

**Comparative study of Cu uptake and early transcriptome responses in the green microalga *Chlamydomonas reinhardtii* and the macrophyte *Elodea nuttallii***

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1 **Comparative study of Cu uptake and early transcriptome responses in the green microalga**

2 ***Chlamydomonas reinhardtii* and the macrophyte *Elodea nuttallii***

3

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5

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13

14 **Abstract**

15 Microalgae are widely used as representative primary producers in ecotoxicology, while  
16 macrophytes are much less studied. Here we compared the bioavailability and cellular toxicity  
17 pathways of 2 h-exposure to  $10^{-6}$  mol·L<sup>-1</sup> Cu in the macrophyte *Elodea nuttallii* and the green  
18 microalga *Chlamydomonas reinhardtii*.

19 Uptake rate was similar but faster in the algae than in the macrophyte, while RNA-Sequencing  
20 revealed a similar number of regulated genes. Early-regulated genes were congruent with  
21 expected adverse outcome pathways for Cu with Gene Ontology terms including gene  
22 regulation, energy metabolism, transport, cell processes, stress, antioxidant metabolism and  
23 development. However, the gene regulation level was higher in *E. nuttallii* than in *C. reinhardtii*  
24 and several categories were more represented in the macrophyte than in the microalga.  
25 Moreover, several categories including oxidative pentose phosphate pathway (OPP), nitrate  
26 metabolism and metal handling were only found for *E. nuttallii*, whereas categories such as cell  
27 motility, polyamine metabolism, mitochondrial electron transport and tricarboxylic acid cycle  
28 (TCA) were unique to *C. reinhardtii*. These differences were attributed to morphological and  
29 metabolic differences and highlighted dissimilarities between a sessile and a mobile species. Our  
30 results highlight the efficiency of transcriptomics to assess early molecular responses in biota,  
31 and the importance of studying more aquatic plants for a better understanding on the impact and  
32 fate of environmental contaminants.

33

34 **Keywords:** copper; primary producers; speciation modelling; toxicokinetics; transcriptomics.

35

36 **Capsule:** Cu accumulation is faster in the algae, but greater transcriptome response occurred in  
37 the macrophyte.

38

## 39 **Introduction**

40 Primary producers are key organisms of aquatic ecosystems: phytoplankton sustains the largest  
41 ecosystem on the Earth, contributing to about half of the primary production on our planet  
42 although accounting for less than 1% of photosynthetic biomass (Bañuelos et al., 1998).  
43 Macrophytes, including plants dominate primary production in shallow waters including littorals,  
44 rivers, marshes, ponds and lakes (Noges et al., 2010). In addition they are key elements of the  
45 aquatic ecosystems by providing support, shelter, food and oxygen to many organisms including  
46 epiphytes (Thomaz and Cunha, 2010). Studying primary producers' response to a variation of the  
47 concentrations of vital and toxic trace metals is thus an important step to understand and estimate  
48 their impact in aquatic ecosystems. Indeed, if primary producers are affected they will also  
49 indirectly influence higher trophic levels in an ecosystem through food webs (Daam et al., 2009;  
50 Fleeger et al., 2003). Often microalgae are hypothesized as representative primary producers  
51 based on the assumption that all organisms respond to stresses similarly (Clemens, 2006).  
52 Nevertheless, seldom comparisons, for example of plants with algae (Beauvais-Fluck et al.,  
53 2018a; Paz et al., 2007) or mosses (Rother et al., 2006), revealed the existence of different stress  
54 and tolerance mechanisms. In such a context, the precise mechanisms of cellular handling (and  
55 toxicity) are to further elucidate to better understand the similarities and differences in various  
56 primary producers and anticipate trace metals effect in the environment.

57 Copper (Cu) is an essential metal to all plants and animals. It participates in fundamental  
58 physiological processes (e.g. photosynthetic electron transport, mitochondrial respiration) and is  
59 a cofactor for many enzymes (e.g. superoxide dismutases, cytochrome c oxidases) (Castruita et  
60 al., 2011). Due to its high reactivity, Cu concentration is tightly regulated inside cells by a  
61 complex homeostasis network (Andres-Colas et al., 2006). This homeostasis network has been

62 studied in several model species and there are evidences of a high conservation throughout the  
63 evolution (Burkhead et al., 2009; Page et al., 2009). However, when in excessive concentrations  
64 Cu causes oxidative stress and photosynthesis inhibition due to adverse effects on the same  
65 cellular processes where it is needed, such as enzyme activity and photosynthetic electron  
66 transport (Monferran et al., 2009; Razinger et al., 2010; Upadhyay et al., 2011). Thus, Cu  
67 concentrations, and its biological availability are important parameter for environmental quality  
68 in natural environments. Elevated Cu concentrations in aquatic ecosystems are directly related to  
69 human activities involving the production of industrial (e.g. pesticide use and agricultural run-  
70 off, mine tailings) and domestic wastes (e.g. urbanization, automobile exhausts). Naturally  
71 occurring concentrations of Cu range between  $10^{-9}$  mol·L<sup>-1</sup> to  $10^{-8}$  mol·L<sup>-1</sup> in freshwater systems,  
72 but Cu can easily reach  $10^{-6}$  M in locations receiving anthropogenic inputs such as freshwater  
73 ecosystems close to vineyards or mining areas (Kupper and Andresen, 2016).

