

1 *PUBLISHED IN 2013. GEODERMA. 202-203: 18-29.*

2

3

4 **INFLUENCE OF AFFORESTATION ON SOIL: THE CASE OF**
5 **MINERAL WEATHERING**

6

7 Benoit Lafleur¹, David Paré², Yves Claveau¹, Évelyne Thiffault² and Nicolas Bélanger^{1,3*}

8

9 ¹Centre d'Étude de la Forêt, Université du Québec à Montréal, C.P. 8888, Succ. Centre-
10 Ville, Montréal, QC H3C 3P8, Canada

11

12 ²Natural Resources Canada, Canadian Forest Service, Laurentian Forestry Centre, 1055
13 du P.E.P.S., P.O. Box 10380, Stn. Sainte-Foy, Québec, Québec, QC G1V 4C7, Canada

14

15 ³Téluq, Université du Québec, 5800, rue Saint-Denis, Montréal, QC H2S 3L5, Canada

16

17 * Corresponding author: Phone (514) 843-2015 ext 810900; Fax (514) 843-2160; Email
18 nicolas.belanger@teluq.ca

19

20

21

22

23

24

25

26

27

28

29

30 **Abstract**

31 Although concerns have been raised that increased nutrient demand by fast
32 growing tree species could deplete soil nutrient pools, recent research suggests that some
33 species are able to obtain nutrients via soil mineral weathering. Hybrid poplars, which are
34 fast growing and nutrient demanding species, are increasingly used in intensive
35 silvicultural settings. Understanding whether hybrid poplars have an effect on long term
36 nutrient availability and can promote soil mineral weathering is therefore important. We
37 investigated the levels of base cations (i.e. K, Ca, Mg, and Na) of surface soils (0-20 cm)
38 in 13 hybrid poplar plantations in Quebec, and compared the results with those of
39 adjacent abandoned agricultural fields. To evaluate whether exchangeable base cation
40 pools and non-exchangeable pools (i.e. those in the crystal lattice of minerals) were being
41 depleted, we used a sequential leach with diluted salt (BaCl_2 for exchangeable) and weak
42 acid solutions (HCl and HNO_3 for non-exchangeable). Levels of exchangeable and non-
43 exchangeable cations were not statistically different between land use types. Exploratory
44 analyses, however, revealed trends toward a greater depletion of Ca, Mg and Na in non-
45 exchangeable forms following afforestation. The depletion of these non-exchangeable
46 base cations due to afforestation occurred at sites where greater levels were initially
47 present in soil. The results suggest increased soil mineral weathering due to greater
48 amounts of minerals susceptible to dissolution and, in part, high clay content. Based on
49 Ca, Mg and K concentrations of the different leaches and their molar ratios $\text{Ca}/\Sigma\text{Al+Fe}$,
50 $\text{Mg}/\Sigma\text{Al+Fe}$ and $\text{K}/\Sigma\text{Al+Fe}$), we propose a lesser role of soil mineral weathering on Ca
51 cycling than Mg and K, which could lead to faster depletion of exchangeable Ca pools of
52 the surface soil due to fast growth and high Ca demand by the poplars.

53

54 *Keywords:* Base cations, Intensive silviculture, *Populus*, Sequential leach, Long-term soil
55 fertility, Tree nutrition.

56

57 **1. Introduction**

58 Throughout the world, the increasing demand for wood products and the growing
59 pressures to set aside forested areas for conservation purposes are generating an
60 increasing interest in fast-growing tree species. By 2050, FAO (2001) predicts that
61 plantations will cover 5 to 10% of the world's forested land area and that close to 50% of
62 commercially harvested wood will come from these plantations. For example, poplars
63 (*Populus spp.*) have the ability to propagate from cuttings and can be used to create
64 hybrids possessing very high growth rates (Reimenschneider et al., 2001; Stanturf et al.,
65 2001). Poplar plantations therefore have the potential to quickly produce large amounts of
66 fiber to be used in valuable wood products such as pulp, lumber, panels, and engineered
67 wood products (Heilman, 1999; Zhang et al., 2003). However, concerns about the effects
68 of such intensive plantations on long term nutrient availability and site productivity have
69 been raised (Vanguelova and Pitman, 2009) and fertilization may be required to avoid
70 nutrient depletion (Fox, 2000; Jokela et al., 2010).

71 The magnitude of the reduction in soil nutrient availability is likely influenced by
72 the species involved and their growth rate. A study by Paré et al. (2002) on nutrient
73 contents in stem wood of common North American temperate tree species suggests that
74 Ca, Mg and K (hereafter referred to as base nutrients) immobilization rates in the stem in
75 mesic sites follow the pattern *Picea mariana*/*Pinus banksiana* < *Abies balsamea* < *Betula*

76 *papyrifera* < *Populus tremuloides*. This was demonstrated on a site index basis (15, 18,
77 21 and 24 m) at 50 years. In Minnesota, Alban (1982) showed a decrease in mineral soil
78 Ca pools following rapid immobilization by trees in 40-year-old stands. In this case,
79 mineral soil Ca pools followed the pattern *Populus tremuloides* < *Picea glauca* < *Pinus*
80 *resinosa*/*Pinus banksiana*. Alban (1982) explained that Ca uptake by the roots and
81 immobilization in the stem occurred at a greater rate with *Populus tremuloides* (and *Picea*
82 *glauca*) because of faster growth and greater Ca requirements compared to the two *Pinus*
83 species. This apparently led to the impoverishment of mineral exchangeable Ca pools, a
84 phenomenon also observed by Ruark and Bockheim (1988) in Wisconsin with *Populus*
85 *tremuloides*.

86 The negative correlation between soil nutrient availability and increased growth
87 (and nutrient uptake) in intensive silviculture is not, however, consistent with all
88 scientific literature. For example, intensive silviculture (Eriksson and Rosen, 1994) or
89 aggrading natural stands (Paré and Bergeron, 1996) did not always result in impoverished
90 mineral soil nutrient pools. The lack of effects of fast tree growth on mineral soil pools
91 may be due to a high buffer capacity of the soil (e.g. high clay with high cation exchange
92 capacity). However, if soils are poorly buffered (e.g. loamy sand with low cation
93 exchange capacity), this lack of effect could also be due to the functional traits of the tree
94 species. For example, *Picea abies* uses long-term strategies to maintain the soil
95 exchangeable base nutrient pools intact such as the : (i) filtering of aerosols due to a
96 canopy with a large surface area; (ii) increase of nutrient fluxes by increasing soil mineral
97 weathering (Binkley and Giardina, 1998; Augusto et al., 2002); and (iii) possible

98 reduction of nutrient leaching by using more water in fast growing sites (Bélanger et al.,
99 2004).

100 Both in Europe and North America, some tree species were shown to favor soil
101 mineral weathering, thus increasing the availability of some nutrients for tree growth. In
102 France, Augusto et al. (1998; 2000) showed that *Picea abies*, *Pinus sylvestris*, *Quercus*
103 *petraea*, *Quercus rubor*, *Fagus sylvatica* were capable of lowering soil pH and in turn, of
104 dissolving test-minerals inserted in the soil. Results suggested that hardwood species
105 were not as effective as conifers to lower soil pH and to dissolve the test-minerals.
106 Similarly, Leyval and Berthelin (1991) showed enhanced weathering of phlogopite
107 (mica) by *Pinus sylvestris* in test lysimeters. In North America, Quideau and Bockheim
108 (1997) observed greater Ca losses under *Pinus resinosa* than under prairie vegetation
109 following afforestation of prairie with pine. The Ca losses were attributed to increased
110 soil mineral weathering due to afforestation. In sand-box experiments, Bormann et al.
111 (1998) and Quideau et al. (1996) showed that two other North American *Pinus* species
112 were also effective in releasing non-exchangeable base cations by promoting weathering
113 reactions, whereas *Quercus berberidifolia* was slightly less effective.

114 The ability of tree species to increase nutrient fluxes by increasing soil weathering
115 is likely an important mechanism by which trees may compensate rapid growth and
116 nutrient uptake and, as such, avoid soil nutrient depletion, at least in the short-term
117 (Bormann et al., 1998). The literature suggests that this process is more efficient under
118 conifers (notably *Picea abies*) than deciduous tree species (Augusto et al., 2002;
119 Bormann et al., 1998; Leyval and Berthelin, 1991), probably because the large amounts
120 of low molecular-weight acid exudates that conifer roots produce act as effective

121 chelating agents that enhance base cation release from the crystal lattice of soil minerals
122 (Raulund-Rasmussen et al., 1998; Strobel et al., 1999). As a whole, however, studies on
123 the effects of deciduous tree species on soil mineral weathering are lacking. For example,
124 Dijkstra et al. (2003) studied the effects of different North American temperate deciduous
125 species (along with *Tsuga canadensis*) in Connecticut, USA, but they found that the low
126 weathering rates were more controlled by parent material than by tree species (despite
127 differences in mycorrhizae, i.e. ecto vs. endo). The effects of different land uses and
128 associated vegetation covers (e.g. forest, pasture or agriculture) on soil mineral
129 weathering are also poorly elucidated (Kelly et al., 1998).

130 If the ability of tree species to increase nutrient fluxes by increasing soil
131 weathering has often been overlooked for most species, even less is known about the
132 potential of trees to induce soil mineral weathering across a range of soil productivity.
133 Contradictory results have been reported in the literature. On the one hand, Finzi et al.
134 (1998) found that the levels of exchangeable nutrients are positively correlated to the
135 levels of total soil nutrients and thus suggested that more intense soil mineral weathering
136 had to occur where soil productivity levels were at their highest. On the other hand,
137 Wallander and Nylund (1992) and Wallander and Thelin (2009) observed that soil
138 nutrient deficiency induced ectomycorrhizal growth in forest trees. Because mycorrhizae
139 are well known to favor soil mineral weathering (Hoffland et al., 2004), the observations
140 by Wallander and coworkers suggest that soil mineral weathering by trees (and associated
141 ectomycorrhizae) is more intense where nutrient availability is low.

