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## Pathways to bridge the biophysical realism gap in ecosystem services mapping approaches

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1 **Title: Pathways to bridge the biophysical realism**  
2 **gap in ecosystem services mapping approaches**  
3

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25

## 26 **Abstract**

27 The mapping of ecosystem service supply has become quite common in ecosystem service  
28 assessment practice for terrestrial ecosystems, but land cover remains the most common  
29 indicator for ecosystems ability to deliver ecosystem services. For marine ecosystems,  
30 practice is even less advanced, with a clear deficit in spatially-explicit assessments of  
31 ecosystem service supply. This situation, which generates considerable uncertainty in the  
32 assessment of ecosystems' ability to support current and future human well-being, contrasts  
33 with increasing understanding of the role of terrestrial and marine biodiversity for ecosystem  
34 functioning and thereby for ecosystem services. This paper provides a synthesis of available  
35 approaches, models and tools, and data sources, that are able to better link ecosystem  
36 service mapping to current understanding of the role of ecosystem service providing  
37 organisms and land/seascape structure in ecosystem functioning. Based on a review of  
38 literature, models and associated geo-referenced metrics are classified according to the way  
39 in which land or marine use, ecological processes and especially biodiversity effects are  
40 represented. We distinguish five types of models: proxy-based, phenomenological, niche-  
41 based, trait-based and full-process. Examples from each model type are presented and data  
42 requirements considered. Our synthesis demonstrates that the current understanding of the  
43 role of biota in ecosystem services can effectively be incorporated into mapping approaches  
44 and opens avenues for further model development using hybrid approaches tailored to  
45 available resources. We end by discussing ways to resolve sources of uncertainty associated  
46 with model representation of biotic processes and with data availability.

47

48

49 **Keywords:** Ecosystem Service Provider; spatial modelling; biophysical assessment;  
50 species distribution; functional traits; large-scale ecosystem model

51

## 52 1. Introduction

53 Ecosystem services (ES) originate from spatially structured ecosystems and land/seascapes,  
54 and their dynamics over time. Quantifying ES provisioning therefore must account for spatio-  
55 temporal patterns and processes. Although this is evident, so far this challenge has been  
56 insufficiently resolved (Bennett et al., 2015). Spatially-explicit quantification of ES using geo-  
57 referenced metrics and GIS-based approaches has recently gained prominence through the  
58 needs from policy and decision-makers for global to local ES assessments (Maes et al.,  
59 2012; Martinez-Harms et al., 2015). Similar needs follow from emerging practices of land and  
60 marine planning (Outeiro et al., 2015; von Haaren and Albert, 2011) or land management  
61 decision (e.g. in agriculture or forestry; Doré et al., 2011; Grêt-Regamey et al., 2013;  
62 Soussana et al., 2012) that incorporate ecosystem services among use allocation and  
63 management criteria.

64 However the reliability of ES mapping varies as a function of the methods employed. For  
65 instance in a review of 107 studies, Lautenbach et al. (2015) found that, while half of  
66 ecosystem service studies were based on relatively simple look-up table approaches  
67 attributing fixed values for given land cover types, nearly a third of the studies of ecosystem  
68 services conducted between 1966 and 2013 mapped ecosystem services. This mapping is  
69 done in most cases based on land use composition ignoring land use configuration and land  
70 use intensity (Lautenbach et al., 2015 ; Mitchell et al., 2015; Verhagen et al., 2016). More  
71 specifically, regulating services have been the most commonly mapped, followed by  
72 provisioning services (Egoh et al., 2012; Lautenbach et al., 2015; Martinez-Harms and  
73 Balvanera, 2012; Seppelt et al., 2011). For marine and coastal systems, among a total of 27  
74 available studies from an exhaustive search of the Web of Science on ES mapping and ES  
75 modelling studies, almost half (52%) focused on Regulation & Maintenance services, of  
76 those 22% concentrated on coastal protection (wind & flood protection) and 33% on carbon  
77 sequestration and storage. A further third of the studies (33%) focused on provisioning  
78 services, particularly on food production (i.e. fish). The rest of the studies (19%) mapped  
79 cultural services.

80 Linked with this increased practice of mapping ES provisioning, several recent reviews have  
81 summarised available methods used to map ES. In the following we refer to 'models' as  
82 quantitative representations of ES variables depending on abiotic, biotic and social  
83 parameters. Overall, statistical models quantifying ES supply based on relationships with  
84 biophysical and social variables are prevalent, while process models based on causal  
85 relations are still rare (Crossman et al., 2013; Egoh et al., 2012; Lautenbach et al., 2015;  
86 Martinez-Harms and Balvanera, 2012). For terrestrial ecosystems, static maps of land use  
87 and land cover are the most commonly used indicator for ES in Europe (Egoh et al., 2012)  
88 and the second most common globally (Martinez-Harms and Balvanera, 2012). This  
89 widespread application of methods with weak links to ecosystem processes leads to severe  
90 uncertainty in the mapped ES supply from national (Eigenbrod et al., 2010) to landscape  
91 (Lavorel et al., 2011) scales. More advanced approaches incorporate estimates of above-  
92 and sometimes below-ground biomass, along with vegetation type, and soil parameters for  
93 the estimation of ecosystem functions from which services are derived. Species observation  
94 data, although potentially useful for the estimation of cultural services, is used only rarely.

95 Contrasting with these statistical models, process models, with explicit description of causal  
96 relationships between driver variables and ecosystem functions and properties underpinning  
97 ES provision, have primarily been used to map climate regulation and erosion control as well  
98 as the provisioning of food, fuel and fibre. Mapping and modelling assessments for marine  
99 and coastal ES are still in their infancy (Liquete et al 2013). Considering the 27 available  
100 studies from the Web of Science, 31% of the models were geostatistical while less than 20%  
101 were process-based.

102 Beyond the limitations of specific mapping methods, the large variety of primary indicators  
103 currently used to express one single ES is a large source of uncertainty for ES maps that  
104 limits their usefulness to managers and decision makers (Egoh et al., 2012). Level of process  
105 understanding, modelling methodology and data sources are three of the critical, yet poorly  
106 understood or documented sources of uncertainty for ES maps (Grêt-Regamey et al., 2014a;  
107 Hou et al., 2013; Kandziora et al., 2013). A systematic comparison of four sets of ecosystem  
108 service maps at the continental scale for five ecosystem services (climate regulation, flood  
109 regulation, erosion protection, pollination and recreation) showed considerable disagreement  
110 among spatial patterns across Europe (Schulp et al., 2014a), attributed to differences in the  
111 mapping aim, indicator definitions, input data and mapping approaches. The four original  
112 studies encompassed a land-cover look-up approach (Burkhard et al., 2012), environmental  
113 indicator modelling (Kienast et al., 2009) and two hybrid approaches combining  
114 environmental indicators, landscape effects and process modelling (Maes et al., 2012;  
115 Schulp et al., 2008; Stürck et al., 2014; Tucker et al., 2014; van Berkel and Verburg, 2011).  
116 In addition to highlighting the need for mapmakers to clearly justify the indicators used, the  
117 methods and related uncertainties, this study provided additional support for the urgent need  
118 for better process understanding and data acquisition for ES mapping, modelling and  
119 validation. Progress on these issues will be essential to support the uptake of ES spatial  
120 assessments for national ecosystem service assessments, national accounts, land planning  
121 and broader policy and natural resource management decisions (Crossman et al., 2013;  
122 Egoh et al., 2012).

123

124 Given this context, the common use of relatively simple statistical approaches contrasts with  
125 increasing evidence on the role of biodiversity for ecosystem functioning and ecosystem  
126 services (Cardinale et al., 2012), which has been referred to as a *lack of biophysical realism*  
127 (Seppelt et al., 2011). Ecosystem service supply is related to the presence, abundance,  
128 diversity and functional characteristics of service-providing organisms (also referred to as  
129 Ecosystem Service Providers, ESP henceforth; Luck et al., 2009). Positive relationships have  
130 been found between species richness and ecosystem services such as fodder and wood  
131 production, regulation of water quality through soil nutrient retention, carbon sequestration or  
132 regulation of pest and weed species (Cardinale et al., 2012). Similarly, the presence of key  
133 coastal and marine species has been found to enhance carbon sequestration, coastal  
134 protection, food provision or water quality through nutrient retention and particle trapping  
135 (Fourqurean et al., 2012; McLeod et al., 2011; Ondiviela et al., 2014; van Zanten et al.,  
136 2014). However such observed relationships between species richness and ES often reflect  
137 species functional traits and their diversity within communities, rather than species richness  
138 per se (Diaz et al., 2007). Lastly, land/sea-scape diversity and connectivity can strongly

139 influence the ES provided by mobile organisms and vegetation (Fahrig et al., 2011;  
140 Mellbrand et al., 2011; Mitchell et al., 2015). To provide more reliable estimates of service  
141 supply capacity by ecosystems, such fundamental ecological understanding needs to be  
142 better incorporated into ES models (Bennett et al., 2015).

143  
144 This paper aims to address the biophysical realism gap in ecosystem service mapping by  
145 synthesising available approaches, models and tools, and data sources (with special  
146 reference to Europe) for mapping ecosystem services, and focusing on how the role of  
147 ecosystem service providing biota can be better incorporated. Based on a review of  
148 published mapping studies, modelling methods and associated geo-referenced metrics are  
149 classified into five categories according to the way in which the contribution of ecosystem  
150 service providing organisms is represented. This review highlights the diversity of individual  
151 methods, which increasingly combine different model categories. We end by discussing  
152 associated uncertainties and pathways towards resolving them. Our review focuses on  
153 assessment of ecosystem capacity to deliver services and does not address the social and  
154 economic aspects of ecosystem service demand.

