The role of geodiversity in providing ecosystem services at broad scales

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HIGHLIGHTS

- Geodiversity was mainly positively related to ecosystem services (ESs)
- Geodiversity complemented biodiversity in explaining ESs
- Geodiversity should be more deeply integrated into ES research

32 **ABSTRACT**

33 Mapping of ecosystem services (ESs) provide valuable information on the geographical variation of
34 ESs and their relation to overall diversity. Although the relationship between biodiversity and ESs
35 has been intensively explored, little is known how geodiversity (i.e., variety of geological,
36 geomorphological and soil features) is associated with different ESs. We studied 1) the spatial
37 variation of geodiversity and biodiversity in relation to six ESs (i.e., forest carbon budget, potential
38 supply of groundwater, milk and meat production, crop production, amount of free-time residences
39 and nationally valuable landscapes) using variation partitioning (VP), and 2) the spatial overlap
40 between geodiversity and biodiversity and ESs using generalized additive models (GAM) in 1006
41 intensively surveyed grid cells of 100 km² located across Finland. In the VP, biodiversity
42 independently explained more of the variation than geodiversity for majority of the ESs. However,
43 shared explanation ability of biodiversity and geodiversity was considerable for majority of ESs
44 (forest carbon budget: 41.3%, crop production: 15.0%, free-time residences: 15.2% and valuable
45 landscapes: 7.3%), often exceeding that of both independent contributions. GAMs indicated that
46 increase in both biodiversity and geodiversity enhances forest carbon budget ($D^2 = 66.8\%$ and 12.4% ,
47 respectively), potential production of groundwater (8.3% and 0.1%), crop production (35.7% and
48 8.9%), free-time residences (40.0% and 7.9%) and valuable landscapes (11.6% and 6.9%). However,
49 the positive relationship between diversity and ESs levelled off for many of the ESs. Our findings
50 suggest that geodiversity is an important complementing factor in explaining spatial variation of the
51 ESs in high-latitude regions. We also found dominantly synergic effects between abiotic diversity
52 and ESs. Thus, our study results highlight the need to more deeply incorporate abiotic diversity into
53 ESs research. Environmental conservation and management would benefit from the more
54 comprehensive integration of geodiversity to ESs research along with the changing environmental
55 conditions of future decades.

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57 **KEYWORDS:** Biodiversity, Boreal, Ecosystem service trade-off, Geodiversity; High-latitude;
58 Mapping of ecosystem services, Spatial

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84 **1. INTRODUCTION**

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86 Ecosystems provide various goods and services to mankind, thus contributing through these
87 ecosystem services (ESs) to human well-being and economic wealth (Millennium Ecosystem
88 Assessment 2005; Anderson et al. 2009; Morelli et al. 2017; Dobbs et al. 2018; Li and Wang 2018).
89 ESs are fundamentally linked to biodiversity, which can be, depending on the definition, a regulator
90 of ESs, a final ESs or a good (Mace et al. 2012). One approach to study this relationship between
91 biodiversity and ESs has been to map the spatial variation between biodiversity and ESs at different
92 scales (Naidoo et al. 2008; Anderson et al. 2009; Holt et al. 2016). However, biodiversity (i.e., biotic
93 diversity) is only another half of (overall) diversity, composing also of abiotic (i.e., inanimate physical
94 nature) component, and inclusion of this abiotic diversity has been largely neglected in the previous
95 mapping studies (Gray 2013; Lawler et al. 2015; Bailey et al. 2017; Tukiainen et al. 2017a, 2017b).
96 Hence, more emphasis should be focussed on investigating how abiotic diversity and ESs are related
97 at different spatial scales (e.g., Gray 2012; Gordon and Barron 2013; van Ree and van Beukering
98 2016). This lack of research is also associated with ecosystem multi-functionality, as abiotic diversity
99 can deliver combinations of a variety of overlapping functions, each of which delivers different ESs
100 to society (Lee and Lautenbach 2015). These overlapping functions can yield synergetic or trade-off
101 effects between diversity patterns and ESs, suggesting which ESs people may either get (synergic) or
102 lose (trade-off) at a certain time (Rodrigues et al. 2006; Mastrangelo et al. 2014; Lee and Lautenbach
103 2015). However, no previous study has considered whether the relationship between abiotic diversity,
104 in addition to biodiversity, and multiple ESs provide synergic or trade-off effects at broad scales.

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106 Understanding how diversity patterns of abiotic features influence on and shape surrounding
107 environment has gained wider interest only recently (Benito-Calvo et al. 2009; Hjort and Luoto 2010;

108 Gordon et al. 2012; Gray 2013; Pereira et al. 2013; Pellitero et al. 2015). These abiotic features are
109 referred as geodiversity, which is commonly defined as the variety of geological (rocks, minerals,
110 fossils), geomorphological (land form, processes), and soil features (Gray 2008; 2013). Geodiversity
111 as the abiotic equivalent of biodiversity provides the basis upon which living creatures from plants to
112 human exist and interact, thus connecting people, nature, landscapes and cultural heritage in a holistic
113 manner (Gordon and Barron 2013; Matthews 2014; Lawler et al. 2015). Geodiversity also underlies
114 the aesthetic value of landscapes and contributes to sustainable economic development and benefits
115 public health by providing opportunities for outdoor recreation (Gordon and Barron 2013; Gray
116 2013). Although, it has been recognized, through the continued interaction with natural processes and
117 the implementation of integrated approaches in land and water control and conservation, that
118 geodiversity strongly contributes to sustainable environmental management and decision-making
119 (Gordon and Barron 2013; Gray 2013; Hjort et al. 2015), it has only recently been more widely
120 accepted to the ESs framework (van Ree and van Beukering 2016; CICES 2018).

