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Avoid, tolerate, or escape? Native vegetation responses to invasion vary between functional groups

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18 **Abstract**

19 Biological invasions are one of the greatest threats to biodiversity and ecosystem
20 functioning. However, the constraints imposed by the invaders on native organisms and their
21 associated response, remain poorly understood. Native species can survive invasion through
22 multiple resistance strategies (avoidance, tolerance, or escape), but the relative importance of each
23 strategy and how they vary among functional groups have been little explored.

24 In this study, we examined the resistance strategies of native forbs and graminoids facing
25 invasion by *Solidago canadensis*. First, we characterized the general impacts of invader density on
26 native plant biomass production and diversity. Then, we investigated specific constraints linked to
27 the invasion (competition for light, nutrients and mycorrhizal fungi), and the associated resistance
28 strategies of native species.

29 *S. canadensis* had different negative impacts on native vegetation biomass production and
30 diversity – depending on functional groups – due to increased competition for light, nutrients, and
31 mycorrhizal interactions. The increased competition for light was partially (i) avoided (tall forbs
32 and graminoids) or (ii) tolerated (small, shade-resistant graminoids). The effects of (iii) allelopathic
33 compounds and (iv) increased competition for nutrients were avoided by some forbs (high
34 mycorrhizal infection rates). Finally, some forbs and graminoids (v) escaped all constraints by
35 completing their cycle early in the season.

36 Our results highlight the diversity of non-exclusive strategies (avoidance, tolerance, escape)
37 by which different functional groups can respond to invasion-induced constraints. They suggest that
38 to improve understanding of the mechanisms underlying invasion, the native community responses
39 should be decomposed into strategies specific to functional groups.

40

41 **Key words:** plant invasions, resistance strategies, competition, allelopathy, mycorrhiza,
42 functional traits, diversity indices, community weighted mean.

43

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47 their insightful comments that helped us to significantly improve the manuscript.

48

Introduction

49

50 Invasive plants are known to alter native plant communities and their functions in an
51 ecosystem through a variety of mechanisms (Vilà et al. 2011; Pyšek et al. 2012; Castro-Díez et al.
52 2016). They are often strong competitors for resources (Gioria and Osborne 2014), can affect
53 biogeochemical cycles (Zhang et al. 2019), arthropod and mycorrhizal communities (Litt et al.
54 2014; Yuan et al. 2014; Davis et al. 2018), and the interactions of these groups with the native
55 vegetation (Albrecht et al. 2014). Through these mechanisms, they may jeopardize the functioning
56 of the entire ecosystem (Gordon 1998; Vilà et al. 2011).

57 The constraints exerted by an invader alter resource availability (e.g., light, water, soil
58 nutrients, pollinators, mycorrhizal fungi) and filter native plants depending on their ability to resist
59 these constraints (Stotz et al. 2019). Such filtering modifies the composition, structure and
60 functioning of the community. These changes can be described by summary indices of taxonomic
61 and functional diversity, and biomass production. Community-level metrics provide broad measures
62 of changes. However, they do not help to identify the mechanisms underlying the changes, nor to
63 understand why some native species are more resilient to invader constraints than others (Gallien
64 and Carboni 2017).

65 Native plant species can employ three possible strategies to resist invasion: avoidance,
66 tolerance, and escape (Figure 1) (Levitt 2015; Yıldırım and Kaya 2017). Little is known about the
67 relative importance of the three strategies to allow persistence in the face of invasion, although
68 these strategies are well known regarding other stresses such as drought (Bodner et al. 2015; Volaire
69 2018). The *avoidance strategy* refers to native species with sufficiently good abilities to acquire the
70 resources they need regardless of the invader presence (e.g., being tall if the constraint is on light
71 interception, Craine and Dybzinski 2013). The *tolerance strategy* refers to species requiring limited
72 amounts of resources to complete their life cycle (e.g., shade tolerant species, Valladares and

73 Niinemets 2008). Finally, the *escape strategy* refers to species completing their critical
74 developmental stages before the invader starts its annual development (temporal niche
75 differentiation, Huang et al. 2019). Escape may alter the temporal pattern of floral resources for
76 pollinators (Moroń et al. 2018), while avoidance or tolerance can alter biogeochemical cycles and
77 the likelihood of establishment of other invasive species (Cavieres 2021). In addition, within the
78 same community, different strategies may be deployed by different species in response to the same
79 constraint. To better understand the long-term consequences of invasion on biodiversity and
80 ecosystem functioning, we need to identify and quantify the relative importance of different native
81 species strategies.

82 Changes in the functional traits of native vegetation can reveal the constraints they experience
83 during invasion and the strategies by which some of the native plants resist these constraints. For
84 each invasion constraint, only the native species that are able to cope with the constraint – by
85 avoiding, tolerating or escaping it – will remain in the community (filtering effects). This will leave
86 a signature in the functional trait space of native species specific to both the constraint and the
87 selected resistance strategi(es). For instance, tall species may avoid competition for light, so an
88 increase in native plant height after invasion may reveal a selection for species with a light
89 competition avoidance strategy. By filtering out native plant species unable to resist invasion-
90 induced constraints, invasive plants can alter the community weighted mean (CWM) of functional
91 traits, as well as decrease or increase their variance (CWV) (via filtering toward one strategy or
92 selecting for different strategies (Sodhi et al. 2019)). Traits' CWM and their comparison to the
93 invader's traits are commonly used and can detect trait displacement in the invaded community, but
94 they still fail to detect the existence of different strategies within the community. Therefore, traits'
95 CWM and CWV should be used together to detect the diversity of strategies that permit some of the
96 native plants to resist the new constraints brought by the invader.

97 The lack of studies considering the variations of species responses across functional groups
98 also prevents a better understanding of the impact of invasive plants on native vegetation. The
99 vegetation is often considered as a homogeneous assemblage of species, whereas different
100 functional groups (e.g., forbs, graminoids and N-fixers; (Blondel 2003; Münkemüller et al. 2014))
101 have different development and foraging strategies. For instance, graminoids are more wind
102 pollinated and resistant to herbivory than forbs, and forbs and graminoids have different acquisition
103 systems for some minerals (Marschner 1995). They thus experience different constraints and can
104 respond differently to a biological invasion (Fenesi, Vágási, et al. 2015). Studying the different
105 responses of native functional groups to invasion, in particular regarding resistance strategies,
106 should provide a better understanding of their responses and of the consequences on the ecosystem.

