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1 **Earthworms impact the availability of Si to plants in Northern**
2 **Vietnamese paddy fields.**

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14

15

16 **Abstract**

17 Silicon (Si) is an essential element for the growth and development of rice plants, playing a
18 crucial role in their overall health and productivity. This study aimed to measure earthworm's
19 impact on Si dynamics northern Vietnam's paddy fields. The properties of earthworm casts
20 from 23 different sites were compared to the surrounding topsoil. The results showed that the
21 casts were enriched in biogenic silica (herein phytoliths) and plant-available Si (measured
22 through acid acetic extraction, Si_{AC}) compared to the reference topsoil. Also, casts had a higher
23 sand content, while their carbon content was similar to the reference soils. This suggests a
24 possible preference for sand particles by earthworms (e.g., for grinding plant material within
25 their gizzards) and/or the consumption of soil from another layer enriched in sand content. The
26 influence of earthworms on Si dynamics was found to be dependent on the soil's environmental
27 properties. In soils with low fertility (characterized by a higher proportion of sand and lower
28 concentrations of C and oxides), earthworms increased the concentration of Si_{AC}. However,
29 beyond a certain level, the effect of earthworms on Si availability became neutral. While this
30 study highlights the critical role of earthworms in paddy fields, further research is needed to
31 understand how earthworms enhance the concentration in Si_{AC} in the topsoil, and the
32 consequences to rice growth and resistance to environmental hazards.

33

34

35 **Keywords**

36 Bioturbation, flooded environment, *Glyphidrilus papillatus*, phytoliths, available silicon

37 **1. Introduction**

38 Bioturbation refers to the biological reworking of soils and sediments, or in other words to the
39 ability of organisms to move particles and to modify their physical and chemical properties
40 through direct actions, such as burrowing or the production of soil aggregates with specific
41 properties (e.g., earthworm casts and termite sheeting) [1, 2]. The main soil bioturbators are
42 earthworms, termites, and ants [3-8], although many other soil taxa can also locally be
43 considered important soil bioturbators (e.g., dung beetles and millipedes). Research on the
44 impact of soil bioturbation is dominated by studies describing the impact of earthworms and
45 termites on the decomposition of soil organic matter and the cycling of nutrients [9-11].
46 However, a growing number of studies shows that the impact of bioturbation on soil physical
47 properties and biogeochemistry goes beyond its effect on the cycling of C and major nutrients
48 (N and P) and that it varies depending on the properties of the environment [9, 12-14]. Soil
49 bioturbation can also influence the distribution and the diversity of the soil microbiome [15],
50 the availability of heavy metals [16] or the bioavailability of other chemical elements, which
51 play a vital role in plant growth and resistance to environmental hazards. This is especially the
52 case in recent studies that have described the impact of soil bioturbators on the dynamic of
53 silicon (Si) and its bioavailability to plants [17-20].

54 Si is the second most abundant element in the earth's crust after oxygen [21, 22], and it
55 is a major component of parent rock materials (e.g., quartz and feldspars) and secondary
56 minerals (clays and amorphous silica). Biogenic Si can also be found in the form of phytoliths,
57 diatom frustules or thecamoebian tests [23, 24]. Although it is not considered a macronutrient,
58 per se, nor an element essential for plants, there is a growing literature showing the beneficial
59 effects of Si on the resistance of plants to parasites and other environmental stresses [25-27].
60 This positive effect of Si on plant performance has been evidenced with several plant models,

61 including rice [28-30], and the amendment of Si is proposed as a potential practice to
62 compensate the deficiency in Si in paddy fields [31].

63 Very limited number of studies have looked at the impact of earthworms on Si
64 availability in rice and they showed some contradictory results on European soils. For instance,
65 **Bityutskii et al. [17]** showed an increase of water-extractable Si in casts in Saint Petersburg
66 (Russia), while **Georgiadis et al. [18]** showed that the amount of mobile and adsorbed Si,
67 considered bioavailable to plants, tended to decrease after the passage through the earthworm
68 guts. The presence of earthworms can be very important in paddy fields (e.g., > 160 ind m⁻² and
69 > 50 g m⁻² in paddy fields in North East India, [32]), where they can interfere with several
70 ecological functions such as those associated to the decomposition of organic matter and the
71 emission of greenhouse gases [33]. Except for a few examples showing that earthworms can
72 act as pests and damage rice growth [34-36], earthworms usually impact positively rice
73 development [37-41]. While the influence of earthworms on soil properties is known to be
74 variable and dependent on the nature of the soils they inhabit [9], the positive effect of
75 earthworms on rice growth is usually attributed to the higher levels of C, N and P in earthworm
76 casts compared to the surrounding soil environments [42-45]. However, how earthworm
77 bioturbation affects Si availability to rice, and whether this impact varies based on the properties
78 of the surrounding soil environment, remain unknown.