142 Soil weathering by trees has traditionally been considered to be a very slow
143 process and unlikely to change over short periods of time (i.e. a few decades) (Mareschal

144 et al., 2012). However, if some tree species augment soil mineral weathering relative to
145 other species (e.g. relative to herbs, grasses and agricultural crop species in an
146 afforestation context), they could lead to increased CO₂ sequestration, not just due to a
147 change in C sequestration rates in biomass, but also because of the increased release and
148 leaching of Ca (and Mg) and HCO₃⁻ from the soil system, which will eventually
149 precipitate in oceans as carbonate minerals (Berner, 1997; Gaillardet et al., 1999). In this
150 paper, we sought to assess the effects of afforestation (i.e. fast growing hybrid poplar
151 plantations) on the soil base cation status (Ca, Mg, K, Na) by using a sequential leaching
152 method that separates exchangeable cations from those in the crystal lattice of minerals.
153 Contrary to most studies which focused on microscale experiments to explore the
154 specifics of soil mineral dissolution by trees, this study uses a macroscale approach to
155 show how different land use types (i.e. tree plantation vs. abandoned agricultural fields),
156 soil properties and time influence mineral weathering. This approach allowed testing the
157 following hypotheses: (i) hybrid poplars increase soil mineral weathering relative to
158 plants that occupy nearby abandoned agricultural fields; (ii) soil mineral weathering
159 induced by hybrid poplars is increased in base poor soils.

160

161 **2. Material and Methods**

162 *2.1 Site selection and location*

163 Plantations were selected in order to cover the largest possible range in terms of
164 age, soil texture and climatic conditions. Plantations were either commercial plantations
165 established by private producers or forest companies or experimental plantations
166 established by the Quebec Ministry of Natural Resources for clonal testing (Boutin et al.,

167 2006). Plantations were established with various hybrids of *P. maximowiczii* crossed with
168 *P. deltoides*, *P. nigra*, and *P. balsamea*. Prior to plantation, each agricultural field had
169 been abandoned. A total of thirteen plantations aged from 1 to 22 years with different
170 growth rates were selected for the study (Table 1, Fig. 1). Most soils are Podzols or
171 Gleysols (Soil Classification Working Group 1998), have clay, loam or silt textures and
172 are well drained with the exception of the Gleysols (Table 1). The age sequence was used
173 to infer the prolonged effects of poplar growth and nutrient sequestration on soil nutrient
174 availability.

175

176 2.2 Soil sampling and analysis

177 Three 400 m² circular plots were established in each of the thirteen plantations:
178 two were located within the plantation, and one was established in an adjacent non-
179 planted abandoned agricultural field to serve as a control. Within the plantations, plots
180 were located approximately 50 m apart, in areas showing the least variability in tree size.
181 This procedure was chosen to avoid areas with high tree mortality which could have
182 masked afforestation effects on soil weathering. The location of the control plot was
183 carefully selected for the best representativity of conditions prior to poplar planting at
184 each site. Specifically, the control plot was installed in the nearest abandoned agricultural
185 field, approximately 30 m from the plantation, where soil texture assessed in the field was
186 thought to be similar to the plantation. Soil texture assessed in the laboratory (see below
187 for details) later confirmed that it was similar between treatments (c.v. <50%).

188 Within each plot, soils were sampled at four locations at a distance of 2 m from
189 the center of the plot and aligned along north-south and east-west axes. Mineral soil

190 samples were collected at 0-20 cm depth [corresponding to the Ap horizon or plowed
191 layer, Soil Classification Working Group (1998)] using a steel cylinder (diameter 4.8 cm;
192 length 25 cm). Samples were then taken to the soil laboratory where they were kept at
193 4°C. Prior to analysis, soil samples were oven dried at 70°C for 72 h and sieved through a
194 2-mm mesh to remove any coarse fragments. For each plot, soil samples were analyzed
195 individually.

196 In order to determine the concentration of exchangeable (i.e. adsorbed on
197 exchange surfaces) and non-exchangeable (i.e. contained in the crystal lattice of
198 minerals) base cations (i.e. Ca, Mg, K, and Na) and acid cations (i.e. Al, Fe) in the
199 mineral soil, we combined the sequential leaching procedure developed by Nezat et al.
200 (2007) to selectively dissolve minerals from soils, notably apatite, with a simple weak
201 HCl leach to dissolve calcite (Drouet et al., 2005) and possibly apatite (Bélanger et al.
202 2012). Nezat et al. (2007) separated individual silicate minerals from granitic material,
203 assessed the chemistry of each mineral, and sequentially leached synthetic mineral
204 mixtures to link mineral dissolution to each leach. Apatite, including free apatite and
205 armoured apatite found along grain boundaries or mineral fractures, was almost entirely
206 dissolved with 1 N HNO₃ at 20°C for 20 h at a soil:solution ratio of 10. Weaker leaches
207 such as 0.1 HNO₃ failed to dissolve apatite and are therefore only appropriate for soils
208 containing calcite or other readily dissolved minerals. The method was validated using
209 soils from the Hubbard Brook Experimental Forest where the mineralogy is well known
210 and other soils from northeastern U.S.A. (Nezat et al., 2008). Their work along with
211 subsequent field studies (Bélanger and Holmden, 2010; Holmden and Bélanger, 2010)
212 helped determine that other minerals are being leached in each sequential steps. The latter

213 studies specifically showed that small amounts of hornblende, biotite (or chlorite or
214 vermiculite) and epidote are also attacked with a 1 N HNO₃ leach.

215 In our study, exchangeable cations were initially extracted from a 3-g sample for 2
216 h using 30 mL of unbuffered 0.1 M BaCl₂ (Hendershot et al., 2007). Then, cations from
217 highly soluble minerals such as free calcite were retrieved using 30 mL of 0.1 N HCl for
218 2 h. Finally, cations from more refractory minerals such as apatite, hornblende, biotite
219 and epidote were retrieved using 30 mL of 1 N HNO₃ for 2 h. Plagioclase feldspars, K-
220 feldspars, muscovite, quartz and other refractory minerals are only marginally attacked by
221 these leaches (Nezat et al. 2007). All leaches were done on an end-over-end shaker at
222 room temperature (20-21°C). Cations were determined by atomic absorption (Ca, Mg, Al,
223 Fe) and emission (K, Na) (Varian AA240FS Sequential Atomic Spectrometer). The
224 method is used to provide operationally-defined mineral groupings of weathering
225 susceptibilities. In reality, acid leaches cannot be used to abruptly divide mineral groups
226 as easily because a relative continuum of mineral susceptibilities to weathering exists.
227 This continuum reflects the chemical structure as well as the "historical" exposure of the
228 surface to weathering agents and in turn, the weakening of the crystal lattice of the
229 mineral prior to the leaching steps. For example, the 1 N HNO₃ leach only partially
230 dissolves biotite and subsequent, stronger leaches (e.g. concentrated HNO₃ and HF), are
231 generally required to completely dissolve the mineral [as seen from dissolution results of
232 mineral separates from Nezat et al. (2007)]

233 The sites were also characterized in terms of soil texture, bulk elemental
234 composition and mineralogy. Particle size distribution was determined using the Horiba
235 Partica LA-950 Laser Particle Analyzer. Because all samples had <2% C content, no pre-

236 treatment was needed to break down aggregates. Instead, sodium hexametaphosphate (4
237 mg per sample cell) and sonication for 1 min at level 7 were used on all samples for
238 particle dispersion before measurement. Bulk elemental composition was determined on
239 32-mm-diameter fused beads prepared from a 1:4 soil:lithium tetra(meta)borate mixture
240 heated at 1000°C for 18 minutes. An automated X-ray fluorescence Philips PW2440
241 spectrometer system with a Rhodium 60 kV end window X-ray source, operating at 3
242 kW, was used for analysis. The bulk elemental compositions were then used to assign
243 elements to their respective minerals using the UPPSALA norms for soils (Sverdrup and
244 Warfvinge, 1992). Similar to CIPW norms, UPPSALA is a normative back-calculation
245 model for reconstructing empirical soil mineralogy from bulk elemental composition. It is
246 based on the stoichiometric compositions of soil minerals of granitic origin (i.e., Swedish
247 Precambrian Shield). The minerals are grouped based on similar composition and
248 dissolution rates. Muscovite includes muscovite, secondary dioctahedral chlorite, and
249 vermiculite of secondary weathered type. Chlorite is composed of trioctahedral chlorite,
250 primary illite, trioctahedral vermiculite of primary type, and biotite, phlogopite and
251 glauconite. Also, hornblende includes all amphiboles (e.g. hornblende, glaucophane and
252 tremolite), and epidote includes all epidotes (e.g. epidote, pyroxenes and zoisites). The
253 UPPSALA norms are in the following order (the oxide and mineral units are in per cent,
254 %):

255
$$\text{K-feldspars (KF)} = 5.88 \times \text{K}_2\text{O} - 0.588 \times \text{Na}_2\text{O}$$

256
$$\text{Plagioclase (PL)} = 11.1 \times \text{Na}_2\text{O} - 0.22 \times \text{KF}$$

257
$$\text{Apatite (AP)} = 2.24 \times \text{P}_2\text{O}_5$$

258
$$\text{Hornblende (HO)} = 6.67 \times \text{CaO} - 3.67 \times \text{AP} - 0.2 \times \text{PL}$$

259
$$\text{Muscovite (MU)} = 2.08 \times \text{K}_2\text{O} - 0.208 \times \text{Na}_2\text{O}$$

260
$$\text{Chlorite (CL)} = 3.85 \times \text{MgO} - 0.39 \times \text{HO} - 0.39 \times \text{MU}$$

261
$$\text{Epidote (EP)} = 0.1 \times \text{HO} + 0.03 \times \text{OL} - 0.3$$

262
$$\text{Calcite (CA)} = 1.79 \times \text{CaO} - 3.67 \times \text{AP} - 0.2 \times \text{PL}$$

263
$$\text{Quartz (QU)} = \text{SiO}_2 - 0.63 \times \text{PL} - 0.68 \times \text{KF} - 0.38 \times \text{MU} - 0.33 \times \text{CL} - 0.45 \times \text{HO} -$$

264
$$0.42 \times \text{EP}$$

265 The sum of these minerals is then rounded to 100%. Semi-quantitative X-ray
 266 diffraction results and UPPSALA norms were compared by Houle et al. (2012) in
 267 Quebec. It was concluded that the UPPSALA norms apply well to the granitoid soils of
 268 Quebec.