74 The present study aimed thus to compare Cu toxicokinetic and transcriptomic responses in two  
75 aquatic primary producers: a macrophyte *Elodea nuttallii* (Planch.) St. John and a green  
76 microalga *Chlamydomonas reinhardtii* P.A. Dangeard, respectively representing aquatic plants  
77 and phytoplankton typically found in the benthic environment and the water column. In the  
78 present study, we hypothesized that bioavailability and responses to toxic metals were similar in  
79 a microalgae and a macrophyte exposed in similar experimental conditions. More in detail, we  
80 compared cellular toxicity pathways of Cu in both organisms using transcriptomics  
81 (RNAsequencing; RNAseq) and determining the uptake. This research will thus increase our  
82 level of understanding of the functioning of key organisms, and eventually, the data produced  
83 will provide a scientific base to conduct sound risk assessment of our freshwater ecosystems to  
84 preserve their high socio-economic and environmental value.

85

## 86 **Material and methods**

### 87 *Labware*

88 All material was washed in 10% HNO<sub>3</sub> baths, thoroughly rinsed with ultrapure water (MilliQ  
89 Direct system, Merck Millipore) and dried under a laminar flow hood. Material for culture and  
90 experiments, including media, were additionally autoclaved (1 bar, 121 °C, 20 min) to avoid  
91 microbial contamination.

92

### 93 *Exposure of algae and macrophytes*

94 Typical growth and exposure conditions were used for each species. *Chlamydomonas reinhardtii*  
95 P.A. Dangeard (wild type strain CPCC11, Canadian Phycological Culture Centre) were grown  
96 under axenic conditions in an incubator (Multitron Infors HT) at  $20.2 \pm 0.5$  °C with a continuous  
97 light cycle (3600 lux) and a rotary shaking (115 rpm). Cells were cultured in a 4× diluted Tris-  
98 Acetate-Phosphate medium (TAP) (Rensing et al., 2008). At the mid-exponential growth phase  
99 (62 h after inoculation), cells were harvested by centrifugation (10 min, 1300g), rinsed and re-  
100 suspended in the exposure medium at a final density of  $(8.1 \pm 1.1) \cdot 10^5$  cells·mL<sup>-1</sup>.

101 Shoots of *Elodea nuttallii* (Planch.) St. John were collected in Lake Geneva, and a culture  
102 established and maintained in microcosms at  $20 \pm 1$  °C with a 16/8 h light/dark cycle (1000 lux  
103 (Regier et al., 2013b). Exposures were initiated 5 h after the start of light on three 10 cm-long  
104 shoots without roots.

105 Exposures were conducted in the laboratory under the same controlled conditions than during  
106 culture. Both organisms were exposed in triplicates to nominal concentration of  $1 \cdot 10^{-6}$  mol·L<sup>-1</sup>  
107 and  $2 \cdot 10^{-6}$  mol·L<sup>-1</sup> Cu added as CuSO<sub>4</sub> (Sigma Aldrich) for *E. nuttallii* and *C. reinhardtii*

108 respectively, in an artificial medium ( $8.2 \cdot 10^{-4} \text{ mol} \cdot \text{L}^{-1} \text{ CaCl}_2$ ,  $3.6 \cdot 10^{-4} \text{ mol} \cdot \text{L}^{-1} \text{ MgSO}_4$ ,  $2.8 \cdot 10^{-4}$   
109  $\text{mol} \cdot \text{L}^{-1} \text{ NaHCO}_3$ ,  $1.0 \cdot 10^{-4} \text{ mol} \cdot \text{L}^{-1} \text{ KH}_2\text{PO}_4$  and  $5.0 \cdot 10^{-6} \text{ mol} \cdot \text{L}^{-1} \text{ NH}_4\text{NO}_3$ , pH  $6.9 \pm 0.1$ ) during  
110 10, 30 min, 1, 4 and 8 h. Organisms exposed in the absence of metal in the medium were used as  
111 control. The choice of Cu exposure concentration corresponds to a sublethal concentration in  
112 similar experimental conditions, e.g. resulting in the EC20 growth inhibition in *C. reinhardtii* for  
113 24 h-long exposure (Cheloni et al., 2014) and is 4× lower than the concentration resulting in a  
114 15% decrease of chlorophyll content in *E. nuttallii* after 2 h-long exposure (Regier et al., 2015).

115

#### 116 *Cu uptake and modelling*

117 Cu uptake by microalgae and macrophyte was characterized by total and intracellular Cu ( $\text{Cu}_{\text{int}}$ )  
118 contents. Half of exposed organisms was rinsed with  $10^{-3} \text{ mol} \cdot \text{L}^{-1}$   
119 ethylene·diamine·tetraacetic·acid (EDTA; Sigma-Aldrich, Buchs, Switzerland) prepared in the  
120 exposure medium, to rinse metal surface-adsorbed or loosely bound to the cell wall and  
121 determine  $\text{Cu}_{\text{int}}$ . The other half of exposed organisms was rinsed with medium without Cu  
122 (media-rinsed) and therefore represents the sum of adsorbed Cu ( $\text{Cu}_{\text{ads}}$ ) and  $\text{Cu}_{\text{int}}$ .