79 Therefore, this study aimed to measure the impact of earthworms on the availability of
80 Si to rice. Our two main hypotheses were: (1) that the consumption of fresh litter (rice straw
81 residues) and soil organic matter and minerals by earthworms improves the amount of phytolith
82 in casts, and increases the availability of plant available Si, thus explaining previous studies
83 showing a beneficial impact of earthworms on rice performance; and (2) that this effect depends
84 on the properties of the soil environment.

85

86 **2. Materials and Methods**

87 **2.1 Study site and soil sampling**

88 Earthworm casts produced by *Glyphidrilus papillatus* (Almidae family) were sampled on the
89 soil surface in twenty-three paddy fields located in the Red River delta in Northern Vietnam
90 (See **Figure 1**) (Coordinates of sample pairs are given in Table S1 in **Dang et al. [46]**). The
91 study site area is covered by fluvial sediments, and soils are described as dytric and eutric
92 Fluvisols [46]. Clay mineralogy is dominated by illite and kaolinite (> 55% of the soil mineral
93 composition) [47]. The annual rainfall precipitation is greater than 1600 mm year⁻¹. Casts and
94 the surrounding soil surface (distance to casts 15-20 cm) were sampled at 5-10cm depth at the
95 beginning of the rainy season in April 2022, when paddy fields start to be partially flooded,
96 allowing a clear distinction of casts on the ground from the surrounding reference topsoil (see
97 **Figure 1b** for an illustration of the casts produced on the ground by *G. papillatus*). Casts and
98 the reference topsoils were sampled from 3 to 6 random plots, which were approximately 20 m
99 apart from each other, and then mixed in order to get one composite sample per site and
100 category.

101

102 **2.2 Soil analysis**

103 Physical and chemical properties were measured from samples that were air-dried for four days.
104 Particle size distribution was determined in water after removing soil organic matter (SOM)
105 with H₂O₂. Complete dispersion was achieved with calgon (i.e., a combination of Na-
106 hexametaphosphate and sodium carbonate) and shaken for 16 hours [48]. Three particle size
107 classes were considered: clay (<2 μm), silt (2–50 μm), and sand (50–2000 μm). Soil pH was
108 determined using 1M KCl (w/v = 1:2.5) and soil electrical conductivity (EC) was determined
109 in soil/water suspension (soil:solution = 1:5) (ISO 10390: 2021 and 112265:1994, respectively).
110 Before chemical analysis, samples passed through a 0.25 mm sieve. Total Si, Al, and Fe

111 contents were analyzed by ICP–MS (model: 7900, Agilent Technologies) after digestion with
112 aqua regia solution (a highly corrosive mixture of nitric acid and hydrochloric acid used to
113 dissolve metals) in a microwave at 180°C for 40 minutes (EPA method 3051). Phytoliths were
114 estimated using the 1% Na₂CO₃ method outlined by DeMaster [49] (1981) (detailed protocols
115 are described by Nguyen et al. [50]). The plant-available Si was estimated using 0.5 M acetic
116 acid after shaking the samples for 2 hours (Si_{AC}, [51]). The same method was used to measure
117 the amount of extractable Fe, Al, and P contents. The organic carbon (C) content was quantified
118 using O-I Analytical Aurora model 1030D and solids model 1030S. To quantify the magnitude
119 of changes in cast properties, we used the Response Ratio (R). R was measured in comparing
120 the properties of casts to those of the bulk soil (in % relative to bulk soil) as follow: $R =$
121 $V_{\text{cast}}/V_{\text{ref}}$, where V represents the value of the response variable for earthworm casts (cast) or
122 for the surrounding soil, considered as reference (ref). R values were calculated for the sand
123 content (R_{Sand}), phytoliths (R_{Phyto}), and Si_{Ac} (R_{SiAc}). Values were log-transformed to facilitate
124 a straightforward assessment of whether casts were enriched (R>0) or impoverished (R<0) in
125 comparison with the reference soil.