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122 Despite the lack of recognition during the past in the ES framework, geodiversity is intimately related
123 to ESs. It contributes to every ESs categorization from provisioning, and regulating and maintaining
124 services to cultural services (CICES 2018), thus having a crucial role in providing benefits to society.
125 For example, abiotic environment provides habitat for biota combination with biotic and cultural
126 resources, fresh water and mineral resources, regulates climate conditions, controls hydrology and
127 erosion, facilitates nutrient cycling and enhances recreation and ecotourism (Gray 2013; Gordon and
128 Barron 2013; van Ree and van Beukering 2016; Bailey et al. 2017; CICES 2018). Although the link
129 between geodiversity and ESs is evident and ESs definitions recognize that an ecosystem includes
130 the abiotic component of habitat, most published empirical case studies on ESs refer entirely or
131 mainly on services originated exclusively from biodiversity (Gray 2013; but see Gordon and Barron

2013). This shortage of individual studies hinders our possibilities to comprehensively understand beyond conceptual perspectives the relationship between geodiversity and ESs.

Our focus is to determine 1) the spatial variation of geodiversity and biodiversity in relation to six ESs (i.e., forest carbon budget, potential supply of groundwater, milk and meat production, crop production, amount of free-time residences and nationally valuable landscapes), and 2) the spatial overlap between geodiversity and biodiversity and ESs in Finland at broad scale (10 km resolution). For the spatial overlap, we focussed on the geo-biophysical constraints (i.e., geodiversity and biodiversity) that may promote (synergy; e.g. monotonically increasing or non-linear positive relationship), limit (trade-off) or have no effect (no-effect) in delivering the six ESs (following the terminology of Lee and Lautenbach 2016), without considering social or economic constraints or relationships among the ESs itself (see Cavender-Bares et al. 2015). We founded our spatial overlap hypothesis on a simplified interpretation how changes in diversity (i.e., both biodiversity and geodiversity) are predicted to affect three types of ecosystem services (de Groot et al. 2010; Science for Environment Policy 2015; Fig. 1). For regulating services (forest carbon budget and potential supply of groundwater in our study), enhancing diversity typically increases the degree of services, but the pattern varies in the highest diversity environments depending on the type of service. For provisioning services (milk and meat production, and crop production), no services exist in pristine environments, because ecosystem needs to be at least temporarily disturbed in order to obtain provisioning services from nature. In lowering diversity with increasing intensity of use, more provisioning services are only gained by adding human input (e.g., fertilizer, water or labour) to ecosystem. The production of provisioning services finally diminishes as diversity clearly decreases in monotonic urban-like environments. Cultural services are separated to two different ones. For cultural-recreation services (amount of free-time residences), a crucial feature in valuing these services is accessibility, because pristine systems are often inaccessible. Thus, increased accessibility

157 leads to more active use of cultural services until a subsequent drop in service value is reached in
 158 highly remote systems. For cultural-information services (nationally valuable landscapes), increase
 159 in diversity increases also this service value.

161 Fig. 1. Conceptual illustration of the relationship between diversity (i.e., biodiversity and
 162 geodiversity) and ecosystem services (ESs) (Cr: sum of cultural-recreation value, Ci: sum of cultural-
 163 information value including aspects such as cultural heritage and education). Broken lines indicate
 164 alternative patterns for geodiversity depending, for example, on studied region and magnitude of
 165 human pressures (Gordon and Barron 2013; Gray et al. 2013). The patterns are partly based on
 166 Science for Environment Policy (2015). However, there is no comprehensive empirical evidence
 167 existing how geodiversity and ESs are related. Moreover, the relationships are tentative and specific
 168 situations will have specific versions of these generalized curves. Both the shape of these curves and
 169 the magnitude of the different corresponding ESs levels determine the shape of the overall ESs level
 170 curve and whether an overall optimum can be reached (de Groot et al. 2010).

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172 2. MATERIAL AND METHODS

173 2.1 Study area

174 The study area consisted of 1006 100 km² grid cells that were dispersed across Finland, located in
 175 northern Europe approximately between 60° and 70° N and between 20° and 31° E (Fig. 2). Grid
 176 cells containing more than 80 per cent of land area (i.e. maximum of 20% water areas) were included
 177 in the study. The total land area of Finland is 303 891 km² with the population of 5.5 million. Finland
 178 formed a good model environment to study the relationship between geodiversity and ESs, because
 179 variable geological and geomorphological exist and detailed information on the particular ESs were
 180 available there. In addition, human disturbance is relatively modest in Finland compared to many
 181 other countries, enabling us to investigate geodiversity and biodiversity in more natural settings.

182 Moreover, it is important to study high-latitude environments, which are especially sensitive to
183 climate warming (Vilmi et al. 2017).