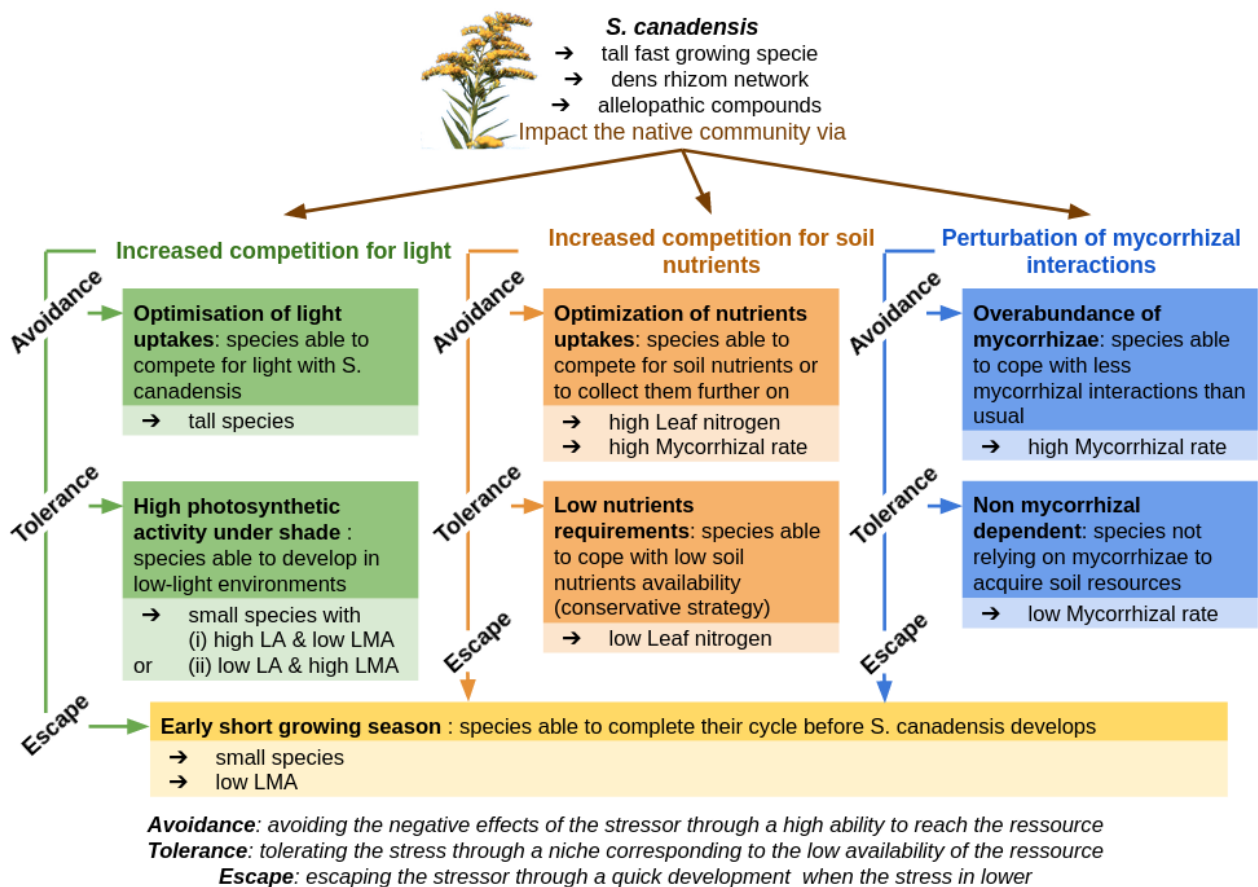
107 In this study, we characterized the impacts of *Solidago canadensis* (L., 1753) on native plant
108 communities and the mechanisms underlying these impacts in recently colonized (less than 50 years
109 old) French wet meadows encompassing a broad invasion gradient. *S. canadensis* one of the most
110 invasive plants in European and Asian wet meadows (Weber 1998; Morales and Traveset 2009). In
111 experimental conditions, it is able to alter the native plant community through (i) competition
112 (Fenesi, Geréd, et al. 2015), (ii) changes in soil nutrients (Zhang et al. 2009; Scharfy et al. 2010),
113 and (iii) production of allelopathic compounds that affect native species interactions with arbuscular
114 mycorrhizal fungi (AMF) (Yuan et al. 2013; Zubek et al. 2016). However, because these
115 experiments were conducted only on a few native species or in experimental conditions, it remains
116 unknown whether and how these mechanisms occur at the community scale *in natura*, and how they
117 affect the composition and functions of species-rich native communities.

118 In order to better understand of the mechanisms involved in *S. canadensis* invasions, we
119 investigated how the invasion gradient (which is directly related to the time since *S. canadensis*
120 became established in the plot) affected the entire native plant community and two main
121 constitutive functional groups (forbs and graminoids). We identified and compiled, for most of the

122 species present in our study area, six functional traits linked to three mechanisms suspected to be at
 123 work during *S. canadensis* invasion: competition for light, competition for nutrients and disturbance
 124 of mycorrhizal interactions. We expected the distribution of trait values in the native community to
 125 vary depending on the constraints exerted by the invader and the resistance strategies of native
 126 plants [Figure 1].

127 To test these hypotheses, we used a two steps framework: First, we analyzed the overall
 128 impact of *S. canadensis* on the taxonomic and functional diversity of the native communities. Next,
 129 we investigated the mechanisms that might lead to these impacts by jointly analyzing the response
 130 of the five traits (in terms of CWM and CWV) to *S. canadensis* density with structural equation
 131 models (SEM) [Figure 2].

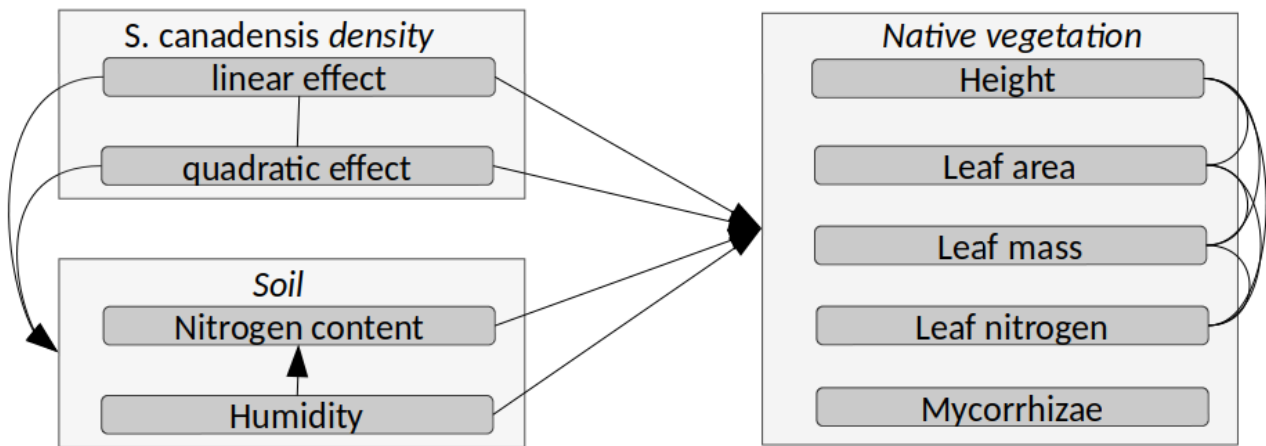
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133

134 *Figure 1: Three ecological strategies allowing native species to persist under S. canadensis*
 135 *invasion. We consider three major constraints entailed by the presence of S. canadensis:*
 136 *competition for light, competition for nutrients, and perturbation of mycorrhizal interactions, and*
 137 *three possible resistance strategies: avoidance, tolerance, and escape strategies (definition in the*
 138 *bottom panel). For each constraint and each resistance strategy, we present our working*
 139 *hypotheses regarding the expected functional characteristics of native species. LA: leaf area. LMA:*
 140 *leaf mass per area.*

141



142

143 *Figure 2: A priori structure of the structural equation models. Arrows represent directed links*
 144 *(causal relationships), and lines connecting traits represent undirected links (residual correlations)*
 145 *included in the model to account for allometric constraints and the relationship between the linear*
 146 *and quadratic component of S. canadensis density. When an arrow points from a variable to a*
 147 *compartment, the variable is an explanatory variable for all variables in the compartment.*

148

Materials Methods

1. Study system

149
150
151 *Solidago canadensis* (L., 1753) is a rhizomatous Asteraceae from North America, introduced
152 to Europe as an ornamental species during the 18th century and now naturalized in many countries
153 (Pyšek et al. 2009). Since then, it has become one of the most invasive plants in European and
154 Asian wetlands, where it forms dense, monospecific stands (Weber 1998; de Groot et al. 2007;
155 Moroń et al. 2018). *S. canadensis* affects native plant communities, not only through direct
156 competition for light, space, and soil resources (Werner et al. 1980; Gordon 1998), but also
157 indirectly through modification of biogeochemical cycles and soil characteristics such as water and
158 nutrient availability (Vilà et al. 2011). In addition, *S. canadensis* produces allelopathic compounds
159 impacting associations with mycorrhizal fungi (Zhang et al. 2007).

160 We selected six wet meadows with similar vegetation types (belonging to EUNIS categories
161 E3.41; E3.51 and D4.13, depending on the meadow) and management (late mowing with organic
162 matter removal), in two protected areas of the French Alps. All meadows are geographically and
163 environmentally close to each other so they can be considered as pseudo-replicates, and they show a
164 broad gradient of *S. canadensis* density (0 to 170 stems of *S. canadensis* per m², representing 0 to
165 99 % vegetation cover). In each meadow, we selected four 100 m² plots representative of the *S.*
166 *canadensis* density gradient, except for two meadows where we could only place two plots due to
167 spatial constraints (see map and plots individual density in Supporting information).

168 The advantage of this study system is that the density gradient of *S. canadensis* likely
169 represents the time since its establishment – not the invasibility of the different areas. This is
170 because the meadows were homogeneous in native species prior to invasion and the distribution of
171 *S. canadensis* independent of local edaphic conditions (no significant effect of humidity, nitrogen
172 content, pH, organic matter or granulometry in a mixed-effect model, results not shown). If *S.*

173 *canadensis* has established in meadows regardless of the resistance of native vegetation and soil
174 conditions, then its density can be assumed to reflect the time since establishment, or invasion stage.
175 The corollary to this assumption is that the variations in native vegetation along *S. canadensis*
176 gradients are indeed the result from invasion-induced constraints (e.g., increased competition for
177 light).

178 All fieldwork was conducted during two consecutive weeks of Jun 2019. During this year, the
179 mean annual temperature of the sites was 11.7 °C (mean of the coldest month: 1.4 °C; mean of the
180 warmest month: 22.3 °C), and the mean annual precipitation was 1157.9 mm (Climatologie de
181 l'année 2019 à Annecy-Meythet - Infoclimat).