126

127 **2.4. Statistical analyses**

128 Data were balanced (equal number of observations for each factor). Homoscedasticity and the
129 normal distribution of residues were tested using the Levene and Shapiro-Wilk tests. Two way
130 mixed anova with the sampling site as a random factor was used to look at differences in soil
131 properties between the casts and the reference soil. Pearson correlations were used to analyse
132 the relationship between the concentration of Si_{AC} or Si_{Phyto} and soil's physical and chemical
133 properties. A linear regression was used to assess the relationship between R_{Sand} and the sand
134 content in the surrounding topsoil, after a log-transformation of R values to reduce the
135 variability. In addition, linear multiple regression analyses [52] were used to test relationships

136 between R values, as the dependent criterion, and the physical and chemical properties of the
137 reference soil, as independent predictors. Statistical calculations were carried out using
138 smartPLS software version 4.0 [53] and R version 4.3.1 (<https://www.r-project.org/>) with the
139 packages ggplot2.

140

141 **3. Results**

142 **3.1. Cast properties and earthworm impacts.**

143 Comparisons between means (Table 1) show that, on average, the electrical conductivity (EC)
144 was higher with casts than the reference soils, and that casts were significantly impoverished in
145 clay, but enriched in sand in comparison with the reference soils ($n = 23$). Figure 2 also shows
146 that the lower the sand content in the surrounding soil, the more earthworms enriched their casts
147 in sand ($\log(R_{\text{Sand}}) > 0$), with a threshold at $\sim 50\%$ sand content in soil. Above this value, no
148 increase or a decrease in sand content ($\log(R_{\text{Sand}}) = 0$ and < 0 , respectively) was measured in
149 casts in comparison with the surrounding soils (see supplementary file 1 showing the triangle
150 of texture and the enrichment in sand in casts).

151 Phytolith and Si_{AC} contents, and the total amount in Al were significantly higher in
152 earthworm casts than in the reference soils ($P < 0.05$). However, no significant differences in
153 pH, silt, and Al and Fe (extracted by acid acetic) and Fe (total) contents could be measured
154 between casts and the reference soils ($P > 0.05$ in all cases). R values testing the enrichment in
155 phytoliths (R_{Phyto}) and Si_{AC} (R_{SiAC}) reached 1.96 and 1.20, respectively (Figure 3), and these
156 values were significantly higher than 1 (T-test, $P < 0.001$ in both cases).

157 Linear multiple regression models showed that R_{SiAC} was explained by the C, phytolith,
158 and total Fe contents (negative relationships), the total contents of Al and sand (positive
159 relationships) in the reference soil (Figures 4, linear models testing relationships between
160 variables are given in supplementary files 2-7). R_{Phyto} was only explained by the phytolith

161 content in the reference soil. The R^2 values reached 0.82 and 0.36 for R_{SiAC} and R_{Phyto} ,
162 respectively.

163

164 **3.2. Relationships between Si contents and other soil properties**

165 Pearson's tests did not hint at significant correlations between the amount of phytoliths and the
166 other soil variables ($P > 0.05$ in all cases) (Table 2). The concentration in Si_{AC} was positively
167 correlated to the pH, the C content, and the amounts in Fe (both Fe_{AC} and Fe_{tot}). Conversely, a
168 negative relationship was measured between Si_{AC} and clay contents.

169

170 **4. Discussion**

171 **4.1. Earthworm and the dynamics of OM and soil particles**

172 An abundant literature has described the specific properties of earthworm casts (see for instance
173 the meta-analysis carried out by Van Groeningen et al. [9]). Less is known, however, on the
174 functional impact of sub-aquatic species, such as *G. papillatus*, which are widely distributed in
175 paddy fields in Southeast Asia [31, 38, 46]. While earthworm casts are usually enriched in clay
176 in sandy soils [38], we found that casts produced by *G. papillatus* were enriched in sand relative
177 to soil composition of the surrounding topsoil. We also showed that the lower the sand content
178 in the surrounding topsoil, the more earthworm casts were enriched in sand. This finding was
179 unexpected and it is the first time, as far as we know, that an enrichment in sand particles by
180 earthworms is evidenced. While this finding suggests a preference for the consumption of large-
181 size minerals by earthworms, it is also possible that this result reflects the specific properties of
182 the soil at the depth at which earthworms live and feed, or the specific environmental conditions
183 they require when soils are flooded (e.g., presence of macropores, burrows, and chambers
184 containing the oxygen necessary for the earthworms to breath).