269

270 *2.3 Data analysis*

271 The plantation setup allowed testing for the effect of time since poplar planting on
 272 soil characteristics. We therefore performed a series of analyses of covariance
 273 (ANCOVA) to test for differences in exchangeable and non-exchangeable cations
 274 between land use types, using time as a covariate. These analyses, however, did not
 275 reveal any significant differences ($p > 0.14$) between treatments. In this context, molar
 276 ratios (i.e. $\text{Ca}/\Sigma\text{Al}+\text{Fe}$, $\text{Mg}/\Sigma\text{Al}+\text{Fe}$ and $\text{K}/\Sigma\text{Al}+\text{Fe}$) were tested, again using ANCOVA
 277 and time as a covariate, as an attempt to homogenize the soil data across the sites.
 278 Residuals were tested for normality and homogeneity of variances. The data were log or
 279 square-root transformed when necessary.

280 Exploratory analyses were also performed to identify potential changes in cation
 281 concentrations following leaches. Specifically, the direction and magnitude of change in

282 cation concentrations were examined graphically using scatter plots as described in Ens et
283 al. (2013). The thirteen sites included in this study represent a wide range of climatic
284 conditions, parent material and soil texture, which affect cation concentrations with
285 plantation establishment. The net effect on cation concentrations depends upon the initial
286 conditions of the soil (i.e. initial concentration of Na, K, Mg, and Ca), the exchange
287 capacity of the soil, and the ability of poplars to alter the soil (i.e. by uptake, weathering,
288 biocycling, etc.). By using the control plots as proxies for initial cation concentrations, it
289 was possible to represent change from plantation establishment as a function of initial
290 conditions. We therefore produced scatter plots where initial concentrations of the control
291 plots are on the x -axis and concentrations of the plantations are on the y -axis. Linear
292 regression of the controls (x -axis) and plantations (y -axis) yields a line that can be
293 visually and statistically compared to the 1:1 line (i.e. the control plots), with any
294 deviation from the 1:1 line indicating a change resulting from plantation establishment.
295 Differences in slope, tested against a slope of 1.0, also describe the nature of the change.
296 A slope <1.0 means that there is more depletion at higher initial concentrations, whereas
297 a slope >1.0 means that there is increased concentrations with high initial concentrations.
298 A slope of one indicates that any change is independent of initial conditions.

299 Statistical analyses were performed using JMP 7.0.1 (SAS Institute, Cary, North
300 Carolina).

301

302 **3. Results and Discussion**

303 *3.1 Soil exchangeable and non-exchangeable cation concentrations*

304 Scatter plots and slope analyses between the exchangeable and non-exchangeable
305 cations in abandoned agricultural fields and those of plantations revealed an interesting
306 response pattern of soils to land use change. Specifically, a higher non-exchangeable
307 cation concentration in some abandoned agricultural field soils (x axis) was associated
308 with a lower cation concentration in respective plantation soils. This was the case for Ca,
309 Mg and Na with the HCl and HNO₃ leaches, and K with the HCl leach (Figs. 2 to 5).

310 These results suggest that hybrid poplars are able to promote soil mineral
311 weathering relative to plant species in abandoned agricultural fields. This ability,
312 however, appears to be associated with soil characteristics. Indeed, a depletion of the
313 pools of non-exchangeable base cations was observed only at sites where soils initially
314 had high non-exchangeable base cation levels as represented by the abandoned
315 agricultural field soils (Figs. 2 to 5). This is in agreement with the findings of Finzi et al.
316 (1998) that trees induce greater soil mineral weathering on richer soils, but contradictory
317 to those of Wallander and coworkers that trees induce soil mineral weathering on poor
318 soils where base cation deficiencies may be a concern (Wallander and Nylund, 1992;
319 Wallander and Thelin, 2009). Hence, our results suggest that induced soil mineral
320 weathering and base cation release by hybrid poplar roots may be a mechanism that
321 operates more efficiently on richer soils. Ste-Marie et al. (2007), in agreement with
322 Bélanger et al. (2004), observed that nutrient demanding stands increased soil nutrient
323 exchangeable pools even on poor sites. Our results suggest that the contribution of soil
324 mineral weathering to the maintenance of exchangeable soil nutrient pools may be lower
325 on poor than on rich soils.

326 In this study, the differences in non-exchangeable Ca, Mg, K and Na between the
327 plantations and agricultural fields suggest that they were most likely released from more
328 soluble minerals (e.g. calcite, apatite, epidote, hornblende, phyllosilicates such as biotite)
329 rather than recalcitrant minerals (e.g. plagioclase feldspars, K-feldspars, muscovite)
330 because the later minerals are not being efficiently attacked by the leaching treatments
331 (Bélanger and Holmden, 2010; Nezat et al., 2007). The high amounts of non-
332 exchangeable base cations measured in the richer abandoned agricultural field soils
333 therefore indicate that Ca, Mg, K and Na containing minerals that are susceptible to
334 weathering are more abundant in these soils (see Table 2 and Figs. 2 to 5). Because the
335 *Populus* genera can produce acid root exudates with chelating powers (Qin et al., 2007),
336 such minerals are therefore presumably more vulnerable to dissolution in the plantations
337 relative to the abandoned agricultural field soils. Bulk elemental composition and
338 UPPSALA simulations show a large range in soil chemical and mineralogical conditions
339 across the sites, with some being more felsic than others (Table 2). The fact that trees
340 induce greater soil mineral weathering on richer soils can be confirmed with the
341 UPPSALA mineralogy (Table 2) and, in part, particle size distribution (Table 1). The site
342 that showed the greatest difference between land use types is SHW, followed by NORM
343 and SJG2 and finally SCH1 (Fig. 2 to 5):

344 (1) SHW — At that site, the lower non-exchangeable cation concentrations in the
345 plantation, especially for Ca, can be explained by a soil mineralogy with high amounts of
346 more easily weathered minerals such as apatite, epidote and hornblende, all of which
347 contain large amounts of Ca. Moreover, this site has the highest clay content (52%). This
348 translates into a greater area of reactive surfaces which is conducive to greater attack and

349 dissolution of minerals by acid root exudates. Because Ca is the dominant base cation in
350 the HCl leachate (compare Fig. 5 to Figs. 2-4), calcite could also be an important source
351 of Ca (Drouet et al., 2005). UPPSALA has been known to underestimate or even omit
352 calcite where it is actually present and significantly releasing Ca into the soil solutions
353 (Bélanger et al., 2012);

354 (2) NORM and SJG2 — These sites showed lower non-exchangeable Mg, and to a lesser
355 extent Na, concentrations in the plantation. The NORM site has a low clay content (6%)
356 relative to most other sites (average of 20%), whereas SJG2 is close to average at 23%
357 clay. In either case, one has to turn to soil mineralogy to explain the impacts of
358 afforestation of mineral weathering. Indeed, both sites have amongst the highest
359 hornblende and epidote contents, which contain significant amounts of Mg (Note: with
360 the UPPSALA classification, epidote also includes all ferromagnesian pyroxenes). The
361 sites also have high plagioclase, which some species are rich in Na. Plagioclase minerals
362 were shown to play a role in releasing base cations (notably Ca) to forest ecosystems, but
363 the process is believed to be slow (Bailey et al., 1996), likely too slow to detect an effect
364 induced by 22 years of afforestation or less;

365 (3) SCH1 — This sites showed lower non-exchangeable Mg concentrations in the
366 plantation. It has relatively high clay at 31% and exhibits the highest MgO and chlorite
367 content of all the sites. It is impossible to determine whether it is primary or secondary
368 chlorite. Nevertheless, the combination of having high surface area due to high clay and
369 the presence of a Mg saturated phyllosilicate mineral (chlorite) appears to have been
370 conducive to trees promoting the release of non-exchangeable Mg.

371 It should be reminded that the UPPSALLA norms are based on bulk chemistry
372 only and thus, the model yields a normative mineralogy for the bulk soil, not the clay
373 fraction specifically. It would seem reasonable to think that the easily weathered minerals
374 are clay sized for most sites. However, the relationship between soil texture and easily
375 weathered minerals was not straightforward for the four sites showing a response to
376 afforestation, i.e. SHW had the highest clay content, NORM had the lowest clay content,
377 and SJG2 and SCH1 sites had average clay content. We therefore suggest that mineralogy
378 (bulk) is the most useful variable explaining induced weathering by afforestation and that
379 clay content interacts only at some sites.

380 The high productivity at SCH1 relative to most sites (Table 1) could have
381 facilitated soil mineral weathering. However, the most productive STN site is an older
382 site — yet, the accumulation of root biomass did not appear to induce soil mineral
383 weathering more than the plants in the abandoned agricultural field. The more felsic
384 nature of the STN soils (72.0% SiO₂ or 43.6% quartz) compared to those of SHW,
385 NORM and SJG2 (59.6 to 63.4% SiO₂ or 16.4 to 27.6% quartz) could partly explain the
386 lack of sensitivity of soil minerals to afforestation at that site (Table 2).

