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1 **A combined approach utilizing UAV 3D imaging methods, *in-situ* measurements, and laboratory**
2 **experiments to assess water evaporation and trace element uptake by tree species growing in a**
3 **red gypsum landfill**

4
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16 **Abstract**

17 The extractive industry is increasingly faced with problems of managing contaminated sites. The red
18 gypsum landfill at the Ochsenfeld site is representative of the typology byproduct storage of the Ti-
19 extraction activity. The management of the elemental content and the water body are the issues at this
20 site. The aim of this study was to evaluate the canopy conductance (g_{cmax}) of various tree species and
21 the content of elements in the leaves, utilizing the opportunity of a demonstration plantation setup in
22 2014 with sixteen tree species, combined with a growth chamber experiment. We combined the gas
23 exchange measurements with the data from two multispectral cameras with RGB and NIR bands
24 embarked on an unmanned aerial vehicle (UAV). In the field, *Ostrya carpinifolia*, *Maclura pomifera*,
25 and *Rhus copallina* had the highest g_{cmax} of all planted tree species, and the high transpiration rate in *O*.
26 *carpinifolia* was confirmed in a pot-based controlled experiment. Except *R. copallina*, the species with
27 a high Mn content (*O. carpinifolia*, *Betula pendula*, and *Salix aquatica grandis*) had high stomatal
28 conductance. *O. carpinifolia* could therefore be a species to exploit in the management of landfill
29 leachates, especially in the context of climate change since this species is well adapted to dry
30 environments.

31

32

33 **Keywords:** UAV Remote Sensing; LAI; Canopy conductance; Transpiration; *Ostrya carpinifolia*

34 **1. Introduction**

35 According to the Joint Research Centre (JRC), since the 1970s, the extraction of metals has increased
36 by more than 75% worldwide (Joint Research Centre, 2017). This significant increase in extractive
37 activities has had a strong impact on the environment. In European Union countries, there are overall
38 between 150,000 and 500,000 mine landfills, the majority of which are no longer active (Vaverková,
39 2019), which raises the question of the management of these landfills. Red gypsum landfills represent
40 an environmental and ecological model of the typology of byproduct storage of Ti-extraction activity
41 (high content of some trace elements (TEs): notably Fe and Mn and low biodiversity) (Edraki et al.,
42 2014; Huang et al., 2012; Zapata-Carbonell et al., 2020). Extraction of Ti from ilmenite using the
43 sulfuric process leads to the production of red gypsum during the neutralization of the company's
44 wastewater with limestone. This red gypsum, accumulated over decades, allows the formation of a
45 technosol, on which the development of vegetation is lessened due to the presence of various mineral
46 oxides and TEs (Ciadamidaro et al., 2019; Zapata-Carbonell et al., 2019). The lack of vegetation
47 potentially leads to mineral (including TEs) leaching and dust enriched in TEs. Moreover, this red
48 gypsum is stored on a waterproof structure that requires appropriate management of the incoming and
49 outgoing water masses. The revegetation of landfills is therefore an important issue to better manage
50 water flows via evapotranspiration and to limit the spread of dust. Phytomanagement, which has recently
51 become an alternative for site and soil management, comprises a set of sustainable techniques using tree
52 species *in situ*, for example, to restore some ecosystem services, to control erosion, and more relevantly
53 here to regulate water flow (Cundy et al., 2016). Trees indeed contribute to water balance through
54 transpiration. Using a lysimeter-based approach, *Populus* sp. was found to enhance evapotranspiration
55 and to reduce bore leaching by accumulation in aerial biomass (Robinson et al., 2007). Important mass
56 flow may enhance plant nutrient acquisition by promoting the movement of nutrients from the soil to
57 the root and aerial parts of the plant (Huang et al., 2017). Mn moves freely in the xylem sap and is
58 transported to leaves via transpiration stream with little redistribution (Ducic and Polle, 2005). Barber
59 (1995) described and modelled nutrient uptake by crop tree species and concluded that the water flux is
60 a key parameter. Element uptake modelling was used to describe K, P, Zn and Mn uptake by different
61 tree species and to further demonstrate the role of water flux (Adhikari and Rattan, 2000; Brouder, 1994;
62 Chen, 1990; Sadana and Claassen, 2000). Previous studies have reported negative relationships between

63 foliar TE content and transpiration rate in tree species (Kitao et al., 1997; Milan, 2012; Pajevic et al.,
64 2009; Arsenov et al., 2020). In plants, metals exert their toxic action, mostly by damaging chloroplast
65 and disturbing photosynthesis and the inhibition of photosynthesis is the consequence of interference of
66 metal ions with photosynthetic enzymes and chloroplast membranes, thus inducing a biochemical
67 limitation of stomatal conductance, as reviewed in Aggarwal et al., (2011). Many studies have shown
68 that an excess supply of TEs leads to significant changes in the water relations of tree species (Pandey
69 and Sharma, 2003; Vernay et al., 2007). It has also been observed in experiments conducted under
70 greenhouse conditions with *Populus* hybrids that the transpiration rate decreased with an increase in
71 mixed TE (Cd, Cr, Cu, and Zn) content (Chandra and Kang, 2016). The transpiration rate and stomatal
72 conductance in *Phaseolus vulgaris* were reduced by a high Zn content (Van Assche et al., 1980) or by
73 ZnSO₄ at 600 mg/kg in peat moss soil (Kasim, 2007). Mn, which is one of the major components of the
74 red gypsum sediment at the Ochsenfeld site (Zapata-Carbonell et al., 2019), accumulates predominantly
75 in the plant shoot (Page et al., 2006). High Mn content leads to excess TE deposition in photosynthetic
76 cells and might potentially impair cellular metabolism (Fernando et al., 2013), which may lead to metal
77 toxicity in cells. High Mn content can decrease the net photosynthetic rate, stomatal conductance,
78 internal carbon dioxide concentration and transpiration in several genotypes of cotton (Tavanti et al.,
79 2019). The transpiration of plants depends not only on tree species physiology, *i.e.*, the ability to regulate
80 the stomatal aperture but also the leaf area. The transpiration capacity is estimated by the transpiring
81 surface of plants and thus by the leaf area index (LAI). This index is the ratio between the sum of the
82 foliar area and the unit of ground area (Watson, 1947). LAI is traditionally obtained by harvesting all
83 leaves of a plot and by measuring the surface of each leaf. Modern alternative methods have been
84 developed. Flatbed scanners have made this process more efficient, but it is still laborious, time
85 consuming and destructive. It is possible to use instruments based on atmospheric sensors (LI-COR
86 LAI-2000 Plant Canopy Analyser and CI-100 Plant Canopy Analyser) or a linear array of
87 photosynthetically active radiation sensors (AccuPAR Ceptometer) to estimate the LAI (Breda, 2003;
88 Peper and McPherson, 1998; Wilhelm et al., 2000). These indirect non-destructive techniques comprise
89 the application of a logarithmic regression and allometric equation, which is faster to set up for
90 homogeneous covers but has not yet been applied for multispecific row plantations (Nowak, 1996). As
91 the alternative method, the Light Detection and Ranging (LiDAR) can be used as an active sensor which