123 EDTA-rinsed and media-rinsed samples were freeze-dried (Beta 1-8 K), digested with 65%  
124  $\text{HNO}_3$  (Suprapur Merck KGaA) at  $90 \text{ }^\circ\text{C}$  for 1 h and analyzed by inductively coupled plasma  
125 mass spectrometry (ICP-MS; 7700x, Agilent Technologies). Concentration in media was  
126 measured in acidified samples (0.5% v/v  $\text{HNO}_3$  Suprapur) by ICP-MS. Cu concentration in  
127 unspiked artificial medium was  $2.3 \pm 0.3 \cdot 10^{-9} \text{ mol} \cdot \text{L}^{-1} \text{ Cu}$ . Measured initial concentration in  
128 spiked media were  $1.09 \pm 0.20 \cdot 10^{-6} \text{ mol} \cdot \text{L}^{-1} \text{ Cu}$  ( $1.85 \pm 0.47 \cdot 10^{-7} \text{ mol} \cdot \text{L}^{-1} \text{ Cu}^{2+}$ ) and  $2.26 \pm$   
129  $0.2 \cdot 10^{-6} \text{ mol} \cdot \text{L}^{-1} \text{ Cu}$  ( $3.84 \pm 0.51 \cdot 10^{-7} \text{ mol} \cdot \text{L}^{-1} \text{ Cu}^{2+}$ ), for *E. nuttallii* and *C. reinhardtii*,  
130 respectively.



131 The Cu uptake was modelled using a first-order mass transfer model following two-compartment  
132 system and equations below (eq 1 and 2):

133

$$134 \quad C_t = C_0 + \frac{a}{k(1 - e^{-kt})} \quad (\text{eq 1})$$

$$135 \quad a = k_1 \times C_e \quad (\text{eq 2})$$

136

137 where  $C_t$  is the metal concentration in cells ( $\mu\text{mol}_{\text{Cu}} \cdot \text{g}^{-1} \cdot \text{dw}$ ) at time  $t$  (hours),  $k$  is the elimination  
138 rate constant ( $\text{h}^{-1}$ ) and  $a$  is the uptake flux ( $\mu\text{mol}_{\text{Cu}} \cdot \text{g}^{-1} \cdot \text{dw} \cdot \text{h}^{-1}$ ),  $k_1$  is the uptake rate constant  
139 ( $\mu\text{mol}_{\text{Cu}} \cdot \text{g}^{-1} \cdot \text{dw} \cdot \text{h}^{-1}$ ),  $C_e$  is the bioavailable concentration in the medium ( $\mu\text{mol}_{\text{Cu}} \cdot \text{g}^{-1} \cdot \text{dw}$ ), and  $C_0$   
140 is the constitutive metal concentration measured in cells at the beginning of the exposure  
141 (Gimbert et al., 2008; Martins and Boaventura, 2002). Statistics (t tests) and plots were done in  
142 SigmaPlot.

143

#### 144 *RNA-sequencing (RNAseq) and quantification of differential gene expression*

145 Transcriptome response of *C. reinhardtii* and *E. nuttallii* exposed 2 h to Cu was assessed through  
146 RNASeq (Illumina HiSeq 2500 System). Total RNA was extracted as previously described using  
147 TRI Reagent (Sigma-Aldrich, Buchs, Switzerland), and libraries were prepared following  
148 manufacturer's protocols (Beauvais-Fluck et al., 2016, 2017; Regier et al., 2016). For *C.*  
149 *reinhardtii*, reads were aligned with TopHat2 (Kim et al., 2013) to the genome *Creinhardtii* 236  
150 V.9.0 (Conesa et al., 2005). For *E. nuttallii*, reads were mapped using the Burrows-Wheeler  
151 Alignment (BWA v.0.7.10) tool (Li and Durbin, 2010) on the *de novo* transcriptome available  
152 for this organism entailing 181'663 contigs with an average length of 880 bp (Regier et al.,  
153 2016). We selected contigs showing a minimum coverage of 20 raw counts in all samples,

154 resulting in 99'030 sequences analyzed for differential gene expression in CLC Main Workbench  
155 (Version 7, CLC bio, QIAGEN, Denmark). 50% of contigs are covered by the reads of at least in  
156 one sample.

157 For both organisms reads were counted using the Python package HTSeq (Anders et al., 2015).  
158 Differential gene expression analysis was performed in the software CLC Main Workbench  
159 (Version 7, CLC bio, QIAGEN, Denmark) based on normalized counts and EdgeR package  
160 (Robinson et al., 2010). Significant differently expressed transcripts vs Control were defined  
161 with a threshold of false discovery rate (FDR) <0.1%. Ontology term assignments were done  
162 using MapMan (Table S1) (Thimm et al., 2004; Usadel et al., 2009). Data are available in the  
163 Gene Expression Omnibus database (GSE65109).

164

## 165 **Results and discussion**

### 166 *Cu uptake by primary producers*

167 Accumulation of Cu was measured in media-rinsed and EDTA-rinsed *E. nuttallii* and *C.*  
168 *reinhardtii* over time (Figure 1). The one-compartment model well fitted Cu accumulation in *E.*  
169 *nuttallii* and *C. reinhardtii*. In both organisms significant and similar (*a*) and (*k*) were estimated  
170 by the model normalized by the effective concentration in media (Table 1). Modelling further  
171 allowed estimating that the steady state was approached in less than 2 h for *C. reinhardtii*.  
172 Concentrations measured in media-rinsed *C. reinhardtii* (up to 40  $\mu\text{mol}\cdot\text{g}^{-1}$  dw) reached a plateau  
173 in 2 h. Similar, fast uptake and plateau has been observed in *C. reinhardtii* exposed to increasing  
174 concentrations of  $^{65}\text{Cu}$  (Jamers et al., 2013). The cellular concentrations of *C. reinhardtii* were in  
175 the same order of magnitude as in previous studies with *C. reinhardtii* and other green freshwater  
176 algae (Stoiber et al., 2012). For comparison, media-rinsed *E. nuttallii* (8  $\mu\text{mol}\cdot\text{g}^{-1}$  dw at 8h)

