soils associated with woody species at Carrières-sous-Poissy (A, B), Leforest (C, D, E), and Thann (F), including unplanted controls (CON). Abbreviations are provided in Table S1; complete data are reported in Tables S2–S4. Multi-group comparisons were performed separately for each element using Kruskal–Wallis tests followed by Dunn’s tests with Holm adjustment. Compact letters are based on adjusted p-values; groups sharing at least one letter are not significantly different at $\alpha = 0.05$.

absence of dry biomass is a limitation because differences in fresh weight may partly reflect variation in tissue water content. Nevertheless, destructive excavation provides uncommon empirical information on aboveground and belowground field performance for a large panel of woody taxa, whereas most studies rely on aboveground measurements or allometric estimates (Le Goff and Ottorini, 2001; Peri et al., 2006; Niijama et al., 2010; Yuen et al., 2013).

3.2. Impact of woody species on soil pH and TE at the three experimental sites

Soil pH after five years of tree establishment showed some numerical variation among species and across the three experimental sites (Leforest, Carrières-sous-Poissy, and Thann) relative to unplanted control soils (Fig. 3). However, no statistically significant differences among tree species and the unplanted control were detected at any of the three sites. Site differences for unplanted soils were evident, with control pH values ranging from moderately acidic at Leforest (pH 5.09) to almost neutral at Carrières-sous-Poissy (pH 6.81) and Thann (pH 6.86). Although non-significant, the observed numerical trends appeared to vary among sites, with a more frequent tendency toward lower pH values at the initially acidic Leforest site and comparatively limited variation at Carrières-sous-Poissy. At Leforest, most tree species were associated with slightly lower mean soil pH values than the control, suggesting a possible, but statistically unsupported, tendency toward acidification. The lowest mean values were recorded under *S. caprea* (pH 4.79), *S. acutifolia* (pH 4.79), and *S. fragilis* (pH 4.79). In contrast, some species showed little numerical change or slightly higher values than the control, including *P. orientalis* (5.22) and *P. 'Oxford'* (5.09). At Carrières-sous-Poissy, mean soil pH values remained close to that of the control, ranging from 6.64 to 6.79. Slight numerical decreases were observed under *Q. cerris* (6.64) and *Q. pedunculata* (6.68), whereas *A. saccharinum*, *E. umbellata*, and *S. aquatica* 'Grandis' maintained values close to the control. At Thann, the mean pH values showed a somewhat broader, although non-significant, numerical range. Lower values were recorded under *Q. acutissima* (6.30) and *C. speciosa* (6.41), whereas higher values than the control were observed under *U. pumila* and *S. alba* (7.02) and *R. copallina* (6.97). Overall, these results indicate contrasting numerical tendencies among species and sites, but they do not provide statistical evidence of tree-species effects on soil pH after five years.

Elemental analyses were performed on the CaCl₂-extractable fractions of the soils (Table S2). A statistical analysis of the whole dataset is provided in Table 1. The elemental composition of soils varied strongly among sites, reflecting contrasting parent material and historical anthropogenic inputs. In particular, planted Leforest soils exhibited elevated Zn and Cd concentrations, whereas Carrières-sous-Poissy soils were characterized by higher P availability, and Thann soils showed exceptionally high S contents likely related to the industrial process.

Pairwise comparisons with the site-specific controls identified differences in selected CaCl₂-extractable elements (Table 1; Fig. 4; Tables S2–S4). At Carrières-sous-Poissy, several planted groups had higher Zn and Ni concentrations than CON, including multiple *Quercus* and *Fraxinus* taxa. At Leforest, lower Mn and P values and higher S values were observed for several planted groups. At Thann, comparatively few differences were detected, with lower K values in a limited number of groups. These comparisons describe associations between planted groups and soil chemistry at harvest; they do not, by themselves, demonstrate the processes that produced the observed differences.