92 is based on the emission of a highly collimated laser pulse and analysing the reflected signal (Lin, 2015)
93 to estimate LAI using volumetric methods such as surface differencing (Loudermilk et al., 2009) where
94 the digital terrain model (DTM) is subtracted to the digital surface model (DSM). In a recent review
95 (Wang and Fang, 2020), where LiDAR technology, LAI retrieval and validation methods are reviewed,
96 it is concluded that terrestrial laser scanning (TLS), airborne laser scanning (ALS) or spaceborne laser
97 scanning (SLS) data can be used for the estimation of the vegetation LAI. While the use of LiDAR for the
98 estimation of LAI have shown promising results especially in forest application (Alonzo et al., 2015;
99 Lefsky et al., 1999), other approaches have been developed. Among these new technologies, the use of
100 unmanned aerial vehicles (UAVs) to record low-altitude images is becoming increasingly widespread
101 (Zhang and Kovacs, 2012) and is the only automated alternative for heterogeneous cover. LAI
102 estimation from UAV-based remote sensing multispectral imagery (Hunt et al., 2008) is increasingly
103 reported, for instance in agriculture (Yao et al., 2017), in mangrove (Tian et al., 2017) and forest (Lin et
104 al., 2021) ecosystems. Although UAV have been used in landfill monitoring (Rauhala et al., 2017;
105 Shahmoradi et al., 2020), to our knowledge, no studies have been conducted on the use of UAV to
106 estimate LAI at landfills under phytomanagement. Most authors have used vegetation indices based on
107 photogrammetry analysis, such as the normalized difference vegetation index (NDVI), which is used to
108 monitor the degree of vegetation greenness (Tucker, 1979; Zarco-Tejada et al., 2012). NDVI data have
109 proven to be a robust approach for estimating biotic stress (chlorophyll deficiency) and abiotic stress
110 (water drought). NDVI is a ratio of operation of reflectance per specific bands ($\text{NIR}-\text{R}/\text{NIR}+\text{R}$) for
111 multispectral signature where NIR and R are respectively the near-infrared and red bands. It is also a
112 measure of reflectance and an estimation of vegetation growth and biomass (Gandhi et al., 2015);
113 however, this index is not quantitative and has to be calibrated using field data.

114 The present study focuses on the Ochsenfeld red gypsum landfill, located in northeastern France, with
115 an area of 80 ha. The main management issues at the Ochsenfeld site are (i) to revegetate the site to
116 stabilize the soil, thus limiting the dispersion of dust and TEs, or for producing a valuable Mn-enriched
117 biomass and (ii) to increase the evapotranspiration potential of the site, thus reducing the volume of
118 water stored in the landfill that remains to be treated. On part of the site, we set up a phytomanagement
119 trial in 2014 with different tree species to select the tree species best suited to the site conditions
120 (Ciadamidaro et al., 2019). Considering these particular objectives and conditions, our hypothesis was

121 that the selection of tree species for TE uptake capacity would not be antagonist to the selection of
122 species with a high transpiration rate. The opportunity of the 5-year-old demonstration plantation was
123 used to estimate leaf area with a surface integration method using UAV-based remote sensing, to screen
124 transpiration capacity and to determine TE content in leaves. The leaf surface and surface area of the
125 trees were originally developed using a surface integration method to quantitatively estimate the LAI.
126 In the present study, we further used low-altitude photos obtained with UAVs that allow three-
127 dimensional integration to obtain developed surfaces. The transpiration rate of some selected tree species
128 growing on anthroposol from Ochsenfeld site and its relationship with the Mn content were further
129 explored under controlled conditions with a more accurate method (by utilizing the weight loss method)
130 to potentially confirm the field results. The objectives of these experiments were (i) to test the method
131 of LAI estimation by using UAV 3D-imaging-based remote sensing on landfill, (ii) to combine LAI
132 estimation by using UAV 3D-imaging and gas exchange measurements for estimating the maximum
133 canopy cover conductance as an estimator of tree performance for their capacities of management of
134 water flow, and (iii) to test a potential concomitance between transpiration performance and leaf element
135 uptake performance in a phytomanagement context.

136 2. Materials and methods

137 2.1. Experimental design

138 2.1.1. Field experiment

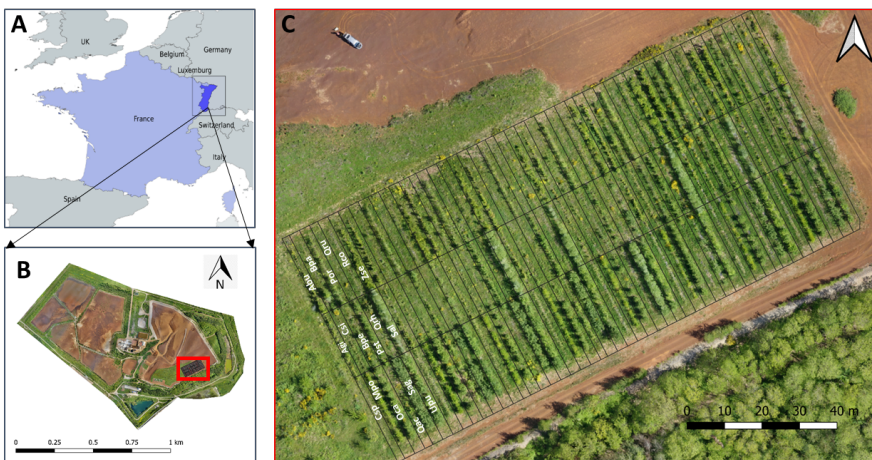
139 The pilot site of a 1-ha area was implemented in April 2014 on a storage landfill of mining byproducts
140 located in the municipality of Thann in Northeast France (Fig. 1) and was fully described by
141 Ciadamidaro et al. (2019). The soil has silty and alkaline characteristics and is enriched mainly in Mn,
142 Fe, and S (Assad et al., 2017). A 30 cm layer of backfill was added on top of the red gypsum before
143 planting. According to Ciadamidaro et al. (2019), only 16 species of the 18 planted species with a
144 significant growth performance were selected for this study (Table 1).

145 Table 1. List of the tree species used in the present study and their abbreviations

Abu	<i>Acer buergerianum</i>	Por	<i>Platanus orientalis</i>
Agi	<i>Acer ginnala</i>	Pst	<i>Pterocarya stenoptera</i>

Bpa	<i>Betula papyrifera</i>	Qac	<i>Quercus acutissima</i>
Bpe	<i>Betula pendula</i>	Rco	<i>Rhus copallina</i>
Csp	<i>Catalpa speciosa</i>	Sag	<i>Salix aquatica grandis</i>
Csi	<i>Cedrela sinensis</i>	Sal	<i>Salix alba</i>
Mpo	<i>Maclura pomifera</i>	Upu	<i>Ulmus pumila</i>
Oca	<i>Ostrya carpinifolia</i>	Zse	<i>Zelkova serrata</i>

146



147

148 Fig. 1. The experimental Ochsenfeld site at Thann (France). (A) Geographic location of the red gypsum
 149 landfill. (B) Aerial view of the site showing the location of the experimental plot (red rectangle). (C)
 150 Partition of the experimental area: each partition corresponds to the plantation of one row of one species,
 151 and 8 rows were planted per species.

152 2.1.2. Growth chamber experiment

153 A pot experiment was performed in a controlled growth chamber on five tree species showing
 154 contrasting growth and elemental contents in the leaves (according to Ciadamidaro et al., 2019): *B.*
 155 *pendula*, *S. aquatica grandis*, *O. carpinifolia*, *P. stenoptera*, and *A. buergerianum* (20 plants per
 156 species). *B. pendula* seeds were collected from the Ochsenfeld site and sown on peat (Brill Typical,
 157 Germany) for 3 months. *O. carpinifolia*, *P. stenoptera* and *A. buergerianum* seedlings and *S. aquatica*
 158 *grandis* seedlings were provided by Soupe Nursery (Chatillon sur Chalaronne, France). They were
 159 grown directly on the anthroposol at the Ochsenfeld site in 4 L pots. The climatic conditions present for
 160 the growth chamber experiments were as follows: day illumination duration of 16 h; night time of 8 h;
 161 day/night temperature of 23 °C/21 °C; day/night humidity of 70%; and day illumination intensity of

162 approximately 600 $\mu\text{mol}/\text{m}^2/\text{s}$ of photon photosynthetic activity. The measurements were conducted at
163 intermediate (90 days) and final times (152 days).