177 showed no obvious evidence of a plateau. Moreover, after 2 h exposure *E. nuttallii* internalized  
178 (EDTA-washed)  $1.33 \pm 0.31 \mu\text{mol}\cdot\text{g}^{-1} \text{ dw}$  ( $1.04 \pm 0.24 \mu\text{mol}\cdot\text{g}^{-1} \text{ dw}$  in control), while *C.*  
179 *reinhardtii* internalized  $4.69 \pm 0.18 \mu\text{mol}\cdot\text{g}^{-1} \text{ dw}$  ( $1.44 \pm 0.06 \mu\text{mol}\cdot\text{g}^{-1} \text{ dw}$  in control). Data  
180 showed that internalization is similar when normalized by the effective concentration in media,  
181 differences reflecting exposure condition, but faster in the algae than in the macrophyte. This  
182 difference can be attributed to the fact that the full surface of the unicellular algae is in contact  
183 with the media, whereas in the macrophyte only the external layer of cells is directly exposed,  
184 most certainly resulting in a gradient of metal concentrations between cells. Besides, the surface-  
185 to-volume ratio is much higher in an unicellular organism and thus is expected to result in higher  
186 uptake, that is not observed in our experimental conditions, but could also result in a faster  
187 uptake (Lindemann et al., 2016). However, proportion of Cu accumulated in cell walls was  
188 higher in *C. reinhardtii* than in *E. nuttallii*, suggesting that adsorption of Cu was predominant in  
189 *C. reinhardtii* and/or EDTA-washing procedure was more efficient. Cell walls are known to play  
190 a central role in plant and microalgal tolerance to metals: for example, 50% of Cu was  
191 accumulated in the cell walls in *Cystoseira tamariscifolia* (Celis-Pla et al., 2018), 20% was  
192 adsorbed (or EDTA-extractable) for *Chlorella kessleri* (Lamelas et al., 2009). In the charophyte,  
193 *Nitellopsis obtusa* exposed 3 h to both Cu-nanoparticles or CuSO<sub>4</sub>, the major part of Cu  
194 accumulated in cell walls (Manusadzianas et al., 2017). Similarly, a previous study in *E. nuttallii*  
195 measured an increased proportion over time of cadmium and mercury in cell walls,  
196 concomitantly with an increased lignification of cell walls after 7 d exposure (Larras et al.,  
197 2013).

198 Circadian clock and light are also known to be central for nutrient acquisition in plants because  
199 nutrient demands of a plant change according to the time of day, e.g. to drive photosynthesis in

200 chloroplasts and daily rhythms in transpiration rates (Haydon et al., 2015). Light intensity and  
201 spectral composition also affected Cu uptake to *C. reinhardtii* (Cheloni et al., 2014). Here the  
202 differences in light cycle applied to the microalgae (continuous) and the macrophyte (16 h light)  
203 might also affect uptake because here plants have a synchronized circadian rhythm, while  
204 microalgae show an average of all circadian stages. In *Arabidopsis thaliana*, cytosolic Cu was  
205 shown to increase during light period and decrease during dark period (Penarrubia et al., 2009).  
206 It is unclear if this is also the case here, but if this is the case, the different light regimes used for  
207 both species could also explain in part the higher Cu concentrations reached in the microalgae  
208 than the macrophyte. However, in similar experimental conditions including light regime, *E.*  
209 *nutallii* exposed to Hg and Cd showed a plateau around 48 h-long exposure (Larras et al., 2013),  
210 supporting that metal uptake in this species takes longer to reach equilibrium than in *C.*  
211 *reinhardtii*. Nonetheless, because experimental settings can affect uptake and typical  
212 experimental conditions are in general different for microalgae and plants, future research should  
213 test organisms in completely identical conditions to allow a detailed comparison of  
214 bioaccumulation data.

#### 215 *Transcriptomic response*

216 In total 1397 and 1258 genes were regulated by 2 h exposure to  $10^{-6}$  mol·L<sup>-1</sup> Cu in *C. reinhardtii*  
217 and *E. nuttallii* respectively. The similar number of regulated genes, used as a proxy of stress,  
218 suggested that both *E. nuttallii* and *C. reinhardtii* faced a similar level of stress (Dranguet et al.,  
219 2017). However, among those, 841 (67%) and 624 (44%) genes were upregulated, while 417 and  
220 773 were down-regulated in *E. nuttallii* and *C. reinhardtii*, respectively (Table S2 and S3).  
221 Besides, the level of gene regulation was higher in *E. nuttallii* (log<sub>2</sub>FC<sub>range</sub>= 17.9) than in *C.*  
222 *reinhardtii* (log<sub>2</sub>FC<sub>range</sub>= 8.8), suggesting a higher impact of Cu in the macrophyte than the

223 microalgae (Figure 2), in line with similar observations made for Hg in controlled and in the  
224 field exposure comparing the same species in identical conditions (Beauvais-Fluck et al., 2018a;  
225 Dranguet et al., 2017).