387

388 *3.2 Elemental molar ratios and cycling of base cations*

389 Average molar ratios (i.e. Ca/ΣAl+Fe, Mg/ΣAl+Fe and K/ΣAl+Fe) following the
390 HCl and HNO₃ leaches were between 18.9 and 22.0% lower under plantations than
391 abandoned agricultural fields, except for the K/ΣAl+Fe ratio of the HCl treatment with
392 plantations having the highest ratios (Table 3). Some molar ratios (i.e. Ca/ΣAl+Fe of the
393 HCl and HNO₃ leaches and K/ΣAl+Fe of the HNO₃ leach) were also marginally

394 statistically lower ($p \leq 0.13$) under plantations than abandoned agricultural fields (Table
395 3). Because weathering indices are based on the principle that the ratio between levels of
396 mobile (Si, Ca, Mg, K and Na) and immobile elements (Al, Fe, Zr and Ti) decrease with
397 time due to more leaching (Birkeland, 1999; Chittleborough, 1991), these results partially
398 reinforce the idea that the process of Ca, Mg and K removal/mobilization from the crystal
399 lattice of minerals is more exhaustive under hybrid poplars than abandoned agricultural
400 field. The lower molar ratios of the HCl and HNO₃ leaches under plantations could be
401 due to a weathering "residue" that is impoverished in easily weathered minerals and thus
402 enriched in recalcitrant aluminosilicates with high and low molar ratios, respectively
403 (Munroe et al., 2007). A selective removal of Ca, Mg and K relative to Al and Fe through
404 incongruent dissolution is a less likely mechanism. Such indices may be more sensitive
405 variables than individual base cations to investigate the influence of afforestation on soil
406 mineral weathering and should be considered for future studies.

407 All average molar ratios decreased in absolute terms in the order BaCl₂ > HCl >
408 HNO₃ (Table 3). This reflects Al and Fe increasing in the order BaCl₂ < HCl < HNO₃ and
409 Ca concentrations largely decreasing in the order BaCl₂ > HCl > HNO₃, whereas Mg and
410 K concentrations did not vary much across the leaches. As a whole, these trends suggest
411 that, as the leach got stronger, aluminosilicates with lower leachable amounts of Ca
412 (relative to the soil exchangeable complex) were being dissolved. On the one hand, this is
413 indicative of a large long-term build-up of an exchangeable pool of Ca by plants (Jobbágy
414 and Jackson, 2004) and that plants in these systems now rely heavily on that pool and its
415 internal cycling to satisfy their nutritional demand. On the other hand, the more

416 homogeneous Mg and K concentrations across the BaCl₂, HCl and HNO₃ leaches imply a
417 larger role of soil mineral weathering on plant Mg and K nutrition for these systems.

418 Markewitz et al. (1998) showed that 34 years of tree growth (*Pinus taeda*)
419 significantly decreased soil pH and effective base saturation in the surface soil at the
420 Calhoun Experimental Forest. Soil exchangeable Ca and Mg depletions were also large,
421 whereas exchangeable K depletions were negligible. The sum of Ca and Mg removals
422 from immobilization in wood and the forest floor as well as net leaching (the latter being
423 linked to acid deposition) were relatively well balanced with depletions, suggesting that
424 mineral weathering and biocycling failed to match losses (Richter and Markewitz, 2001).
425 Likewise, we speculate that the release of Ca from mineral weathering and biocycling
426 was also outpaced by removals of Ca by the hybrid poplar plantations in our study.
427 However, this inference is based on Ca/ΣAl+Fe ratios alone (i.e. non-significant decline
428 of 15% following afforestation for the BaCl₂ leach, see Table 3) and not from individual
429 exchangeable Ca, and therefore clearly implies that acidification of the Quebec soils due
430 to afforestation is not as severe as Calhoun soils. The fact that Quebec soils were
431 "recently" glaciated and contain fresh and unaltered minerals (Brais et al., 2009) could be
432 one reason for the greater buffer capacity compared to Calhoun soils (kaolinite-
433 dominated). Shorter tenure of the poplar trees (1 to 22 years) compared to pine at the
434 Calhoun site (34 years) could be another. In the Canadian Prairies, Steckler et al.
435 (submitted) built a complete nutrient budget to show no expected impact of hybrid poplar
436 plantations on soil exchangeable Ca and Mg due to large Ca and Mg weathering fluxes of
437 calcareous soils. The Ca and Mg budgets were slightly negative, neutral or positive,
438 depending on site characteristics, growth rates and harvesting treatments. However, the

439 weathering fluxes far surpassed weathering rates calculated for various soils in Quebec
440 (Courchesne et al., 2002; Houle et al., 2012). *Populus* species generally have high Ca
441 demand (Bowersox and Ward, 1977; Lamarche et al., 2004; Pinno et al., 2010; Zasada et
442 al., 2001) and thus, the monitoring of soil exchangeable and foliar Ca levels may prove
443 important in the long term in hybrid poplar plantations of Quebec.

444 Conversely, Quebec soils generally have a high content of Mg and K bearing
445 minerals as they generally originate from granitoid rocks, rich in hornblende and chlorite,
446 containing Mg, as well as biotite, illite and some more recalcitrant muscovite or alkali
447 feldspars, containing K (Brais et al., 2009). This is supported by the relatively large
448 concentrations of MgO and K₂O (relative to CaO) of the studied soils as well as their
449 large estimated amounts of K-feldspars, muscovite, hornblende and chlorite (which
450 contains illite and biotite according to UPPSALA classification) (Table 2). This data
451 along with (i) the more homogeneous Mg and K concentrations across the BaCl₂, HCl
452 and HNO₃ leaches compared to Ca and (ii) the lack of a decreasing effect of trees
453 (relative to plants of the abandoned agricultural land) on Mg/ΣAl+Fe and K/ΣAl+Fe
454 ratios of the BaCl₂ leach relative to Ca/ΣAl+Fe (Table 3) are consistent with soil systems
455 where mineral weathering impacts Mg and K cycling more than Ca cycling.

456 Indeed, the generally higher concentrations of K in abandoned agricultural fields
457 with the BaCl₂ and HCl leaches indicate that the K released from minerals can be
458 efficiently cycled and retained by the hybrid poplar trees in surface soil. Potassium,
459 which is found in very low concentration in wood (typically <0.1%), is highly mobile
460 within trees and cycles rapidly in the plant-soil system (Likens et al., 1994; Maliondo et
461 al., 1990; Ruark and Bockheim, 1988). The high K levels in foliage of *Populus* lead to

462 high K returns to the soil via litterfall [as much as $30 \text{ kg ha}^{-1} \text{ yr}^{-1}$ according to Berthelot et
463 al. (2000)] and can buffer a loss in exchangeable K at the soil surface because of high K
464 demand by fast growing poplar trees (Camiré and Brazeau, 1998; Steckler et al.,
465 submitted). At the Calhoun Experimental Forest, for example, Richter and Markewitz
466 (2001) attributed the negligible change in exchangeable K at the soil surface (despite
467 large immobilization in pine biomass and forest floor) to a significant source of K from
468 weathering of K-bearing minerals and effective biocycling by the pine trees. These
469 authors also found that Mg sources and recycling better matched Mg removals from
470 immobilization in the trees and forest floor as well as leaching than Ca, which could
471 imply, like this study, a larger role of mineral weathering for Mg cycling. Finally,
472 complex reactions involving K occurs in soils of cold temperate regions to form
473 secondary (clay) minerals. The generally higher concentrations of K in abandoned
474 agricultural fields with the HCl leach (Fig. 3) possibly indicate that the soil conditions are
475 adequate for some K ions, brought about by hybrid poplars from mineral weathering and
476 biocycling, to become structurally bound into secondary minerals (Wilson, 2004).

477

478 **4. Conclusion**

479 Both in Europe and North America, some tree species were shown to favor soil
480 mineral weathering, thus increasing the availability of some nutrients for tree growth (e.g.
481 Augusto et al., 1998, 2000; Bormann et al., 1998; Leyval and Berthelin, 1991; Quideau
482 and Bockheim, 1997; Quideau et al., 1996). As tree species with high growth rates are
483 generally accompanied by large nutrient uptake rates, those capable of releasing nutrients
484 contained in soil minerals could be less vulnerable to nutrient depletion.

485 In our study, the main soil factors that can explain different site responses to
486 hybrid poplar growth include soil particle size distribution, chemistry and mineralogical
487 composition. Root growth and biomass, root exudate production and nutrient uptake
488 rates, which are all linked to overall poplar productivity, are also important biological
489 factors to consider. Improved base cation availability, notably Ca, can possibly support
490 higher *Populus* yields, but also lead to faster depletion of the soil exchangeable complex.
491 The overall regression results suggest that hybrid poplars are able to promote soil mineral
492 weathering relative to abandoned agricultural field vegetation; this ability could well be
493 related to *Populus*' high growth and nutrient uptake rates. Higher root biomass could lead
494 to an increased production of acid root exudates, which was shown to enhance soil
495 mineral weathering. However, our results also suggest a lesser role of soil mineral
496 weathering on Ca cycling than Mg and K, which could lead to faster depletion of
497 exchangeable Ca pools of the surface soil due to fast growth and high Ca demand by the
498 poplars.

499 It is not yet fully elucidated why soil mineral weathering is favored relative to
500 plants in abandoned agricultural fields only at some sites. Growth rates, nutrient demand,
501 root exudates production, mycorrhizal associations, and differences in plant community
502 composition could play a role, but the limited number of sites and interactions between
503 soil productivity, plantation age and yields did not allow establishing a statistical
504 relationship of these factors with soil mineral weathering. Only soil mineralogy and clay
505 content could be linked to the dissolution of Ca, Mg and Na containing minerals. Our
506 findings confirm Finzi et al.'s (1998) observation that trees induce soil mineral
507 weathering on richer soils as well as Mareschal et al.'s (2012) suggestion that changes in

508 soil chemistry induced by mineral weathering can be detected fairly rapidly (i.e. less than
509 20 years) following the establishment of the plantation.

510

511 **Acknowledgements**

512 This study was conducted as part of the *Forest 2020 Plantation Demonstration*
513 *and Assessment initiative* program, implemented by the Canadian Forest Service.
514 Additional funding was provided by NSERC to N. Bélanger (Discovery Grant) and B.
515 Lafleur (Postdoctoral Fellowship). We wish to acknowledge the cooperation of all land
516 owners who allowed us to use their plantations for the purpose of the study. We also wish
517 to acknowledge the work of M. Pierre Périnet (Direction de la recherche forestière,
518 Ministère des Ressources naturelles du Québec) who was the instigator of this plantation
519 network. Finally, we thank Marie Bélanger, Gilles Thébau, Ricardo Morin and René
520 Paquet for field and laboratory work performed, and Alain Courcelles for chemical
521 analyzes.