164 2.2. Ecophysiological analysis

165 For the field experiment, the maximum stomatal conductance (g_{max} expressed in $\text{mol H}_2\text{O}/\text{leaf m}^2/\text{s}$)
166 was monitored between June and July 2019 on one fully sun-exposed leaf ($n=9$ randomly chosen by
167 species) using a portable gas-exchange system (Licor-6400 Lincoln, Nebraska) at 400 ppm CO_2 , 30 °C
168 block temperature, photosynthetically active radiation at 1400 $\mu\text{mol}/\text{m}^2/\text{s}$ and ambient air humidity (min
169 = 50% and max = 80%). Each measurement was recorded when the stabilization of g_{max} was observed
170 (approximately 3 min). Minimum leaf water potentials (Ψ_{min} expressed in MPa) were measured
171 immediately after on the same twig with a pressure chamber (Scholander et al., 1965). These
172 measurements were collected between 10 a.m. and 4 p.m. local time to ensure light conditions supported
173 maximum photosynthetic rates and minimum Ψ_{min} .

174 For the growth chamber experiment, the plant transpiration stream was measured through water loss
175 method by weighing pots packed in a plastic bag for 4 h to limit the evaporation of the soil. To express
176 the transpiration per unit leaf area, an estimation of the total leaf area was performed by measuring the
177 leaf length of all leaves of each measured plant. The etalon curve leaf area – leaf length and leaf area –
178 and leaf dry mass, realized for intermediate time and final time measurements, respectively, were
179 measured for a subset of leaves from each species with a WinRHIZO scanner (Regent Instrument,
180 Quebec, Canada). Details of the equations used are provided in the supplemental information Fig. S1.

181 2.3. Remote sensing

182 UAV-based remote sensing was used to calculate the height of tree species and vegetation indices (LAI
183 and NDVI). Two high-resolution digital cameras, Sony (RX100 M3; Tokyo, Japan) for red (R: 620 to
184 670 nm), green (G: 490 to 570 nm), and blue (B: 450 to 490 nm) bands and Canon (S110; Tokyo, Japan,
185 modified by LDP LLC Max, Carlstadt, USA) for near-infrared (NIR: 680 to 800 nm) bands with a
186 resolution of 8 megapixels, were embarked on the drone TurtleQuad® designed by Gilles Gallinet. On
187 24 May 2019, on a clear and sunny day a flight of the UAV was conducted aloft at 30 to 35 metres from
188 the ground between 11:30 a.m. and 12:40 a.m. local time to collect spectral radiance at ground from
189 aerial photos. A total of 547 photos were taken to generate the first 3-D model (dense cloud and shaded

190 model) using Metashape-AGISOFT photogrammetric software (version 1.6.1, Agisoft LLC, Saint
191 Petersburg, Russia). This 3-D model used 11 ground targets (GCPs) for the 3-dimensional calibration
192 of the photogrammetric model, recorded by traditional terrestrial acquisition using a high-precision real-
193 time kinematic - global positioning system (RTK-GPS). From this 3-D model, still using Metashape-
194 AGISOFT, an orthomosaic projection generated two multiband orthophotographs: one with red (band1),
195 green (band2), and blue (band3) bands, and the second with near-infrared (band1), green (band2), and
196 blue (band3) bands. The data from these multiband orthophotographs were then processed using QGIS
197 version 3.10.1-A Coruña (QGIS Development Team, 2018).

198 The source images had the following resolution: 9.89 mm/pix for RGB and 1.46 cm/pix for NIR. The
199 two RGB and NIR orthomosaics were first calculated using Metashape, each separately with their native
200 resolution. They were then resampled when exported by Metashape to provide images with a GSD
201 (Ground Spatial Distance) of 10 cm/pix. Processing in QGIS was then performed with this resampled
202 resolution of 10 cm/pix for all bands used. The sampling algorithm during orthomosaic generation
203 process and the resampling algorithm during export were the same *i.e.* bilinear interpolation. The
204 geometric calibration of the optics was carried out using the Metashape software, which has built-in
205 tools for this. The overlay between the captured images was chosen to be greater than 80% in both length
206 and width. Furthermore, the flight lines overlapped. Therefore, each pixel of the orthomosaic was
207 calculated from at least nine photographs (see supplemental information Fig. S2 and S3). The mapping
208 was deliberately done beyond the perimeter of the study area to avoid any edge effect. The maps
209 extended at least 25 m beyond the lateral limits of the actual study area.

210 The tree height (TH) was calculated in QGIS by calculating the difference in altitude between the DSMs
211 and the DTM (Eq. 1). The DSM was the 3D surface of the cover canopy of vegetation. The precision of
212 the DSM was $x = 3$ cm, $y = 3$ cm and $z = 5$ cm. The DTM was a 3-D area of the soil without vegetation.
213 The DTM was recorded by traditional terrestrial acquisition using a high precision RTK-GPS. This
214 DTM integrated the reading of the 11 ground targets used for the 3-dimensional calibration of the
215 photogrammetric model. The accuracy of the RTK GPS reading on the ground was $x, y = 1$ cm and $z =$
216 2 cm. The soil DTM and vegetation canopy DSM were in the same projection system and the same
217 altimeter setting.

$$TH = DSM - DTM$$

219 (1)

220 To obtain the LAI, we calculated the ratio between the leaf area of canopy cover (LA) and the area
221 projected at the ground of the canopy cover (GC) of the tree species (Eq. 2). The leaf area of the canopy
222 cover was measured on Agisoft Metashape by manual delineation of the tree crown (Fig. 2). The area
223 of the canopy cover projected on the ground was calculated on QGIS also by manual delineation of the
224 tree crown.

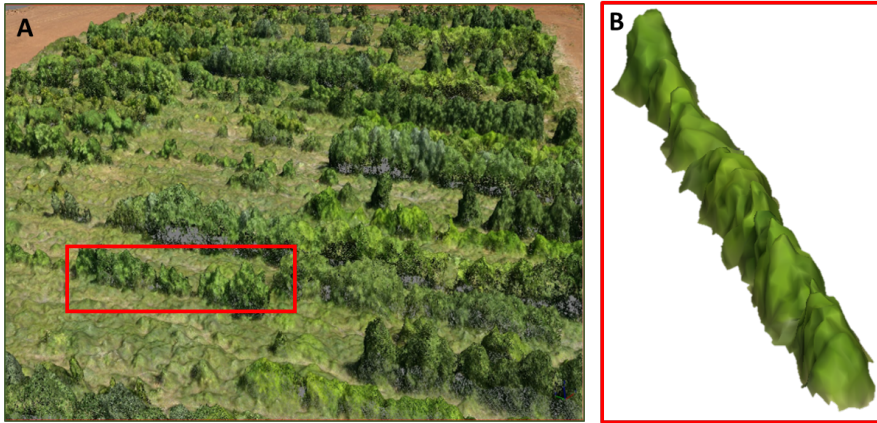
$$LAI = \frac{LA}{GC} \quad (2)$$

227 The LAI multiplied by the mean of the g_{smax} allowed us to obtain the canopy conductance (g_{cmax})
228 expressed in mol H₂O/ground m²/s, which is controlled mainly by these two variables (Granier et al.,
229 2000).

230 The NDVI values were calculated according to the following equation (Eq. 3) using QGIS, where NIR
231 and R are reflectance values in the near-infrared and red wavelengths, respectively, given by Tucker
232 (1979). The NDVI values range from 0.2 to 0.8 for vegetation and are unitless. High NDVI values
233 indicate healthy and dense green vegetation, and low NDVI values indicate moisture-stressed and sparse
234 vegetation (Drisya et al., 2018; Gessesse and Melesse, 2019).

$$NDVI = \frac{NIR - R}{NIR + R} \quad (3)$$

237 The experimental site was divided into eight different plots as described by Ciadamidaro et al. (2019).
238 Each plot consisted of a replicate of the 18 different tree species planted in rows (one row by species).
239 For the present UAV-based study, the experimental site was partitioned row-by-row, constituting eight
240 replicates per species (Fig. 1C). The results for each species were the median and the quartiles of these
241 eight rows.



242

243 Fig. 2. Three-dimensional UAV view of the canopy cover at the experimental Ochsenfeld site. (A)
244 General view of the demonstration site generated at-sensor reflectance orthomosaics using Metashape-
245 AGISOFT photogrammetric software. (B) Detailed view of one plot corresponding to one tree species
246 obtained by manual delineation of the tree crown. Each row of a tree species was cut, isolated and
247 trimmed, which further allowed us to estimate the developed leaf area using a surface integration
248 method.