226 Among the 20 most highly regulated genes, 13 and 14 had an unknown function in in *C.*  
227 *reinhardtii* and *E. nuttallii*, respectively (Table 2). The 7 most highly regulated genes with  
228 known function were homologous to genes involved in reduction-oxidation (RedOx)  
229 metabolism, in gene regulation and nutrient transport, as well as multigenic families with  
230 numerous biochemical functions which precise function is therefore difficult to establish based  
231 on sequence homologies. More globally, in term of abundance of GO terms for genes  
232 significantly regulated in both species, a predominant part of regulated genes had unknown  
233 function (62% for *C. reinhardtii* and 33% for *E. nuttallii*; Figure 3) indicating considerable  
234 potential for new discovery in the biology of Cu. In *C. reinhardtii*, the most abundant GO  
235 categories regulated by Cu exposure were involved in “gene regulation” (44%, i.e. RNA, protein,  
236 signaling) and “cell processes” (10%; i.e. cell organization and cell motility) suggesting an  
237 adaptation of the cell metabolism and structure (Figure 3). Transport and photosynthesis both  
238 represented 8% of regulated genes. In *E. nuttallii*, the most abundant GO categories regulated by  
239 Cu exposure were involved in “gene regulation” (34%, i.e. RNA, protein, signaling) and  
240 “transport” (10%). The GO category “stress” represented 8% of regulated genes, while “cell  
241 processes” represented 6% of regulated genes. Other GO categories including hormone  
242 metabolism, stress, RedOx metabolism and development were less than 5% of regulated genes.

243 Enriched pathway analysis revealed a response of both species to avoid stress (e.g. oxidative  
244 stress) and effects on development/growth and nutrition with a significant modification of the  
245 energy metabolism. Regulated genes were thus in line with expected adverse outcome pathways

246 for Cu, i.e. impact on photosynthesis, RedOx, growth and nutrition, although only 2 h exposure  
247 was performed. This confirms the potential of transcriptomics to reveal early-responses at  
248 environmental concentrations (Beauvais-Fluck et al., 2018b; Dranguet et al., 2017; Regier et al.,  
249 2013a). Not surprisingly this short exposure resulted in few physiological endpoints significantly  
250 different vs control (Table S4 and S5) (Jamers et al., 2013; Jiang et al., 2016). More in detail,  
251 here photosynthesis efficiency is reduced in *C. reinhardtii* by 7% (Table S5) and class III  
252 peroxidase activity (POD) is reduced 50× in *E. nuttallii* (Table S2). In the same line, another  
253 study with *C. reinhardtii* revealed that exposure to a similar free ion concentration  $10^{-7}$  mol·L<sup>-1</sup>  
254 Cu<sup>2+</sup>, induced Glutathione Peroxidase genes after 2 h and reduced growth after 24 h, although no  
255 cellular impact was measured including membrane permeability, reactive oxygen species  
256 production and lipid peroxidation (Cheloni et al., 2014).

257 A previous study showed that exposure of *E. nuttallii* to  $10^{-6}$  mol·L<sup>-1</sup> Cu reduced superoxide  
258 dismutases activity after 1 h and reduced root growth after 24 h, but had no significant effect on  
259 chlorophyll content, photosynthesis efficiency and class III peroxidase activity (Regier et al.,  
260 2015). Similar observation has been obtained with Cu toxicity in *C. reinhardtii*: exposure to  
261 excess Cu induced ROS production and antioxidative response in *C. reinhardtii* (Cheloni et al.,  
262 2019; Jamers et al., 2006; Jiang et al., 2016; Stoiber et al., 2013). In the same line, a study on the  
263 rootless submerged shoots of *Ceratophyllum demersum* exposed 6 weeks to a range of  
264 concentrations between  $10^{-9}$ - $10^{-7}$  mol·L<sup>-1</sup> Cu, showed that nutrient uptake/distribution,  
265 photosynthesis efficiency and chlorophyll content were affected by Cu (Thomas et al., 2013).  
266 Nutrition is impacted because an excess Cu competes with the various essential metals according  
267 to the Irving–William series and induces deficiency of essential ions (Mg<sup>2+</sup>, Zn<sup>2+</sup>, etc.) (Mosulen  
268 et al., 2003) and impairment of metalloprotein functioning. However, although all toxic metals

269 might induce the same core stress related changes on genes, transcriptome analysis has resulted  
270 in the identification of genes specific to each metal (Kovalchuk et al., 2005; Simon et al., 2008;  
271 Weber et al., 2006). Nonetheless, data have rarely been compared between species exposed in  
272 similar experimental settings (Beauvais-Fluck et al., 2018a; Dranguet et al., 2017).

273 Here, several categories were more represented in the macrophyte than in the microalga (Figure  
274 2), including stress (abiotic), development, cell vesicle transport, hormone metabolism (abscisic  
275 acid, ethylene, jasmonate), cell wall (cellulose, hemicellulose and pectin synthesis), secondary  
276 metabolism (phenylpropanoid, wax, flavonoids), and transport (transport P- and V-ATPases,  
277 Major Intrinsic Proteins, nitrate). The present data for *E. nuttallii* were in agreement with a  
278 microarray analysis in roots of rice exposed 3 h to  $5 \cdot 10^{-6}$  mol·L<sup>-1</sup> Cu, notably concerning  
279 dysregulation of genes involved in vesicle transport, flavonoids metabolism and jasmonate (Lin  
280 et al., 2013). Authors further showed by knockout of genes necessary for this vesicle transport  
281 and exposure of roots to vesicle trafficking inhibitors, that Cu interacts with vesicle transport and  
282 that this vesicle transport is essential for signaling via ROS for activating defenses (Lin et al.,  
283 2013). Results of the present study allowed to propose a possible model of cellular mechanisms  
284 involved in Cu detoxification and protection in *E. nuttallii*: Cu increases intracellular transport,  
285 e.g. vesicle trafficking and ABC transport, and induces a flavonoid-mediated detoxification  
286 pathway. In addition, the toxicity mechanisms such as JA biosynthesis and cellular component  
287 biogenesis were regulated in response to Cu exposure. In comparison, the categories of OPP,  
288 nitrate metabolism and metal handling were absent in Cu regulated genes in *C. reinhardtii*.  
289 Conversely, cell motility, DNA, polyamine metabolism, mitochondrial electron transport, and  
290 TCA categories were found in *C. reinhardtii*, while absent in *E. nuttallii*. Moreover, the level of  
291 regulation of the categories found in common in both species was higher in *E. nuttallii* than in *C.*