522

523 **References**

- 524 Alban, D.H., 1982. Effects of nutrient accumulation by aspen, spruce, and pine on soil
525 properties. *Soil Science Society of America Journal* 46, 853-861.
- 526 Augusto, L., Bonnaud, P., Ranger, J., 1998. Impact of tree species on forest soil
527 acidification. *Forest Ecology and Management* 105, 67-78.
- 528 Augusto, L., Turpault, M.-P., Ranger, J., 2000. Impact of tree species on feldspar
529 weathering rates. *Geoderma* 96, 215-237.

530 Augusto, L., Ranger, J., Binkley, D., Rothe, A., 2002. Impact of several common tree
531 species of European temperate forests on soil. *Annals of Forest Science* 59, 233-
532 253.

533 Bailey, S.W., Hornbeck, J.W., Driscoll, C.T., Gaudette, H.E., 1996. Calcium inputs and
534 transport in a base-poor forest ecosystem as interpreted by Sr isotopes. *Water*
535 *Resources Research* 32, 707-719.

536 Bélanger, N., Paré, D., Bouchard, M., Daoust, G., 2004. Is the use of trees with superior
537 growth a threat to soil nutrient availability? A case study with Norway spruce.
538 *Canadian Journal of Forest Research* 34, 560-572.

539 Bélanger, N., Holmden, C., 2010. Influence of landscape on the apportionment of Ca
540 nutrition in a Boreal Shield forest of Saskatchewan (Canada) using $^{87}\text{Sr}/^{86}\text{Sr}$ as a
541 tracer. *Canadian Journal of Soil Science* 90, 267-288.

542 Bélanger, N., Holmden, C., Courchesne, F., Côté, B., Hendershot, W.H., 2012.
543 Constraining soil mineral weathering $^{87}\text{Sr}/^{86}\text{Sr}$ for calcium apportionment studies of
544 a deciduous forest growing on soils developed from granitoid igneous rocks.
545 *Geoderma* 185:84-96

546 Berner, R.R., 1997. The rise of plants and their effect on weathering and atmospheric
547 CO_2 . *Science* 276, 544-546.

548 Berthelot, A., Ranger, J., Gelhaye, D., 2000. Nutrient uptake and immobilization in a
549 short-rotation coppice stand of hybrid poplars in north-west France. *Forest Ecology*
550 *and Management* 128, 167-179.

551 Binkley, D., Giardina, C., 1998. Why do tree species affect soils? The warp and woof of
552 tree-soil interactions. *Biogeochemistry* 42, 89-106.

553 Birkeland, P.W., 1999. Soils and Geomorphology. Oxford University Press, New York.

554 Bormann, B.T., Wang, D., Bormann, F.H., Benoit, G., April, R., Snyder, M.C., 1998.

555 Rapid, plant-induced weathering in an aggrading experimental ecosystem.

556 Biogeochemistry 43, 129-155.

557 Boutin, R., Joncas, G., Daoust, G., 2006. Évaluation des stocks de carbone dans des

558 plantations de peupliers hybrides au Québec. Ressources naturelles Canada, Service

559 canadien de forêts, Centre de foresterie des Laurentides, Québec, 49 p.

560 Bowersox, T.W., Ward, W.W., 1977. Soil fertility, growth, and yield of young hybrid

561 poplar plantations in central Pennsylvania. Forest Science 23, 463-469.

562 Brais, S., Bélanger, N., Brazeau, M., Brown, J.-L., Camiré, C., Drouin, P., Paré, D.,

563 Robitaille, A., 2009. Géologie, dépôts de surface et sols forestiers, in Doucet, R.,

564 Côté, M. (Eds.), Manuel de foresterie. Éditions MultiMondes et Ordre des

565 Ingénieurs Forestiers du Québec, Québec, pp. 47-124.

566 Camiré, C., Brazeau, M., 1998. Culture des genres Populus et Larix au Québec: sols,

567 exigences nutritionnelles et productivité. Report to the Ministère des ressources

568 naturelles (C-122), Direction de l'environnement forestier, Québec, 132 p.

569 Chittleborough, D.J., 1991. Indices of weathering for soils and paleosols formed on

570 silicate rocks. Australian Journal of Earth Science 38, 115-120.

571 Courchesne, F., Hallé, J.-P., Turmel, M.-C., 2002. Bilans élémentaires holocènes et

572 altération des minéraux dans trois sols forestiers du Québec méridional. Géographie

573 Physique et Quaternaire 56, 5-17.

574 Dijkstra, F.A., Van Breemen, N., Jongmans, A., Davies, G.R., Likens, G.E., 2003.
575 Calcium weathering in forested soils and the effects of different tree species.
576 Biogeochemistry 62, 253-275.

577 Drouet, T., Herbauts, J., Gruber, W., Demaiffe, D., 2005. Strontium isotope composition
578 as a tracer of calcium sources in two forest ecosystems in Belgium. Geoderma 126,
579 203-223.

580 Eriksson, H.M., Rosen, K., 1994. Nutrient distribution in a Swedish tree species
581 experiment. Plant and Soil 164, 51-59.

582 FAO, 2001. Future production from forest plantations. Forest plantations thematic papers,
583 Working paper FP/13, Forest Resources Development Service, Forest Resources
584 Division.

585 Finzi, A.C., Canham, C.D., Van Breemen, N., 1998. Canopy tree-soil interactions within
586 temperate forests: Species effects on pH and cations. Ecological Applications 8,
587 447-454.

588 Fox, T.R., 2000. Sustained productivity in intensively managed forest plantations. Forest
589 Ecology and Management 138, 187-202.

590 Gaillardet, J., Dupré, B., Louvat, P., Allègre, C.J., 1999. Global silicate weathering and
591 CO₂ consumption rates deduced from the chemistry of large rivers. Chemical
592 Geology 159, 3-30.

593 Heilman, P.E., 1999. Planted forest poplars. New Forests 17/18, 89-93.

594 Hendershot, W.H., Lalande, H., Duquette, M., 2007. Ion exchange and exchangeable
595 cations, in Carter, M.R., Gregorich, B.G. (Eds.). Soil Sampling and Methods of
596 Analysis. CRC Press, Boca Raton, pp. 197-206.

597 Hoffland, E., Kuyper, T.W., Wallander, H., Plassard, C., Gorbushina, A.A.,
598 Haselwandter, K., Holmström, S., Landeweert, R., Lundström, U.S., Rosling, A.,
599 Sen, R., Smits, M.M., van Hees, P.A.W., van Breemen, N., 2004. The role of fungi
600 in weathering. *Frontiers in Ecology and the Environment* 2, 258-264.

601 Holmden, C., Bélanger, N., 2010. Ca isotope cycling in a forested ecosystem.
602 *Geochimica et Cosmochimica Acta* 74, 995-1015.

603 Houle, D., Lamoureux, P., Bélanger, N., Bouchard, M., Gagnon, C., Couture, S.,
604 Bouffard, A., 2012. Soil weathering rates in 21 catchments of the Canadian Shield.
605 *Hydrology and Earth System Sciences* 16, 685-697.

606 Jobbágy, E.G., Jackson, R.B., 2004. The uplift of soil nutrients by plants: biogeochemical
607 consequences across scales. *Ecology* 85, 2380-2389.

608 Jokela, E.J., Martin, T.A., Vogel, J.G., 2010. Twenty-five years of intensive forest
609 management with southern pines: Important lessons learned. *Journal of Forestry*
610 108, 338-347.

611 Kelly, E.F., Chadwick, O.A., Hilinski, T.E., 1998. The effect of plants on mineral
612 weathering. *Biogeochemistry* 42, 21-53.

613 Lamarche, J., Bradley, R.L., Paré, D., Légaré, S., Bergeron, Y., 2004. Soil parental
614 material may control forest floor properties more than stand type or stand age in
615 mixedwood boreal forests. *Ecoscience* 11, 228-237.

616 Leyval, C., Berthelin, J., 1991. Weathering of a mica by roots and rhizospheric
617 microorganisms of pine. *Soil Science Society of America Journal* 55, 1009-1016.

618 Likens, G.E., Driscoll, C.T., Buso, D.C., Siccama, T.G., Johnson, C.E., Lovett, G.M.,
619 Ryan, D.F., Fahey, T., Reiners, W.A., 1994. The biogeochemistry of potassium at
620 Hubbard Brook. *Biogeochemistry* 25, 61-125.

621 Maliondo, S.M., Mahendrappa, M.K., Van Raalte, G.D., 1990. Distribution of biomass
622 and nutrients in some New Brunswick forest stands: possible implications of
623 whole-tree harvesting. *For. Can. Marit. For. Res. Cent. Inf. Rep. M-X-170E-F*.

624 Mareschal, L., Turpault, M.-P., Bonnaud, P., Ranger, J., 2012. Relationship between the
625 weathering of clay minerals and the nitrification rate: a rapid tree species effect.
626 *Biogeochemistry* doi 10.1007/s10533-012-9725-0.

627 Markewitz, D., Richter, D.D., Allen, A.L., Urrego, J.B., 1998. Three decades of observed
628 soil acidification in the Calhoun Experimental Forest: Has acid rain made a
629 difference? *Soil Science Society of America Journal* 62, 1428-1439.

630 Munroe, J.S., Farrugia, G., Ryan, P.C., 2007. Parent material and chemical weathering in
631 alpine soils on Mt. Mansfield, Vermont, USA. *Catena* 70, 39-48.

632 Nezat, C.A., Blum, J.D., Yanai, R.D., Hamburg, S.P., 2007. A sequential extraction to
633 determine the distribution of apatite in granitoid soil mineral pools with application
634 to weathering at the Hubbard Brook Experimental Forest, NH, USA. *Applied*
635 *Geochemistry* 22, 2406-2421.