249 2.4. Elemental analysis

250 For each tree species, the leaves used for gas exchange measurements were washed with deionized water
251 and dried at 70 °C for 72 h. These dried leaf samples were ground using a ball mill (Retsch MM300,
252 Eragny, France). Mineralization was realized by acid digestion with concentrated HNO₃ using a VELP
253 DK6 heating digester (VELP Scientifica, Usmate Velate, Italy). As described by Assad et al. (2017), the
254 total elemental content (Al, B, Ca, Cd, Cu, Fe, K, Mg, Mn, Na, P, S, Si, Sr, Ti, and Zn) in the leaves
255 from the field samples was determined using inductively coupled plasma atomic emission spectrometry
256 (ICP-AES, Radial ICAP 6500 Model, Thermo Fischer Scientific, Inc., Pittsburgh, USA). For the pot
257 experiment, Mn content was determined by atomic absorption spectroscopy (AAS, Agilent
258 Technologies, Inc., Santa Clara, USA).

259 2.5. Statistical Analysis

260 All statistical analyses were performed using R software version 4.0.4, the R Foundation for Statistical
261 Computing (R Core Team, 2021), at a significance level when $P < 0.05$. To verify the homoscedasticity
262 and the normality of the all dataset, we had used a Levene test (Levene, 1960) and Shapiro–Wilk test
263 (Shapiro and Wilk, 1965) respectively. As dataset did not fit the assumption of the normal distribution,

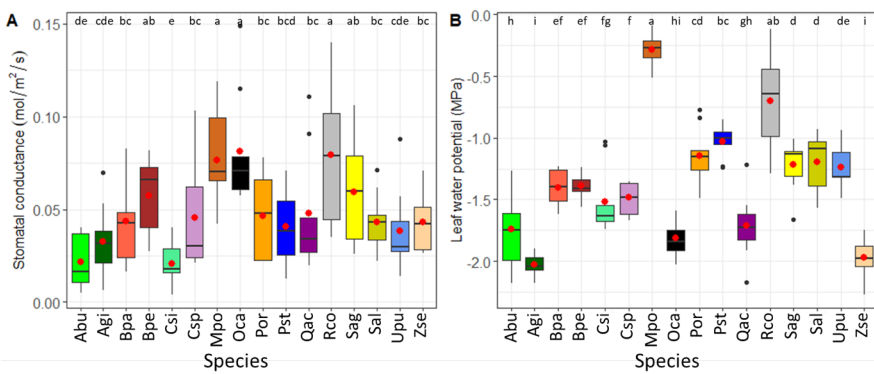
264 they were analysed with non-parametrical tests. For all considered variables, the statistically significant
 265 difference between tree species within a variable was analysed using a Kruskal-Wallis test by ranks.
 266 Spearman's rank-order correlation was performed to compare the different variables assayed and to
 267 compare the rank of different tree species for each variable. A confusion matrix with a 10-fold cross-
 268 validation was performed to estimate the generalized accuracy average and to evaluate confusion
 269 between the different tree species, using caret package (version 6.0-90).

270 3. Results

271 3.1. *In-situ* measurements

272 3.1.1. Transpiration proxies

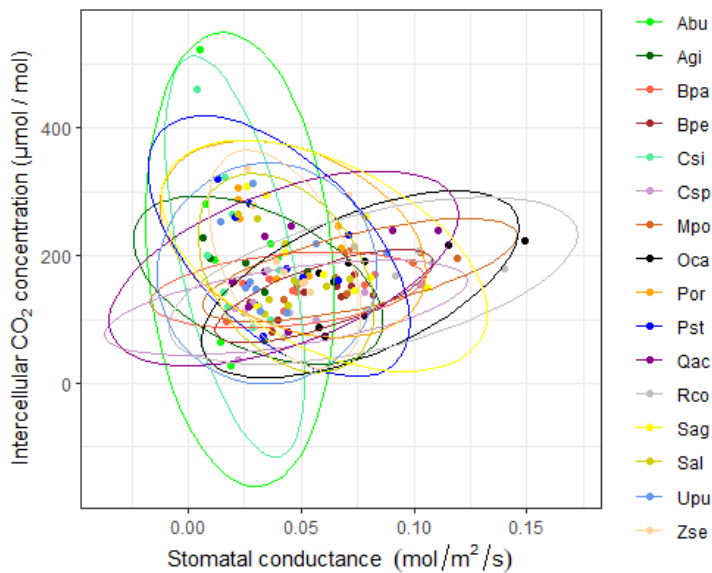
273 We observed significant differences in g_{smax} and Ψ_{min} values among the 16 tree species (Fig. 3). *O.*
 274 *carpinifolia*, *R. copallina* and *M. pomifera* exhibited significantly higher g_{smax} to water vapour than a
 275 group of 11 other species (Fig. 3A). The two species, *S. aquatica grandis* and *B. pendula*, had
 276 intermediate g_{smax} values. The Ψ_{min} ranged from -2.27 to -0.09 MPa, with Ψ_{min} values of -0.28 ± 0.13
 277 MPa and -2.03 ± 0.08 MPa for *M. pomifera* and *A. ginnala*, respectively (Fig. 3B). The rank of the
 278 different tree species for their Ψ_{min} value was significantly similar to the rank obtained for the g_{smax}
 279 values (Spearman rank correlation with $P = 0.003$), suggesting that the two proxies could be used for
 280 estimating differences in the transpiration stream. As exceptions, *M. pomifera* and *R. copallina*
 281 combined a high g_{smax} with a high Ψ_{min} .



282

283 Fig. 3. Transpiration proxies (mean (red dot), median, quartiles, range, and outliers) (n=9). (A) g_{smax}
 284 (mol H₂O/leaf m²/s) and (B) Ψ_{min} (MPa), measured on the 16 tree species growing at the experimental
 285 Ochsenfeld site. Boxes with the same letter did not differ significantly from each other using a pairwise
 286 Kruskal–Wallis test ($P < 0.05$).
 287

288 The analysis of the C_i (concentration of CO₂ in the intercellular spaces of the leaf) versus g_{smax} graph
 289 underlined that for the two species, *C. sinensis* and *A. buergerianum*, the lowest conductance might be
 290 attributed to a biochemical limitation (Fig. 4). These two species were clearly limited in their CO₂
 291 assimilation among all tested tree samples, with a negative correlation between C_i and g_{smax} . The other
 292 species, e.g., *O. carpinifolia*, *R. copallina* and *M. pomifera*, seemed to cope better with the soil
 293 conditions.

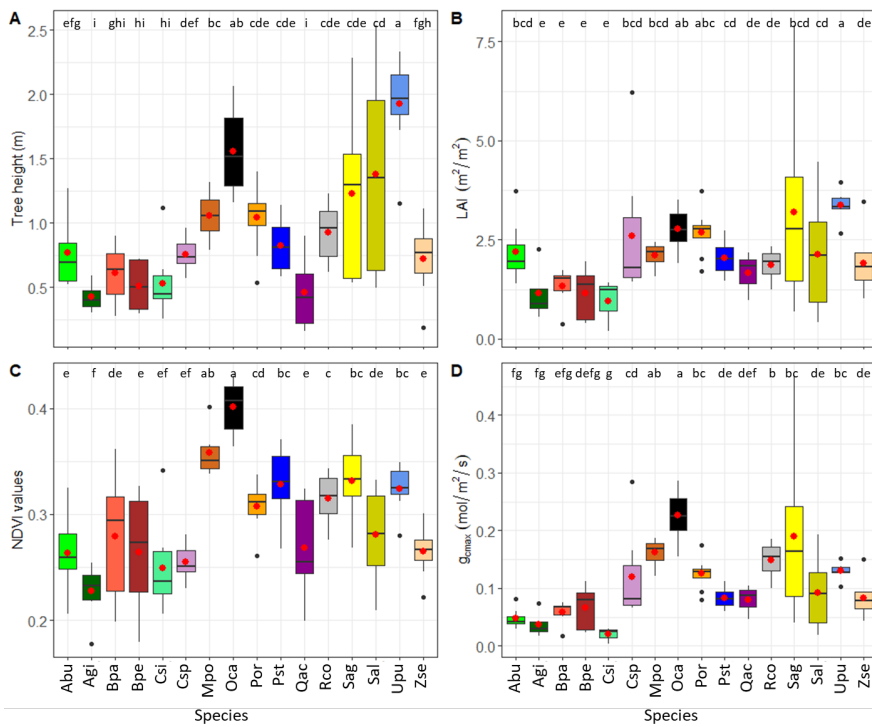


294
 295 Fig. 4. Relationship between intercellular CO₂ concentration (C_i expressed in $\mu\text{mol CO}_2/\text{mol air}$) and
 296 maximal stomatal conductance to water vapour (g_{smax} expressed in mol H₂O/leaf m²/s) for the 16 tree
 297 species growing at the experimental Ochsenfeld site. Each colour represents one of the 16 trees studied,
 298 with 9 measurements per tree, and ellipses correspond to the 0.95 confidence interval.