292 *reinhardtii*. These differences certainly highlight the dissimilarities between basal and  
293 background metabolism in two different species, as well as between a sessile and a mobile  
294 organism (Dranguet et al., 2017). Besides, genome sequencing has revealed that *C. reinhardtii*  
295 possesses numerous genes derived from the last plant-animal common ancestor that have been  
296 lost in angiosperms, including transporters and the possibility of extensive metabolic flexibility  
297 (Merchant et al., 2007). Taken together, our divergent observations on how an unicellular and a  
298 multicellular organism take up and are impacted by Cu may imply that homeostasis networks are  
299 more species-specific than generally thought.

300 We further found several differences at the level of subcategories. For example, in the  
301 'Photosynthesis' category, genes of *C. reinhardtii* were mainly involved in the light reaction, in  
302 particular photosystem I (PSI), while in *E. nuttallii* genes were involved both in PS I and PS II,  
303 as well as photorespiration, suggesting that the photosynthesis was impacted more widely by Cu  
304 toxicity in the macrophyte. Generally, Cu has been reported to impact more PS II than PS I in  
305 plants. In PS II, the reaction center and LHC II by substitution of  $Mg^{2+}$  in its chlorophyll have  
306 been shown to be targets of Cu toxicity (Kupper and Andresen, 2016; Kupper et al., 1996). In the  
307 macrophyte *C. demersum* nanomolar concentrations of Cu affected the PS II reaction center  
308 (Thomas et al., 2013). In this regard, our finding of Cu impact on PSI in *C. reinhardtii* is striking  
309 and might point to structural differences between photosystems as well as background defense  
310 pools such as metallothioneins, phytochelatins and redox enzymes in the studied species  
311 (Castruita et al., 2011).

312

313 **Conclusion**



314 Overall, the exposure to  $10^{-6}$  mol·L<sup>-1</sup> Cu resulted in different cellular toxicity pathways in a  
315 microalga and a macrophyte. This fact together with the distinct exposure routes of the benthic  
316 macrophyte and lentic microalgae suggest that similar Cu concentrations might affect differently  
317 both species in the ecosystem. Nonetheless, because experimental settings are known to affect  
318 responses and experimental conditions are in general different for microalgae and plants, special  
319 attention has to be put in future research in testing organisms in completely identical conditions.  
320 Defining ecological thresholds of adverse outcomes for environmental contaminants represents a  
321 critical component of chemical assessment and management programs. Our data also call for  
322 including more species of aquatic plants for determining ecological thresholds for environmental  
323 contaminants, e.g. more tests using representative species of plants in the laboratory and *in situ*  
324 will be necessary in future studies (Beauvais-Fluck et al., 2018a; Dranguet et al., 2017).  
325 However, transcriptomics is confirmed as a useful tool to assess early responses at environmental  
326 concentrations and is promising for contaminated sites.

327

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335

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518

519 **Table 1:** Modelled parameters of Cu uptake in ethylenediaminetetraacetic acid (EDTA)-rinsed *E.*  
520 *nutallii* or *C. reinhardtii* exposed to  $10^{-6}$  mol·L<sup>-1</sup> Cu. Uptake flux (*a*) and elimination rate  
521 constant (*k*) of Cu were divided by the effective concentration of metal at beginning of the test to  
522 allow inter species comparison and are thus presented as *a'* and *k'*.

	<i>C. reinhardtii</i>	<i>E. nutallii</i>
<i>a'</i> (L·g <sup>-1</sup> ·h <sup>-1</sup> )	0.32 ± 0.05	0.74 ± 0.87
<i>k'</i> (μmol·L <sup>-1</sup> ·h <sup>-1</sup> )	0.07 ± 0.04	0.06 ± 0.08
R <sup>2</sup>	0.85	0.93

523

524 Table 2: List of the 10 most up-regulated and 10 most down-regulated genes in *C. reinhardtii* and *E.nuttallii* exposed 2 h to Cu.  
525 Identification, differential expression analysis (log2FC, FDR) and GO annotation are shown (NA = not assigned; Table S2 and S3  
526 show complete analysis).