636 Nezat, C.A., Blum, J.D., Yanai, R.D., Byung, B.P., 2008. Mineral sources of calcium and
637 phosphorus in soils of the northeastern United States. *Soil Science Society of*
638 *America Journal* 72, 1786-1794.

639 Paré, D., Bergeron, Y., 1996. Effect of colonizing tree species on soil nutrient availability
640 in a clay soil of the boreal mixedwood. *Canadian Journal of Forest Research* 26,
641 1022-1031.

642 Paré, D., Rochon, P., Brais, S., 2002. Assessing the geochemical balance of managed
643 boreal forests. *Ecological Indicators* 1, 293-311.

644 Pinno, B.D., Thomas, B.R., Bélanger, N., 2010. Predicting the productivity of a young
645 hybrid poplar clone under intensive plantation management in northern Alberta,
646 Canada using soil and site characteristics. *New Forests* 39, 89-103.

647 Qin, R., Hirano, Y., Brunner, I., 2007. Exudation of organic acid anions from poplar roots
648 after exposure to Al, Cu and Zn. *Tree Physiology* 27, 313-320.

649 Quideau, S.A., Chadwick, O.A., Graham, R.C., Wood, H.B., 1996. Base cation
650 biogeochemistry and weathering under oak and pine: a controlled long-term
651 experiment. *Biogeochemistry* 35, 377-398.

652 Quideau, S.A., Bockheim, J.G., 1997. Biogeochemical cycling following planting to red
653 pine on a sandy prairie soil. *Journal of Environmental Quality* 26, 1167-1175.

654 Raulund-Rasmussen, K., Borggaard, O.K., Hansen, H.C.B., Olsson, M., 1998. Effect of
655 natural organic soil solutes on weathering rates of soil minerals. *European Journal*
656 *of Soil Science* 49, 397-406.

657 Reimenschneider, D.E., Stanton, B.J., Vallée, G., Périnet, P., 2001. Poplar breeding
658 strategies, in Dickmann, D.I., Isebrand, J.G., Eckenwalder, J.E., Richardson, J.
659 (Eds.), *Poplar culture in North America*. NRC Press, Ottawa, pp. 43-76.

660 Richter, D.D., Markewitz, D., 2001. Understanding soil change. *Soil sustainability over*
661 *millenia, centuries, and decades*. Cambridge University Press.

662 Ruark, G.A., Bockheim, J.G., 1988. Biomass, net primary production, and nutrient
663 distribution for an age sequence of *Populus tremuloides* ecosystems. Canadian
664 Journal of Forest Research 18, 435-443.

665 Soil Classification Working Group, 1998. The Canadian System of Soil Classification,
666 3rd ed. Agriculture and Agri-Food Canada, Publication 1646,

667 Stanturf, J.A., van Oosterm, C., Netzer, D.A., Coleman, M.D., Portwood, C.J., 2001.
668 Ecology and silviculture of poplar plantations, in Dickmann, D.I., Isebrand, J.G.,
669 Eckenwalder, J.E., Richardson, J. (Eds.), Poplar culture in North America. NRC
670 Press, Ottawa, pp. 153-206.

671 Steckler, M.K., Lafleur, B., Van Rees, K.J.C., Bélanger, N., Quantifying nutrient pools
672 and fluxes in fast-growing hybrid poplar plantations. Submitted.

673 Ste-Marie, C., Paré, D., Gagnon, D., 2007. The contrasting effects of aspen and jack pine
674 on soil nutritional properties depend on parent material. Ecosystems 10, 1299-1310.

675 Strobel, B.W., Bernhoft, I., Borggaard, O.K., 1999. Low-molecular-weight aliphatic
676 carboxylic acids in soil solutions under different vegetations determined by
677 capillary zone electrophoresis. Plant and Soil 212, 115–121.

678 Sverdrup, H., Warfvinge, P., 1992. Critical loads, in Sandén, P., Warfvinge, P. (Eds.),
679 Modelling groundwater response to acidification. Swedish Meteorological and
680 Hydrological Institute, Report 5, pp. 171-186.

681 Vangelova, E., Pitman, R., 2009. Impacts of short rotation forestry on soil sustainability,
682 in McKay, H. (Ed.) Short rotation forestry: Review of growth and environmental
683 impacts. Forest Research Monograph, 2, Forest Research. pp. 37-78.

- 684 Wallander, H., Nylund, J.-E., 1992. Effects of excess nitrogen and phosphorus starvation
685 on the extrametrical mycelium of *Pinus sylvestris* L. ectomycorrhizae. New
686 Phytologist 120, 495-503.
- 687 Wallander, H., Thelin, G., 2009. The stimulating effect of apatite on ectomycorrhizal
688 growth diminishes after PK fertilization. Soil Biology and Biochemistry 40, 2517-
689 2522.
- 690 Wilson, M.J., 2004. Weathering of the primary rock-forming minerals: processes,
691 products and rates. Clay Minerals 39, 233-266.
- 692 Zasada, J.C., David, A.J., Gilmore, D.W., Landhäusser, S.M., 2001. Ecology and
693 silviculture of natural stands of *Populus* species, in Dickmann, D.I., Isebrand, J.G.,
694 Eckenwalder, J.E., Richardson, J. (Eds.), Poplar culture in North America. NRC
695 Press, Ottawa, pp. 119-151.
- 696 Zhang, S.Y., Yu, Q.B., Chauret, G., Koubaa, A., 2003. Selection for both growth and
697 wood properties in hybrid poplar clones. Forest Science 49, 901-908.

Table 1
Summary of study site features

Site	Age (yr)	Plantation type	Soil type	Particle size distribution (%)			Drainage	Mean annual increment (m ³ ha ⁻¹ yr ⁻¹)
				Sand	Silt	Clay		
AG2	1	Commercial	Glayed Regosol	20	62	18	Variable	0.2
FP7	2	Commercial	Orthic Gleysol	16	57	27	Poor	0.2
SCH4	4	Commercial	Podzol	29	46	25	Good	4.1
HPC	5	Commercial	Podzol	32	41	27	Good	4.3
SJG2	5	Commercial	Brown Podzolic and Podzol	34	44	22	Good to moderate	1.8
SCH2	6	Commercial	Podzol	36	53	11	Good	4.4
FP2 ¹	6	Commercial	Orthic Gleysol	57	33	4	Poor	5.9
SCH1	7	Commercial	Podzol	26	43	31	Good	15.0
NORM ¹	10	Experimental	Podzol	48	37	6	Good	6.5
SHW	13	Experimental	Brown Podzolic	11	37	52	Good	6.3
PLA8	14	Experimental	Red-yellow Podzolic	34	56	10	Good to imperfect	8.3
STN	17	Experimental	Grey-brown Podzolic	27	52	21	Good to excessive	21.5
STH	22	Experimental	Grey-brown Podzolic	52	43	5	Good to excessive	11.5

¹ Particle size distribution does not sum up to 100% because of pebbles in the soil matrix

Table 2
Soil bulk elemental composition and normative (UPPSALA) mineralogy

Site	Total chemistry								
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	MnO
	g kg ⁻¹						mg kg ⁻¹		
AG2	733	125	50,5	14,8	10,5	19,4	16,0	1485	1750
FP7	798	95,3	36,1	11,9	5,15	15,8	12,9	1070	300
SCH4	769	94,3	46,1	14,4	11,6	17,6	16,9	2725	955
HPC	769	94	46,1	14,4	11,6	17,6	16,9	2725	955
SJG2	690	156	49,2	17,3	7,3	10,7	30,2	1480	325
SCH2	740	102	61,3	16,8	11,6	17,6	17,8	2620	1695
FP2	720	127,1	40,2	9,40	24,4	26,4	25,3	1445	680
SCH1	750	93,6	50,1	29,0	11,5	17,2	17,4	1460	1060
NORM	634	156	63,1	24,4	31,1	31,5	25,4	2145	1125
SHW	596	170	64,3	28,4	44,2	33,0	30,4	2670	1030
PLA8	690	156	49,2	17,3	7,25	10,7	30,2	1480	325
STN	720	127	40,2	9,4	24,4	26,4	25,3	1445	680
STH	728	124	42,1	9,4	21,7	24,4	23,8	1710	800

	Mineralogy (%)								
	Quartz	K-Feldspar	Plagioclase	Muscovite	Hornblende	Chlorite	Apatite	Epidote	Calcite
AG2	58,1	9,27	22,1	3,28	2,06	4,28	0,37	0,53	0,00
FP7	68,3	7,24	17,4	2,56	0,00	3,97	0,26	0,20	0,00
SCH4	60,9	9,60	19,0	3,40	2,10	3,83	0,66	0,46	0,00
HPC	19,5	11,6	37,7	4,10	23,2	0,00	0,45	3,13	0,30
SJG2	24,7	17,5	31,5	6,20	15,4	1,76	0,79	2,15	0,00
SCH2	58,3	10,5	19,3	3,70	2,25	4,85	0,66	0,47	0,00
FP2	69,4	8,50	16,9	3,01	0,00	1,67	0,29	0,19	0,00
SCH1	55,4	9,77	18,1	3,46	3,24	9,18	0,35	0,55	0,00
NORM	27,2	14,1	34,6	5,00	13,5	2,90	0,52	2,07	0,00
SHW	16,0	16,9	35,0	5,97	21,9	0,73	0,63	2,92	0,00
PLA8	56,2	20,1	9,45	7,13	2,36	4,11	0,39	0,17	0,00
STN	41,4	13,9	27,6	4,93	10,2	0,00	0,34	1,54	0,00
STH	45,7	13,3	25,8	4,72	8,70	0,00	0,41	1,32	0,00

Table 3Means (± 1 S.E.) of molar ratios and results of ANCOVAs using time as a covariate