299 **3.1.2. Remote sensing**

300 UAV-based remote sensing allowed us to obtain the tree height (expressed in m) (Fig. 5A), LAI
 301 (expressed as the ratio of m² of leaf area to m² of ground area, Fig. 5B), and NDVI value (Fig. 5C) of
 302 the tree species present at the Ochsenfeld site. For these three parameters obtained using UAV-based

303 remote sensing, the rank order of the tree species was highly similar, with $P < 0.001$ (Spearman's rank-
304 order correlation). We further combined the LAI data (Fig. 5A) and g_{smax} data (Fig. 3A) to obtain the
305 maximal canopy conductance (g_{cmax} expressed as mol H₂O/ground m²/s, Fig. 5D).
306 *U. pumila*, *O. carpinifolia*, *M. pomifera*, *S. aquatica grandis* and *P. orientalis* had the greatest heights
307 among the tree species planted at the Ochsenfeld site in 2014, whereas *A. ginnala*, *C. speciosa*, *Q.*
308 *acutissima*, *B. pendula* and *B. papyrifera* had the lowest heights. The other tree species had an
309 intermediate height (Fig. 5A). The LAI data followed the same trend, with *U. pumila*, *O. carpinifolia*,
310 *P. orientalis*, *S. aquatica grandis* and *M. pomifera* having the greatest LAI values, while *A. ginnala* and
311 *B. pendula* had the lowest LAI values (Fig. 5B). The NDVI values for the study area plotted in the 0.23
312 (*A. ginnala*) - 0.40 (*O. carpinifolia*) range (Fig. 5C), which reflects the difference in tree growth and
313 cover as discussed above. As an exception, the *P. stenoptera* species, despite a relatively low height,
314 had one of the highest NDVI values. With the highest LAI and g_{smax} values, *O. carpinifolia* had the
315 greatest g_{cmax} (Fig. 5D), while *A. ginnala* had values 10 times lower than those of *O. carpinifolia*. Among
316 the tree species studied, only *O. carpinifolia*, *M. pomifera*, *R. copallina*, *S. aquatica grandis*, *U. pumila*,
317 *P. orientalis* and *C. speciosa* had on average a g_{cmax} greater than 0.1 mol H₂O/ground m²/s.



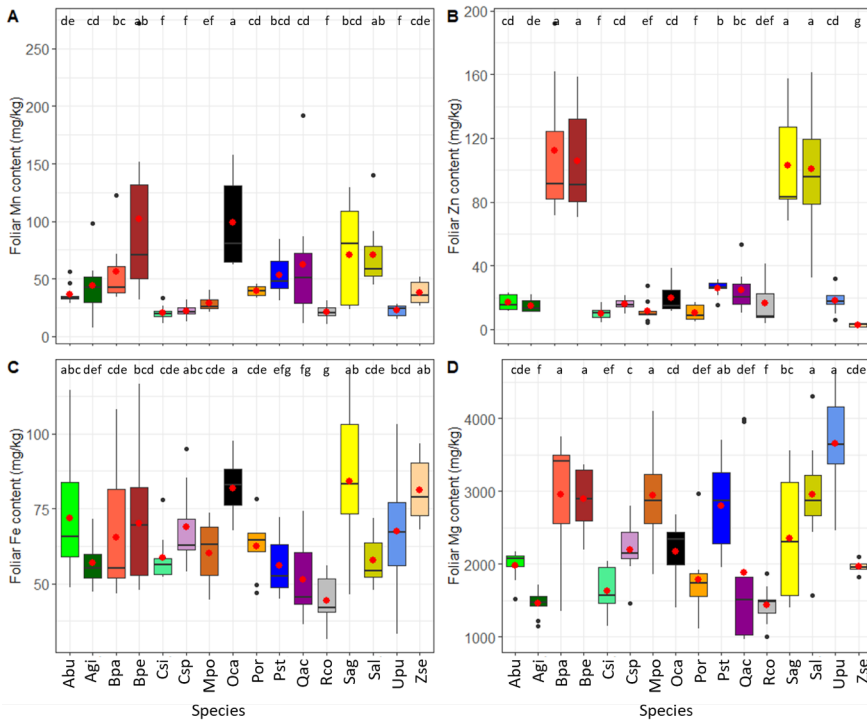
318

319 Fig. 5. UAV-based remotely sensed parameters of the 16 tree species growing at the experimental
 320 Ochsenfeld site (mean (red dot), median, quartiles, range, and outliers) (n=8). (A) Tree height (m), (B)
 321 LAI values (leaf m²/ground m²), (C) NDVI values and (D) g_{max} (mol H₂O/ground m²/s). Boxes with the
 322 same letter did not differ significantly from each other based on a pairwise Kruskal–Wallis test (P <
 323 0.05).

324 3.1.3. Foliar elemental content and leaf water status

325 The elemental content detected in leaves was significantly different among species (Fig. 6). Mn, the
 326 major element to be considered for the management of red gypsum sediment, was found in greater
 327 amounts in species belonging to the Betulaceae (*B. pendula*, *B. papyrifera*, and *O. carpinifolia*) and
 328 Salicaceae (*S. alba* and *S. aquatica grandis*) families. *B. pendula* and *O. carpinifolia* had the highest Mn
 329 contents, with values 3 times greater than those of *C. sinensis*, for example. Similarly, Zn was found at
 330 significantly higher levels in Salicaceae and Betulaceae species, except for *O. carpinifolia* (Fig. 6). *O.*
 331 *carpinifolia*, *Z. serrata*, and *S. aquatica grandis* had on average 4–5 times higher Fe content than *Q.*
 332 *acutissima* and *R. copallina* (Fig. 6C). The remaining 11 species had intermediate values. Mg was the
 333 element for which the largest variations in leaf content among tree species were observed. *A. ginnala*

334 and *R. copallina* had Mg leaf contents 4 to 5 times lower than those of *B. pendula*, *B. papyrifera*, *U.*
 335 *pumila*, *S. alba* and *M. pomifera*. Leaf contents and associated statistical data for the entire ICP set of
 336 16 elements are provided in supplemental Table S1.



337
 338 Fig. 6. Elemental content (mg/kg DM) (mean (red dot), median, quartiles, range, and outliers) (n=9)
 339 measured in leaves of the 16 tree species at the experimental Ochsenfeld site with (A) Mn, (B) Zn, (C)
 340 Fe and (D) Mg. Boxes with the same letter did not differ significantly from each other using a pairwise
 341 Kruskal–Wallis test ($P < 0.05$).
 342

343 To highlight the potential concomitance between the foliar elemental content and transpiration stream
 344 proxies (g_{smax} and Ψ_{min}), the rank of the different tree species was obtained using the Spearman rank
 345 coefficient (Table 2). The species were ranked for g_{smax} significantly similarly to their foliar elemental
 346 contents in K, Mn (Fig. 6) and Sr. The relationship between leaf Mn content and g_{smax} showed that tree
 347 species that had a high Mn content also had high g_{smax} (*O. carpinifolia*, *B. pendula*, and *S. alba*). Four of
 348 the tree species with the lowest g_{smax} also had low Mn contents (*A. ginnala*, *U. pumila*, *A. buergerianum*,
 349 and *C. sinensis*). *R. copallina* and *M. pomifera* combined a low foliar Mn content with high g_{smax} values.