<b>ID</b>	<b>log2FC</b>	<b>FDR</b>	<b>GO</b>
<b><i>C. reinhardtii</i></b>			
g9712	5.64	6.05E-79	alpha/beta-Hydrolases superfamily protein
Cre07.g321800	4.63	1.68E-69	--NA--
Cre08.g360200	3.73	1.32E-09	solute:sodium symporters;urea transmembrane transporters
Cre12.g494600	3.55	3.89E-06	--NA--
Cre03.g173100	3.51	7.93E-83	--NA--
Cre02.g143900	3.22	2.01E-10	GDSL-like Lipase/Acylhydrolase superfamily protein
Cre12.g497550	2.90	1.05E-17	NAD(P)-binding Rossmann-fold superfamily protein
Cre10.g431050	2.88	4.50E-29	--NA--
Cre17.g737300	2.81	1.18E-69	--NA--
Cre12.g525450	-2.02	8.26E-23	--NA--
Cre13.g587350	-2.20	5.70E-17	--NA--
Cre12.g540100	-2.21	2.11E-12	--NA--
Cre06.g305100	-2.22	3.32E-18	--NA--
g5945	-2.22	2.34E-04	Histone superfamily protein
Cre12.g493100	-2.25	6.29E-07	--NA--
Cre16.g681350	-2.44	6.14E-06	--NA--
Cre16.g668850	-2.64	7.29E-44	--NA--
Cre16.g651050	-2.79	1.89E-10	Cytochrome c
Cre06.g253000	-3.12	7.92E-49	--NA--
<b><i>E. nuttallii</i></b>			
Locus_106988_Transcript_1_1_Confidence_1.000_Length_217	9.26	2.63E-12	---NA---
Locus_74420_Transcript_1_1_Confidence_1.000_Length_486	6.24	8.01E-67	---NA---
Locus_50101_Transcript_1_1_Confidence_1.000_Length_289	6.13	1.37E-10	probable e3 ubiquitin-protein ligase bah1-like 1

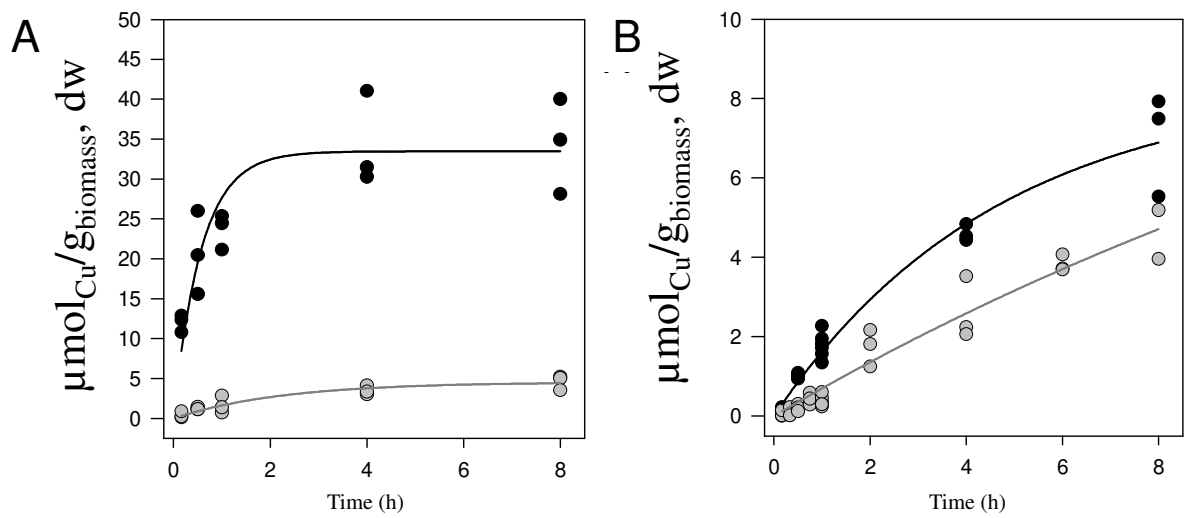
Locus_46396_Transcript_2_2_Confidence_0.750_Length_415	5.65	2.67E-08	---NA---
Locus_99585_Transcript_1_1_Confidence_1.000_Length_553	5.63	2.45E-34	---NA---
Locus_31732_Transcript_1_2_Confidence_0.667_Length_327	5.47	2.79E-10	---NA---
Locus_56031_Transcript_1_1_Confidence_1.000_Length_615	5.12	1.01E-36	---NA---
Locus_26963_Transcript_1_1_Confidence_1.000_Length_256	5.06	2.98E-13	---NA---
Locus_22115_Transcript_2_4_Confidence_0.375_Length_528	5.01	1.75E-06	Uncharacterized protein TCM_030494
Locus_25722_Transcript_4_7_Confidence_0.389_Length_809	4.91	1.84E-12	---NA---
Locus_5098_Transcript_3_4_Confidence_0.625_Length_746	-3.41	7.18E-05	octicosapeptide phox bem1p
Locus_155_Transcript_2_8_Confidence_0.474_Length_2350	-3.46	9.23E-29	nitrate reductase
Locus_6174_Transcript_8_8_Confidence_0.524_Length_1224	-3.52	1.18E-08	fe(2+) transport protein 1-like
Locus_6580_Transcript_4_11_Confidence_0.433_Length_1496	-3.58	4.77E-10	hpp family expressed
Locus_1727_Transcript_3_9_Confidence_0.450_Length_2249	-3.88	7.64E-12	uroporphyrinogen-iii c-methyltransferase-like
Locus_97468_Transcript_1_2_Confidence_0.667_Length_399	-4.40	9.24E-05	---NA---
Locus_97468_Transcript_2_2_Confidence_0.667_Length_399	-5.26	5.69E-11	---NA---
Locus_104442_Transcript_1_1_Confidence_1.000_Length_777	-5.40	1.72E-17	---NA---
Locus_7125_Transcript_1_3_Confidence_0.600_Length_453	-8.54	5.50E-08	---NA---
Locus_71727_Transcript_1_1_Confidence_1.000_Length_499	-8.65	6.76E-05	---NA---

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531 **Figure 1:** Cu toxicokinetics in *C. reinhardtii* (A) and *E. nuttallii* (B) exposed to  $10^{-6} \text{ mol}\cdot\text{L}^{-1}$  Cu.