155

156

## 157 2. Methods

158 We reviewed ES biophysical modelling approaches in the literature that incorporate  
159 descriptions of ecosystem service providers (ESP) and their contribution to ES supply. [Given](#)  
160 [our objective of analysing the merits and limitations of available models rather than](#)  
161 [producing a quantitative analysis of the state of the art](#), for terrestrial systems we did not  
162 attempt to reiterate the several systematic reviews that have already been published  
163 (Lautenbach et al., 2015; Martinez-Harms and Balvanera, 2012; Seppelt et al., 2011), while  
164 for marine systems a systematic analysis of publications was conducted. [As we aimed to](#)  
165 [assess how biophysical realism was incorporated in different approaches, we chose to](#)  
166 [classify](#) models and associated geo-referenced metrics according to the way in which the  
167 relationships between ESP and biophysical processes are represented, [using the following](#)  
168 [terminology](#): spatial proxy models, phenomenological models, [niche-based models](#), trait-  
169 based models and full process-based models (Figure 1). Briefly, spatial proxy models refer to  
170 simple models based on expert knowledge or statistical associations relating abiotic and  
171 biotic indicators to ES provision. Phenomenological models add to these by explicitly  
172 incorporating effects of land/seascape configuration through spatial processes. [Niche-based](#)  
173 models deduce ES provision from the geographic distribution of ESP, while trait-based  
174 models depict statistical relationships between ecosystem processes and indicators of ESP  
175 community functional composition. Lastly, we refer to full process-based models as those  
176 incorporating explicit representations of geochemical, physical and biotic processes  
177 underpinning ecosystem functioning.

178 For each category of models we describe and exemplify based on published studies  
179 (supported by standard model descriptions presented in Appendix 1 **Erreur ! Source du**  
180 **renvoi introuvable.**) the principles and mechanics of application of these models, with

181 specific reference to how ESP are represented. Main biodiversity components for ESP  
182 characterisation and the strengths and weaknesses of different model types for practice are  
183 summarised in Table 1. Table 2 summarises main data sources for each model type, with  
184 specific reference to Europe for terrestrial (Table 2a) and marine (Table 2b) systems  
185 respectively. Lastly, key data sources and strengths and weaknesses for practice are  
186 discussed.

187

188

## 189 **3. Results**

190

### 191 **3.1. Proxy models**

192 We define proxy models as models that relate ES indicators to land or marine cover, abiotic  
193 and possibly biotic variables by way of calibrated empirical relationships or expert  
194 knowledge. It is desirable, and in practice most common for such models to use selected  
195 proxy variables that are based on well-known causal relationships between environmental  
196 variables (Kienast et al., 2009; Martinez-Harms and Balvanera, 2012). In proxy models  
197 habitat type (or biotope) or (more rarely) species composition are considered as the ESP.  
198 Most commonly land cover types, ranging from coarse vegetation types (e.g. evergreen vs.  
199 deciduous forest) to detailed habitat types such as those of the European Union's Habitats  
200 Directive, are associated with levels of ES supply, with the possible incorporation of  
201 additional environmental modifiers (e.g. altitude, soil type, climate...). Likewise, for marine  
202 ecosystems different habitat types depending on bathymetry or substrate may be used to  
203 model ES associated with the presence or activity of particular species.

204 One simple, and often used method consists in combining look-up tables allocating ES  
205 values per land cover with modifying categorical variables describing abiotic factors and  
206 ecological integrity (Burkhard et al., 2012). For example, in the Austrian Stubai valley,  
207 Schirpke et al. (2013) combined maps of vegetation types with measures of ES to map past,  
208 current or future fodder quantity and quality, carbon sequestration, soil stability, natural  
209 hazard regulation and aesthetic value. In traditional forest landscapes of Lapland, Vihervaara  
210 et al. (2010) illustrated how multiple biophysical and social data sources can be combined to  
211 quantify regulation service supply by different biotopes. In marine ecosystems, bathymetry,  
212 habitat distribution, sediment type, wave and currents regime, tidal range and water  
213 temperature are most frequently used proxies. Liqueste et al. (2013) developed a proxy-based  
214 model to assess coastal protection at European level based on 14 biophysical and  
215 socioeconomic variables describing coastal protection capacity, coastal exposure and  
216 demand for protection. Statistical models developed from observations or analysis of regional  
217 data sets may also be applied. Multiple regression models, Generalized Additive Models  
218 (Yee and Mitchell, 1991) or more sophisticated methods for capturing uncertainty in  
219 relationships, such as Bayesian modelling (Grêt-Regamey et al., 2013) may be used here. In  
220 general, the application of models developed at larger scale to smaller extents and greater  
221 resolution generates uncertainty as they do not capture context-dependent relationships

222 (Purtauf et al., 2005) and the effects of finer-grained relevant variables such as soils. Site-  
223 specific models may be developed based on field data collection (as encouraged by  
224 Martinez-Harms and Balvanera, 2012 – see Lavorel et al., 2011) [and on remote sensing data](#)  
225 [\(Table 2, Figure 2\)](#). On the other hand, the validity of up-scaling from site-specific models to  
226 larger spatial scales depends on whether sites represent the average conditions at the larger  
227 scale. It has further been shown by Grêt-Regamey et al. (2014b) that spatially explicit  
228 information about non-clustered, isolated ES tends to be lost at coarse resolution, mainly in  
229 less rugged terrain, which calls for finer resolution assessments in such contexts.

230 In the marine case, proxy models have generally been used to map the distribution of coastal  
231 vegetation such as mangrove coverage, which then has been used to estimate carbon  
232 sequestration and storage. In contrast, proxy models have had a limited application for the  
233 assessment of “underwater” marine ES, and we contend that this mainly reflects the  
234 limitations of remote sensing for correctly determining underwater habitat coverage.

235

## 236 **Strengths and weaknesses for practice**

237 Sophisticated proxy models have been recommended for national assessment of ecosystem  
238 services (Maes et al., 2014). They help move from a pure ‘benefit transfer’ approach based  
239 on land cover (Eigenbrod et al., 2010; MAES Tier 1), to more precise assessments (MAES  
240 Tier 2) using classic GIS methods accessible to all (Kienast et al., 2009). Also, they can be  
241 easily combined with socio-economic variables in order to provide at least first level  
242 assessments of benefits (Burkhard et al., 2012; Grêt-Regamey et al., 2008; Vihervaara et al.,  
243 2010) and allow consistent mapping of different ecosystem services, which is essential for  
244 avoiding data artefacts when studying trade-offs. Model applications are however  
245 constrained by the availability of different data layers depending on scales and regions. For  
246 instance, while effects of soil parameters on regulation services (e.g. carbon sequestration,  
247 erosion control) are well understood by scientists and practitioners, soil maps are often not  
248 available at suitably fine resolution.

249

250

## 251 **3.2. Phenomenological models**

252 Phenomenological models are based on qualitative or semi-quantitative relationships  
253 between ESP and ES supply, based on an understanding of biological mechanisms  
254 underpinning ES supply. In difference to simple proxy models, at least part of the parameters  
255 and relationships are transferred from in-depth process-based studies or meta-analyses of  
256 observations. They assume, but do not represent explicitly, a mechanistic relationship  
257 between elements of the landscape, considered as ESP units, and the provisioning of ES.  
258 This often implies considering landscape configuration explicitly, contrary to simple land  
259 cover proxy models. This relationship might be represented by a functional relationship  
260 between landscape attributes and services, or might also incorporate spatial configuration.  
261 For example, the ES supply of a forest patch might depend on land cover, patch size and  
262 additional attributes such as soil quality or topography. However, quantitative biodiversity  
263 indicators are not commonly used in this type of models that are often dominated by the



264 influence of land cover/use, although biodiversity indicators might be used, e.g. by  
265 incorporating a statistical relationship between plant or bird species richness and recreational  
266 value of a location. Typically, these approaches are used at the regional to the global scale  
267 since the assumed relationships ignore most often smaller scale details and focus on  
268 patterns emerging at coarser scales.

269 Phenomenological approaches have been applied for ecosystem services provided by  
270 mobile organisms and ecosystem services relating to lateral flows [for which consideration of](#)  
271 [spatial configuration is essential \(Mitchell et al., 2015; Verhagen et al., 2016\)](#). As a simple  
272 example of mobile ESP, in the Swiss valley of Davos, the cultural service of habitat for the  
273 protected bird species Capercaillie was modelled by combining habitat suitability criteria  
274 relating to quality and spatial pattern with GIS-modelled vegetation distribution (Grêt-  
275 Regamey et al., 2008). Phenomenological approaches that incorporate landscape  
276 configuration are commonly used to model pollination through the interplay between habitats  
277 suitable for wild pollinators and demand from insect-pollinated crops (Grêt-Regamey et al.,  
278 2014a; Lautenbach et al., 2011; Maes et al., 2011; Schulp et al., 2014b). Based on a meta-  
279 analysis by Ricketts et al. (2008) these models represent realized pollination as a decay  
280 function based on the distance between pollinator habitat and fields with pollination-  
281 dependent crops. The InvEST pollination model (Lonsdorf et al., 2009) includes the location  
282 of crops to be pollinated and the habitat quality for different pollinator species or guilds, as  
283 well as the availability of floral resources. More sophisticated versions also limit the number  
284 of cells that can be pollinated by pollinator source (Lautenbach et al., 2011), and Grêt-  
285 Regamey et al. (2014a) used knock-off thresholds based on connectivity to modulate habitat  
286 quality.