The site- and taxon-dependent differences in CaCl₂-extractable elements may be associated with several processes, including litter inputs, root activity, and interactions with soil microorganisms. Although root exudation, microbial activity, nitrification, and element fluxes between soil pools were not directly assessed, these processes may have contributed to the observed variation in soil element availability.

3.3. Element concentrations in *S. aquatica* 'Grandis' and *O. carpinifolia*

Salix aquatica 'Grandis' and *Ostrya carpinifolia*, which occurred at all three sites, were selected for detailed tissue analysis because the earlier screening suggested contrasting accumulation profiles (Ciadamidaro et al., 2019). Mean element concentrations in trunk, bark, and leaves are reported in Tables S5–S7, and selected Cd, Zn, and P data are shown in Fig. 5.

Element concentrations differed among tissues, species, and sites (Tables S5–S7). Macronutrient concentrations were generally higher in leaves and bark than in trunk, particularly for K, Mg, P, and S. A similar descriptive gradient was observed for several trace elements. These concentration patterns identify tissue compartmentalization but do not directly demonstrate the cellular uptake, chelation, storage, or transport mechanisms involved.

Salix aquatica 'Grandis' generally had higher mean Cd and Zn concentrations than *Ostrya carpinifolia* across sites (Fig. 5; Tables S5–S7). *Ostrya carpinifolia* showed comparatively low concentrations of most trace elements, consistent with a low-accumulation profile. In trunk tissue, *Salix aquatica* 'Grandis' also had higher concentrations of several elements than *Ostrya carpinifolia*. These results support contrasting accumulation profiles, but the present measurements do not distinguish among reduced root uptake, root retention, xylem loading, or intracellular sequestration as underlying causes.

Bark concentrations were often higher than trunk concentrations, particularly for Ca, K, Fe, Mg, Mn, Cd, and Zn (Table S6). *Salix aquatica* 'Grandis' had higher Cd and Zn concentrations in bark than *Ostrya carpinifolia* at all sites, whereas *Ostrya carpinifolia* generally contained more Mg and K. High Mn concentrations in *Ostrya carpinifolia* tissues at Thann coincided with the Mn-rich Thann substrate, although the large variability warrants cautious interpretation.

Ostrya carpinifolia generally contained lower macronutrient and TE concentrations in leaves than *Salix aquatica* 'Grandis' (Table S7). Leaves of *Salix aquatica* 'Grandis' contained the highest measured Cd and Zn concentrations among its analysed tissues. This tissue distribution indicates that foliage represents the main aboveground compartment for Cd and Zn in *Salix aquatica* 'Grandis' and highlights contrasting element-partitioning patterns between the two species.

Concentrations generally followed the order leaves > bark > trunk for several elements. In *Salix aquatica* 'Grandis', bark-to-trunk concentration ratios ranged from 2.7 to 3.5 for Cd, 3.9–6.7 for Zn, and 2.9–4.1 for Pb. *Ostrya carpinifolia* showed lower Cd bark-to-trunk ratios. These ratios describe tissue partitioning but do not establish active sequestration or protection of xylem functions. Bark can receive elements through internal transport and external atmospheric deposition (Ayrault et al., 2007; Catonin et al., 2009), and the relative contribution of these pathways was not quantified here.

Leaves contained high concentrations of K, P, Mg, S, and Na, whereas Ca and Sr were abundant in bark and leaves. Nutrient concentrations also varied among sites; for example, the highest mean P concentration was measured at Thann for *Salix aquatica* 'Grandis' and at Carrières-sous-Poissy for *Ostrya carpinifolia* (Fig. 5). Cd and Zn concentrations were highest in leaves, intermediate in bark, and lowest in trunk for *Salix aquatica* 'Grandis' (Fig. 5).