Variable	Extraction treatment					
	BaCl ₂		HCl		HNO ₃	
	Abandoned	Plantation	Abandoned	Plantation	Abandoned	Plantation
Ca/ Σ Al+Fe	210.1 (86.7)	178.9 (39.9)	0.452 (0.128)	0.355 (0.069)	0.025 (0.006)	0.020 (0.004)
	<i>p</i> = 0.43		<i>p</i> = 0.09		<i>p</i> = 0.13	
Mg/ Σ Al+Fe	19.4 (6.7)	23.7 (9.9)	0.069 (0.016)	0.056 (0.010)	0.051 (0.013)	0.041 (0.009)
	<i>p</i> = 0.89		<i>p</i> = 0.17		<i>p</i> = 0.23	
K/ Σ Al+Fe	3.0 (1.2)	2.7 (0.7)	0.012 (0.002)	0.015 (0.002)	0.009 (0.002)	0.007 (0.001)
	<i>p</i> = 0.54		<i>p</i> = 0.23		<i>p</i> = 0.07	

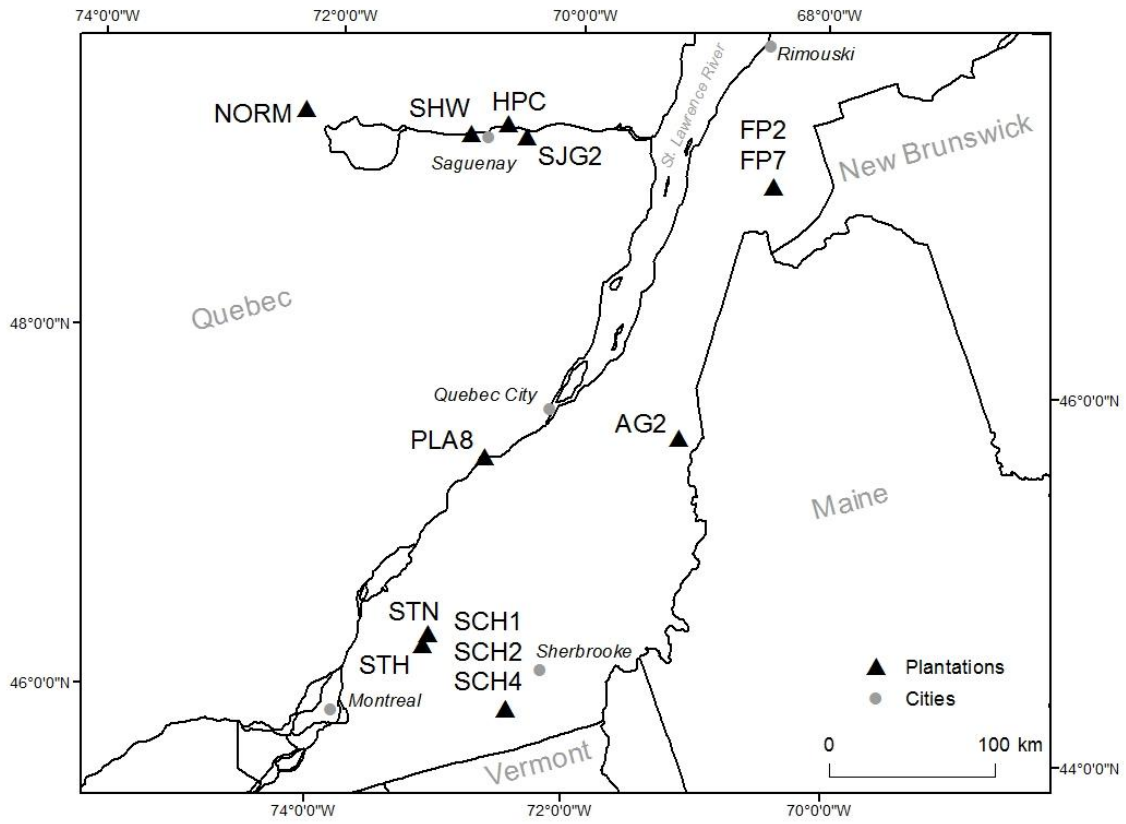


Fig. 1. Location of study sites

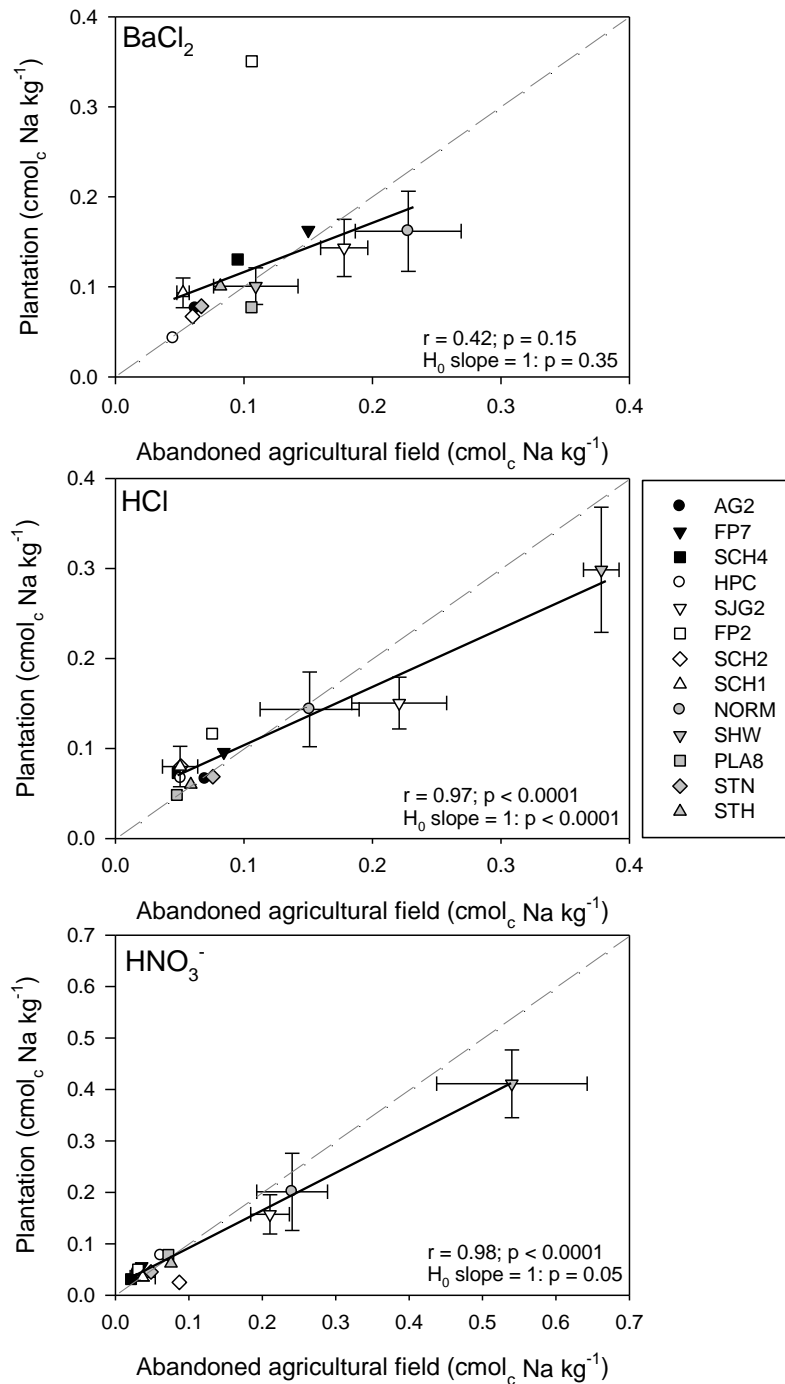


Fig. 2. Relationship for leached (i.e. BaCl₂, HCl and HNO₃) soil Na concentrations between abandoned agricultural fields and plantations. The grey dashed line is the 1:1 line. Standard deviation along the x and y axes are given only for the four sites showing an effect of afforestation, i.e. SJG2, SHW, NORM and SCH1. Black symbols denote plantations that are <5 years-old; open symbols denote plantations that are ≥5 and <10 years-old; grey symbols denote plantations that are ≥10 years-old