287 The assessment of water quality regulation and recreation by Lautenbach et al. (2011), and  
288 the universal soil loss equation (USLE) and related approaches (Wischmeier and Smith,  
289 1978) for the quantification of erosion control (Schirpke et al., 2013) represent examples of  
290 commonly used phenomenological approaches for ES depending on lateral flows.

291 In the marine environment phenomenological models have been rarely used, however  
292 Townsend et al. (2014) developed a method whereby services were defined from a series of  
293 principles based on ecosystem functioning and linked to marine biophysical parameters to  
294 develop ES maps for an area in New Zealand (Figure 3). Other studies have used  
295 phenomenological models to link the coverage of key habitats and their level of connectivity  
296 to fisheries production (Yee et al., 2014).

297

## 298 **Strengths and weaknesses for practice**

299 Phenomenological approaches depend on the validity of the qualitative or semi-quantitative  
300 relationships underlying the model. Typically, the required parameters are transferred from  
301 other study sites or obtained through meta-analysis. Results should therefore be interpreted  
302 as indicators of the direction or spatial variation of an effect or of the relative importance of  
303 an effect (e.g. by comparing different land use scenarios or historic land use data) rather  
304 than absolute values. The strength of the approach it incorporates land use configuration  
305 effects while requiring only limited data. It can therefore be used to get first estimates at  
306 scales where data availability is limited, such as the regional scale, or for the assessment of

307 past conditions for which required data for more sophisticated approaches will not become  
308 available.

309

### 310 **3.3. Niche-based models**

311 We define as **niche-based** models of ES models that assess ES supply based on the  
312 presence (or abundance) of ESP (often species) depending on their geographic distribution  
313 (Figure 4). ES can be modelled by aggregating distribution maps for different ESP if there  
314 are more than one contributing species, thus considering for instance the number of ESP  
315 species as a proxy for ES supply. A frequent limitation to such an approach is the lack of  
316 continuous distribution maps of ESP occurrence. To overcome this, Species Distribution  
317 Modelling (SDM) (Elith and Leathwick, 2009; Guisan and Thuiller, 2005) can be used to  
318 produce statistical relationships that predict the probability of occurrence of a given species  
319 (or group of species) over geographic areas depending on parameters such as climate, soil  
320 or land use, and generate continuous distribution maps of these taxa. There are also more  
321 sophisticated, mechanistic models, which (akin to full process models – see below) model  
322 species distributions based on physiological mechanisms (e.g. temperature tolerance  
323 thresholds, temperature responses), phenology (the timing of specific life cycle events such  
324 as bud burst or flowering in plants) or animal behaviour. The contribution of e.g. different  
325 species or functional groups to the ES of interest is assessed based on specific traits (e.g.  
326 trophic guilds) or expert knowledge.

327 **Niche-based** models may in particular apply to cultural services provided by well-identified  
328 species (e.g. protected species, species of particular aesthetic value) or to provisioning  
329 services by particular species such as in the case of wild foods (Schulp et al., 2014c). In  
330 Mediterranean regions provisioning services such as timber, fuelwood or cork production can  
331 be related to the presence of particular species (e.g. *Fagus sylvatica* or *Quercus ilex*, or  
332 *Quercus suber* respectively) and to forest species richness (Vilà et al., 2007; von Essen,  
333 2015), while spiritual and aesthetic values are supported by *Quercus suber* and *Pinus*  
334 *halepensis*, and the regulation of fire hazards is promoted by *Quercus suber* but negatively  
335 affected by *Pinus halepensis* (Lloret et al., 2003). **Niche-based** modelling was applied to  
336 model biocontrol of vertebrate and invertebrate pests by terrestrial vertebrates (birds,  
337 mammals, reptiles) in Europe, considering predator species richness as a proxy for  
338 biocontrol potential (Civantos et al., 2012). As SDMs enable the projection of ESP  
339 distribution under changing environmental conditions, this approach showed that under  
340 future climate change scenarios pest control would be substantially reduced, especially in  
341 southern European countries, whereas in much of central and northern Europe climate  
342 change would likely to benefit pest-control providers. In coastal and marine environments  
343 **niche-based** models have been primarily used to model the distribution of mangroves and  
344 thus their carbon capture and storage capacity (Hutchison et al., 2014; Sunny and Juha,  
345 2014) and fisheries production, based on species distribution models (Jordan et al., 2012).

346 In principle, any method of aggregation is possible, although so far species richness for ESP  
347 (i.e. added contributing species) has been considered as the proxy for ES without applying  
348 any weighting to different species. Though in their infancy, approaches considering  
349 relationships between taxonomic, phylogenetic and functional diversity and their links to ES

350 (Flynn et al., 2011) are good candidates to expand existing ones. These approaches build on  
351 the premise that since functional diversity, or functional composition tend to be better related  
352 to ES supply than species richness or diversity (Cardinale et al., 2012), then [niche-based](#)  
353 models of species distributions could be translated to functional diversity in order to generate  
354 projections of ES. The incorporation of phylogenetic diversity, which can be easily computed  
355 based on taxonomic data granted the availability of phylogenetic data (e.g. Thuiller et al.,  
356 2011), adds a further means to approach functional diversity and thereby to quantify ES  
357 (Cadotte et al., 2009).

358

### 359 [Strengths and weaknesses for practice](#)

360 Overall, [niche-based](#) modelling of species distributions is a well-developed approach with  
361 free accessible tools, suitable for future scenario projections (.e.g BIOMOD: Thuiller et al.,  
362 2009; Maxent: Elith et al., 2011). Species distribution data are often the critical bottleneck for  
363 [niche-based](#) approaches. Limitations of SDM and strengths and weaknesses of different  
364 distribution modelling methods have been discussed extensively (e.g. Bellard et al., 2012;  
365 Elith and Leathwick, 2009), and improvements proposed (Zurell et al., 2016). Apart from the  
366 intrinsic limitations of the approach, such as ignoring population dynamics, species  
367 interactions, or potential adaptive responses, the main avenue for improvement towards the  
368 application to ES modelling regards the understanding and quantitative specification of  
369 relationships between ESP and ES supply. This gap requires both greater ecological  
370 understanding (Cardinale et al., 2012; Nagendra et al., 2013), and research into the demand  
371 for ES in terms of the identities and relative weights of contributing species.

372

373

## 374 **3.4. Trait-based models**

375 There is increasing evidence for the relevance of traits of organisms as ES providers (De  
376 Bello et al., 2010; Lavorel, 2013; Luck et al., 2009). Trait-based models quantify ES supply  
377 based on statistical, quantitative relationships between an ecosystem property underpinning  
378 ES supply and trait-based metrics, as well as, if significant additional effects of abiotic  
379 parameters such as climate or soil variables (Gardarin et al., 2014; Lavorel et al., 2011).  
380 (Lavorel et al., 2011) demonstrated that trait-based models reduce uncertainty in ES  
381 prediction over space as compared to models based on land use alone, or even land use  
382 and soil variables (Eigenbrod et al., 2010; Martinez-Harms and Balvanera, 2012). Such  
383 models are constructed based on empirical measures of ecosystem functioning, which are  
384 then related to explanatory variables including: land cover/use, trait-based metrics  
385 quantifying functional diversity of ESP (Mouchet et al., 2010), soil variables and, for regional  
386 to continental scale or topographically complex landscapes climate / microclimate variables.  
387 Models may combine metrics for several individual traits, e.g. plant height and leaf nitrogen  
388 concentration to model grassland productivity (Lavorel et al., 2011); or use multi-trait metrics  
389 such as a compound index of different traits, e.g. the leaf economics spectrum (Laliberté and  
390 Tylianakis, 2012; Lienin and Kleyer, 2012; Mokany et al., 2008) or multivariate trait diversity  
391 (e.g. Conti and Diaz, 2013; Mokany et al., 2008). A review of known relationships between

392 indicators of ecosystem biogeochemical functioning for plants, relevant to the modelling of  
393 ES such as for instance fodder or timber production, climate regulation through carbon  
394 sequestration or the maintenance of water quality, suggested that, for available studies so  
395 far, community mean values of single traits tended to capture most of the variance in these  
396 ecosystem properties (Lavorel, 2013). The recent extension to ES associated with other  
397 biota such as soil fauna and microorganisms (Mulder et al., 2013), insects (Ibanez, 2012;  
398 Moretti et al., 2013), terrestrial vertebrates (Luck et al., 2012), aquatic invertebrates  
399 (Engelhardt, 2006) or marine fish (Albouy et al., 2013) holds high promises. Multitrophic trait-  
400 based models quantify ecosystem services resulting from the interaction between several  
401 trophic levels such as pollination, biotic control of pests and weeds or maintenance of soil  
402 fertility (Grigulis et al., 2013; Lavorel et al., 2013a). These models capture not only the effects  
403 of environmental change on ES via their effects on e.g. plant traits, but by also integrating the  
404 traits that underpin biotic interactions between plants and other organisms such as  
405 pollinators (Pakeman and Stockan, 2013), herbivores (Ibanez et al., 2013), or soil  
406 microorganisms (de Vries et al., 2012; Legay et al., 2014), and their effects of ES supply  
407 (Grigulis et al., 2013; Moretti et al., 2013). In principle, and similar to [niche-based](#) models, a  
408 wide range of modelling methods are suitable, although selected methods must allow  
409 spatially-extensive extrapolation over space for which explanatory variables are available,  
410 and preferably across time under scenarios.