TFs and BCFs calculated from site-level mean concentrations are reported in Table 2. Cd TF_{leaf/trunk} and TF_{leaf/bark} were > 1 for *Salix aquatica* 'Grandis' at all sites, whereas values for *Ostrya carpinifolia* were generally lower. Both taxa had Zn TF values > 1, with the largest ratio observed for *Salix aquatica* 'Grandis' at Carrières-sous-Poissy. BCFs were also much higher for *Salix aquatica* 'Grandis' as compared to *Ostrya carpinifolia*, especially for bark tissues that are known to accumulate substantially more TE than wood tissues (Chalot et al., 2020). The BCF values highlighted the accumulation capacity of *Salix aquatica* 'Grandis' for Cd and Zn, with values among the highest observed for the taxa investigated. However, these BCF values were calculated using CaCl₂-extractable rather than total soil concentrations and therefore

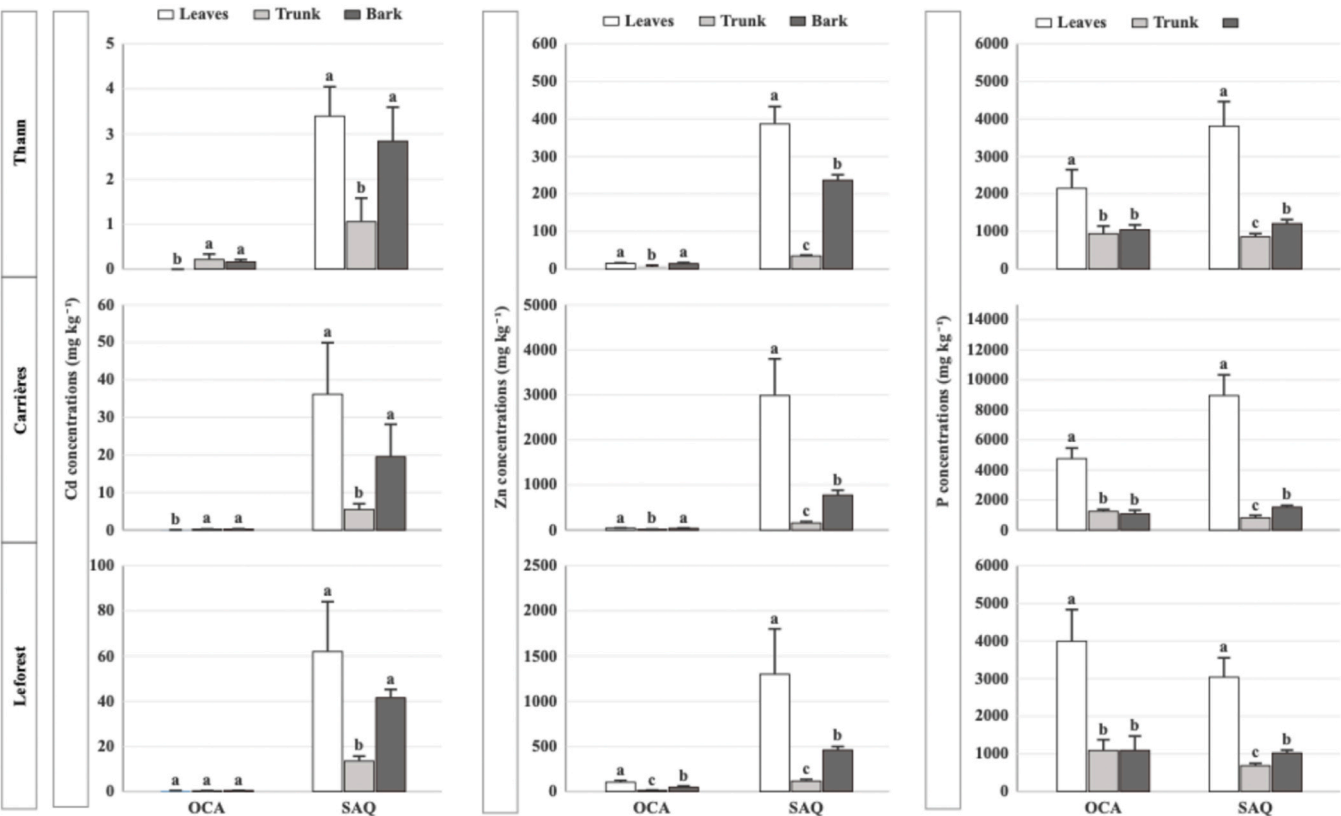


Fig. 5. Element concentrations in leaves, bark, and trunk (mg kg⁻¹ DW) of *Ostrya carpinifolia* (OCA) and *Salix aquatica* ‘Grandis’ (SAQ) after five years at Thann, Carrières-sous-Poissy, and Leforest. Complete data are reported in [Tables S5–S7](#). For each site and element, plant compartments were compared using Kruskal–Wallis tests followed by Dunn’s tests with Holm adjustment. Compact letters are based on adjusted p-values; groups sharing at least one letter are not significantly different at $\alpha = 0.05$.

Table 2
Translocation factor (TF) and bioconcentration factor (BCF) calculated from site- and species-specific mean dry-weight concentrations. $TF_{leaf/trunk} = C_{leaf}/C_{trunk}$ and $TF_{leaf/bark} = C_{leaf}/C_{bark}$. $BCF_{trunk/soil} = C_{trunk}/C_{soil}$ and $BCF_{bark/soil} = C_{bark}/C_{soil}$, where C_{soil} is the mean CaCl₂-extractable concentration in the rhizosphere soil associated with each species and site. “na” indicates