182 **2. Sampling design**

183 **2.1. Soil characteristics**

184 In each plot, we extracted and pooled 15 soil cores (using a 15 cm deep, 5 cm wide auger).
185 We then measured five soil characteristics: pH, humidity at the date of sampling (hereafter
186 humidity), organic matter, total C, and total N (see details in Supporting information). pH did not
187 vary significantly between plots (7.19 to 7.69), and organic matter content as well as total C were
188 strongly correlated with humidity (Pearson's r of 0.87 and 0.89). Therefore, we considered only soil
189 humidity and N content in subsequent analyses. All soil samples were extracted within two days to
190 be representative of the differences between plots during the vegetative period, even if they do not
191 inform on winter water regime.

192 **2.2. Vegetation surveys**

193 We characterized the plant communities using a point-intercept sampling method (Jonasson
194 1988) in four 1 m² quadrats per plot, hence for a total of 80 quadrats. All quadrats were visited
195 within two weeks, starting with the meadows where the vegetation development seemed most
196 advanced. In each quadrat, we placed 16 vertical pins on a grid and recorded the number of contacts

197 of each species (multiple contacts per species per pin being recorded). Because the meadows are
198 mown annually at the end of the summer, the total number of contacts (excluding *S. canadensis*
199 contacts) represents both the yearly biomass production, and the abundance of the native plant
200 community during the year (Bråthen and Hagberg 2004). For *S. canadensis*, the number of contacts
201 is directly linked to the number of stems, and we used this metric to quantify its density.

202 We classified each species as either graminoid (Poaceae, Juncaceae and Cyperaceae) or forb,
203 because these functional groups have different developmental and foraging strategies and may thus
204 respond differently to invasion (Münkemüller et al. 2014). For example, we expected forbs to be
205 more affected than graminoids by allelopathic perturbation of AMF interactions, as they are
206 generally more dependent on AMF for nutrient acquisition (Wilson and Hartnett 1998). Some N-
207 fixing species were also present, but too scarce to be taken into account in the analyses as a group in
208 itself.

209 **3. Data analysis**

210 **3.1. Compiling native plant traits**

211 For each plant taxon, we reported vegetative height (Height (cm)), Leaf area (LA (cm²)), leaf
212 mass per area (LMA (g/cm)), leaf nitrogen per leaf area (LNA (mmol/m²)), end of the flowering
213 season (flowering date (day)) and rate of root colonization by arbuscular mycorrhizal fungi (AMF
214 rate (%)). All traits were available for at least 75 % of the biomass production of each functional
215 group in each quadrat (Pakeman and Quested 2007), and were less than 30 % correlated with each
216 other (except graminoid Height and LA, see Supporting information). The five traits were extracted
217 from freely available databases such as TRY (Kattge et al. 2020), LEDA (Knevel et al. 2003),
218 BiolFlor (Kühn et al. 2004), and Ecoflora (Fitter and Peat 1994). Since plant functional traits can be
219 plastic, using mean trait values from databases prevents us from identifying resistance strategies
220 operating via trait variation within species (e.g., individuals growing taller when *S. canadensis*

221 present). Nevertheless, given the high interspecific trait variability in our study system (Figure S2),
222 we could still detect filtering processes operating at the species level (e.g., decreasing abundance of
223 short species with *S. canadensis* density). We propose that native species can resist the constraints
224 induced by *S. canadensis* invasion via three main resistance strategies: avoid, tolerate, escape, and
225 that each strategy should leave a distinct functional trait signal (Figure 1). For example, increased
226 competition for light and soil nutrients due to *S. canadensis* could select species with an avoidance
227 strategy, i.e., species highly competitive for these resources (tall species and species with high
228 LNA), and/or species with a tolerance strategy, i.e., species with low requirements for these
229 resources (low shade-tolerant species, species with low LNA adapted to poor soils). Allelopathic
230 compounds released by *S. canadensis* could select for species having strong interactions with AMF
231 (high infection rate), as these species are able to compete with *S. canadensis* for AMF interactions,
232 and could suffer minimal damage if some are lost (avoidance strategy). Alternatively, the
233 allelopathic compounds could select species that do not rely on interactions with AMF (tolerance
234 strategy). Finally, *S. canadensis* invasion could select for species able to escape these constraints by
235 completing their cycle before it starts developing (small species flowering early).

236 **3.2. Taxonomic and functional diversity**

237 For each quadrat, we calculated two taxonomic and three functional diversity indices based on
238 the traits presented above: (i) taxonomic richness (Richness), (ii) taxonomic equitability of
239 abundances (exponential of the Shannon index, hereafter called Evenness, Hill 1973; Jost et al.
240 2010), (iii) functional richness (FRich), (iv) functional evenness (FEve), (vi) functional divergence
241 (FDiv) (Mason et al. 2005). FRich, FEve, and FDiv indicate, respectively, the size of the
242 community's functional space, the equitability of biomass repartition, and the eccentricity of
243 biomass repartition in that space (at the center or periphery of the space). We calculated these
244 indices for the entire plant community, and separately for forbs and graminoids. Because invasion
245 by *S. canadensis* induces new constraints - due to its high competitiveness and allelopathic

246 compounds production - we expected it to lead to a decrease in biomass production, taxonomic
247 diversity, functional richness, and functional evenness, but also to an increase in functional
248 divergence (selection of species resisting to different constraints and/or with different resistance
249 strategies).

250 We also calculated the community weighted mean (CWM) and community weighted variance
251 (CWV) of the five functional traits selected for forbs and graminoids separately, as we expected the
252 two functional groups to respond differently to *S. canadensis* density. We hypothesized that these
253 CWM and CWV would vary according to the resistance strategy of the focal functional group
254 (Figure 1).

255 **3.3. Statistical analyses**

256 All variables were standardized prior to analyses to avoid size effects and to make it
257 possible to compare the estimated parameters within and between analyses.

258 First, we assessed the impact of *S. canadensis* density on native plant communities in terms
259 of biomass production and diversity (Richness, Evenness, FRich, FEve, FDiv). We designed mixed-
260 effect linear models to analyze the response of each of these variables to *S. canadensis* density (with
261 both linear and quadratic effects), soil humidity and nitrogen content. We included the meadow
262 identity (hereafter called meadow ID) as a random effect to account for differences among sites. We
263 built the models considering the entire native communities, as well as for native forb and graminoid
264 assemblages separately. We assessed model performance using marginal and conditional R^2
265 goodness-of-fit.

266 Second, we used structural equation models (SEMs) to disentangle the direct and indirect
267 mechanisms (through plant-soil interactions) through which *S. canadensis* impacts native forbs and
268 graminoids. We built four SEMs, corresponding to two summary statistics of trait distribution
269 (CWM and CWV) applied to the two native species functional groups (forbs and graminoids). In

270 each SEM, *S. canadensis* density (linear and quadratic effects) could directly affect soil
271 characteristics and plant traits distribution. Soil characteristics could directly affect each trait, and
272 soil humidity could directly affect soil nitrogen content. To account for allometric constraints in
273 plants (Weiner 2004; Lefcheck 2016), correlations between plant traits were integrated into the
274 SEMs (except for Mycorrhiza). We used the hypothesized linkages between plant-soil
275 compartments to design the structure of our initial SEMs [Figure 2], which we simplified and
276 improved following a three-step procedure. We (i) ran our initial model, and improved it by (ii)
277 iteratively adding links when independence claims were not supported by the test of directed
278 separation (p -value < 0.05), and (iii) iteratively removing links that were not significant (p -value $>$
279 0.05) (Grace et al. 2015). To confirm that *S. canadensis* impacted soil characteristics and not the
280 reverse, we constructed another set of models where we reversed the direction of the links between
281 *S. canadensis* and the soil compartment. The BIC, AIC, and Fisher's C-value confirmed our
282 hypothesis for all models.

283 All statistical analyses were conducted in R v.3.6.3 (R Core Team 2020) with the packages
284 TR8 (Bocci 2020), lme4 (Bates et al. 2021), lmerTest (Kuznetsova et al. 2020), MuMIn (Bartoń
285 2020) and piecewiseSEM (Lefcheck 2016).

286 **Results**

287 We recorded a total of 102 plant species and 24 taxa identified to a higher taxonomic level
288 (Supporting information), with an average of 14 species and 129 contacts per quadrat. 41 % of
289 contacts represented forbs species and 59 % represented graminoid species.