411 As an example, models of mountain grassland ES supply were developed based on plant  
412 traits (Lavorel et al., 2011), and further complemented by traits of soil microorganisms  
413 (Grigulis et al., 2013). In these models which focused principally on components of carbon  
414 and nutrient cycling, ecosystem properties were linked to plant height and easily  
415 measureable leaf traits such as dry matter content and nitrogen concentration, with additional  
416 effects of soil parameters. Both traits and soil parameters were related to grassland  
417 management to produce ES maps (Figure 5). These models were also applied to project  
418 effects of combined climate and socio-economic scenarios translated into grassland  
419 management projections and parameterised from observations and experiments (Lamarque  
420 et al., 2014).

421 The initial construction of trait-based ES models requires observational or experimental data  
422 sets measuring ecosystem properties underpinning ES supply along with community  
423 composition of ESP. ESP community composition can then be combined with original, site-  
424 level trait data, or data extracted from trait data bases, but considering uncertainties resulting  
425 from intraspecific trait variability (Kazakou et al., 2013; Violle et al., 2012). Scenario  
426 projections can be parameterised by combining projected values for land use and  
427 environmental parameters with new community-level trait values calculated based on  
428 species compositional turnover from e.g. state-and-transition models (Quétier et al., 2007)  
429 and on intraspecific variability measured along environmental gradients (Albert et al., 2010)  
430 or through experiments (Jung et al., 2014).

431 Increasing trait data availability through communal data bases and remote sensing offers  
432 high promises for the development of trait-based models of ES (Table 2a). There are definite  
433 geographic gaps, but overall European vegetation tends to be increasingly well covered,  
434 although more extreme environments such as Mediterranean or alpine, where intraspecific

435 variability hinders the use of data measured in more temperate regions, still require collection  
436 efforts.

437

### 438 **Strengths and weaknesses for practice**

439 Although trait-based models of ES supply are in their infancy they rely on rapidly increasing  
440 conceptual and empirical evidence. Such models also provide a mechanistic basis for the  
441 understanding of biophysical bundles and trade-offs in ES supply (Lavorel and Grigulis,  
442 2012; Mouillot et al., 2011). The existence of so called ‘response – effects overlaps’ (Lavorel  
443 and Garnier, 2002; Suding et al., 2008) enables mechanistic ES projections under future  
444 scenarios using relatively simple models (Lamarque et al., 2014). As with any statistical  
445 model however, the greatest care should be taken when attempting to apply such models  
446 beyond the parameter space for which they were derived. So far trait-based ES models have  
447 rarely been validated across sites, although inter-site analyses have identified generic trait-  
448 based models of fodder production, fodder digestibility and litter decomposability (Fortunel et  
449 al., 2009; Gardarin et al., 2014; Lavorel et al., 2013b), and the model by Gardarin et al.  
450 (2014) was applied to map fodder quality at national scale (Violle et al., 2015). Lastly, trait-  
451 based models will become increasingly attractive as trait data bases become more generally  
452 available, although the lack of soil data layers in many regions will remain problematic.

453

### 454 **3.5. Full process-based models**

455 Full process-based models of (terrestrial) ecosystems rely on the explicit representation,  
456 using mathematical formulations, of ecological, physical, and biogeochemical processes that  
457 determine the functioning of ecosystems. The predictive algorithms simulate a large range of  
458 variables, which can then be post-processed to quantify ES. Process-based models have  
459 been most widely applied to quantify i) climate regulation (Bayer et al., 2015; Duarte et al.,  
460 2013; Metzger et al., 2008; Naidoo et al., 2008; Ooba et al., 2012; Watanabe and Ortega,  
461 2014), ii) water supply, water quality, flood and erosion regulation (Gedney et al., 2006;  
462 Lautenbach et al., 2012a; Lautenbach et al., 2013; Logsdon and Chaubey, 2013), iii) food,  
463 fodder, and bioenergy provision (Bateman et al., 2013; Beringer et al., 2011; Lindeskog et  
464 al., 2013; Müller et al., 2014), iii) natural hazard regulation (Elkin et al., 2013), but also in the  
465 wider frame of habitat characterisation (Hickler et al., 2012; Huntingford et al., 2011). Here,  
466 we discriminate between large-scale and local to landscape scale process-based models.

467 [Appendix 1 lists examples using Dynamic Vegetation Models \(DVM\) \(LPJ-GUESS and](#)  
468 [LPJmL: Bondeau et al., 2007; Sibyll et al., 2013; Sitch et al., 2003; Smith et al., 2001\), Earth](#)  
469 [System Models \(ESM\) \(JULES and ORCHIDEE: Cox, 2001, Krinner et al., 2005; Zaehle and](#)  
470 [Friend, 2010\), hydrological models \(SWAT and others: Neitsch et al., 2005; Stürck et al.,](#)  
471 [2014\), forest dynamic models \(e.g. Elkin et al., 2013; Bugmann, 1996\) and models for](#)  
472 [ecological restoration \(e.g. Chen and Twilley, 1998; Duarte et al., 2013\). Figure 6 represents](#)  
473 [the typical steps of ES assessments with process-based models and possible mapping](#)  
474 [outputs.](#)

475



## 476 Large-scale process models

477 Several large-scale process models have been used for ES quantification. Dynamic  
478 Vegetation Models (DVMs) and Earth System Models (ESMs) are large-scale models that  
479 provide functional representations of plant and ecosystem processes that are universal  
480 rather than specific to one biome or region (Prentice and Cowling, 2013). Hydrological  
481 models represent water-related processes within river catchments (Gudmundsson et al.,  
482 2012). Global models typically apply a spatial resolution of  $0.5^\circ \times 0.5^\circ$ , but can be run at finer  
483 resolution, or even ecosystem scale if the required drivers are available. In that case, model  
484 adjustment might be necessary (e.g. re-calibration, re-formulation to better account for  
485 important processes of the region). Applications of these models that include a  
486 representation of regional specific features are often designed for local to regional scale  
487 application, like forest dynamic models and crop models.

488 This type of models uses a set of process formulations for representing key biogeochemical  
489 and physical processes as a function of prevailing atmospheric  $\text{CO}_2$  concentration, climate,  
490 soil characteristics and eventually land use and management or nutrient deposition.  
491 Vegetation is represented as a mixture of plant functional types (PFTs) or species that are  
492 distinct in terms of bioclimatic limits and ecological parameters (see Lavorel et al., 2007;  
493 Woodward and Cramer, 1996), simulated or prescribed. Age or size classes may be  
494 distinguished, but more typically the modelled properties represent averages of the entire  
495 grid cell population of a given PFT (Prentice et al., 2007), possibly under a given  
496 management type. Soil profile is described using up to ten layers. Hydrological models  
497 consider also shallow and deep aquifer storages, and a river routing module simulates the  
498 discharge to the rivers network. "Fast" processes are modelled on a daily or sub-daily basis  
499 and include energy and gas exchange, photosynthesis, respiration and plant-soil water  
500 exchanges. Processes with seasonal dynamics such as plant phenology, growth and  
501 biomass allocation are implemented on a daily or monthly basis. Mortality, disturbance,  
502 management, are represented on an annual or sub-annual basis, eventually stochastically.  
503 By using a small number of PFTs which represent a low-dimensional continuum of plant trait  
504 combinations, process-based models generally underestimate the functional diversity of biota  
505 in favour of a manageable number of classes. Yet the rise of super computers allows to run  
506 DVMs with flexible individual traits (Sakschewski et al., 2015), making it possible to account  
507 for functional diversity.

508

509

## 510 Local to landscape scale process models

511 At local to landscape scales, forest dynamic models with similar philosophy and structure as  
512 DVMs have been used for the assessment of bundles of ecosystem services including timber  
513 production, natural hazard regulation (avalanches, rockfalls), carbon sequestration,  
514 conservation of forest diversity for greater drought resilience and habitat for protected bird  
515 species (Elkin et al., 2013; Grêt-Regamey et al., 2008; Temperli et al., 2012).

516 As another type of full-process models with strong potential for ES modelling, watershed  
517 models have been designed to simulate hydrological flows and often water quality at the

518 landscape to regional scale. Soil infiltration, surface and subsurface flows as well as  
519 evapotranspiration and snowmelt are the main hydrological processes. For modelling water  
520 quality the transport and turnover of nutrients and other chemicals need to be represented as  
521 well as soil erosion processes, along with agricultural practices. Given the importance of  
522 vegetation for the water cycle a vegetation growth model is part of all watershed models.  
523 Specifically differences between different plants (or plant functional types) are considered for  
524 water use, and in nutrient use for crops. As an example, Stürck et al. (2014) quantified the  
525 supply of flood control by running a hydrological model for a number of representative  
526 catchment types to quantify the regulating effect of different land use types in different  
527 positions in the catchments. Results were extrapolated on a European map accounting for  
528 catchment type, location in the catchment, land use and soil conditions. The soil water  
529 assessment tool (SWAT) (Neitsch et al., 2005) is an example of an advanced watershed  
530 model applied to agricultural landscapes map water purification services (Lautenbach et al.,  
531 2012a), to assess fresh water provisioning, fuel provisioning, erosion regulation and flood  
532 regulation (Logsdon and Chaubey, 2013) and to describe trade-offs between food and fodder  
533 provisioning, biofuel provisioning, water quality regulation and discharge regulation  
534 (Lautenbach et al., 2013) depending on crop rotations and crop management.