that the BCF could not be calculated because the CaCl₂-extractable soil concentration was zero or <LOD. Underlying tissue concentrations and standard deviations (n = 12 biological samples per species and site) are reported in [Tables S5–S7](#), and soil concentrations in [Tables S2–S4](#).

Site		TF _{leaf/trunk}		TF _{leaf/bark}		BCF _{trunk/soil}		BCF _{bark/soil}	
Cd	Leforest	OCA	SAQ	OCA	SAQ	OCA	SAQ	OCA	SAQ
	Carrières-sous-Poissy	1.27	4.58	0.90	1.49	0.50	19.29	0.67	59.29
	Thann	0.24	6.56	0.21	1.85	2.00	55.00	2.00	195.00
Zn	Leforest	na	3.24	na	1.20	na	na	na	na
	Carrières-sous-Poissy	8.46	11.15	2.15	2.82	NA	13.30	NA	52.27
	Thann	2.55	18.95	1.13	3.85	6.38	65.83	14.42	323.75
		2.04	10.98	1.05	1.63	na	na	na	na

reflect plant accumulation relative to the readily extractable soil fraction. This should be considered when comparing the present BCF values with those reported in studies based on total soil concentrations. TFs and BCFs support contrasting tissue-distribution profiles between *Salix aquatica* ‘Grandis’ and *Ostrya carpinifolia*, but should not be interpreted as direct measurements of transport rates.

The parallel Cd and Zn accumulation patterns in *Salix aquatica* ‘Grandis’ are compatible with the chemical similarities and partly shared uptake pathways of these elements (Das et al., 1997; Robinson et al., 2000; Ciadamidaro et al., 2014; Zhao et al., 2023). The high concentrations measured in harvestable leaves and bark support the consideration of this taxon for Cd- and Zn-oriented phytoextraction or biomonitoring at suitable sites. Its lower fresh biomass at Carrières-sous-Poissy was associated with high tissue concentrations, but the present field design did not test whether Cd or Zn exposure caused

the lower growth. Other site properties, species establishment history, and environmental heterogeneity may also have contributed.