290 **1. Impacts of *S. canadensis* native plant biomass production and diversity**

291 The density of *Solidago canadensis* had distinct effects on graminoids and forbs. Increase in
292 invader density was correlated to a decrease in graminoid Richness (linear effect) and Biomass
293 production (quadratic, unimodal effect), whereas for forbs it was associated to a decrease in the

294 taxonomic and functional evenness, and to an increase in the functional divergence (linear effects).
295 Indices calculated on the whole community varied in the same direction, but were significant only
296 for Biomass production, Evenness, and FDiv. We observed a negative effect of soil humidity and a
297 positive effect of soil nitrogen on: Richness (community and functional group levels), Evenness
298 (community and functional group levels), FRich (community and graminoids), and Biomass
299 production (forbs). In addition, the random effect on meadow ID explained a large part of the
300 observed variations (up to 68 %). The coefficients and their p-values as well as the marginal and
301 conditional R^2 of all mixed-effect models are presented in Table 1, and the response curves of
302 models with a significant effect of *S. canadensis* are presented in Supplementary information.

303 *Table 1: Parameter estimates of the mixed effect models of the impact of S. canadensis (linear*
304 *and quadratic effects) and soil resources on the diversity indices for the whole community, as well*
305 *as for forbs and of graminoids taken apart. Values in bold indicate significant effects (* p-value <*
306 *0.05; ** p-value < 0.01; *** p-value < 0.001). Model performance is reported with both marginal*
307 *R^2 (proportion of variance explained by fixed factors) and conditional R^2 (proportion of variance*
308 *explained by fixed and random factors).*

	Response variable	Explanatory variables					marginal R ²	conditional R ²
		Intercept	invader density	invader density ²	soil humidity	soil nitrogen		
Whole community	Productivity	0.20		-0.11**			0.03	0.71
	Richness	0.01			-1.27***	0.79***	0.45	0.70
	Evenness	0.16		-0.15***	-1.60***	1.05***	0.46	0.71
	FRich	-0.03			-0.73*	0.48*	0.14	0.33
	FEve	-0.01					0.00	0.03
	FDiv	-0.06	0.44***			0.41**	0.25	0.48
Forbs	Productivity	0.05			-0.69*	0.67**	0.12	0.36
	Richness	-0.02			-0.99**	0.60**	0.33	0.53
	Evenness	-0.02	-0.37***		-0.93**	0.47*	0.33	0.49
	FRich	-0.06					0.00	0.23
	FEve	0.00	-0.22*			-0.32**	0.13	0.13
	FDiv	0.00	0.39***				0.15	0.15
Graminoids	Productivity	0.21		-0.11**			0.04	0.65
	Richness	0.04	-0.21*		-1.51***	0.84***	0.42	0.69
	Evenness	0.04			-1.41***	0.96***	0.34	0.61
	FRich	-0.02			-0.61*	0.54*	0.09	0.21
	FEve	0.00					0.00	0.01
	FDiv	0.00					0.00	0.01

309 **2. *S. canadensis* impacts on native trait distribution**

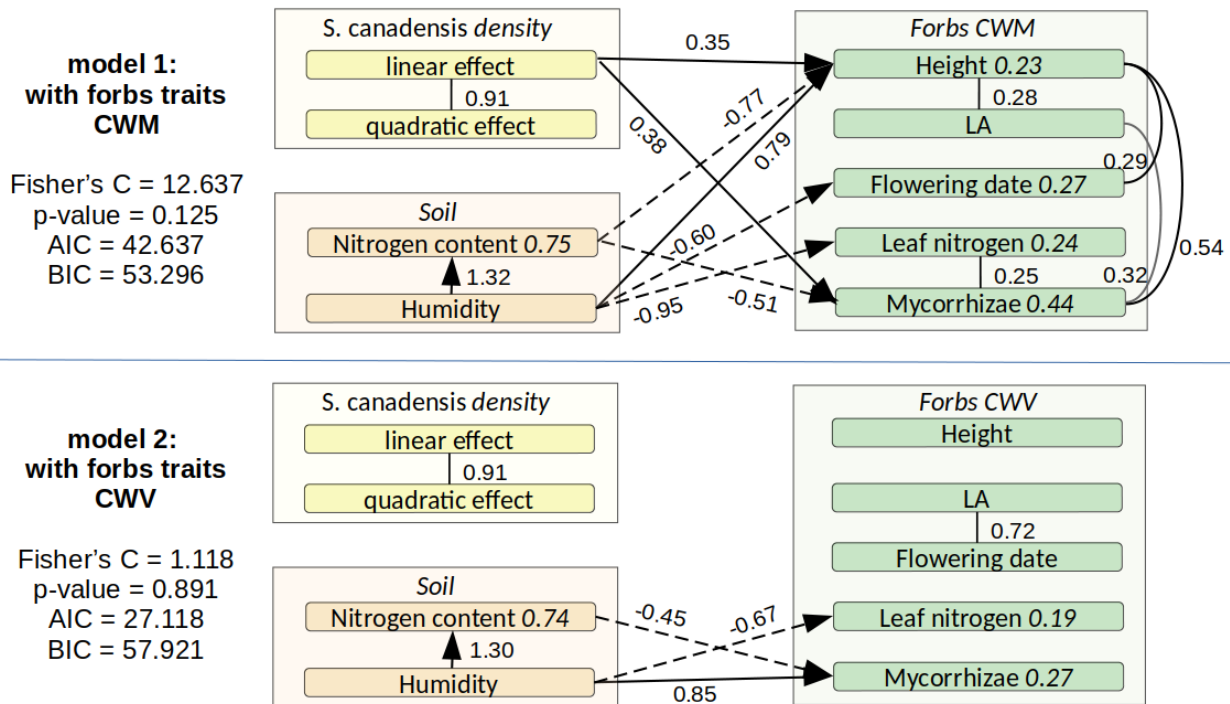
310 The four structural equation models (SEMs) had statistically robust structure (Fisher's C p-
311 value > 0.45). They revealed no significant relationship between *S. canadensis* density and soil
312 variables (humidity and N content), and humidity had a positive effect on soil nitrogen content.

313 The effects of soil characteristics and *S. canadensis* density on native plant characteristics (in
314 terms of trait mean or variance) varied between forbs and graminoids (Figures 3, 4). It can be noted
315 that all significant *S. canadensis* density effects were linear (no hump-shaped relationship detected).

316 Within the native forbs, *S. canadensis* directly selected for tall species, species with high LNA
317 and species with high AMF infection rates. It also selected indirectly for species with high LA, high
318 LMA and early end of flowering (via allometric constraints with plant heights, LNA and AMF
319 infection rates) (Figure 3.a). We found no impact of *S. canadensis* on the variance of forb traits

320 (Figure 3.b). Regarding the effects of soil characteristics, we found that N-richer soils favored
 321 smaller species, species with low AMF infection rates and species with an early end of flowering.
 322 Soil humidity favored tall species, species with low LMA and species with intermediate LNA, while
 323 counter-selecting species with intermediate AMF infection rate [Figure 3].

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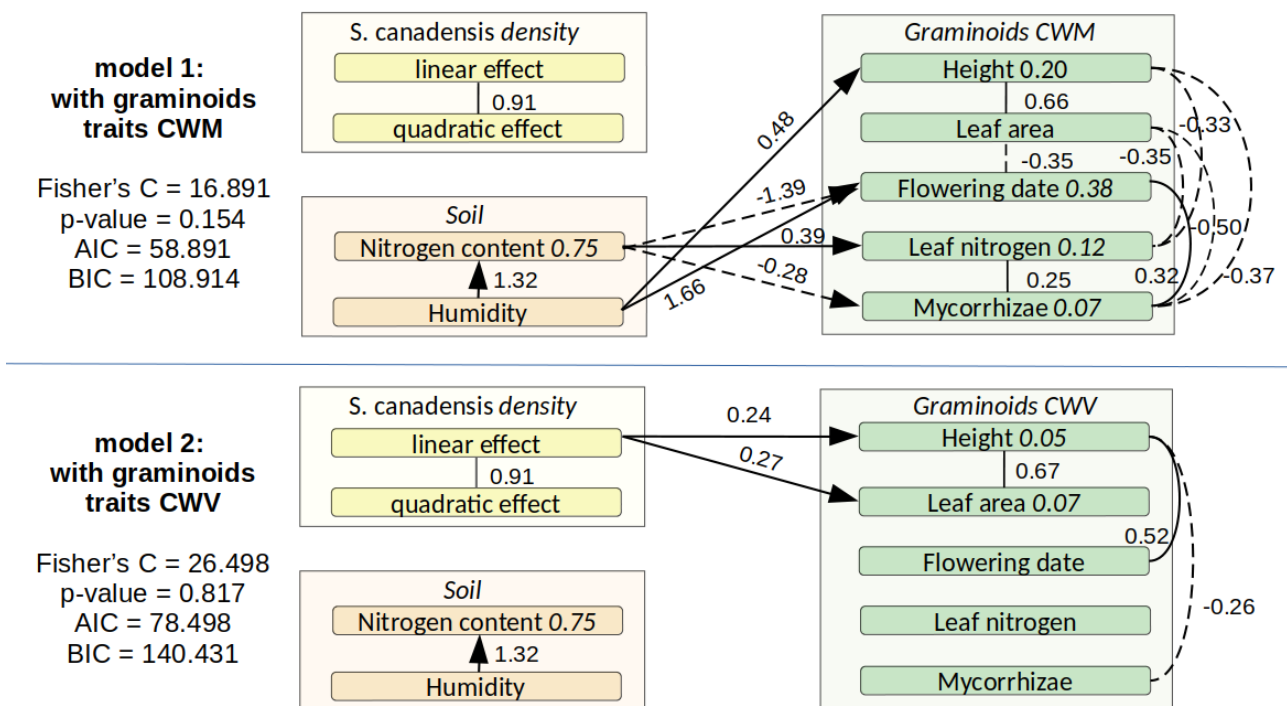