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186 **2.2 Geodiversity and biodiversity**

187 Geodiversity variables, i.e. geomorphological, soil and rock richness, were assembled following Hjort
188 and Luoto (2010, 2012, Table 1). Geomorphological richness was measured using landform
189 observations, GIS-based environmental variables and generalized additive modelling (see Supporting
190 Information for details, Tukiainen et al. 2017a), and calculated as the mean of landform types in each
191 grid cell (Fig. 2). Soil and rock richness were counted by summing the number of different soil and
192 rock types in each grid cell separately. Soil types were derived from a digital soil map, in which soil
193 was divided into eight classes: 1) rock (bare rock or thin soil cover; < 1 m), 2) till (glacigenic
194 deposits), 3) stony areas and block fields, 4) sand and gravel, 5) silt, 6) clay, 7) gyttja (lake and sea
195 sediments; > 6 % organic material), and 8) peat. Rock types were determined using a digital bedrock
196 map,. For exploring the spatial overlap between geodiversity and ESs a compound measure of
197 geodiversity ('total georichness') was computed by summing the standardized values of
198 geomorphological, soil and rock richness.

199

200 Biodiversity variables consisted of the total number of vascular plant, nesting bird and butterfly
201 (Macrolepidoptera) species recorded in each 10 x 10 km grid cell (Fig. 2). These data sets are widely
202 used in the research (e.g., Kivinen et al. 2008) and they are the best available data on these biological
203 assemblages covering the whole country (Table 1). We focused on total biodiversity instead of e.g.
204 threatened species, of which vascular plants and butterflies have been studied elsewhere (Tukianen

205 et al. 2017a), to maintain comparability with the (total) geodiversity. The vascular plant data
206 comprised the presence records of all observed vascular plant species in each inventoried grid cell
207 (subspecies and hybrids were excluded). Only comprehensively mapped grid cells were included into
208 the dataset. The nesting bird data consisted of professional- and voluntary-based observations of
209 nesting birds across the Finland. The used data comprised the presence records of all nesting birds in
210 each grid cell. The butterfly data was based presence observations per each grid cell with observations
211 made by professional and volunteer amateur lepidopterists using a uniform 10610 km² grid system
212 across the Finland. A measure comparable to the total georichness (i.e. ‘total species richness’) was
213 computed by summing the standardized values of vascular plant, nesting bird and butterfly richness.

214 Table 1. Summary of the geodiversity, biodiversity and ecosystem services (ESs) variables used in the study. All the variables were upscaled to
 215 the resolution of 100km². See detailed information about the variables in the text.

	Original resolution	Survey period	Values per 100 km² grid cell (mean/min- max)	Value unit	Maintained by	Reference
Geodiversity variables						
Geomorphological richness	1 km ²	-	5.2 (3-11)	Richness	University of Oulu	Hjort & Luoto 2010, 2012; Tukiainen et al. 2017a: Supporting Information
Soil richness	1km ²	-	5.6 (2-8)	Richness	Geological Survey of Finland, University of Oulu	GSF 2010a, Tukiainen et al. 2017a

Rock richness	1km ²	-	3.9 (1-10)	Richness	Geological Survey of Finland, University of Oulu	GSF 2010b, Tukiainen et al. 2017a
Biodiversity variables						
Vascular plants	100km ²	1980- 2011	367 (111- 1178)	Richness	Finnish Museum of Natural History	Lampinen & Lahti 2015
Nesting birds	100km ²	2006- 2010	85 (7-153)	Richness	Finnish Museum of Natural History	Valkama et al. 2011
Butterflies	100km ²	2001- 2011	144 (1-756)	Richness	Finnish Museum of	

					Natural History	
Ecosystem services						
Forest carbon budget	1:25 000	2013	3828 (15- 6333)	10 kg C ha-1	Multi- Source National Forest Inventory	Tomppo et al. 2014
Potential supply of groundwater	1:20 000	2013	3328 (0- 71000)	m ³ /d	Finnish Environment Institute	http://metatieto.ymparisto.fi:8080/geoportal/
Milk and meat production	Actual location of farms	2012- 2013	4017 (0- 64028)	GJ		Luke 2016; OSF 2016
Crop production	1:20 000	2012	4373 (0- 43533)	GJ/ha	Natural Resources	Luke 2012, 2014; Fineli 2018

					Institute Finland, Agency for rural affairs	
Free-time residences	250m x 250m	2014	189 (0- 2321)	Number of	Statistics Finland	OSF 2014
Valuable landscapes	100km ²	1995	3.7 (0-99.8)	km ²	The Finnish Ministry of the Environment (managed by the Finnish Environment Institute)	Ala-Hulkko et al. 2016

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218 **2.3. Studied ecosystem service variables**

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220 In this study, we considered six different ESs which belong either regulation and maintenance,
221 provisioning or cultural ESs, following CICES V4.3 (Haines-Young and Potschin, 2013, Mononen
222 et al. 2016). We used these six ESs variables, because they represented different ESs sections and
223 reliable information was available for these variables on the national scale. Forest carbon budget and
224 potential supply of groundwater both represent regulation and maintenance services. Milk and meat
225 along with crop production belong to the provisioning services and amount of free-time residences
226 together with nationally valuable landscapes are classified to cultural services. For our conceptual
227 study approach (Fig. 1), we distinguished cultural services to two different categories based on
228 Environment Policy (2015): cultural-recreation and cultural-information services.