Salix aquatica ‘Grandis’ survived for five years while accumulating high Cd and Zn concentrations, confirming a strong field accumulation capacity. The maximum mean foliar Zn concentration reached approximately 2987 mg kg⁻¹ DW at Carrières-sous-Poissy, placing it very close to the operational hyperaccumulation threshold of 3000 mg kg⁻¹ DW (Fig. 5). The maximum mean foliar Cd concentration reached 62 mg kg⁻¹ DW at Leforest, remaining below the corresponding threshold of 100 mg kg⁻¹ DW (van der Ent et al., 2013; Reeves et al., 2018). Thus, although the available evidence does not support formally classifying *Salix aquatica* ‘Grandis’ as a hyperaccumulator, its foliar Zn concentration approached the recognized threshold and confirms its strong Cd- and Zn-accumulation capacity under field conditions. *Ostrya carpinifolia*, in contrast, showed a comparatively low-accumulation

profile.

Site-specific accumulation patterns were consistent with the contrasting substrate properties and contamination histories of the three sites. Thann was enriched in Fe, S, and Mn, whereas Leforest and Carrières-sous-Poissy were mainly affected by Pb, Cd, and Zn contamination (Zappellini et al., 2018; Ciadamidaro et al., 2019). The high Zn concentrations measured in leaves despite low CaCl₂-extractable concentrations in soil may reflect the different time scales and soil pools represented by these measurements. CaCl₂ extraction provides an estimate of the readily exchangeable fraction at the time of sampling, whereas perennial tissues integrate element uptake over several years and across a larger soil volume. Progressive replenishment of the soil solution from less-labile pools may therefore contribute to sustained Zn uptake over time (Harmsen, 2007; Smolders et al., 2009, 2012).

4. Conclusions

Overall, the five-year field trial demonstrated that the performance of woody species on TE-contaminated soils was strongly dependent on both species identity and local site conditions. Large differences in whole-tree fresh biomass were observed among taxa, and no single species consistently outperformed the others across the three sites. *Elaeagnus umbellata* and *Acer saccharinum* showed the greatest biomass production at Carrières-sous-Poissy, *Salix alba* and *Alnus subcordata* at Leforest, and *Ostrya carpinifolia* and *Salix alba* at Thann. These contrasting responses highlight the importance of selecting woody species according to the characteristics and management objectives of each contaminated site rather than applying general species rankings. In contrast to biomass production, no significant species-specific effect on soil pH was detected after five years of tree establishment.

The contrasting accumulation profiles of *Salix aquatica* 'Grandis' and *Ostrya carpinifolia* illustrate two complementary phytomanagement strategies. *Salix aquatica* 'Grandis' accumulated high concentrations of Cd and Zn, particularly in leaves and bark, confirming its potential as a strong accumulator for phytoextraction or biomonitoring where the management and potential valorization of metal-enriched biomass can be ensured. Conversely, *Ostrya carpinifolia* combined comparatively low TE concentrations in its aerial tissues with high biomass production at Thann, making it a promising candidate for phytostabilization and ecological restoration where limiting contaminant transfer is a priority. Overall, these findings demonstrate that the selection of woody species for contaminated land management should balance long-term establishment, biomass production, element-accumulation profiles, site characteristics, and the intended use of the harvested biomass. Further assessment of dry-matter production and cumulative element removal would help determine the operational efficiency of the most promising taxa.

CRedit authorship contribution statement

Stéphane Pfendler: Writing – review & editing, Writing – original draft, Validation, Methodology, Data curation, Conceptualization. **Lisa Ciadamidaro:** Writing – review & editing, Writing – original draft, Validation, Investigation, Conceptualization. **Shinji Ozaki:** Software, Data curation. **Cyril Zappellini:** Methodology, Investigation, Data curation. **Damien Blaudez:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Michel Chalot:** Writing – review & editing, Writing – original draft, Resources, Project administration, Investigation, Conceptualization.

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Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Chat GPT (OpenAI; GPT-5.6 Sol) in order to produce the graphical abstract. After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ecoenv.2026.120820.

Data availability

Data will be made available on request.

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