325

326 *Figure 3: Structural equation models representing the impact of S. canadensis density on trait*
 327 *means (CWM, model 1) and variances (CWV, model 2) of forb species. Black solid and dashed*
 328 *arrows represent significant positive and negative directed impacts (p-value < 0.05), respectively.*
 329 *Black lines represent significant positive undirected relationships (p-value < 0.05). The coefficients*
 330 *associated with each significant link are indicated beside the corresponding arrows and lines, and*
 331 *the values beside the response variables are their associated marginal R². The structure of the*
 332 *initial model (i.e., before variable and link selection) is shown on Figure 2. Some links were*
 333 *removed (when not significant) and others added (to support independence claims) to the initial*
 334 *models following the model building procedure described in Materials and Methods.*

335 In the graminoid, high densities of *S. canadensis* was directly correlated to a decrease in
 336 species of medium height (positive effect on the variance of plant heights in graminoids), and/or
 337 medium LA (positive effect on CWV). Invader density was also indirectly linked to a decrease in
 338 species with an intermediate end of flowering, and extreme values of mycorrhizal infection (via
 339 allometric constraints with plant heights) (Figure 4.b). We found no impact of *S. canadensis* on the
 340 mean values of graminoid traits (Figure 4.a). Regarding the effects of the soil characteristics, we
 341 found that richer soils (high N content) favored species with low LMA and AMF infection rate. Soil
 342 humidity favored tall species, species with high LMA, species with intermediate LNA and selected
 343 against species with intermediate end of flowering (Figure 4).

344



345

346 *Figure 4: Structural equation models representing the impact of S. canadensis density on trait*
 347 *means (CWM, model 1) and variances (CWV, model 2) of graminoid species. Black solid and*
 348 *dashed arrows represent significant positive and negative directed impacts (p-value < 0.05),*
 349 *respectively. Black lines represent significant positive undirected relationships (p-value < 0.05). The*

350 coefficients associated with each significant link are indicated next to the corresponding arrows and
351 lines, and the values beside the response variables are their associated marginal R^2 . The structure
352 of the initial model (i.e., before variable and link selection) is shown on Figure 2. Some links were
353 removed (when not significant) and others added (to support independence claims) to the initial
354 models following the model building procedure described in Materials and Methods.

355

356

Discussion

357 We found an overall negative impact of *Solidago canadensis* on native vegetation biomass
358 production and diversity, but the magnitude of these impacts depended on functional groups (native
359 forbs vs. graminoids). For example, *S. canadensis* reduced the richness and biomass production of
360 graminoids, but not those of forbs. A high density of *S. canadensis* tended to select only forb species
361 avoiding the new constraints (competition for light, nutrients and perturbation of mycorrhizal
362 interaction) through their high ability to reach the resources with low LMA and AMF infection rate.
363 In contrast, it selected graminoid species that either avoid (competition for light), tolerate
364 (competition for light), or escape (rapid early season growth) the constraints due to *S. canadensis*
365 preemption of light. Finally, soil conditions are important determinants of native community
366 structure and composition in the sampled wet meadows (Maltby and Barker 2009), but are
367 independent from *S. canadensis* density. Thus, we observed no indirect effect of *S. canadensis* on
368 native plants through changes in soil humidity or nitrogen due to the invasion. This also supports
369 our hypothesis that *S. canadensis* randomly established within the meadows, independently of local
370 variations in edaphic conditions and native plant communities.

371

1. Impacts of *S. canadensis* on native species biomass production and diversity: different

372

responses between functional groups

373 Invasion by *S. canadensis* negatively impacted both forbs and graminoids in terms of biomass
374 production, taxonomic or functional diversity, but the metrics of diversity that were affected
375 differed between the two functional groups. These results support the idea that the two functional
376 groups respond differently to abiotic and biotic constraints (Bowman et al. 1995; Freschet et al.
377 2018; Raavel et al. 2018) and reveal that one invader can affect different functional groups of plants
378 via different mechanisms. Importantly, at the community level, we only detected part of the *S.*
379 *canadensis* effects detected at the functional group level: loss of Biomass production, loss of
380 Evenness and gain in FDiv. This demonstrates that differences in response to invasion between
381 functional groups, in terms of taxonomic and functional diversity, can blur signals at the community
382 level and lead to an underestimation of the impacts of invasions (Münkemüller et al. 2014).

383 For forb species, we showed that as *S. canadensis* density increased, the biomass production
384 of forbs was less evenly distributed across species and traits (reduced taxonomic and functional
385 evenness), and species with intermediate traits became less abundant compared to those at the
386 periphery of the community's functional space (increased FDiv). This may create vacant niches at
387 the center of forbs functional space that could increase the probability of other exotic species
388 invasion (Moles et al. 2008). In contrast, for graminoid species, an increase in *S. canadensis* density
389 entailed decreasing richness and biomass production, but we did not detect any signal on functional
390 diversity.

391 **2. Impacts of *S. canadensis* on native plant traits: resistance strategies differ depending on** 392 **functional groups and constraints**

393 **2.1. Competition for light**

394 *Solidago canadensis* is a tall species (up to 2 m), with an abundant foliage all along the stem
395 and close stems. High densities of *S. canadensis* can thus generate a strong competition to native
396 species requiring direct light. We detected this constraint for both forbs and graminoids: we

397 observed taller native species at higher invader density. Tall forbs and graminoids are able to
398 intercept light with their upper parts and are thus less affected by the shade of *S. canadensis*, which
399 corresponds to an avoidance strategy. Interestingly, in parallel, short graminoids were also
400 increasingly prevalent along the invasion gradient. This could be due to their naturally good
401 capacity to tolerate shade, since short species are often under the canopy of native species as well,
402 corresponding to a tolerance strategy. In addition, short graminoids could benefit from the fact that
403 they also tend to flower earlier than tall species (due to allometric constraints; Supplementary
404 materials) and may thus be able to complete their cycle before *S. canadensis* outgrows them (stem
405 elongation starting in late April and reaching final size late July), corresponding to an escape
406 strategy. *S. canadensis* also indirectly selects forb species with an early end of flowering that might
407 be able to escape competition for light, soil nutrients and mycorrhizal interactions.

408 **2.2. Competition for soil nutrients and mycorrhizal interactions**

409 *S. canadensis* is known to be a fast-growing species, building a dense network of rhizomes
410 and small roots with a high mycorrhizal infection rate that allows efficient nutrient uptake (Werner
411 et al. 1980; Yang et al. 2014; Dong et al. 2021). It is also known to produce allelopathic compounds
412 in the soil that inhibit the growth of other plants and their interactions with mycorrhizae (Zhang et
413 al. 2007; Zubek et al. 2016). We detected this constraint only for forbs: *S. canadensis* selected forbs
414 with high AMF infection rate (direct effect) and high leaf nitrogen content per leaf area (LNA,
415 indirect effect via AMF infection rate). These species are able to (i) avoid competition for local soil
416 nutrients by reaching resources outside the rhizosphere of *S. canadensis* (high LNA, Cunningham et
417 al. 1999), and possibly (ii) avoid part of the allelopathic perturbations of AMF interactions as they
418 easily form interactions and may lose part of them without being too much affected. The fact that
419 graminoids were not affected by the increased competition for nutrients and the perturbation of
420 mycorrhizal interactions may be due to the fact that they have nutrients uptake strategy is different

421 from that of forbs (different root systems) and they already have low mycorrhizal interactions
422 (Figure S2).