229

230 Forest carbon budget (10 kg C ha⁻¹) was estimated using the carbon stock of biomass as a proxy
231 variable (Fig. 2, Table 1). We used only forest carbon budget in our study, because 72% of Finland's
232 surface area is covered by forests. Spatially explicit biomass estimates were derived from the Multi-
233 Source National Forest Inventory (hereafter MS-NFI) dataset from year 2013. The MS-NFI forest
234 resource maps are based on the NFI field plot data, satellite images and digital maps using a non-
235 parametric k Nearest Neighbours estimation (Katila and Tomppo, 2001; Tomppo et al., 2008). The
236 total tree biomass in forest land was calculated by summing up the biomass estimates of Scots pine,
237 Norway spruce and deciduous forests. The carbon content was assumed to be 50% of the biomass.

238

239 Potential supply of groundwater (m³/d) includes those groundwater areas that are investigated and
240 classified for the water supply purposes (Fig. 2, Table 1, Supporting Information). The dataset

241 includes boundaries of groundwater areas, groundwater recharge areas and sub-areas as well as
242 classifications and information about possible protection plans.

243

244

Fig. 2. Spatial distribution of biodiversity, geodiversity and ecosystem services in 1006 studied grid cells (10 x 10 km) found across Finland.

249 Crop production was mapped according to the capacity of field plots to provide a food service
250 (Supporting Information). The capacity to provide crops is calculated based on Finnish field plot
251 register (Table 1). In addition, there is information on the location and size of fields in the register.

252 Only crops which were mainly used for food production ($\geq 40\%$) were chosen in the study, because
253 the majority of the crop yield is used as animals' feed and industry (Supporting Information). Such
254 crops are potato (51% of yield has been used to production of the food in year 2012), wheat (45%)
255 and rye (93%). The percentage values are based on the statistics of the Balance Sheet of Food
256 Commodities in 2012 (Luke 2012). The information of crop yield (kg/ha/year) has been obtained
257 from Luke (2014). For better comparability the crop yield has been converted into the energy units
258 (GJ/ha). The information for Finnish food nutrient values was obtained from food product register of
259 *Fineli* (managed by National Institute for Health and Welfare, Fineli 2017). Food energy provision
260 per 10 x 10 km was finally calculated by proportioning the year 2012 crop yield (GJ/ha) to overall
261 field area of each crop.

262

263 The milk production (GJ) was based on the data which contain information about the number of
264 producers as well as milk production volumes (liters) from years 2012 and 2013 (Fig. 2, Table 1,
265 Supporting Information), respectively (Luke 2016, OSF 2016). The statistics contain information also
266 on-farm usage volumes and the average yield of dairy cows. The meat (pork and beef) production
267 statistics contain information on slaughter volumes (number of carcasses and weight in kilos) and
268 average carcass weights (OSF 2016) from years 2012 and 2013. The mean production values of milk
269 and meat were converted to energy units (GJ) to represent final ESs. GJ values were calculated based
270 on the *Fineli* (2017). We combined milk and meat production to a single variable, because their
271 geographical variation is more restricted to farm houses.

272

273 Amount of free-time residences consisted of geographical statistics on 500,400 existing free-time
274 residences in each grid cell for year 2014 (Fig. 2, Table 1, Supporting Information, OSF 2014). A
275 free-time residence refers to a residential building intended for free-time use that is permanently
276 constructed or erected on its site, or to a residential building that is used as a holiday or free-time
277 dwelling (OSF 2014). The statistics describe the existing stock and number of buildings and free-time
278 residences, excluding for example rental holiday cottages (OSF 2014).

279

280 Nationally valuable landscapes or places, which have high historical or cultural value on
281 maintenance(Supporting Information), were officially inventoried in Finland in 1995 based on a
282 decision by the Finnish Ministry of the Environment (Fig. 1, Table 1). The GIS data on nationally
283 valuable cultural environments (managed by the Finnish Environment Institute) consist of data layer
284 on culturally valuable natural diversity, traditional architecture and cultivated agricultural landscape
285 polygons (n = 156 in total, the size of the areas varies between 0.005 and 4 km², Ala-Hulkko et al.
286 2016). Landscapes are protected by means of legislation and collaboration between environmental
287 and cultural administrations.

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289 **2.4. Statistical analysis**

290 Partial generalized linear model (GLM, McCullagh and Nelder, 1989) analyses (i.e. variation
291 partitioning, VP, Borcard et al., 1992) were used to study the spatial variation of biodiversity,
292 geodiversity and six ESs across Finland (n = 1006). We applied the approach of Hawkins et al. (2003)
293 in which the coefficients of determination [here $D^2 = (\text{null deviance} - \text{residual deviance}) / \text{null deviance}$]
294 was used to determine the independent and shared contributions of the explanatory
295 variables. Thus, for each response (i.e. ESs) variable we calibrated three GLMs and computed D^2
296 using biodiversity variables (vascular plant, nesting bird and butterfly species richness), geodiversity
297 variables (geomorphological, soil and rock richness) and variables from both groups. Based on D^2

values extracted from these three separate GLM runs, we calculated the independent and shared fractions for the two explanatory variable groups. VP analysis with two groups produced four fractions: (i) the independent effect of biodiversity variables, (ii) the independent effect of geodiversity variables, (iii) the shared effect between the two variable groups, and (iv) unexplained variation not captured by independent or shared components (Hawkins et al., 2003). Due to the relatively large sample size GLMs were calibrated using a step-wise Bayesian information criterion (BIC) approach, with standard *glm* function in R (The R Project for Statistical Computing, 2017).