350 Similarly, the Ψ_{\min} values were also positively correlated with several elements, namely, Ca, Cd, Mg
 351 and Sr, and negatively correlated with Cu, Fe and Si. The other elements, *i.e.*, Al, B, Na, P, S, Ti and
 352 Zn, were only related to the tree species and did not correlate to any of the two transpiration proxies.

353 Table 2. Spearman rank-order correlation between g_{\max} , Ψ_{\min} , and the foliar elemental content

354 *** P < 0.001, ** P < 0.01, * P < 0.05, ns = not significant

	Al	B	Ca	Cu	Cd	Fe	K	Mg	Mn	Na	P	S	Si	Sr	Ti	Zn
g_{\max}	ns	ns	ns	ns	ns	ns	*	ns	*	ns	ns	ns	ns	*	ns	ns
Ψ_{\min}	ns	ns	**	*	**	*	ns	**	ns	ns	ns	ns	***	**	ns	ns

355

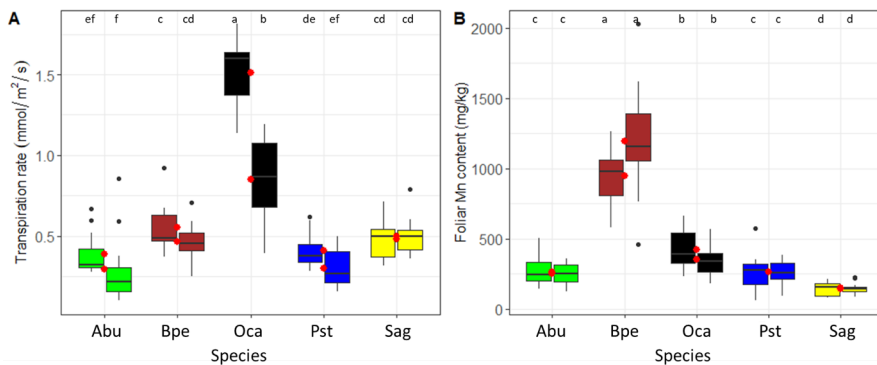
356 We further performed a 10-fold cross-validation confusion matrix on all tree species that includes all
 357 studied parameters (supplemental Table S2). A 80% generalized accuracy was determined, with 6
 358 species showing 100% accuracy (Csi, Qac, Rco, Sal, Upu and Zse). Most of confusion occurred between
 359 species of the same plant genera (*e.g.* Bpa *versus* Bpe, Sal *versus* Sag), that showed similar g_{\max} values
 360 (Fig. 5) and elemental content (Fig. 6). The g_{\max} values contributed in increasing confusion among
 361 species of different genera (*e.g.* Qac *versus* Pst).

362 3.2. Growth chamber experiments

363 Five of the 16 tree species at the Ochsenfeld site were further chosen to analyse the transpiration rate
 364 and compare with field proxy data (measured after 90 and 152 days of growth). This will allow us to
 365 obtain quantitative transpiration rate data at the scale of the whole plant for each of the species studied,
 366 which is not easy to obtain at the field scale. *O. carpinifolia* had the highest transpiration rate, with a
 367 value greater than 1.5 mmol H₂O/leaf m²/, which was higher than that for the other 4 tree species at day
 368 90 (Fig. 7A). The transpiration rates were not significantly different at the intermediate time (90 days)
 369 and at the end time (152 days), except for *O. carpinifolia*, for which a significant decrease was observed,
 370 but its transpiration rate remained twice that of all other species. The rank order of these five tree species
 371 according to their transpiration rate was the same as that obtained with g_{\max} in the field experiment (*O.*
 372 *carpinifolia* > *B. pendula* > *S. aquatica grandis* > *P. stenoptera* > *A. buergerianum*).

373 The foliar Mn content of *B. pendula* was significantly higher (approximately 1000 mg/kg DM) than the
 374 Mn content of the other tree species, which values ranging from 100 to 400 mg/kg DM. *O. carpinifolia*

375 had an intermediate Mn content, which was significantly higher than that of *A. buergerianum*, *P.*
 376 *stenoptera* and *S. aquatica grandis* (Fig. 7B). There was no significant difference between the two
 377 measurement times despite a slight increase (1.2 on average) in leaf Mn content for *B. pendula*, which
 378 is a Mn-accumulating species. No significant rank-order correlation was observed between foliar Mn
 379 content and transpiration rate.



380
 381 Fig. 7. (A) Transpiration rate (mmol H₂O/leaf m²/s) and (B) leaf Mn content (mg/kg DM) (mean (red
 382 dot), median, quartiles, range, and outliers) (n = 24) measured on the 5 tree species grown in Ochsenfeld
 383 soil in chamber experiments. For each species, the first boxplot was measured at 90 days, and the second
 384 was measured at 152 days. Boxes with the same letter did not differ significantly from each other based
 385 on a pairwise Kruskal–Wallis test (P < 0.05).
 386

387 4. Discussion

388 4.1. *O. carpinifolia* exhibited the highest transpiration capacity at the leaf level

389 According to their ecophysiological traits, the field experiment allowed us to identify three groups of
 390 tree species. The first group comprised *R. copallina* and *M. pomifera*, which had the highest g_{smax} ,
 391 combined with the highest Ψ_{min} values, close to 0 MPa. We hypothesized that this performance of these
 392 two species could be due to their highly developed root system (Ciadamidaro, unpublished data), which
 393 provides them access to deep water, allowing them to maintain their Ψ_{min} close to zero despite a high
 394 maximum stomatal conductance to water vapour. The second group included *A. buergerianum* and *C.*
 395 *sinensis*, with the lowest g_{smax} and Ψ_{min} ; the negative relationship among g_{smax} and CO₂ intercellular
 396 concentration underlines a biochemical limitation of the stomatal aperture, which is in agreement with
 397 their low growth performance. This group of tree species would not be able to grow optimally on this

398 site and could not be retained for revegetation. The third group was composed of all other tree species,
399 including *O. carpinifolia*, characterized by a stomatal limitation of C_i concentration and a classical
400 negative correlation between the stomatal aperture and leaf water potential (Comstock and Mencuccini,
401 1998; Cowan, 1965). Stomata regulate water loss from the leaves to maintain xylem pressure in a range
402 that will protect xylem from embolism. Ψ_{50} is the xylem water potential provoking a 50% loss of
403 hydraulic conductivity. At this potential, which is species-dependent, water transport in the xylem is
404 highly impaired and can lead to drastic damage in the plant. In the current study, considering the Ψ_{min}
405 between -2.27 and -0.09 MPa compared with Ψ_{50} recorded in the literature for the main temperate forest
406 tree species (Choat et al., 2012), the water constraint was not sufficiently severe for all tree species to
407 cause water transport damage. For example, we recorded a Ψ_{min} of -1.39 ± 0.1 MPa for *B. pendula*
408 compared with a Ψ_{50} of -2.4 MPa that is known for this species (Herbette and Cochard, 2010). Ψ_{min} for
409 *O. carpinifolia* was -1.81 ± 0.14 MPa in this study compared with a Ψ_{50} equal of -4.31 MPa in the study
410 conducted by Kiorapostolou et al. (2019). In contrast, the Ψ_{min} of *S. aquatic grandis* was -1.22 ± 0.2
411 MPa and was close to the Ψ_{50} commonly described for this genus (-0.91 to -2.32 MPa) (Cochard et al.,
412 1992), while no data are available in the literature for this species to date to the knowledge of the authors.
413 Therefore, with a Ψ_{min} greater than Ψ_{50} , there was no risk for creating trapped gas emboli in the water
414 transport system (Choat et al., 2012), and stomata should be fully or partially opened. Indeed, *Salix*
415 species are well known to exhibit a high transpiration rate and would be interesting candidates to
416 improve the evapotranspiration of landfills in phytomanagement solutions (Frédette et al., 2019).
417 However, based on our site conditions, the stomatal limitation clearly moderated its performance, and
418 the maximum stomatal conductance recorded for *B. pendula* or *O. carpinifolia* remained higher.
419 Regarding the g_{smax} for *O. carpinifolia*, Tomasella et al. (2019) obtained values more than twice as high
420 as ours, but *O. carpinifolia* was grown in a greenhouse under controlled conditions in pots containing
421 lightweight substrate and potting compost irrigated at field capacity. Indeed, a measurement of g_{smax}
422 over a few days would have been influenced by meteorological conditions, while we chose a sunny
423 week and recorded a moderate decrease in Ψ_{min} . In our pot study under controlled conditions, a ranking
424 similar to that obtained with the field experiment was found for the transpiration rate in well-irrigated
425 conditions after three and five months of growth (Fig. 7), based on their g_{smax} values on a subset of
426 species with different performances (*O. carpinifolia* > *B. pendula* > *S. aquatica grandis* > *P. stenoptera*