423 **3. Conclusions on the different strategies**

424 Overall, our results indicate that, in our study system, the impacts of *S. canadensis* on
425 graminoids are primarily due to competition for light, while forbs are also affected by competition
426 for soil nutrients and alteration of mycorrhizal interactions. Furthermore, the positive impact of *S.*
427 *canadensis* density on forbs functional divergence suggests that the selection for height and AMF
428 interactions does not apply to the same species: different species may be selected for their ability to
429 resist to different constraints. *S. canadensis* being a forb, it has a below- and above-ground structure
430 more similar to native forbs than to native graminoids. Because competition arises when different
431 species have similar ways to access the same resource, *S. canadensis* compete more with native
432 forbs and this may explain why we found evidence of three different constraints of invasion on
433 forbs but just of one of them on graminoids. Interestingly, we found no indirect effect of *S.*
434 *canadensis* on native vegetation through the soil compartment, as *S. canadensis* did not affect soil
435 humidity and nitrogen content, supporting the results found by Scharfy et al. (2010) on similar wet
436 meadows (but Zhang et al. (2009) found effects of *S. canadensis* on soil properties under a
437 subtropical monsoon climate).

438 **4. Limits and Perspectives**

439 In invasion studies, it is often difficult to disentangle the causes from the consequences of
440 invasion (Gallien and Carboni 2017): do the traits of native species in invaded communities reveal
441 the cause of their invasion (i.e., the driver of their “invasibility”) or their response to the invader
442 (i.e., a sign of the filtering imposed by the invader)? To avoid this pitfall and isolate only native
443 species responses to invasion by *S. canadensis*, we selected the meadows of this study to be as
444 homogeneous as possible in terms of management history, edaphic conditions, and vegetation. In

445 addition, each meadow contained a gradient of invader density independent from any gradient of
446 edaphic conditions. Therefore, we can assume that prior to the invasion, there was no difference
447 within the prospected meadows - in terms of community taxonomic and functional structures - that
448 would explain the current repartition of *S. canadensis*. In other words, the differences we currently
449 observe along this gradient are likely the result of the effects of the invader, and the density of *S.*
450 *canadensis* a function of its stage of invasion (not of community invasibility). It should be noted
451 that we probably underestimated or missed some of these differences because we were not able to
452 detect plastic responses. Studying trait responses at the species level would be the next step to
453 improve our understanding of invasion impacts.

454 Another difficulty when studying the impact of invasions on native vegetation is its dynamic
455 nature. During invasion, the density of the invader increases over time, but native vegetation
456 responses may take years to appear (Rusterholz et al. 2017). At a given density of the invader, some
457 native species may show (i) colonization credit (i.e., natives that were locally excluded by dominant
458 native species before invasion can now colonize sites where *S. canadensis* has replaced these
459 dominant natives), or (ii) extinction debt (i.e., populations that are currently present in the patch, but
460 will disappear because their population growth rate is less than one) (Jackson and Sax 2010;
461 Bagaria et al. 2015; Rumpf et al. 2019). In this study, *S. canadensis* patches were small enough
462 (<300 m²) for the native vegetation to recolonize the patch through a high propagule pressure,
463 potentially leading to lower colonization credits and higher extinction debts compared to large
464 invaded areas. Extinction debt was also promoted by the fact that most species in our study site are
465 perennials: individuals can survive for years even if propagules fail to establish. These dynamic
466 effects are generally difficult to eliminate, but the fact that colonization credits are limited, while
467 extinction debts are likely present, tends to make our results more conservative about the magnitude
468 of *S. canadensis* effects (i.e., we might have missed some mechanisms that are not yet detectable
469 due to the extinction debt).

470 Finally, in this study, we focused on mechanisms and traits linked to the vegetative
471 development of native plant species. However, *S. canadensis* may impact native species through
472 other mechanisms. For example, it could reduce native plant reproduction success through (i)
473 competition for pollinators, (ii) pollen competition, or (iii) allelopathic compounds limiting natives
474 germination and growth (Abhilasha et al. 2008; Yuan et al. 2013; Sun et al. 2013). In particular, *S.*
475 *canadensis* is known to produce abundant, high-quality pollen and nectar at the end of the flowering
476 season, and thus to act as an important resource for honeybees and some wild pollinators (Stefanic
477 et al. 2003; Fenesi, Vágási, et al. 2015; Grange et al. 2021). Dense patches of *S. canadensis* could
478 therefore disturb native pollination networks and fruit sets (i) positively by attracting more
479 generalist pollinators from the landscape pool (concentration effect; Ghazoul 2006), and/or (ii)
480 negatively by increasing inter-specific competition for pollinators (dilution effect; Campbell and
481 Hanula 2007; Morales and Traveset 2009). Further investigation of the *S. canadensis* influences on
482 native plant-pollinator interactions seems thus as an important next step toward a more
483 comprehensive understanding of invasion impacts through cascading effects.

484

Conclusion

485 Our study showed that the invader *S. canadensis* has a complex effect on native vegetation. Its
486 impacts vary between and within functional groups: forbs and graminoids responded to different
487 constraints and we detected different strategies for resisting the same constraint within graminoids.
488 Our results show that those native forbs that survive invasion use an avoidance strategy to respond
489 to increased competition for light, soil nutrients and AMF interactions (i.e. they avoid the stress by
490 having good abilities to reach the resources), whereas graminoids use all types of resistance
491 strategies (avoidance, tolerance and escape) to respond to increased competition for light.
492 Considering traits linked to different constraints and strategies for different functional groups seems
493 thus essential to understand the complexity of the native vegetation response to invasion. Applying

494 such an approach in future studies may ultimately help us understand why the same invasive species
495 can have opposing impacts on native communities of different compositions.

496

References

Abhilasha D, Quintana N, Vivanco J, Joshi J. 2008. Do allelopathic compounds in invasive *Solidago canadensis* s.l. restrain the native European flora? *J Ecol.* 96(5):993–1001. <https://doi.org/10.1111/j.1365-2745.2008.01413.x>

Albrecht M, Padrón B, Bartomeus I, Traveset A. 2014. Consequences of plant invasions on compartmentalization and species' roles in plant–pollinator networks. *Proc R Soc B Biol Sci* [Internet]. [accessed 2019 Sep 20]. <https://royalsocietypublishing.org/doi/abs/10.1098/rspb.2014.0773>

Bagaria G, Helm A, Rodà F, Pino J. 2015. Assessing coexisting plant extinction debt and colonization credit in a grassland-forest change gradient. *Oecologia.* 179(3):823–834. <https://doi.org/10.1007/s00442-015-3377-4>

Bartoń K. 2020. MuMIn: Multi-Model Inference [Internet]. [place unknown]; [accessed 2021 Sep 30]. <https://CRAN.R-project.org/package=MuMIn>

Bates D, Maechler M, Bolker B, Walker S, Christensen RHB, Singmann H, Dai B, Scheipl F, Grothendieck G, Green P, et al. 2021. lme4: Linear Mixed-Effects Models using “Eigen” and S4 [Internet]. [place unknown]; [accessed 2021 Sep 30]. <https://CRAN.R-project.org/package=lme4>

Blondel J. 2003. Guilds or functional groups: does it matter? *Oikos.* 100(2):223–231. <https://doi.org/10.1034/j.1600-0706.2003.12152.x>

Bocci G. 2020. TR8: A Tool for Downloading Functional Traits Data for Plant Species [Internet]. [place unknown]; [accessed 2021 Sep 30]. <https://CRAN.R-project.org/package=TR8>

Bodner G, Nakhforoosh A, Kaul H-P. 2015. Management of crop water under drought: a review. *Agron Sustain Dev.* 35(2):401–442. <https://doi.org/10.1007/s13593-015-0283-4>

Bowman WD, Theodose TA, Fisk MC. 1995. Physiological and production responses of plant growth forms to increases in limiting resources in alpine tundra: implications for differential community response to environmental change. *Oecologia.* 101(2):217–227. <https://doi.org/10.1007/BF00317287>

Bråthen KA, Hagberg O. 2004. More efficient estimation of plant biomass. *J Veg Sci.* 15(5):653–660. <https://doi.org/10.1111/j.1654-1103.2004.tb02307.x>

Campbell JW, Hanula JL. 2007. Efficiency of Malaise traps and colored pan traps for collecting flower visiting insects from three forested ecosystems. *J Insect Conserv.* 11(4):399–408. <https://doi.org/10.1007/s10841-006-9055-4>

Castro-Díez P, Pauchard A, Traveset A, Vilà M. 2016. Linking the impacts of plant invasion on community functional structure and ecosystem properties. Kühn I, editor. *J Veg Sci.* 27(6):1233–1242. <https://doi.org/10.1111/jvs.12429>