185 Phytolith transportation has only been measured considering their downward migration
186 with the percolation of water [54]. Therefore, this study is also the first to show that earthworms

187 can be responsible for an upward migration and accumulation of phytoliths on the soil surface
188 in paddy fields. Although more information is needed on the ecology of *G. papillatus*, the higher
189 amount of phytoliths in casts suggests that plant residues constituted an important part of its
190 diet. This hypothesis is reinforced by the negative relationship between R_{phyto} and the
191 concentration of phytoliths in soil. In soil containing low amounts of plant residues (i.e., low
192 phytolith content), earthworms were likely to feed on large-size plant fractions, such as leaves,
193 which contain more phytoliths than roots, leading to $R_{\text{phytolith}} > 1$. Conversely, when soil
194 contained sufficient plant residues, earthworms did not select more plant residues and
195 consumed the one available in the soil, then leading to $R_{\text{phytolith}} = 1$. However, although the
196 linear model testing the relationship between the amount of phytoliths and $R_{\text{phytolith}}$ was
197 significant, the coefficient of correlation was rather low ($R^2 = 0.36$), suggesting that the
198 enrichment in phytoliths by earthworms is explained by other variables that were not considered
199 in our study, such as the specific agricultural practices of each site (e.g., the burning of rice
200 residues and the soil preparation with the plowing of soil, intercrops and the incorporation of
201 plant material in the first soil layer or deeper).

202 Surprisingly, the consumption of organic matter was not associated with an increase in
203 C content, since casts had similar C content. This discrepancy between the presence of phytolith
204 and the similar C content could be explained by an efficient degradation of C, which could be
205 improved by the ingestion of sand, which enhances the grinding action of the gizzard [55, 56].
206 Another explanation could be that earthworms lived and consumed organic residues at deeper
207 soil depths than the topsoil, where the soil was impoverished in C. Therefore, while the carbon
208 content in casts was similar to that of the topsoil, it was likely to be higher than in the soil that
209 was consumed by earthworms. Therefore, more research is needed to determine the origin of
210 the soil consumed by *G. papillatus*, as well as its organic matter digestion efficiency.

211

212 4.2. Earthworms and plant Si availability

213 Taken as a whole (casts plus soils), Si_{AC} averages 56 ± 36 ppm. This value can be compared to
214 those found in other paddy fields. For instance, [Paye et al. \[57\]](#) found Si concentrations ranging
215 from 15 to 168 ppm using acetic acid extract at a lower duration (1 hour) in loamy to clayey
216 soils in Louisiana (USA). In New South Wales (Australia), [Tavakkoli et al. \[58\]](#) found Si
217 concentrations ranging from 17 to 71 ppm in a red ferralsol and a grey vertisol using a slightly
218 different solution (NH_4OAc , pH 4.8, 4 hours). In another study, [Narayanaswamy and Prakash](#)
219 [\[59\]](#) extracted plant-available Si using an acetic acid solution at two durations with various soils
220 from Southern India. They found values ranging from 11.3 to 73.3 ppm after a 1 hour shaking
221 duration and from 13.2 to 60.2 ppm after an overnight reaction followed by a 1 hour shaking
222 duration. The data of [Narayanaswamy and Prakash \[59\]](#) showed that the duration of the
223 extraction did not significantly affect the values of Si extracted by 0.5M acetic acid. Therefore,
224 despite some slight differences in the methods, the values found in this study are comparable
225 to those found in the literature.

226 Si_{AC} was significantly positively correlated to the soil pH, the amount in C, and the Fe
227 contents (both Fe_{AC} and Fe_{tot}), while a negative relationship was measured between Si_{AC} and
228 the clay content. The correlation between the amount of Si_{AC} and the soil pH is well documented
229 in the literature [\[60\]](#). It suggests that Si_{AC} was controlled by Si adsorbed onto the surfaces of Al
230 and Fe-oxides, or by the solubility of phytoliths. The positive correlation between Si_{AC} and C
231 was also evidenced in agricultural soils in Japan [\[61\]](#), although the interaction between these
232 elements has never been documented either in the laboratory or in the field [\[60–63\]](#). Therefore,
233 while the negative correlation between Si_{AC} and the clay contents is difficult to explain, the
234 possibility of specific protection of Si by organic matter and oxides is in line with the positive
235 correlation between Si_{AC} and both C and Fe.