535

536 For marine ecosystems, the Ecopath with Ecosim (EwE) modelling approach supports  
537 predictions of changes in fish to evaluate ecosystem effects of fishing, explore management  
538 policy options, analyse impacts and placement of marine protected areas, predict movement  
539 and accumulation of contaminants and tracers and model the effects of environmental  
540 changes. At the core of EwE is Ecopath, a static, mass-balance snapshot of fisheries based  
541 on a set of linear equations combining net production that reflects the balance of catch,  
542 predation and other sources of mortality, migration, biomass accumulation, with respiration  
543 and unassimilated food. , The Ecosim and Ecospace modules then build on this basic mass-  
544 balance module to simulate respectively temporal dynamics using differential equations, and  
545 spatial dynamics using spatially explicit distribution of habitat types and fishing effort, along  
546 with lateral movement. Alcamo et al. (2005) applied EwE to model fish consumption and  
547 production for three important regional marine fisheries (North Benguela, Central North  
548 Pacific and Gulf of Thailand) under the four Millennium Ecosystem Assessment global  
549 scenarios, showing that for all scenarios fish catch (by weight) was maintained in North  
550 Benguela, not maintained in the Central North Pacific, whereas results were scenario-  
551 sensitive in the Gulf of Thailand. Another process-based model is available for the long-term  
552 carbon sequestration expected from seagrass restoration programmes (Duarte et al., 2013)  
553 by combining models of patch growth, patch survival in seagrass planting projects and  
554 estimates of seagrass CO<sub>2</sub> sequestration per unit area for the five seagrass species  
555 commonly used in restoration programmes. Results enable the estimation of an optimal  
556 planting density to maximise C sequestration.

557

## 558 Strengths and weaknesses for practice

559 There is a substantially overlapping set of physiological and ecological principles that is used  
560 across process-based models to represent ecosystem dynamics and matter flows, providing

561 robustness and scalability to these models for ES quantification. However, predictions of  
562 response variables, e.g. net primary productivity, vary considerably among individual large-  
563 scale models (e.g. Denman et al., 2007; Friedlingstein et al., 2006; Sitch et al., 2013). This is  
564 due to the lack of a universal set of benchmarks e.g. for terrestrial carbon cycle modelling,  
565 and the lack of consensus about several aspects of ecological processes (Prentice and  
566 Cowling, 2013). Conversely, local and landscape scale process models can be limited by  
567 detailed parameterization and calibration needs and by availability of case-specific validation  
568 data.

569 Most process models have not been designed to model ecosystem services but to model the  
570 underlying ecosystem functions from which an ecosystem service is derived directly or  
571 indirectly. The great strength of this approach is that it allows scenario analysis and if-then-  
572 else experiments if the model has been proven to capture the essential system behaviour.  
573 Because they model processes and their fundamental biological and physical interactions  
574 they also appear particularly promising for exploring mechanisms underpinning synergies  
575 and trade-offs between ES (Viglizzo et al., 2016).

576

577

## 578 **4. Discussion**

579 [Mobilising scientific understanding to assess the spatial distribution of ecosystem services is](#)  
580 [a tremendous challenge to support environmental assessment, planning and sustainable](#)  
581 [futures \(Bennett et al., 2015; Maes et al., 2016\). Because ES lie at the interface between](#)  
582 [social and environmental systems, this endeavour requires an integrated assessment of the](#)  
583 [social and ecological factors determining the production of ecosystem services \(Reyers et](#)  
584 [al., 2013; Villamagna et al., 2013\). In this review, we have focused solely on how the](#)  
585 [biophysical condition of ecosystems, as influenced by biotic, abiotic and management](#)  
586 [factors, determines ES supply, thus not considering ES demand, and how it influences ES](#)  
587 [flows and feedbacks to biophysical condition. Mapping ES demand is an even more](#)  
588 [challenging objective \(Wolff et al., 2015\), and will ultimately need to be coupled in integrated](#)  
589 [spatial ES assessments \(e.g. Schulp et al., 2014b; Schulp et al., 2014c; Stürck et al., 2014\).](#)  
590 [In the following we discuss future avenues for further improvement of the mapping of ES](#)  
591 [supply by increasing biophysical realism, but this will need proceed along with parallel](#)  
592 [progress in accounting for ES demand.](#)

593

### 594 **4.1. Future avenues for increasing biophysical** 595 **realism in ES mapping**

596 Plant and Ryan (2013) identified the lack of an 'ES toolbox' as a barrier to the adoption of ES  
597 by natural resource managers. While this paper does not attempt to produce such a tool box,  
598 it provides a basis for guiding model choice by scientists and practitioners. Here, we  
599 identified two important dimensions which enable the incorporation of greater biophysical  
600 realism in models supporting ES mapping and can be developed into different model



601 categories regardless of their baseline complexity. First, while simple land cover information  
602 is most commonly used to map ES, effects of land use configuration and land use intensity  
603 that can be captured by phenomenological models are too often ignored (Verhagen et al.,  
604 2016). Recent practice also shows the benefits of incorporating explicit land use rather than  
605 simple land cover information for the simplest proxy-based models all the way to advanced  
606 full process-based models. Second, approaches incorporating explicitly the role of ES  
607 providing biota are emerging as powerful methods to reduce uncertainty in ES mapping. This  
608 includes models quantifying individual species effects, species diversity, functional traits, and  
609 ecosystem functions described in this review, and for which tools and data are becoming  
610 increasingly available. Our review also helps the selection of appropriate methods according  
611 to spatial scale, given that scale effects have so far been poorly considered in ES research  
612 (Grêt-Regamey et al., 2014b). Review of practice highlights (1) the predominant effect of  
613 scale on model selection for practical case studies, (2) the prospect within a single case  
614 study to combine different model types, of varying complexity and detail in the representation  
615 of biotic effects, depending on specific ES of interest, skills and data / resources availability.

616 The last point highlights that our categories of methods are not necessarily exclusive and  
617 there may be more of a continuum between approaches. Hybridization is a fruitful avenue for  
618 model improvement depending on context, scale, skills and data availability. This is  
619 illustrated by a number of published examples and ongoing developments that gradually help  
620 progressing from MAES Tier 2 to Tier 3, by gradually incorporating more mechanistic  
621 approaches (Grêt-Regamey et al., 2015), and especially a greater integration of explicit  
622 biodiversity effects into mapping of ES supply. For instance, Grêt-Regamey et al. (2008)  
623 demonstrated how statistical, phenomenological and process-based models of varying level  
624 of complexity can be coupled with a GIS platform in order to assess ecosystem services at  
625 landscape scale. Stürck et al. (2014) used a hybridization between a process-based  
626 hydrological model and a spatial proxy, look-up approach to map flood regulation across  
627 Europe by determining the regulating capacity of different land use-soil combinations within a  
628 catchment. Schirpke et al. (2013) coupled the USLE phenomenological model of soil erosion  
629 with a semi-mechanistic statistical model of plant root trait effects on soil retention to quantify  
630 effects of land use change on soil stability. Large scale full-process models are also evolving  
631 towards the integration of trait-based approaches rather than using a small number of fixed  
632 Plant Functional Types. First, global vegetation models can be reformulated to incorporate  
633 plant traits and their trade-offs as drivers of vegetation distribution (Reu et al., 2011).  
634 Second, recent models have started considering direct trait-based formulation (Scheiter and  
635 Higgins, 2009; Zaehle and Friend, 2010) and/or parameterisation (Verheijen et al., 2013;  
636 Wullschleger et al., 2014). Lastly, for landscape to regional scales so-called 'hybrid' DVMs  
637 pave the way to the integration of niche-based models with dispersal models (Midgley et al.,  
638 2010) and with trait-based process models (Boulangeat et al., 2012), thereby opening new  
639 perspectives for the refinement of the trait-based modelling of ES supply under scenarios of  
640 climate change (Boulangeat et al., 2014). Together, all these recent developments illustrate  
641 how increasing fundamental understanding on the role of different facets of biodiversity for  
642 ecosystem functioning and ecosystem services (Cardinale et al., 2012) can be incorporated  
643 into the spatially explicit modelling of ecosystem service supply.

644

645 Quantifying and mapping marine ecosystem services has lagged behind efforts for terrestrial  
646 ecosystems, but this is in the process of changing (Liquete et al., 2013; Maes et al., 2012).  
647 Data and methods to assess the provision of services from the marine environment are far  
648 behind to those available for terrestrial environments (Barbier, 2012; Costanza, 1999). The  
649 gap is greatest when it comes to the mapping of ES, the main reasons behind this is the lack  
650 of high-resolution spatial information for habitat and species distribution and the incomplete  
651 understanding of ecosystem processes and functions within a highly dynamic three-  
652 dimensional environment with fluid boundaries (Maes et al., 2012). However, efforts towards  
653 mapping marine habitats are increasing. In order to rapidly move towards biophysically  
654 realistic mapping, some large fundamental knowledge gaps regarding ecosystem processes  
655 need to be resolved. First, there is a lack of information at which scales ecosystem  
656 processes and functions occur and how these relate to the provisioning of services. Second,  
657 the relationships between biodiversity and ecosystem functions in marine ecosystems are  
658 still poorly known (Bergström et al., 2015; Moore et al., 2015). The literature search on  
659 marine models/mapping conducted as part of this review highlighted a considerable number  
660 of studies which stopped at the assessment or prediction of ESP distributions without taking  
661 the next step in analysing their implications for ES provision (e.g. Albouy et al., 2013;  
662 Bergström et al., 2015; Moore et al., 2015). Although this is not an easy problem, experience  
663 from terrestrial ecosystems in the integration of biotic processes and biodiversity effects into  
664 ES quantification and mapping may speed up progress for marine and coastal ecosystems.

