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The role of geodiversity in providing ecosystem services at broad scales

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ABSTRACT

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

1. Introduction

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

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addition to biodiversity, and multiple ESs provide synergic or trade-off effects at broad scales.

Understanding how diversity patterns of abiotic features influence on and shape surrounding environment has gained wider interest only recently (Benito-Calvo et al., 2009; Hjort and Luoto, 2010; Gordon et al., 2012; Gray, 2013; Pereira et al., 2013; Pellitero et al., 2015). These abiotic features are referred as geodiversity, which is commonly defined as the variety of geological (rocks, minerals, fossils), geomorphological (land form, processes), and soil features (Gray, 2008; 2013). Geodiversity as the abiotic equivalent of biodiversity provides the basis upon which living creatures from plants to human exist and interact, thus connecting people, nature, landscapes and cultural heritage in a holistic manner (Gordon and Barron, 2013; Matthews, 2014; Lawler et al., 2015). Geodiversity also underlies the aesthetic value of landscapes and contributes to sustainable economic development and benefits public health by providing opportunities for outdoor recreation (Gordon and Barron, 2013; Gray, 2013). Although, it has been recognized, through the continued interaction with natural processes and the implementation of integrated approaches in land and water control and conservation, that geodiversity strongly contributes to sustainable environmental management and decision-making (Gordon and Barron, 2013; Gray, 2013; Hjort et al., 2015), it has only recently been more widely accepted to the ESs framework (van Ree and van Beukering, 2016; CICES, 2018).

Despite the lack of recognition during the past in the ES framework, geodiversity is intimately related to ESs. It contributes to every ESs categorization from provisioning, and regulating and maintaining services to cultural services (CICES, 2018), thus having a crucial role in providing benefits to society. For example, abiotic environment provides habitat for biota combination with biotic and cultural resources, fresh water and mineral resources, regulates climate conditions, controls hydrology and erosion, facilitates nutrient cycling and enhances recreation and ecotourism (Gray, 2013; Gordon and Barron, 2013; van Ree and van Beukering, 2016; Bailey et al., 2017; CICES, 2018). Although the link between geodiversity and ESs is evident and ESs definitions recognize that an ecosystem includes the abiotic component of habitat, most published empirical case studies on ESs refer entirely or 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 constrains 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 leads to more active use of cultural services until a subsequent drop in service value is reached in highly remote systems. For cultural-information services (nationally valuable landscapes), increase in diversity increases also this service value.

2. Material and methods

2.1. Study area

The study area consisted of 1006 100 km^2 grid cells that were dispersed across Finland, located in northern Europe approximately between 60° and 70° N and between 20° and 31° E (Fig. 2). Grid cells containing more than 80 per cent of land area (i.e. maximum of 20% water areas) were included in the study. The total land area of Finland is 303 891 km^2 with the population of 5.5 million. Finland formed a good model environment to study the relationship between geodiversity and ESs, because variable geological and geomorphological exist and detailed information on the particular ESs were available there. In addition, human disturbance is relatively modest in Finland compared to many other countries, enabling us to investigate geodiversity and biodiversity in more natural settings. Moreover, it is important to study high-latitude environments, which are especially sensitive to climate warming (Vilmi et al., 2017).

2.2. Geodiversity and biodiversity

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

Biodiversity variables consisted of the total number of vascular plant, nesting bird and butterfly (Macrolepidoptera) species recorded in each 10 × 10 km grid cell (Fig. 2). These data sets are widely used in the research (e.g., Kivinen et al., 2008) and they are the best available data on these biological assemblages covering the whole country (Table 1). We focused on total biodiversity instead of e.g. threatened species, of which vascular plants and butterflies have been studied elsewhere (Tukiainen et al., 2017a), to maintain comparability with the (total) geodiversity. The vascular plant data comprised the presence records of all observed vascular plant species in each inventoried grid cell (subspecies and hybrids were excluded). Only comprehensively mapped grid cells were included into the dataset. The nesting bird data consisted of professional- and voluntary-based observations of nesting birds across the Finland. The used data comprised the presence records of all nesting birds in each grid cell. The butterfly data was based presence observations per each grid cell with observations made by professional and volunteer amateur lepidopterists using a uniform 10610 km^2 grid system across the Finland. A measure comparable to