236 Phytoliths were probably not a source of Si_{AC} , because no significant correlation was
237 measured between these two parameters. However, besides phytoliths, infra-micrometric
238 particles of biogenic silica or microphytoliths have also been observed in plants [64]. Therefore,
239 the correlation between Si_{AC} and C is likely to be explained also by the dissolution of micro-
240 phytoliths. The lack of correlation between C and phytolith contents is intriguing since the
241 amount in phytolith depends on the amount of organic debris. Therefore, this finding highlights
242 the rapid degradation of organic debris in the topsoil and a rapid turnover of elements.

243 In general, casts were significantly enriched in Si_{AC} in comparison with the surrounding
244 topsoil ($R_{\text{Si}_{\text{AC}}} > 1$). However, regression models showed that $R_{\text{Si}_{\text{AC}}}$ was negatively related to the
245 concentration in C, the amount in phytoliths, and the total Fe content in the topsoil. This finding
246 confirms the fact that the influence of earthworms on Si dynamics depended on soil properties
247 and the availability of organic debris. The positive relationship between the proportion of sand
248 and $R_{\text{Si}_{\text{AC}}}$ may also suggest that the sandier were the soils, the more earthworms increased the
249 availability of plant available Si, in the form of Si_{AC} . This process is likely to be explained by
250 a higher bioturbation activity of earthworms and a grinding of organic matter in earthworm gut
251 using sand particles, which might favor the dissolution of Si and the production of Si_{AC} .
252 Alternatively, some active mechanisms that increase the solubility of Si might occur in the
253 earthworm guts and explain the increase of Si_{AC} . Horn et al. [65] found that the pH values of
254 gut extracts from 47 individual worms collected from six different sites near Bayreuth
255 (Germany) ranged from 6.8 to 7.1, and the values were slightly higher than the pH values of
256 the corresponding soil. Here, although the difference was non-significant, we noticed a slight
257 increase in pH in casts compared to the surrounding soils (respectively 4.92 and 4.74), which
258 could be explained by the rise in soil pH in the earthworm gut. Since the dissolution of silica
259 minerals increased with the soil pH [66], a higher pH in earthworm guts may explain the

260 increase of Si_{AC} in soil, if we assume that *G. papillatus* have a similar gut chemistry that the
261 ones studied by Horn et al. [65].

262

263 **Conclusions**

264 This study confirmed that earthworms are key soil macrofauna bioturbators in paddy fields,
265 with significant impacts on soil properties, and especially on phytolith dynamics and Si
266 availability. Our findings can be seen in line with the few studies showing the positive effect of
267 earthworms on rice performance [38]. More research is now needed to highlight the mechanism
268 by which earthworms increase the availability of Si in soil and the consequences in terms of
269 rice development and resistance to environmental hazards. For instance, the presence of silicate
270 solubilizing bacteria in the guts of *G. papillatus* should now be investigated, as it has been
271 observed with other earthworm species [67].

272 This study also raised the need to better understand *G. papillatus* ecology, such as the
273 origin of the soil it consumed. This information is needed to get an accurate soil reference,
274 allowing us to determine its impact on soil properties, such as their C and sand concentrations.

275 Another striking result of our study concerned the fact that we demonstrated a site-
276 specific effect of earthworms on phytolith and Si_{AC} concentrations. The lower the soil fertility
277 (i.e., a high proportion of sand and low concentration in C and oxides) the more earthworms
278 increased the concentration in Si_{AC} . Conversely, above a certain level, the effect of earthworms
279 on Si availability becomes neutral ($R_{Si_{AC}} \sim 1$).