665

## 666 **4.2. Uncertainty and validation of spatially-explicit** 667 **models of ES supply**

668 While the importance of quantifying uncertainties and of model validation is accepted  
669 knowledge in the environmental and ecological modelling community (Bennett et al., 2012;  
670 Dormann et al., 2008; Jakeman et al., 2006; Laniak et al., 2013), these have been two  
671 enduring challenges for spatial explicit ES assessment (Crossman et al., 2013; Martinez-  
672 Harms and Balvanera, 2012; Seppelt et al., 2011).

673 Uncertainty can be conceptually separated into uncertainty about the model structure,  
674 uncertainty of model parameterization, uncertainty in the data and last but not least the  
675 conceptual uncertainty of the definition of an ecosystem service and underlying processes. In  
676 reality all these different components interact: data availability – especially at larger scales –  
677 drives in many situations the choice of proxys and the model structure for assessing an ES  
678 (Andrew et al., 2015). The use and parameterization of a model is limited by the availability  
679 of data – this can in turn lead to suboptimal decision about model structure which leads in  
680 turn to an increase in uncertainty. Choosing strongly simplified proxy-models to best match  
681 data availability may lead to ignoring the most important processes determining ecosystem  
682 service supply, and especially biotic processes. For ecosystem services that predominantly  
683 rely on mobile biota – such as pest control, or pollination - increased system understanding  
684 on how the different components of biodiversity affect ES provisioning of the services  
685 supports the development of more robust models suitable for spatial and temporal  
686 extrapolation (Kremen et al., 2007). At the same time, using the most advanced process

687 models in the absence of data to parameterise them at the desired scale does not  
688 necessarily lead to higher accuracy. Still, incorporating at least phenomenological  
689 understanding into ES models would likely increase reliability and robustness of ES  
690 assessments and maps. The use of remote sensing data to estimate ecosystem service  
691 proxies (Ayanu et al., 2012; de Araujo Barbosa et al., 2015) and to derive information on  
692 biodiversity (O'Connor et al., 2015; Schmidlein et al., 2012) (Table 2) is promising to  
693 overcome some of the data limitations, although the derivation of information from remote  
694 sensing data requires the use of additional models that bring in their own sources of  
695 uncertainty (Foody and Atkinson, 2002).

696

697 In the previous sections we have illustrated how better biodiversity process understanding  
698 can be incorporated to reduce uncertainty in ES models. The uncertainty introduced by a  
699 selected model structure can be assessed by comparing models of different structure, as  
700 recently done for species-distribution models (Buisson et al., 2009; Morin and Thuiller, 2009).  
701 Such comparisons can be used to highlight areas or situations in which models strongly  
702 agree or disagree. Schulp et al. (2014a) followed this approach by comparing ES maps from  
703 five distinct studies at the European scale, and such practice is now gaining currency to  
704 assess the value of novel model developments. Another strategy is the use of model  
705 ensembles for forecasts and assessments. This strategy which is common practice for full-  
706 process models is now spreading for [niche-based](#) and trait-based based models (e.g. Araújo  
707 and New, 2007; Gritti et al., 2013; Thuiller et al., 2009).

708

709 As the availability on species, phylogenetic and functional biodiversity increases currently,  
710 along with remote sensing derived information, data availability is likely to become less  
711 limiting for using more advanced models (Table 2). But then uncertainty in biodiversity input  
712 data could propagate in ES models (Dong et al., 2015). Researchers will then need to  
713 estimate the effects of increasing model complexity both on feasibility of parameterisation  
714 and on sensitivity to uncertainty in the input data, and to carefully assess potential  
715 mismatches in temporal and spatial scale of the new data (Orth et al., 2015; Perrin et al.,  
716 2001). First, a specific source of uncertainty in ES assessment relates to the scale of the  
717 input data. Although the selection of the modelling scale should be driven by the  
718 requirements of the end user (the scale of the decision to be made) (Grêt-Regamey et al.,  
719 2014b), data availability seriously limits the degrees of freedom for the selection of input  
720 data. There should always be a match between the resolution for ESP biota and  
721 environmental data. This in particular applies to climate, where downscaled layers need to be  
722 available or calculated for adequate species distribution or process modelling. Conversely,  
723 care should also be taken in combining high resolution soil maps with biota data with a  
724 coarser resolution (Grêt-Regamey et al., 2014b). Second extrapolating models beyond the  
725 range of calibration data is a critical source of uncertainty. Black box statistical models, e.g.  
726 some phenomenological, [niche-based](#) or trait-based models that have been (over-)fitted to  
727 data without ensuring a robust model structure are especially prone to effects of  
728 extrapolation. In general, for an analysis of temporal changes or for assessing management  
729 options the projected effects should be compared to the sensitivity of the model outputs

730 against reasonable parameter changes: if the direction of the effect changes or if the  
731 magnitude of the response is weaker than the sensitivity of the model one should hesitate to  
732 draw strong conclusions from the model. Examples for this approach can be found in  
733 (Lautenbach et al. (2011) and (Schulp et al. (2014b). It is also possible to test the sensitivity  
734 towards the uncertainty in the input data, an approach followed in Lautenbach et al. (2012b).

735

736 Thus, ES map users should be aware of the different sources of uncertainty and map  
737 creators should at least list them with respect to their application. In addition to this  
738 qualitative step a quantitative assessment of the uncertainties of model output should be  
739 given. If observed data is used for model parameterisation and calibration, it should be  
740 always possible to quantify the uncertainty attached. If no observed data is available against  
741 which model output could be compared sensitivity analysis is an option to quantify  
742 uncertainties. Lastly, validation of ES models is complicated by the fact that many ES cannot  
743 be directly measured. Water purification for example has to rely on water quality data not on  
744 measured purification rates (Lautenbach et al., 2012a). Therefore, model validation is often  
745 pattern-oriented, considering proxy-data, and tries to at least capture the system behaviour  
746 instead of specific process variables.

747

748 Ultimately, comparing the gains from improved biophysical process understanding to the  
749 possible propagation of uncertainties in biodiversity and ecosystem process data will  
750 determine the net benefits from using models of increasing biophysical complexity.

751

752

## 753 **5. Conclusion**

754 In order to achieve the ambitious political agenda for biodiversity, and to support sustainable  
755 development that both preserves and benefits from natural capital and ecosystem services,  
756 considerable progress is still needed in the practice of quantifying ecosystem service supply.  
757 Today a rich array of methods are available, especially for terrestrial systems, that enable the  
758 incorporation of biodiversity effects on ecosystem functioning into quantitative, spatially-  
759 explicit assessments of ecosystem service supply. We have summarised the main  
760 characteristics, strengths and weaknesses of different approaches for mapping ES supply,  
761 highlighting their complementarity depending on scale, assessment objectives and context,  
762 available skills and data. Review of practice illustrates the predominant effect of scale on  
763 model selection, and the ability within a single case study to combine different model types,  
764 of varying complexity and detail in the representation of biodiversity effects, depending on  
765 specific ES of interest, skills and data / resources availability. Besides, model categories are  
766 not necessarily exclusive and there may be more of a continuum between approaches.  
767 Recent model developments, with innovative hybridization across model types illustrate how  
768 increasing fundamental understanding on the role of different facets of biodiversity for  
769 ecosystem functioning and ecosystem services can be incorporated into the spatially explicit  
770 modelling of ecosystem service supply. As the availability of biodiversity data (species,  
771 phylogenetic and functional) increases and the potential for remote sensing of taxonomic and

772 functional diversity becomes realised, the application of more 'biodiversity realistic' models  
773 should be able to move to from research to practice. Considerable challenges remain for  
774 assessments to embrace good practice in model uncertainty quantification and validation, an  
775 upstream research need to still be addressed. Lastly, while the mapping of terrestrial  
776 ecosystem service supply is now reaching greater maturity, for marine ecosystems research  
777 is still in its infancy. Urgent research needs regard a better understanding of marine  
778 biodiversity effects on ecosystem functioning, and at which scales this influences ecosystem  
779 service supply. The availability of high resolution data also proves to be an obstacle that  
780 needs to be cleared before sound practice can be achieved.