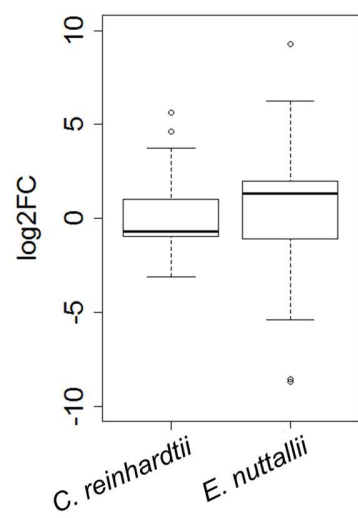
532 Organisms were ethylenediaminetetraacetic acid (EDTA)-rinsed (grey) or media-rinsed (black)

533 to differentiate between adsorbed and internalized metal.

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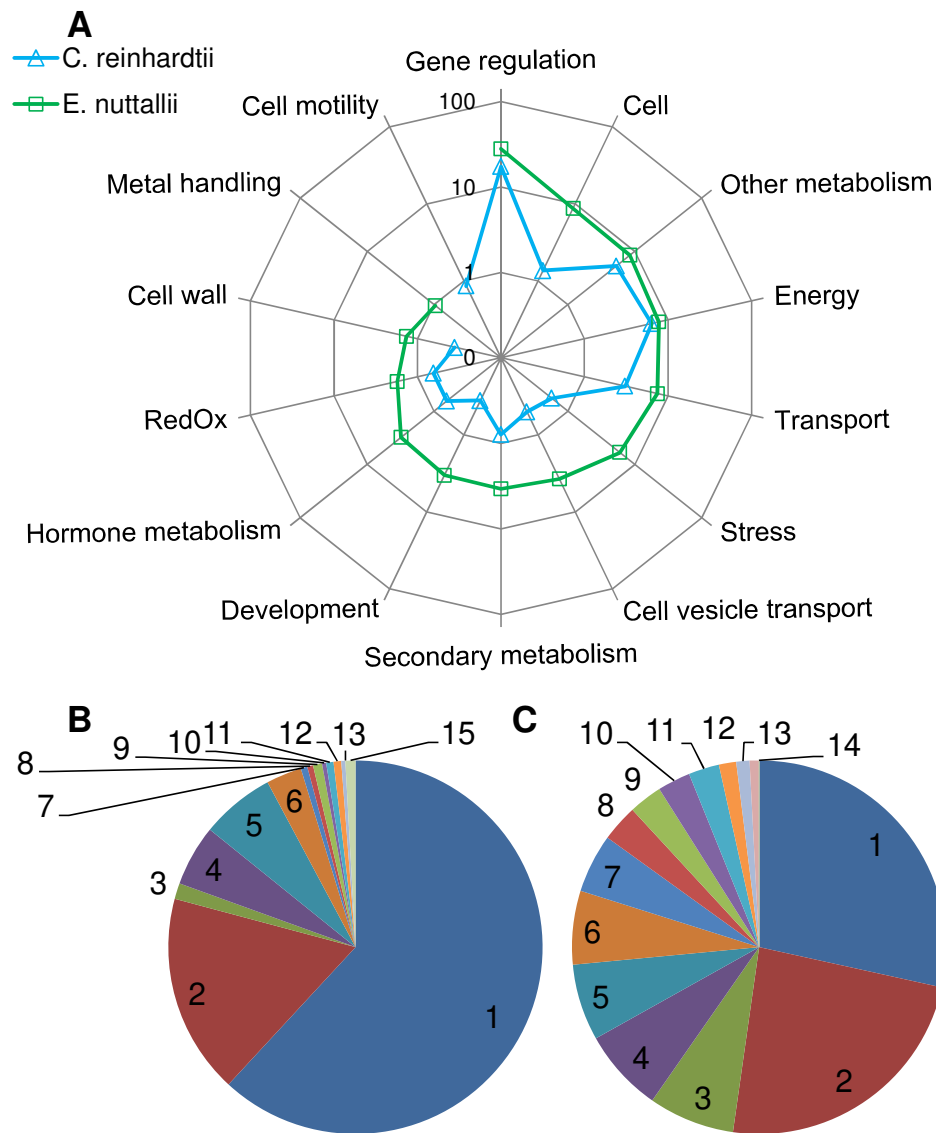
537

538 **Figure 2:** Fold-changes (log2FC) of significant regulated genes in *C. reinhardtii* and *E. nuttallii*

539 exposed 2 h to  $10^{-6}$  mol·L<sup>-1</sup> Cu.

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542 **Figure 3:** Genes regulated in *C. reinhardtii* and *E. nuttallii* exposed 2 h to  $10^{-6}$  mol·L<sup>-1</sup> Cu. The  
 543 total number of significant dysregulated genes (DG) in gene ontology (GO) categories  
 544 (MapMan) in *C. reinhardtii* (triangles) and *E. nuttallii* (square) exposed 2 h to Cu (A). The  
 545 proportion (%) of main functional GO categories ( MapMan) of dysregulated genes in *C.*  
 546 *reinhartii* (B) and *E. nuttallii* (C) (GO categories legend is 1: Unknown, 2: Gene regulation, 3:  
 547 Cell process, 4: Other metabolism, 5: Energy metabolism, 6: Transport, 7: Stress, 8: Cell vesicle

548 transport, 9: Secondary metabolism, 10: Development, 11: Hormone metabolism, 12: Oxidative  
549 stress, 13: Cell wall, 14: Metal handling, 15: Cell Motility).