- Cavieres LA. 2021. Facilitation and the invasibility of plant communities. *J Ecol.* 109(5):2019–2028. <https://doi.org/10.1111/1365-2745.13627>
- Climatologie de l'année 2019 à Annecy-Meythet - Infoclimat. [accessed 2022 Jul 25]. <https://www.infoclimat.fr/climatologie/annee/2019/annecy-meythet/valeurs/07494.html>
- Craine JM, Dybzinski R. 2013. Mechanisms of plant competition for nutrients, water and light. *Funct Ecol.* 27(4):833–840. <https://doi.org/10.1111/1365-2435.12081>
- Cunningham SA, Summerhayes B, Westoby M. 1999. Evolutionary Divergences in Leaf Structure and Chemistry, Comparing Rainfall and Soil Nutrient Gradients. *Ecol Monogr.* 69(4):569–588. [https://doi.org/10.1890/0012-9615\(1999\)069\[0569:EDILSA\]2.0.CO;2](https://doi.org/10.1890/0012-9615(1999)069[0569:EDILSA]2.0.CO;2)
- Davis ES, Kelly R, Maggs CA, Stout JC. 2018. Contrasting impacts of highly invasive plant species on flower-visiting insect communities. *Biodivers Conserv.* 27(8):2069–2085. <https://doi.org/10.1007/s10531-018-1525-y>
- Dong L-J, Ma L-N, He W-M. 2021. Arbuscular mycorrhizal fungi help explain invasion success of *Solidago canadensis*. *Appl Soil Ecol.* 157:103763. <https://doi.org/10.1016/j.apsoil.2020.103763>
- Fenesi A, Geréd J, Meiners SJ, Tóthmérész B, Török P, Ruprecht E. 2015. Does disturbance enhance the competitive effect of the invasive *Solidago canadensis* on the performance of two native grasses? *Biol Invasions.* 17(11):3303–3315. <https://doi.org/10.1007/s10530-015-0954-8>
- Fenesi A, Vágási CI, Beldean M, Földesi R, Kolcsár L-P, Shapiro JT, Török E, Kovács-Hostyánszki A. 2015. *Solidago canadensis* impacts on native plant and pollinator communities in different-aged old fields. *Basic Appl Ecol.* 16(4):335–346. <https://doi.org/10.1016/j.baae.2015.03.003>
- Fitter AH, Peat HJ. 1994. The Ecological Flora Database. *J Ecol.* 82(2):415–425. <https://doi.org/10.2307/2261309>
- Freschet GT, Violle C, Bourget MY, Scherer-Lorenzen M, Fort F. 2018. Allocation, morphology, physiology, architecture: the multiple facets of plant above- and below-ground responses to resource stress. *New Phytol.* 219(4):1338–1352. <https://doi.org/10.1111/nph.15225>
- Gallien L, Carboni M. 2017. The community ecology of invasive species: where are we and what's next? *Ecography.* 40(2):335–352. <https://doi.org/10.1111/ecog.02446>
- Ghazoul J. 2006. Floral diversity and the facilitation of pollination. *J Ecol.* 94(2):295–304. <https://doi.org/10.1111/j.1365-2745.2006.01098.x>
- Gordon DR. 1998. Effects of Invasive, Non-Indigenous Plant Species on Ecosystem Processes: Lessons from Florida. *Ecol Appl.* 8(4):975–989. [https://doi.org/10.1890/1051-0761\(1998\)008\[0975:EOINIP\]2.0.CO;2](https://doi.org/10.1890/1051-0761(1998)008[0975:EOINIP]2.0.CO;2)
- Grace JB, Scheiner SM, Schoolmaster DR. 2015. Structural equation modeling: building and evaluating causal models. In: *Ecol Stat Contemp Theory Appl. First Edition.* [place unknown]: Gordon A. Fox, Simoneta Negrete-Yankelevich, and Vinicio J. Sosa. © Oxford University Press; p. 168–199.
- Grange MC, Munoz F, Moretti M, Varona-Y-Varona S, Renaud J, Colace M-P, Gueguen M, Gallien L. 2021. Designing sampling protocols for plant-pollinator interactions - timing, meteorology,

- flowering variations and failed captures matter. *Bot Lett* [Internet]. [accessed 2021 Aug 30]. <https://www.tandfonline.com/doi/abs/10.1080/23818107.2021.1964596>
- de Groot M, Kleijn D, Jogan N. 2007. Species groups occupying different trophic levels respond differently to the invasion of semi-natural vegetation by *Solidago canadensis*. *Biol Conserv*. 136(4):612–617. <https://doi.org/10.1016/j.biocon.2007.01.005>
- Hill MO. 1973. Diversity and Evenness: A Unifying Notation and Its Consequences. *Ecology*. 54(2):427–432. <https://doi.org/10.2307/1934352>
- Huang L, Xue W, Herben T. 2019. Temporal niche differentiation among species changes with habitat productivity and light conditions. Roxburgh S, editor. *J Veg Sci*. 30(3):438–447. <https://doi.org/10.1111/jvs.12741>
- Jackson ST, Sax DF. 2010. Balancing biodiversity in a changing environment: extinction debt, immigration credit and species turnover. *Trends Ecol Evol*. 25(3):153–160. <https://doi.org/10.1016/j.tree.2009.10.001>
- Jonasson S. 1988. Evaluation of the Point Intercept Method for the Estimation of Plant Biomass. *Oikos*. 52(1):101–106. <https://doi.org/10.2307/3565988>
- Jost L, DeVries P, Walla T, Greeney H, Chao A, Ricotta C. 2010. Partitioning diversity for conservation analyses. *Divers Distrib*. 16(1):65–76. <https://doi.org/10.1111/j.1472-4642.2009.00626.x>
- Kattge J, Bönisch G, Díaz S, Lavorel S, Prentice IC, Leadley P, Tautenhahn S, Werner GDA, Aakala T, Abedi M, et al. 2020. TRY plant trait database – enhanced coverage and open access. *Glob Change Biol*. 26(1):119–188. <https://doi.org/10.1111/gcb.14904>
- Knevel I c., Bekker R m., Bakker J p., Kleyer M. 2003. Life-history traits of the Northwest European flora: The LEDA database. *J Veg Sci*. 14(4):611–614. <https://doi.org/10.1111/j.1654-1103.2003.tb02188.x>
- Kühn I, Durka W, Klotz S. 2004. BiolFlor: A New Plant-Trait Database as a Tool for Plant Invasion Ecology. *Divers Distrib*. 10(5/6):363–365.
- Kuznetsova A, Brockhoff PB, Christensen RHB, Jensen SP. 2020. lmerTest: Tests in Linear Mixed Effects Models [Internet]. [place unknown]; [accessed 2021 Sep 30]. <https://CRAN.R-project.org/package=lmerTest>
- Lefcheck JS. 2016. piecewiseSEM: Piecewise structural equation modelling in r for ecology, evolution, and systematics. *Methods Ecol Evol*. 7(5):573–579. <https://doi.org/10.1111/2041-210X.12512>
- Levitt J. 2015. Water, Radiation, Salt, and Other Stresses. [place unknown]: Elsevier.
- Litt AR, Cord EE, Fulbright TE, Schuster GL. 2014. Effects of Invasive Plants on Arthropods. *Conserv Biol*. 28(6):1532–1549. <https://doi.org/10.1111/cobi.12350>
- Maltby E, Barker T. 2009. The Wetlands Handbook, 2 Volume Set. [place unknown]: John Wiley & Sons.