Generalized additive models (GAM) were employed to examine spatial overlap between (i) geodiversity (i.e., total georichness) and ESs, and (ii) biodiversity (i.e., total species richness) and ESs. More precisely, univariate model-based response curves were used to determine the diversity–ESs relationships. GAMs are useful for developing realistic response curves because they fit non-parametric smoothers to the data without requiring the specification of any particular mathematical model to describe nonlinearity (Hastie and Tibshirani 1990). GAM was performed using the *mgcv* package of R (Wood 2011). We calibrated the GAMs using standard *gam* functions and either a Gaussian or Gamma (with an identity or a log link function) error distribution in the model fitting. The family and link function were determined based on exploration of residuals and generalized cross validation score of the models (Wood 2006, 2011). To explore potential nonlinear relationships, the explanatory variable was fitted to the ESs using a smoothing spline with the degrees of freedom permitted to vary between one (i.e. straight-line relationship) and three.

3. RESULTS

3.1. Spatial variation of biodiversity, geodiversity and ESs

Spearman bivariate correlations (R_s) showed that all three biodiversity variables correlated positively to number of ESs (i.e., forest carbon budget: $R_s = 0.55$ - 0.78 , crop production: $R_s = 0.51$ - 0.66 , and

323 free-time residences: $R_s = 0.52-0.73$, Table 2). In addition, these three biodiversity variables were in
324 positive relationship with soil richness ($R_s = 0.36-0.52$), and butterflies were also related to
325 geomorphological richness ($R_s = 0.43$). Of the geodiversity variables, only soil richness was markedly
326 correlated with forest carbon budget ($R_s = 0.55$), crop production ($R_s = 0.62$) and free-time residences
327 ($R_s = 0.40$). It should also be noted that rock richness (rockS) was not related to other geodiversity
328 variables (i.e., geomorphologyS and soilS).

329 Table 2. Spearman bivariate correlation matrix among the studied variables. ** Correlation is significant at the 0.01 level (2-tailed). S associated
 330 with the biodiversity and geodiversity variables refers to the richness of a particular variable. See details in Material and Methods.

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	PlantsS	BirdsS	ButterfliesS	GeomorphologyS	SoilS	RockS	Carbon	Groundwater	Milk&Meat	Crop	Free-time res.	Landscapes
PlantsS	1	0.748**	0.676**	0.387**	0.518**	0.041	0.780**	0.281**	0.238**	0.641**	0.731**	0.276**
BirdsS		1	0.551**	0.240**	0.503**	-0.033	0.711**	0.290**	0.320**	0.656**	0.619**	0.261**
ButterfliesS			1	0.425**	0.368**	0.011	0.547**	0.218**	0.098**	0.511**	0.522**	0.268**
GeomorphologyS				1	0.206**	-0.041	0.301**	0.159**	-0.174**	0.329**	0.272**	0.176**
SoilS					1	0.003	0.549**	0.142**	0.370**	0.615**	0.403**	0.197**
RockS						1	0.041	-0.013	-0.021	-0.053	-0.008	0.052
Carbon							1	0.222**	0.382**	0.698**	0.731**	0.183**
Groundwater								1	0.093**	0.220**	0.206**	0.100**
Milk&Meat									1	0.569**	0.175**	0.166**
Crop										1	0.457**	0.317**
Free-time res.											1	0.166**
Landscapes												1

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335 In the VP, overall explained variation varied strongly among the six studied ESs, ranging from 3.5%
 336 for potential production of groundwater to 73.8% for forest carbon budget (Fig. 3). The independent
 337 effect of biodiversity was higher than that of geodiversity for forest carbon budget (27.2% and 5.3%,
 338 respectively), potential production of groundwater (4.9% and 1.2%), crop production (10.9% and -
 339 1.7%), amount of free-time residences (28.9% and 4.9%) and nationally valuable landscapes (6.3%
 340 and 1.7%). The shared fraction of biodiversity and geodiversity varied from 0.4% (groundwater) to
 341 41.3% (forest carbon budget).

342
 343 Fig.3. The relative roles of biodiversity (BIO) and geodiversity (GEO) in explaining six ecosystem
 344 services (i.e., forest carbon budget, potential production of groundwater, milk and meat production,
 345 crop production, amount of free-time residences and national valuable landscapes) using variation
 346 partitioning based on generalized linear models.

347
 348 Forest carbon budget and the number of free-time residences were structured by vascular plants and
 349 nesting birds of biodiversity variables and geomorphological and soil richness of geodiversity
 350 variables (Table 3). Although the variation in the ground water data was poorly explained, a total of

351 four variables were in the final VP models, namely vascular plants, nesting birds, geomorphological
352 and rock richness. All the six biodiversity and geodiversity variables explained the meat and milk
353 production, whereas all except the vascular plants variable were in the final crop production and
354 national valuable landscapes models.

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361 Table 3. The linear (L) and quadratic (Q) terms of the explanatory variables selected from biodiversity and geodiversity variable groups and used
362 in the variation partitioning for modelling six ecosystem services. S associated with the biodiversity and geodiversity variables refers to the
363 richness of a particular variable.