427 > *A. buergerianum*). Indeed, we should consider that g_{max} measured during a few days of summer is a
428 good proxy of transpiration performance at the leaf level under these field conditions.

429 **4.2. *Ostrya carpinifolia* had the best growth performance, as estimated by UAV-based remote** 430 **sensing**

431 Among the 16 tree species that were planted in April 2014 at the Ochsenfeld site, *U. pumila*, *O.*
432 *carpinifolia*, *M. pomifera* and *S. aquatica* showed the highest growth (estimated by height) compared
433 with the other tree species, such as *B. pendula* or *Q. acutissima*. The species that had the greatest height
434 in our soil condition, *U. pumila*, was one of the dominant tree species at the Pingshuo mining landfill
435 located in northern Shanxi Province in China (Yuan et al., 2020); *U. pumila* is resistant to drought and
436 fast growing. *U. pumila* is a species with high adaptability to different climates: glacial temperate,
437 temperate and subtropical zones (Zhao et al., 2015). The *O. carpinifolia* species was one of the
438 intermediate-growing species in 2015 (direct height measurements, Ciadamidaro et al., 2019) but
439 became the best-performing tree species during our last measurement in 2018, after 4 years of growth
440 at the Ochsenfeld site. It also performed very well at two other phytomanagement sites (Ciadamidaro,
441 unpublished data). *O. carpinifolia* needs a low amount of resources for growth (Tardella et al., 2019)
442 and plays an important function in the forest vegetation in sub-Mediterranean areas in Italy at altitudes
443 lower than 1200 m. It has been described as a species capable of growing on shallow and poorly
444 developed soils, mainly on limestone and gypsum (Pasta et al., 2016). *M. pomifera* intrinsically has a
445 strong adaptive capacity in nutrient-poor soils and a high resistance to severe drought (Khaleghi et al.,
446 2019). The species belonging to the *Salix* genus is known to be a pioneer species suitable for cultivation
447 in difficult sites with suboptimal soil conditions (Kuzovkina and Volk, 2009). The authors of this review
448 explain that *Salix* species have a good adaptation to soil conditions, rapid growth, and the highest
449 biomass production obtained in short rotations, combined with high transpiration rates; therefore, *Salix*
450 species would be good candidates for phytomanagement in landfills. In contrast, *B. pendula*, which
451 spontaneously colonized the red gypsum landfill, (Zapata-Carbonell et al., 2019) did not grow well in
452 the experimental plot, probably because of the presence of other competing herbaceous species. *Betula*
453 species are known to be affected by planting density, which significantly reduces their crown and branch
454 sizes (Mäkinen, 2002; Wang et al., 2017). The poor growth of *Quercus* species observed at the

455 Ochsenfeld site could be explained by the intrinsic low-growth character of this genus and/or the
456 vulnerability of the species to poor soil nutrient status and moisture deficiency (Demchik and Sharpe,
457 2000).

458 **4.3. UAV-based surface integration method was innovatively applied to a landfill**
459 **phytomanagement to estimate tree LAI and canopy conductance**

460 The LAI values obtained in the present study by using the UAV-based surface integration method were
461 within the same order as those found in previous studies. For instance, the LAI for *S. alba* and *S. aquatica*
462 *grandis* were in the range of 2.1-3.4 leaf m²/ground m² in our study, comparable to the 1-5.5 leaf
463 m²/ground m² range found for other *Salix* species (Mirck and Volk, 2009). In that study, the LAI values
464 measured with a LI-COR LAI 2000 for *Salix*, one of the best shrub willow varieties growing at an
465 industrial landfill, peaked during the beginning of July and August and were minimal in November. The
466 LAI development course of poplar and willow clones was obtained, and LAI values also greatly varied
467 during the season (Rüth et al., 2007). LAI values obtained during May in that study (which correspond
468 to our sampling date) were in the 2-3 leaf m²/ground m² range, similar to the values obtained for our
469 *Salix* clones. *U. pumila* and *O. carpinifolia* had the highest LAI values in our study, which were also
470 well correlated with tree heights. Similar relationships between vegetation height and LAI have been
471 found in other studies (Luo et al., 2015; Rüth et al., 2007). The LAI values that varied on average from
472 0.23 to 0.40 leaf m²/ground m² for the different tree species studied at the Ochsenfeld site showed that
473 the vegetation was dense because the NDVI of a densely vegetated plot or area tends towards positive
474 values (Viana et al., 2019). Therefore, high NDVI values would indicate high NIR reflectance and low
475 red reflectance related to high leaf density and/or high chlorophyll content, while low NDVI values
476 would indicate a diminution of NIR reflectance indicating leaf damage or high red reflectance due to
477 low leaf density. Indeed, the NDVI is intrinsically correlated to LAI by using the calculation mode but
478 integrates chlorophyll content and leaf health (Tucker, 1979). In our study, except for *P. stenoptera*, the
479 five tree species that had significantly higher NDVI values were the species with the greatest g_{smax} (*O.*
480 *carpinifolia*, *R. copallina* and *M. pomifera*) and the highest LAI (*O. carpinifolia*, *U. pumila* and *S.*
481 *aquatica grandis*). Despite a relatively low height, *P. stenoptera* had a high density of long and pinnately
482 leaves, thus could have led to an underestimation of LAI with our method. Regardless, the low g_{cmax}

483 recorded for this species could be mainly attributed to its relatively low stomatal conductance compared
484 to other species with similar NDVI values. The species with the highest NDVI values, *i.e.*, *O.*
485 *carpinifolia*, also had the highest LAI value. These values reflect the acclimation of this tree species to
486 site conditions, as discussed above. Correlation coefficients of 0.77 and 0.99 between NDVI and LAI
487 were obtained at two sites for vegetation grown in a semiarid grassland (Fan et al., 2009). At these sites,
488 NDVI and LAI both reached peak values in August and became the maximum values. The present study
489 underlined that our LAI calculation was robust, as it correlated with the NDVI, the widely used spectral
490 reflectance index. The NDVI remains a qualitative proxy, *i.e.*, an index that needs to be calibrated with
491 LAI field measurements (Fan et al., 2009). The g_{max} proxy used in the present study was innovatively
492 measured by combining the surface integration method using UAV-based remote sensing and 3-D
493 imaging with traditional g_{max} measurements and provided direct quantitative values allowing a better
494 comparison of different tree species performances. The negative point of this surface integration method
495 was the manual delineation of leaf area, which was tedious. With the rapid development of UAV
496 technology, UAV-based remote sensing has been widely used in forestry, agriculture, and vegetation
497 monitoring (Lu et al., 2020). UAV-based remote sensing has many advantages, such as instant
498 information acquisition, high image spatial resolution, convenient operation, high manoeuvrability,
499 freedom from cloud interference, and low cost. Our present study was in line with this, as it combined
500 remote sensing and gas exchange measurements to determine the canopy conductance of different tree
501 species. In view of the diversity of tree species used, other multispectral indices would have been
502 interesting to consider. These indices could take into account spectral ranges between 0.4-2.5 μm (Yang
503 et al., 2017). Remote sensing approaches based on thermal signature as a proxy of transpiration streams
504 (Xue and Su, 2017) through indices such as the Crop Water Stress Index (CWSI) could be used.