280

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Table 1. Soil physical and chemical properties of earthworm casts (CAST) and the surrounding reference soil (REF). Mean values are displayed together with the standard deviations in parenthesis. Results of the two way anova comparing CAST and REF with the sampling site as a random factor are given (n = 23). Significant differences are highlighted in bold characters.

	pH	C (%)	EC ($\mu\text{S cm}^{-1}$)	Clay (%)	Silt (%)	Sand (%)	Phytoliths (mg kg^{-1})	Al _{AC} (mg kg^{-1})	Fe _{AC} (mg kg^{-1})	Si _{AC} (mg kg^{-1})	Al _{tot} (g kg^{-1})	Fe _{tot} (g kg^{-1})
CAST	4.92 (0.96)	1.60 (0.37)	299.0 (116.0)	15.5 (8.5)	42.3 (11.1)	42.2 (14.4)	5024.0 (1541.0)	57.3 (13.4)	164.0 (210.0)	61.2 (39.0)	14.8 (4.7)	26.2 (12.5)
REF	4.74 (0.99)	1.61 (0.52)	252.0 (143.0)	25.0 (10.7)	43.8 (11.8)	31.2 (20.3)	2604.0 (1478.0)	55.1 (16.8)	150.0 (94.0)	52.2 (33.0)	13.2 (4.6)	27.3 (13.7)
<i>F</i> _{1,22}	0.90	0.02	9.06	25.35	0.56	14.77	38.30	0.67	0.14	13.57	8.23	0.52
<i>P</i> -values	0.353	0.878	0.006	<0.001	0.460	<0.001	<0.001	0.423	0.707	0.001	0.009	0.476

Table 2. Pearson correlations (r and *P* values) between soil properties (pH, clay, silt and sand contents, electrical conductivity, C content, Al, Fe and P contents (total or extracted with acid acetic) (n = 46). Significant values are highlighted in bold characters

		pH	C (%)	EC ($\mu\text{S cm}^{-1}$)	Clay (%)	Silt (%)	Sand (%)	Phytoliths (mg kg^{-1})	Al _{AC} (mg kg^{-1})	Fe _{AC} (mg kg^{-1})	Si _{AC} (mg kg^{-1})	Al _{tot} (g kg^{-1})	Fe _{tot} (g kg^{-1})
Phytolith (mg kg^{-1})	r	0.00	0.08	0.10	-0.27	0.06	0.12		0.24	0.07	0.21	0.27	0.14
	<i>P</i>	0.998	0.600	0.495	0.067	0.668	0.432		0.105	0.655	0.165	0.070	0.354
Si _{AC} (mg kg^{-1})	r	0.76	0.43	0.31	-0.19	-0.07	0.15	0.21	0.08	0.55		0.18	0.40
	<i>P</i>	<0.001	0.003	0.322	0.021	0.066	0.318	0.165	0.608	0.001		0.239	0.006

Figure captions

Figure 1. Study sites: (a) Distribution of the sampling plots, and (b) photos showing example of casts produced by *Glyphidrilus papillatus* in paddy fields.

Figure 2. Evolution of R_{sand} according to the concentration of sand in the reference topsoil (in %). The blue line at $y = 0$ shows the limit above which an enrichment in sand is measured in cast, and below which an impoverishment in sand is measured in cast in comparison with the surrounding topsoil ($n = 23$).

Figure 3. Response ratio R_{Phyto} and R_{AC} showing the enrichment in phytoliths and Si extracted by acid acetic by *Glyphidrilus papillatus* in paddy fields ($n = 23$).

Figure 4. Graphic representation of the regression models testing the influence of soil properties (in the rectangle in yellow) on R_{Phyto} and R_{SiAC} . Values in the blue circles represent the R^2 values. Values associated to the arrow represent the unstandardized regression coefficients (positive or negative values), while the P -values is given in parenthesis. Only significant regressions are displayed.

Supplementary files

Suppl File 1. Texture triangle showing the proportion of sand, silt and clay of the topsoil (in grey) and earthworm casts (in red). Lines represent the regression curves ($R^2 = 0.68$ and 0.17 for the reference soils and the casts, respectively) ($n = 23$).

Suppl File 2. Relationship between $R_{\text{Phytolith}}$ and the amount in phytolith (mg kg^{-1}) in the surrounding environment.

Suppl File 3. Relationship between R_{SiAc} and the proportion of sand (%) in the surrounding topsoil.

Suppl File 4. Relationship between R_{SiAc} and the concentration in C (%) in the surrounding topsoil.

Suppl File 5. Relationship between R_{SiAc} and the concentration in Al (total) (mg kg^{-1}) in the surrounding topsoil.

Suppl File 6. Relationship between R_{SiAc} and the concentration in Fe (total) (mg kg^{-1}) in the surrounding topsoil.

Suppl File 7. Relationship between R_{SiAc} and the concentration in phytolith (mg kg^{-1}) in the surrounding topsoil.