	PlantsS	BirdsS	ButterfliesS	GeomorphologyS	SoilS	RockS
Forest carbon budget	+−Q	+−Q		+−Q	+−Q	
Groundwater	+−Q	−+Q		+−Q		−L
Milk and meat production	+−Q	+L	+−Q	−+Q	−+Q	−L
Crop production		−+Q	−+Q	+−Q	−+Q	+−Q
Free-time residences	+−Q	+−Q		+−Q	+L	
Valuable landscapes		−+Q	+−Q	+L	−+Q	−+Q

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368 **3.2. Trade-offs between biodiversity and geodiversity and ESs**

369 GAMs indicated that increase in biodiversity (i.e., total species richness) enhanced forest carbon
370 budget (model's $D^2 = 66.8\%$), potential production of groundwater (8.3%), crop production (35.7%),
371 free-time residences (40.0%) and valuable landscapes (11.6%) (Fig 4). However, this positive trend
372 levelled off for the first three ESs. For the milk and meat production (7.7%), the relationship with
373 biodiversity was hump-shaped.

374

375 Geodiversity (i.e., total georichness) was positively related to forest carbon budget (model's $D^2 =$
376 12.4%), potential production of groundwater (0.1%), crop production (8.9%), free-time residences
377 (7.9%) and valuable landscapes (6.9%) (Fig. 5). This pattern levelled off for forest carbon budget and
378 crop production. A hump-shaped pattern was found between geodiversity and milk and meat
379 production (0.9%).

380

381 Fig. 4. Response curves with 95% confidence limits of biodiversity in relation to the forest carbon
 382 budget, the potential production of groundwater, milk and meat production, crop production, free-
 383 time residences, and valuable landscapes. The response curves were obtained through generalized
 384 additive models (GAMs) using univariate models [y-axis = partial residuals and estimated degrees of
 385 freedom of the smoother (s) function, x-axes = standardized values of explanatory variable i.e. total
 386 biodiversity].

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389 Fig. 5. Response curves with 95% confidence limits of geodiversity in relation to the forest carbon
 390 budget, the potential production of groundwater, milk and meat production, crop production, free-
 391 time residences, and valuable landscapes. The response curves were obtained through generalized
 392 additive models (GAMs) using univariate models [y-axis = partial residuals and estimated degrees of
 393 freedom of the smoother (s) function, x-axes = standardized values of explanatory variable i.e. total
 394 georichness].

395

396 4. DISCUSSION

397 There has been a growing interest to include abiotic diversity to ESs research (Gray 2012; Gordon
 398 and Barron 2013; van Ree and van Beukering 2016). We followed this approach by mapping
 399 geodiversity, biodiversity and six different ESs across 1006 grid cells of 100 km² covering the whole
 400 Finland to better understand whether there are spatial overlapping between different diversity patterns

401 and ESs. We found that geodiversity was an important complementing factor in explaining spatial
402 variation of the studied ESs. Although the independent contribution of geodiversity was low in the
403 variation partitioning, the shared fraction of biodiversity and geodiversity was high, often exceeding
404 that of both independent fractions. In addition, the response curves of GAMs demonstrated that higher
405 geodiversity mainly increased ESs, resulting to synergic (win-win) effects between abiotic diversity
406 and ESs. For forest carbon budget and the two provisioning services there occurred a threshold at
407 higher geodiversity values after which the positive effect levelled off or turned to negative. To our
408 knowledge, this is the first case study where geodiversity, including several abiotic features, has been
409 related to ESs to study their spatial variation, in addition to quantify synergic and trade-off effects, at
410 broad scales.

411

412 **4.1. Biodiversity primarily explains but geodiversity complements spatial variation of ESs**

413 The independent effect of biodiversity was higher than that of geodiversity in explaining spatial
414 patterns of ESs in five cases out of six, with an exception of milk and meat production. This finding
415 suggests that the link between biodiversity and different ESs is much stronger compared to
416 geodiversity and ESs. The importance of biodiversity in regulating ecosystem processes, being a final
417 ES or a good has been well-recognised in literature (Mace et al. 2009; Haines-Young and Potschin
418 2010). However, we also found a high shared effect of biodiversity and geodiversity in structuring
419 ESs across Finland, indicating that these two facets of diversity are essentially interlinked and are
420 both important in explaining spatial variation of ESs at the study scale (Gordon and Barron, 2012;
421 van Ree and van Beukering, 2016). This is not surprising, because abiotic diversity can also interact
422 with biodiversity with important consequences for ESs (Gray 2008; Gordon et al. 2012). For instance,
423 different habitats originate from different geological attributes, landforms and processes. In addition,
424 abiotic components of ecosystems affect micro-climates, facilitate nutrient cycling and create niche

425 space for various species (Nichols et al. 1998; Matthews 2014; Lawler et al. 2015). Higher
426 geodiversity also enables more niches within the same environment, allowing a higher degree of
427 biodiversity to co-exist at broad scales (Parks and Mulligan 2010; Matthews 2014). Thus,
428 geodiversity in the form of variable soil and rock types, in addition to different geomorphological
429 landforms, enables existence of higher number of vascular plants and nesting birds (see Tukiainen et
430 al. 2017b), which were the most important components of biodiversity in our study.