781

782

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## 790 6. References

- 791
- 792 Albert, C.H., Thuiller, W., Yoccoz, N.G., Soudant, A., Boucher, F., Saccone, P., Lavorel, S.,  
793 2010. Intraspecific functional variability: extent, structure and sources of variation within a  
794 French alpine catchment. *Journal of Ecology* 98, 604-613.
- 795 Albouy, C., Velez, L., Coll, M., Colloca, F., Le Loc'h, F., Mouillot, D., Gravel, D., 2013. From  
796 projected species distribution to food-web structure under climate change. *Global Change*  
797 *Biology* 20, 730-741.
- 798 Alcamo, J., van Vuuren, D., Ringler, C., Cramer, W., Masui, T., Alder, J., Schulze, K., 2005.  
799 Changes in nature's balance sheet: Model-based estimates of future worldwide ecosystem  
800 services. *Ecology and Society* 10, 19-19.
- 801 Andrew, M.E., Wulder, M.A., Nelson, T.A., 2014. Potential contributions of remote sensing to  
802 ecosystem service assessments. *Progress in Physical Geography* 38, 328-353.
- 803 Andrew, M.E., Wulder, M.A., Nelson, T.A., Coops, N.C., 2015. Spatial data, analysis  
804 approaches, and information needs for spatial ecosystem service assessments: a review.  
805 *GIScience & Remote Sensing* 52, 344-373.
- 806 Araújo, M.B., New, M., 2007. Ensemble forecasting of species distributions. *Trends in*  
807 *Ecology & Evolution* 22, 42-47.
- 808 Ayanu, Y.Z., Conrad, C., Nauss, T., Wegmann, M., Koellner, T., 2012. Quantifying and  
809 Mapping Ecosystem Services Supplies and Demands: A Review of Remote Sensing  
810 Applications. *Environmental Science & Technology* 46, 8529-8541.
- 811 Barbier, E.B., 2012. Progress and Challenges in Valuing Coastal and Marine Ecosystem  
812 Services. *Review of Environmental Economics and Policy* 6, 1-19.
- 813 Bateman, I.J., Harwood, A.R., Mace, G.M., Watson, R.T., Abson, D.J., Andrews, B., Binner,  
814 A., Crowe, A., Day, B.H., Dugdale, S., Fezzi, C., Foden, J., Hadley, D., Haines-Young, R.,  
815 Hulme, M., Kontoleon, A., Lovett, A.A., Munday, P., Pascual, U., Paterson, J., Perino, G.,  
816 Sen, A., Siriwardena, G., van Soest, D., Termansen, M., 2013. Bringing Ecosystem Services  
817 into Economic Decision-Making: Land Use in the United Kingdom. *Science* 341, 45-50.
- 818 Bayer, A.D., Pugh, T.A.M., Krause, A., Arneith, A., 2015. Historical and future quantification  
819 of terrestrial carbon sequestration from a Greenhouse-Gas-Value perspective. *Global*  
820 *Environmental Change* 32, 153-164.
- 821 Bellard, C., Bertelsmeier, C., Leadley, P., Thuiller, W., Courchamp, F., 2012. Impacts of  
822 climate change on the future of biodiversity. *Ecology Letters* 15, 365-377.
- 823 Bennett, E.M., Cramer, W., Begossi, A., Cundill, G., Diaz, S., Egoh, B., Geijzendorffer, I.R.,  
824 Krug, C.B., Lavorel, S., Lazos, E., Lebel, L., Martín-Lopez, B., Meyfroidt, P., Mooney, H.A.,  
825 Nel, J.L., Pascual, U., Payet, K., Harguindeguy, N.P., Peterson, G., Prieur-Richard, A.-H.,  
826 Reyers, B., Roebeling, P., Seppelt, R., Solan, M., Tschakert, P., Tschardtke, T., Turner, B.L.,  
827 Verburg, P.H., Viglizzo, E.F., White, P.C.L., Woodward, G., 2015. Linking biodiversity,  
828 ecosystem services and to human well-being: Three challenges for designing research for  
829 sustainability. *Current Opinion in Environmental Sustainability* 14, 76-85.
- 830 Bennett, N.D., Croke, B.F.W., Guariso, G., Guillaume, J.H.a., Hamilton, S.H., Jakeman, A.J.,  
831 Marsili-Libelli, S., Newham, L.T.H., Norton, J.P., Perrin, C., Pierce, S.a., Robson, B., Seppelt,

832 R., Voinov, A.a., Fath, B.D., Andreassian, V., 2012. Characterising performance of  
833 environmental models. *Environmental Modelling & Software* 40, 1-20.

834 Bergström, P., Lindegarth, S., Lindegarth, M., 2015. Modeling and predicting the growth of  
835 the mussel, *Mytilus edulis*: implications for planning of aquaculture and eutrophication  
836 mitigation. *Ecology and Evolution* 5, 5920-5933.

837 Beringer, T., Lucht, W., Schaphoff, S., 2011. Bioenergy production potential of global  
838 biomass plantations under environmental and agricultural constraints. *GCB Bioenergy* 3,  
839 299-312.

840 Bondeau, A., Smith, P.C., Zähle, S., Schaphoff, S., Lucht, W., Cramer, W., Gerten, D., Lotze-  
841 Campen, H., Müller, C., Reichstein, M., Smith, B., 2007. Modelling the role of agriculture for  
842 the 20th century global terrestrial carbon balance. *Global Change Biology* 13, 679-706.

843 Boulangeat, I., Georges, D., Thuiller, W., 2014. FATE-HD: A spatially and temporally explicit  
844 integrated model for predicting vegetation structure and diversity at regional scale. *Global*  
845 *Change Biology* 20, 2368-2378.

846 Boulangeat, I., Philippe, P., Abdulhak, S., Douzet, R., Garraud, L., Lavergne, S., Lavorel, S.,  
847 Van Es, J., Vittoz, P., Thuiller, W., 2012. Optimizing plant functional groups for dynamic  
848 models of biodiversity: at the crossroads between functional and community ecology. *Global*  
849 *Change Biology* 18, 3464-3475.

850 Buisson, L., Thuiller, W., Casajus, N., Lek, S., Grenouillet, G., 2009. Uncertainty in ensemble  
851 forecasting of species distribution. *Global Change Biology* 16, 1145-1157.

852 Burkhard, B., Kroll, F., Nedkov, S., Müller, F., 2012. Mapping ecosystem service supply,  
853 demand and budgets. *Ecological Indicators* 21, 17-29.

854 Byczek, C., Longaretti, P.-Y., Lavorel, S., submitted. The benefits of recreational community-  
855 based GPS information for modelling the recreation ecosystem service. *Landscape and*  
856 *Urban Planning*.

857 Cadotte, M.W., Cavender-Bares, J., Tilman, D., Oakley, T.H., 2009. Using Phylogenetic,  
858 Functional and Trait Diversity to Understand Patterns of Plant Community Productivity. *PLoS*  
859 *One* 4, e5695.

860 Canu, D.M., Ghermandi, A., Nunes, P.A.L.D., Lazzari, P., Cossarini, G., Solidoro, C., 2015.  
861 Estimating the value of carbon sequestration ecosystem services in the Mediterranean Sea:  
862 An ecological economics approach. *Global Environmental Change-Human and Policy*  
863 *Dimensions* 32, 87-95.

864 Cardinale, B.J., Duffy, J.E., Gonzalez, A., Hooper, D.U., Perrings, C., Venail, P., Narwani, A.,  
865 Mace, G.M., Tilman, D., Wardle, D.A., Kinzig, A.P., Daily, G.C., Loreau, M., Grace, J.B.,  
866 Larigauderie, A., Srivastava, D.S., Naeem, S., 2012. Biodiversity loss and its impact on  
867 humanity. *Nature* 486, 59-67.

868 Casanoves, F., Pla, L., Di Rienzo, J.A., Díaz, S., 2011. FDiversity: a software package for  
869 the integrated analysis of functional diversity. *Methods in Ecology and Evolution* 2, 233-237.

870 Chen, R., Twilley, R.R., 1998. A gap dynamic model of mangrove forest development along  
871 gradients of soil salinity and nutrient resources. *Journal of Ecology* 86, 37-51.

872 Chytrý, M., Schaminée, J.H.J., Schwabe, A., 2011. Vegetation survey: a new focus for  
873 *Applied Vegetation Science*. *Applied Vegetation Science* 14, 435-439.

874 Civantos, E., Thuiller, W., Maiorano, L., Guisan, A., Araújo, M.B., 2012. Potential Impacts of  
875 Climate Change on Ecosystem Services in Europe: The Case of Pest Control by  
876 Vertebrates. *BioScience* 62, 658-666.

877 Conti, G., Diaz, S., 2013. Plant functional diversity and carbon storage – an empirical test in  
878 semiarid forest ecosystems. *Journal of Ecology* 101, 18-28.

879 Cornelissen, J.H.C., Lavorel, S., Garnier, E., Díaz, S., Buchmann, N., Gurvich, D.E., Reich,  
880 P.B., ter Steege, H., Morgan, H.D., van der Heijden, M.G.A., Pausas, J.G., Poorter, H., 2003.  
881 Handbook of protocols for standardised and easy measurement of plant functional traits  
882 worldwide. *Australian Journal of Botany* 51, 335-380.

883 Costanza, R., 1999. The ecological, economic, and social importance of the oceans.  
884 *Ecological Economics* 31, 199-213.

885 Cox, P., 2001. Description of the "TRIFFID" Dynamic Global Vegetation Model, Hadley  
886 Centre technical note. MetOffice.

887 Crossman, N.D., Burkhard, B., Nedkov, S., Willemen, L., Petz, K., Palomo, I., Drakou, E.G.,  
888 Martin-Lopez, B., McPhearson, T., Boyanova, K., Alkemade, R., Egoh, B., Dunbar, M.B.,  
889 Maes, J., 2013. A blueprint for mapping and modelling ecosystem services. *Ecosystem*  
890 *Services* 4, 4-14.