505 Evapotranspiration estimation at the field level requires water balance measurements using lysimetric
506 methods to collect sap flow measurements, as detailed in a review on classical methods (Rana and
507 Katerji, 2000), or modelling methods based on stomatal conductance measurements, meteorological
508 parameters and extractable soil water measurements (Granier et al., 2000). All of these methods are
509 quantitatively precise and have been improved well but are time-consuming and cannot be applied for
510 rapid screening of plant performance in phytomanagement contexts. However, a key parameter was the
511 estimation of a LAI that conditioned the evaporative surface. This LAI obtained by using the surface

512 integration method combined with g_{smax} allows us to obtain an estimation of the maximal canopy
513 conductance g_{cmax} . Although this proxy is quantitative, it could not replace the methods cited above;
514 however, it allowed obtaining a rapid comparison indicator of the difference in performance for the
515 species to evaporate water at the landfill. We found that the best performing species should be *O.*
516 *carpinifolia*, *M. pomifera*, *R. copallina*, *S. aquatic grandis*, *U. pumila* and *P. orientalis*. However, *R.*
517 *copallina* behaved as an invasive species in the experimental plot at the Ochsenfeld site, which casts
518 doubt on its potential use in phytomanagement scenarios. Although they performed very well in terms
519 of growth, *S. aquatica grandis* and *U. pumila* with a Ψ_{min} close to Ψ_{50} and limited g_{smax} would be sensitive
520 tree species in the event of drought. Therefore, we recommended only three species, *i.e.*, *O. carpinifolia*,
521 *M. pomifera* and *P. orientalis*, to be utilized for phytomanagement at the Ochsenfeld site.

522 4.4. Mn uptake and transpiration rate were correlated

523 In our study, the concentrations of the different elements, including TEs (Table S1), were lower than
524 those generally observed at anthropized sites (Kabata-Pendias, 2011). This might be because tree
525 sampling was conducted in early summer, when the elemental concentrations were not yet at their
526 optimal levels (Migeon et al., 2009). These authors demonstrated that the elemental content in the leaves
527 collected in October was significantly higher than that collected in June, suggesting seasonal variability
528 in the leaf elemental content. The other elemental contents found in our study were lower than the basal
529 physiological compositions recorded in tree species (Fe=150 mg/kg DM, Mn=200 mg/kg DM and
530 Zn=50 mg/kg DM) (Assad et al., 2017; Greger, 2004). Excess of these elements in plant tissues may
531 cause toxicity by damaging the cell structure (Zhao et al., 2012) and therefore may affect plant growth
532 and limit transpiration. With elemental contents slightly lower than usual physiological values, our tree
533 species are therefore unlikely to have problems in their physiological processes, such as transpiration.
534 However, Zn concentrations measured in *Betula* and *Salix* genera in the present field experiments were
535 slightly higher than the physiological levels (Kabata-Pendias, 2011), which is consistent with our
536 previous studies (Ciadamidaro et al., 2019; Zapata-Carbonell et al., 2020). Mn was also found to
537 accumulate in *Betula* species in the present field experiment, which also confirms our previous data
538 (Ciadamidaro et al., 2019; Zapata-Carbonell et al., 2020). In the pot experiment, high Mn content
539 measured in the tree species in particular in *B. pendula*, could be explained by the conditions of the

540 experiment conducted in growth chamber, favorable for the accumulation of ET. However, the use of
541 only five tree species in the laboratory experiment failed to show a rank-order correlation between Mn
542 content and transpiration rate.

543 In addition to other factors, such as mobility of the element, tissue age, and biomass of the tree, water
544 flow in the tree plays an important role in element uptake and translocation to the shoot, and water is
545 necessary for circulation in the transpiration stream (Brown and Shelp, 1997). The foliar Mn content in
546 some tree species grown in the red gypsum sediment at the Ochsenfeld site was correlated with the
547 transpiration rate of the tree. Although the objective at the Ochsenfeld site is not to decontaminate the
548 sediment, the choice of Mn-accumulating tree species with a high transpiration rate may be relevant to
549 phytomining (Ent et al., 2018) or ecocatalysis processes (Escande et al., 2015). Xu et al. (2006) nicely
550 reported that the Mn content in a leaf decreased by approximately 90% when it was wrapped in a
551 transparent plastic bag to suppress the transpiration rate. In contrast, other elemental contents were not
552 related to transpiration, e.g., Zn uptake was not affected by the transpiration capacity of the tree species.
553 Managing both metal uptake and water flow at landfills is therefore highly dependent on tree species
554 and the elements of concern.

555 **5. Conclusions**

556 Here, we combined a UAV-based remote sensing approach and a surface integration method using 3D
557 imagery to determine the LAI values of different species of trees planted in rows. This approach is an
558 alternative to the long and tedious methods of dendrometric and ecophysiological measurements. We
559 utilized the g_{cmax} ($g_{\text{smax}} \times \text{LAI}$) proxy, which was found to be a relevant tool for evaluating the
560 performance of selected trees at the Ochsenfeld site, and in particular for estimating the capacities of
561 trees to manage water flows, compared with traditional proxies, such as NDVI, LAI or g_{smax} when
562 considered separately. With the highest growth and g_{cmax} values compared with other planted woody
563 species, *O. carpinifolia* had the greatest potential to maximize transpiration flows in these harsh
564 conditions. These field measurements were confirmed by measurements performed under controlled
565 conditions on the same substrate. *O. carpinifolia* also retained Mn in its leaves, similar to the other tree
566 species in the Betulaceae family, *B. pendula*, even though Mn concentrations were highest under
567 controlled conditions. This opens new perspectives in phytomining and ecocatalysis research domains

568 that combine phytomanagement with added values in the enriched biomass. High transpiration of the
569 woody cover obtained with this woody species could drastically reduce the volumes of water infiltrating
570 through the landfill and therefore limit the associated environmental risks and treatment costs. Species
571 more classically used in phytomanagement, such as those belonging to the Salicaceae (genus *Salix*), are
572 undoubtedly less relevant at this site because they have a much more limited potential transpiration rate.
573 In the event of multiple choices of tree species to manage these landfills, *M. pomifera* and *P. orientalis*
574 would be preferred tree species, in addition to *O. carpinifolia*. Their potential would now need to be
575 confirmed by, e.g., a lysimeter installation for the accurate and representative measurements of the
576 evapotranspiration rate and water balance at the site. In the future, an atmospheric correction will be
577 provided to manipulate spectral reflectance at ground level to remove potential atmospheric effects. As
578 advanced sensors with large spectral diversity are being developed, we foresee the use of remote sensing
579 as a method to evaluate both plant and soil metal concentrations, and thus correlate metal concentration
580 and UAV-based ecophysiological parameters for a better assessment of phytomanagement strategies in
581 landfill restoration. Regarding the Ochsenfeld study site, which is representative of landfills from the
582 extractive industry, the key issue is the implementation of a plant cover that maximizes water
583 evapotranspiration after deposits have ceased and that limits the aerial dissemination of red gypsum
584 dust, which is imposed by the French regulator. The presence of trees with high evapotranspiration
585 capacities would allow to maximize these impacts. Additionally, we are foreseeing the use of
586 phytomining in future projects to recover metals from the plant biomasses. However, given the huge
587 amounts of metals in the substrate, it would be inappropriate to expect metal depollution.

588

589 **CRedit authorship contribution statement**

590 Abdoulaye Mahamat Malabad: Investigation, Writing -original draft; Fabienne Tatin-Froux and Julien
591 Parelle: Investigation, Writing -original draft; Gilles Gallinet: UAV acquisition, Writing -original draft;
592 Jean-Michel Colin: Writing -original draft, site maintenance; and Michel Chalot: Writing - review &
593 editing, Funding acquisition, Supervision.

594 **Declaration of Competing Interest**

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

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