431

432 The shared effect of geodiversity and biodiversity had the strongest contribution to forest carbon
433 budget, crop production, free-time residences and valuable landscapes. Carbon sequestration in
434 forests is a result of biodiversity, which in turn is founded on geodiversity (Gray 2012; Gordon and
435 Barron 2012). Thus, variety of different soils and geomorphological landforms has likely created a
436 mosaic of habitats that enable efficient carbon binding in the Finnish boreal forests. For the crop
437 production, agricultural activities are often situated in fertile river valleys in Finland, where also exists
438 different soils types and geomorphological landforms. The high shared effect of geodiversity and
439 biodiversity for the free-time residences and valuable landscapes is related to landscape
440 heterogeneity. The free-time residences are situated close to fresh waters in Finland, and these areas
441 show high environmental variation related to geomorphology. Different soil and rock features
442 promote higher variation in geomorphological landforms (Hjort et al. 2012; Matthews 2014).
443 Nationally valuable landscapes are found in diverse environments, ranging from peatlands and
444 traditional agricultural landscapes to topographically variable tree-covered hills (Ala-Hulkko et al.
445 2016), that originate from variable number of abiotic features. As these valuable landscapes with
446 different environments harbor different levels of habitats for species, the strong link between
447 geodiversity and biodiversity is rather evident. Similarly, Gordon and Barron (2012) identified
448 regarding valuable landscapes that the range of habitats explicitly corresponded to geodiversity in
449 Scotland.

450

451 In addition to the environmental perspective, the inclusion of geodiversity to ESs research has an
452 important methodological aspect. Investigation of environmental patterns has become more
453 challenging due to the increasing complexity of study designs and ecosystems (Low-Decarie et al.
454 2014). They showed with an exhaustive review of more than 18 000 papers that explanatory power
455 of ecological studies has decreased likely as a result of the increase in ecosystem complexity. Overall
456 explained variation was improved for majority of ESs when geodiversity was included in our models.
457 For example, geodiversity (together with independent and shared effects) accounted for 63% of
458 overall explained variation for forest carbon budget, 64% of variation for milk and meat production,
459 and 59% of variation for nationally valuable landscapes. This suggests that the consideration of
460 geodiversity in ESs research has benefits beyond merely environmental perspective but it helps us to
461 improve our model performance at broad scales.

462

463 **4.2. Geodiversity and biodiversity promote ESs but for certain services only until a threshold**

464 We assumed based on schematic generalizations (Fig. 1) that increasing diversity increases regulating
465 services, whereas a hump-shaped pattern dominate between diversity and provisioning and cultural
466 services. Our results only partly followed these hypotheses. As expected, there was a hump-shaped
467 or positive but saturating relationship between both diversity measures and the two studied
468 provisioning services. Similarly, biotic and abiotic diversity showed a clear positive pattern in relation
469 to recreation services. However, we found no drop in the pattern between both diversity measures
470 and cultural-recreation service in the high diversity areas suggested by our conceptual framework but
471 the pattern was linearly positive. These findings suggest that synergic (win-win) effects were found
472 between the diversity patterns and cultural services (i.e. diverse landscapes attract people). On the
473 contrary, biodiversity and geodiversity first promoted forest carbon budget and potential production

474 of groundwater but the pattern levelled off until a threshold value. Thus, synergic effects were
475 evidenced for regulating and provisioning services until a threshold after which trade-off effects were
476 dominant between the diversity patterns and these ESs. This means that trade-off effect may be the
477 dominant relationship if biotic and abiotic diversity are at high to very high level. Although human
478 pressures are currently relatively modest in Finland compared to many other regions, many studies
479 have reported that land use and climate change already severely threaten diversity in the boreal and
480 sub-Arctic regions (Hanski 2000; Sala et al. 2000; Vilmi et al. 2017).

481

482 One likely explanation for these unexpected patterns may be that the degree of both biodiversity and
483 geodiversity is relatively small at the boreal environments (Tukiainen et al. 2017b), where high
484 diversity values are mostly lacking. In addition, geographical scale of a study clearly affects how the
485 natural diversity explains ESs (Anderson et al. 2009; Malinga et al. 2015; Burkhard and Maes 2017).
486 In our work, the used broad study scale results to averaging of extreme diversity values. However,
487 the relationship may be different at more finer spatial scales (e.g., resolution and/or extent), although
488 geodiversity is typically most influential at regional scales, where variation among different abiotic
489 features is the widest (Gray 2012; Hjort & Luoto 2012). These two issues (i.e., lack of high diversity
490 and scale) probably explain our findings for those diversity and ESs patterns that differed from the a
491 priori conceptual theory.

492

493 Increase in both geodiversity and biodiversity enhanced forest carbon budget until a certain threshold
494 after which the positive association levelled off (biodiversity) or turned to negative (geodiversity).
495 Thus, the relationship mainly followed the theory at low and moderate but not at high diversity values.
496 The relationship between diversity and regulating services are often dependent on the service under
497 investigation and generalizations over all regulating services are difficult to draw (de Groot et al.