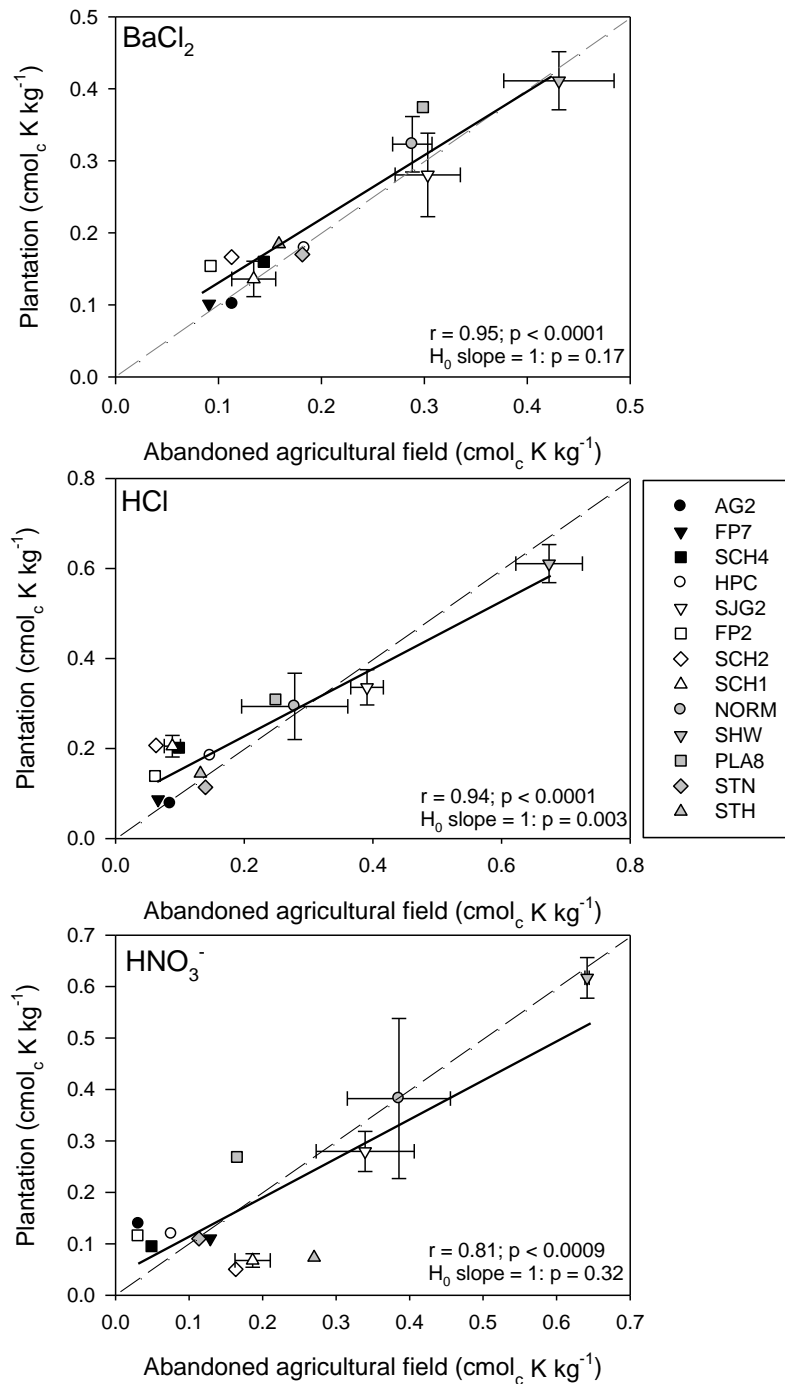


Fig. 3. Relationship between abandoned agricultural field soil K concentration and plantation soil K concentration. The grey dashed line is the 1:1 line. Standard deviation along the x and y axes are given only for the four sites which are discussed in further details, i.e. SJK2, SHW, NORM and SCH1. Black symbols denote plantations that are <5 years-old; open symbols denote plantations that are ≥5 and <10 years-old; grey symbols denote plantations that are ≥10 years-old

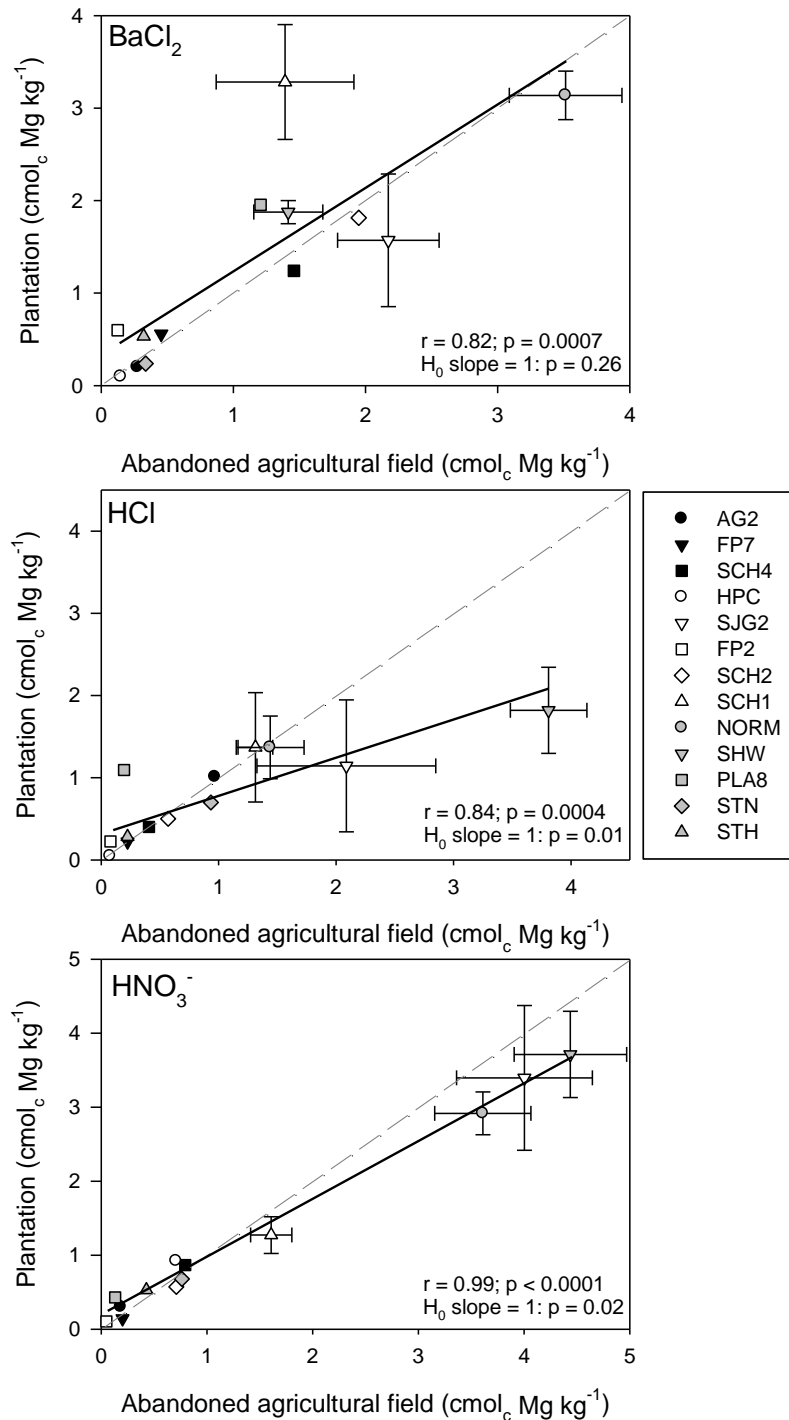


Fig. 4. Relationship between abandoned agricultural field soil Mg concentration and plantation soil Mg concentration. The grey dashed line is the 1:1 line. Standard deviation along the x and y axes are given only for the four sites which are discussed in further details, i.e. SJG2, SHW, NORM and SCH1. Black symbols denote plantations that are <5 years-old; open symbols denote plantations that are ≥ 5 and <10 years-old; grey symbols denote plantations that are ≥ 10 years-old

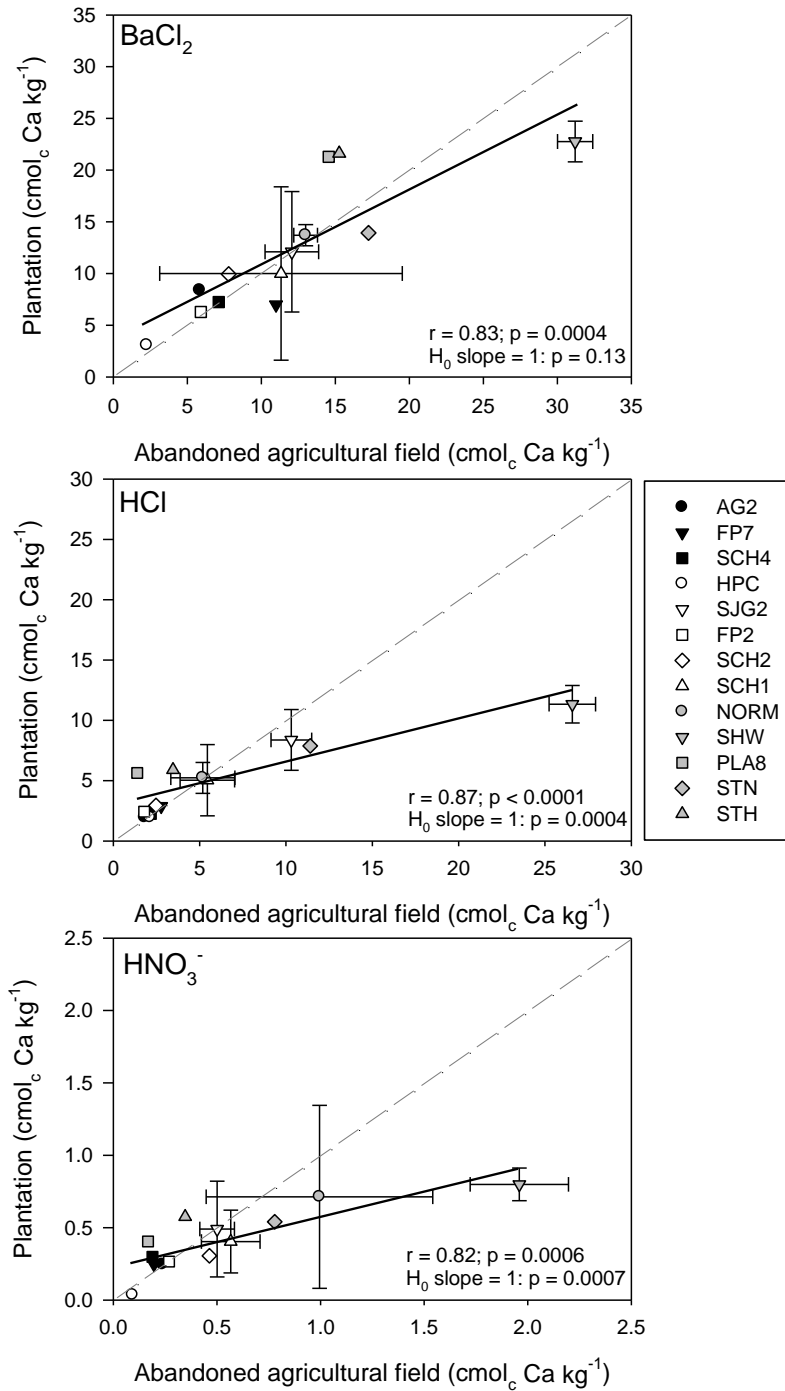


Fig. 5. Relationship between abandoned agricultural field soil Ca concentration and plantation soil Ca concentration. The grey dashed line is the 1:1 line. Standard deviation along the x and y axes are given only for the four sites which are discussed in further details, i.e. SJG2, SHW, NORM and SCH1. Black symbols denote plantations that are <5 years-old; open symbols denote plantations that are ≥ 5 and <10 years-old; grey symbols denote plantations that are ≥ 10 years-old