- Marschner H. 1995. Mineral nutrition of higher plants. 2nd edition. Great Britain.
- Mason NWH, Mouillot D, Lee WG, Wilson JB. 2005. Functional richness, functional evenness and functional divergence: the primary components of functional diversity. *Oikos*. 111(1):112–118. <https://doi.org/10.1111/j.0030-1299.2005.13886.x>
- Moles AT, Gruber MAM, Bonser SP. 2008. A new framework for predicting invasive plant species. *J Ecol*. 96(1):13–17. <https://doi.org/10.1111/j.1365-2745.2007.01332.x>
- Morales CL, Traveset A. 2009. A meta-analysis of impacts of alien vs. native plants on pollinator visitation and reproductive success of co-flowering native plants. *Ecol Lett*. 12(7):716–728. <https://doi.org/10.1111/j.1461-0248.2009.01319.x>
- Moroń D, Skórka P, Lenda M. 2018. Disappearing edge: the flowering period changes the distribution of insect pollinators in invasive goldenrod patches. *Insect Conserv Divers* [Internet]. [accessed 2019 Jan 29] 0(0). <https://doi.org/10.1111/icad.12305>
- Münkemüller T, Gallien L, Lavergne S, Renaud J, Roquet C, Abdulkhak S, Dullinger S, Garraud L, Guisan A, Lenoir J, et al. 2014. Scale decisions can reverse conclusions on community assembly processes. *Glob Ecol Biogeogr*. 23(6):620–632. <https://doi.org/10.1111/geb.12137>
- Pakeman RJ, Queded HM. 2007. Sampling plant functional traits: What proportion of the species need to be measured? *Appl Veg Sci*. 10(1):91–96. <https://doi.org/10.1111/j.1654-109X.2007.tb00507.x>
- Pyšek P, Jarošík V, Hulme PE, Pergl J, Hejda M, Schaffner U, Vilà M. 2012. A global assessment of invasive plant impacts on resident species, communities and ecosystems: the interaction of impact measures, invading species' traits and environment. *Glob Change Biol*. 18(5):1725–1737. <https://doi.org/10.1111/j.1365-2486.2011.02636.x>
- Pyšek P, Lambdon PW, Arianoutsou M, Kühn I, Pino J, Winter M. 2009. Alien Vascular Plants of Europe. In: *Handb Alien Species Eur* [Internet]. Vol. 3. Dordrecht: Springer Netherlands; [accessed 2019 Mar 13]; p. 43–61. https://doi.org/10.1007/978-1-4020-8280-1_4
- R Core Team. 2020. R: A Language and Environment for Statistical Computing [Internet]. Vienna, Austria: R Foundation for Statistical Computing. <https://www.R-project.org/>
- Raevel V, Anthelme F, Meneses RI, Munoz F. 2018. Cushion-plant protection determines guild-dependent plant strategies in high-elevation peatlands of the Cordillera Real, Bolivian Andes. *Perspect Plant Ecol Evol Syst*. 30:103–114. <https://doi.org/10.1016/j.ppees.2017.09.006>
- Rumpf SB, Hülber K, Wessely J, Willner W, Moser D, Gattringer A, Klöner G, Zimmermann NE, Dullinger S. 2019. Extinction debts and colonization credits of non-forest plants in the European Alps. *Nat Commun*. 10(1):4293. <https://doi.org/10.1038/s41467-019-12343-x>
- Rusterholz H-P, Küng J, Baur B. 2017. Experimental evidence for a delayed response of the above-ground vegetation and the seed bank to the invasion of an annual exotic plant in deciduous forests. *Basic Appl Ecol*. 20:19–30. <https://doi.org/10.1016/j.baae.2017.02.004>
- Scharfy D, Güsewell S, Gessner MO, Venterink HO. 2010. Invasion of *Solidago gigantea* in contrasting experimental plant communities: effects on soil microbes, nutrients and plant–soil feedbacks. *J Ecol*. 98(6):1379–1388. <https://doi.org/10.1111/j.1365-2745.2010.01722.x>

- Sodhi DS, Livingstone SW, Carboni M, Cadotte MW. 2019. Plant invasion alters trait composition and diversity across habitats. *Ecol Evol.* 9(11):6199–6210. <https://doi.org/10.1002/ece3.5130>
- Stefanic E, Puskadija Z, Stefanic I, Bubalo D. 2003. Goldenrod: a valuable plant for beekeeping in north-eastern Croatia. *Bee World.* 84(2):88–92. <https://doi.org/10.1080/0005772X.2003.11099581>
- Stotz GC, Gianoli E, Cahill JF. 2019. Biotic homogenization within and across eight widely distributed grasslands following invasion by *Bromus inermis*. *Ecology.* 100(7):e02717. <https://doi.org/10.1002/ecy.2717>
- Sun S-G, Montgomery BR, Li B. 2013. Contrasting effects of plant invasion on pollination of two native species with similar morphologies. *Biol Invasions.* 15(10):2165–2177. <https://doi.org/10.1007/s10530-013-0440-0>
- Valladares F, Niinemets Ü. 2008. Shade Tolerance, a Key Plant Feature of Complex Nature and Consequences. *Annu Rev Ecol Evol Syst.* 39(1):237–257. <https://doi.org/10.1146/annurev.ecolsys.39.110707.173506>
- Vilà M, Espinar JL, Hejda M, Hulme PE, Jarošík V, Maron JL, Pergl J, Schaffner U, Sun Y, Pyšek P. 2011. Ecological impacts of invasive alien plants: a meta-analysis of their effects on species, communities and ecosystems. *Ecol Lett.* 14(7):702–708. <https://doi.org/10.1111/j.1461-0248.2011.01628.x>
- Volaire F. 2018. A unified framework of plant adaptive strategies to drought: Crossing scales and disciplines. *Glob Change Biol.* 24(7):2929–2938. <https://doi.org/10.1111/gcb.14062>
- Weber E. 1998. The dynamics of plant invasions: a case study of three exotic goldenrod species (*Solidago L.*) in Europe. *J Biogeogr.* 25(1):147–154. <https://doi.org/10.1046/j.1365-2699.1998.251119.x>
- Weiner J. 2004. Allocation, plasticity and allometry in plants. *Perspect Plant Ecol Evol Syst.* 6(4):207–215. <https://doi.org/10.1078/1433-8319-00083>
- Werner PA, Gross RS, Bradbury IK. 1980. THE BIOLOGY OF CANADIAN WEEDS.: 45. *Solidago canadensis L.* *Can J Plant Sci.* 60(4):1393–1409. <https://doi.org/10.4141/cjps80-194>
- Wilson GW, Hartnett DC. 1998. Interspecific variation in plant responses to mycorrhizal colonization in tallgrass prairie. *Am J Bot.* 85(12):1732–1738.
- Yang R, Zhou G, Zan S, Guo F, Su N, Li J. 2014. Arbuscular mycorrhizal fungi facilitate the invasion of *Solidago canadensis L.* in southeastern China. *Acta Oecologica.* 61:71–77. <https://doi.org/10.1016/j.actao.2014.10.008>
- Yıldırım K, Kaya Z. 2017. Gene regulation network behind drought escape, avoidance and tolerance strategies in black poplar (*Populus nigra L.*). *Plant Physiol Biochem.* 115:183–199. <https://doi.org/10.1016/j.plaphy.2017.03.020>
- Yuan Y, Tang J, Leng D, Hu S, Yong JWH, Chen X. 2014. An Invasive Plant Promotes Its Arbuscular Mycorrhizal Symbioses and Competitiveness through Its Secondary Metabolites: Indirect Evidence from Activated Carbon. *PLOS ONE.* 9(5):e97163. <https://doi.org/10.1371/journal.pone.0097163>

Yuan Y, Wang B, Zhang S, Tang J, Tu C, Hu S, Yong JWH, Chen X. 2013. Enhanced allelopathy and competitive ability of invasive plant *Solidago canadensis* in its introduced range. *J Plant Ecol.* 6(3):253–263. <https://doi.org/10.1093/jpe/rts033>

Zhang CB, Wang J, Qian BY, Li WH. 2009. Effects of the invader *Solidago canadensis* on soil properties. *Appl Soil Ecol.* 43(2):163–169. <https://doi.org/10.1016/j.apsoil.2009.07.001>

Zhang P, Li B, Wu J, Hu S. 2019. Invasive plants differentially affect soil biota through litter and rhizosphere pathways: a meta-analysis. *Ecol Lett.* 22(1):200–210. <https://doi.org/10.1111/ele.13181>

Zhang Q, Yao LJ, Yang RY, Yang XY, Tang JJ, Chen X. 2007. Potential allelopathic effects of an invasive species *Solidago canadensis* on the mycorrhizae of native plant species. *Allelopathy J.* 20(1):71–78.

Zubek S, Majewska ML, Błaszczowski J, Stefanowicz AM, Nobis M, Kapusta P. 2016. Invasive plants affect arbuscular mycorrhizal fungi abundance and species richness as well as the performance of native plants grown in invaded soils. *Biol Fertil Soils.* 52(6):879–893. <https://doi.org/10.1007/s00374-016-1127-3>

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Statements Declarations

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1. Data availability statement

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The data used in the analyses are available in the supplementary material. All raw and derived

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data supporting the findings of this study are available from the corresponding author Marie

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Charlotte Grange on request.

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4. Author Contributions

514 Marie Charlotte Grange, Laure Gallien and François Munoz contributed to the conception and
515 design of the study. Material preparation and data collection were performed by all authors. The
516 database was created by Julien Renaud. Analyses were performed by Marie Charlotte Grange. The
517 first draft of the manuscript was written by Marie Grange and all authors commented on previous
518 versions of the manuscript. All authors read and approved the final manuscript.