2010; Science for Environment Policy 2015). Our findings indicate that there is a threshold how much forest can bind carbon with increasing landscape heterogeneity. The positive but eventually stabilising relationship between natural diversity and forest carbon budget suggests that there is a win-win situation at low and medium values but this changes to trade-off effect in high diversity values. High geodiversity is probably related to dynamic landscapes with high geomorphological process activity (Hjort and Luoto 2010; Gray 2013) that may reduce growth conditions and carbon binding capacity. Our findings contradict with the other studies, where areas of carbon supply were negative associated with biodiversity in the UK and French Alps (Anderson et al. 2009; Maskell et al. 2013).

507

Similar kind of threshold was discovered between natural diversity and crop productions, as geodiversity and biodiversity boosted crop production in the low and mean values but levelled off at the high diversity values. This was expectable, because extensive crop monocultures cannot exist in abiotically diverse environments and support low levels of biodiversity (e.g., Altieri 1999). Increasing diversity increased crop production until the natural high diversity regions which is inaccessible for human use. Provisioning services are considered to be non-existent or low for an ecosystem in its natural state with poor accessibility (de Groot et al. 2010). Similarly to our study, Anderson et al. (2009) and Maskell et al. (2013) reported a positive relationship between (plant) biodiversity and agricultural value at a country and regional extent, respectively. The patterns between natural diversity and the potential production of groundwater and milk and meat production followed rather well the theoretical expectations (Figs. 1, 4 and 5). However, owing to the low explanatory power of the models extensive conclusions of the relationships cannot be drawn.

520

521 Expectedly, biodiversity and geodiversity were positively related to free-time residences and valuable
522 landscapes, indicating that there is a synergic effect between them. Several studies have reported that
523 synergic effects are easier found between diversity and cultural services than other service categories
524 (Howe et al. 2014; Cavender-Bares et al. 2015; Lee and Lautenbach 2016). However, we did not
525 find an evident decrease in cultural-recreation services in high diversity values illustrated in the
526 theoretical framework. Accessibility to cultural-recreation services fundamentally determines their
527 usability (de Groot et al. 2010). For example, Ala-Hulkko et al. (2016) found that it takes only ca.
528 100 minutes by car to reach their closest national park but ca. 700 minutes to drive to the nearest
529 wilderness area for all Finns. It seems, however, that the studied cultural-recreation services are well-
530 accessed even in high diversity areas situated mostly in Southern Finland. This highlights the
531 importance of accessibility in explaining the relationship between overall diversity and cultural(-
532 recreation) ES.

533

534 Although we found that the inclusion of geodiversity is worthwhile in the broad-scale ES research
535 done in the boreal region, more research is needed to find support for our results in different spatial
536 scales and regions. The importance of geodiversity for biodiversity and ESs is typically highest at the
537 intermediate regional scales (e.g., Lawler et al. 2015) that may limit its use at other scales (but see
538 Bailey et al. 2016 for 1km resolution study and le Roux and Luoto 2014 for local plant community
539 study). In addition, the found patterns may differ in more human disturbed environments. For
540 example, Santos et al. (2017) recently discovered that urbanization impacted a significant portion of
541 the areas classified with high geodiversity in Brazil. It should also be noted that the used ES were not
542 actual final services according to CICES (2018), because we do not know how much of these ES are
543 actually used or consumed by people (see discussion of classification in Boyd and Banzhaf 2007 and
544 Fisher et al. 2009). However, information on the exact consumption was available for all studied ESs.
545 Moreover, milk and meat production are strongly related to farms, not to nature *per se* as suggested

546 by the ES concept (Millennium Ecosystem Assessment 2005). This resulted to the moderate
547 explained variation between both diversity measures and milk and meat production. The potential
548 production of groundwater was similarly poorly explained in our study.

549

550 **5. CONCLUSIONS**

551 Our empirical study lends support for previous synthesis, classifications and theoretical papers that
552 geodiversity should be deeply integrated to ESs research (Gordon and Barron 2012; van Ree and van
553 Beukering 2016; CICES 2018). Geodiversity is an essential part of ecosystem functioning and
554 services (Matthews 2014; Hjort et al. 2015; Lawler et al. 2015), and together with biodiversity, they
555 form foundations for numerous ESs in different ecosystems. Thus, neglecting of geodiversity in ESs
556 research would severely make contemporary scientific efforts to understand the link between humans
557 and the environment deficient. Fortunately, ESs research has woken up to realise the importance of
558 geodiversity in structuring different services at various scales (e.g., van Ree and van Beukering 2016;
559 CICES 2018). In addition, by interlinked with biodiversity through sustaining growing conditions for
560 various species and maintaining ecological niche spaces, geodiversity is fundamentally related to the
561 struggle against climate and land use changes (Anderson and Ferree 2010; Lawler et al. 2015).
562 However, not only is biodiversity under threat of global change, but human actions also compromise
563 the quality and quantity of geodiversity in the future (Gordon and Barron 2012). For example,
564 urbanization and mineral resources extraction create a severe risk to the sustainable use of abiotic
565 environment in the coming years (van Ree and van Beukering 2016; Santos et al. 2017; Tukiainen et
566 al. 2017b). One must remember that many of the abiotic features have established during thousands
567 and millions of years and once they are destroyed or used up, these features are virtually forever lost
568 for the modern society (e.g., Gray 2013). Thus, both environmental conservation and management

569 would benefit from the deeper integration of geodiversity into ESs research in the changing
570 environmental conditions faced in the coming decades.

571

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575

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