891 de Araujo Barbosa, C.C., Atkinson, P.M., Dearing, J.A., 2015. Remote sensing of ecosystem  
892 services: A systematic review. *Ecological Indicators* 52, 430-443.

893 De Bello, F., Lavorel, S., Díaz, S., Harrington, R., Bardgett, R., Berg, M., Cipriotti, P.,  
894 Cornelissen, H., Feld, C., Hering, D., Silva, P.M.d., Potts, S., Sandin, L., Sousa, J.P.,  
895 Storkey, J., Wardle, D., 2010. Functional traits underlie the delivery of ecosystem services  
896 across different trophic levels. *Biodiversity and Conservation* 143, 2873-2893.

897 de Vries, F.T., Manning, P., Tallowin, J.R.B., Mortimer, S.R., Pilgrim, E.S., Harrison, K.A.,  
898 Hobbs, P.J., Quirk, H., Shipley, B., Cornelissen, J.H.C., Kattge, J., Bardgett, R.D., 2012.  
899 Abiotic drivers and plant traits explain landscape-scale patterns in soil microbial  
900 communities. *Ecology Letters*, n/a-n/a.

901 Dengler, J., Jansen, F., Glöckler, F., Peet, R.K., De Cáceres, M., Chytrý, M., Ewald, J.,  
902 Oldeland, J., Lopez-Gonzalez, G., Finckh, M., Mucina, L., Rodwell, J.S., Schaminée, J.H.J.,  
903 Spencer, N., 2011. The Global Index of Vegetation-Plot Databases (GIVD): a new resource  
904 for vegetation science. *Journal of Vegetation Science* 22, 582-597.

905 Denman, K.L., Brasseur, G., Chidthaisong, A., Ciais, P., Cox, P.M., Dickinson, R.E.,  
906 Hauglustaine, D., Heinze, C., Holland, E., Jacob, D., Lohmann, U., Ramachandran, S., da  
907 Silva Dias, P.L., Wofsy, S.C., Zhang, X., 2007. Climate 2007: The Physical Science Basis, in:  
908 Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., M.Tignor, Miller, H.L.  
909 (Eds.). Cambridge University Press, Cambridge.

910 Diaz, S., Lavorel, S., De Bello, F., Quétier, F., Grigulis, K., Robson, T.M., 2007. Incorporating  
911 plant functional diversity effects in ecosystem service assessments. *Proceedings of the*  
912 *National Academy of Sciences* 104, 20684-20689.

913 Döll, P., Lehner, B., 2002. Validation of a new global 30-min drainage direction map. *Journal*  
914 *of Hydrology* 258, 214–31. doi: 10.1016/S0022-1694(01)00565-0



915 Dong, M., Bryan, B.A., Connor, J.D., Nolan, M., Gao, L., 2015. Land use mapping error  
916 introduces strongly-localised, scale-dependent uncertainty into land use and ecosystem  
917 services modelling. *Ecosystem Services* 15, 63-74.

918 Doré, T., Makowski, D., Malézieux, E., Munier-Jolain, N., Tchamitchian, M., Tiftonell, P.,  
919 2011. Facing up to the paradigm of ecological intensification in agronomy: Revisiting  
920 methods, concepts and knowledge. *European Journal of Agronomy* 34, 197-210.

921 Dormann, C.F., Purschke, O., Marquez, J.R.G., Lautenbach, S., Schroder, B., García  
922 Márquez, J.R., Schröder, B., 2008. Components of uncertainty in species distribution  
923 analysis: a case study of the Great Grey Shrike. *Ecology* 89, 3371-3386.

924 Duarte, C.M., Sintes, T., Marba, N., 2013. Assessing the CO<sub>2</sub> capture potential of seagrass  
925 restoration projects. *Journal of Applied Ecology* 50, 1341-1349.

926 European Environment Agency (EEA), 2012. CORINE Land Cover Data.

927 Egoh, B., Drakou, E.G., Dunbar, M.B., Maes, J., Willemen, L., 2012. Indicators for mapping  
928 ecosystem services: a review, JRC Scientific and Policy Reports. European Commission,  
929 Ispra, Italy, p. 113.

930 Eigenbrod, F., Armsworth, P.R., Anderson, B.J., Heinemeyer, A., Gillings, S., Roy, D.B.,  
931 Thomas, C.D., Gaston, K.J., 2010. The impact of proxy-based methods on mapping the  
932 distribution of ecosystem services. *Journal of Applied Ecology* 47, 377-385.

933 Elith, J., Leathwick, J.R., 2009. Species Distribution Models: Ecological Explanation and  
934 Prediction Across Space and Time. *Annual Review of Ecology, Evolution, and Systematics*  
935 40, 677-697.

936 Elith, J., Phillips, S.J., Hastie, T., Dudík, M., Chee, Y.E., Yates, C.J., 2011. A statistical  
937 explanation of MaxEnt for ecologists. *Diversity and Distributions* 17, 43-57.

938 Elkin, C., Gutiérrez, A.G., Leuzinger, S., Manusch, C., Temperli, C., Rasche, L., Bugmann,  
939 H., 2013. A 2 °C warmer world is not safe for ecosystem services in the European Alps.  
940 *Global Change Biology* 19, 1827-1840.

941 Engelhardt, K.A.M., 2006. Relating effect and response traits in submersed aquatic systems.  
942 *Ecological Applications* 16, 1808-1820.

943 Fader, M.M., Rost, S., Müller, C., Bondeau, A., Gerten, D., 2010. Virtual water content of  
944 temperate cereals and maize: Present and potential future patterns. *Journal of Hydrology*  
945 384, 218-231.

946 Fader, M., Von Bloh, W., Shi, S., Bondeau, A., Cramer, W., 2015. Modelling Mediterranean  
947 agro-ecosystems by including agricultural trees in the LPJmL model. *Geosci. Model Dev.* 8,  
948 3545–3561. doi:10.5194/gmd-8-3545-2015

949 Fahrig, L., Baudry, J., Brotons, L., Burel, F.G., Crist, T.O., Fuller, R.J., Sirami, C.,  
950 Siriwardena, G.M., Martin, J.-L., 2011. Functional landscape heterogeneity and animal  
951 biodiversity in agricultural landscapes. *Ecology Letters* 14, 101-112.

952 FAO/IIASA/ISRIC/ISSCAS/JRC, 2012. Harmonized World Soil Database (version 1.2).

953 Feng, X., Fu, B., Yang, X., Lü, Y., 2010. Remote Sensing of Ecosystem Services: An  
954 Opportunity for Spatially Explicit Assessment. *ResearchGate* 20, 522-535.

955 Flynn, D.F.B., Mirotnick, N., Jain, M., Palmer, M.I., Naeem, S., 2011. Functional and  
956 phylogenetic diversity as predictors of biodiversity-ecosystem-function relationships. *Ecology*  
957 92, 1573-1581.

958 Foody, G.M., Atkinson, P.M., 2002. *Front Matter, Uncertainty in Remote Sensing and GIS*.  
959 John Wiley & Sons, Ltd, pp. i-xviii.

960 Fortunel, C., Garnier, E., Joffre, R., Kazakou, E., Quested, H., Grigulis, K., Lavorel, S.,  
961 Ansquer, P., Castro, H., Cruz, P., Dolezal, J., Eriksson, O., Freitas, H., Golodets, C., Jouany, C.,  
962 Kigel, J., Kleyer, M., Lehsten, V., Leps, J., Meier, T., Pakeman, R., Papadimitriou, M.,  
963 Papanastasis, VP, Quétier, F., Robson, M., Sternberg, M., Theau, JP, Thébault, A., Zarovali, M.  
964 2009. Plant functional traits capture the effects of land use change and climate on litter  
965 decomposability of herbaceous communities in Europe and Israel. *Ecology* 90, 598-611.

966 Fourqurean, J.W., Duarte, C.M., Kennedy, H., Marba, N., Holmer, M., Mateo, M.A.,  
967 Apostolaki, E.T., Kendrick, G.A., Krause-Jensen, D., McGlathery, K.J., Serrano, O., 2012.  
968 Seagrass ecosystems as a globally significant carbon stock. *Nature Geosci* 5, 505-509.

969 Friedlingstein, P., Cox, P., Betts, R., Bopp, L., von Bloh, W., Brovkin, V., Cadule, P., Doney,  
970 S., Eby, M., Fung, I., Govindasamy, B., John, J., Jones, C., Joos, F., Kato, T., Kawamiya, M.,  
971 Knorr, W., Lindsay, K., Matthews, H.D., Raddatz, T., Rayner, P., Reick, C., Roeckner, E.,  
972 Schnitzler, K.G., Schnur, R., Strassmann, K., Weaver, A.J., Yoshikawa, C., Zeng, N., 2006.  
973 Climate-carbon cycle feedback analysis. Results from the C4MIP model intercomparison.  
974 *Journal of Climate* 19, 3337-3353.

975 Froese, R., Pauly, D., *FishBase: A Global Information System on Fishes*.

976 Fuchs, R., Herold, M., Verburg, P.H., Clevers, J.G.P.W., 2013. A high-resolution and  
977 harmonized model approach for reconstructing and analysing historic land changes in  
978 Europe. *Biogeosciences* 10, 1543–1559. doi:10.5194/bg-10-1543-2013

979 Gardarin, A., Garnier, E., Carrère, P., Cruz, P., Andueza, D., Bonis, A., Colace, M.P.,  
980 Dumont, B., Duru, M., Farrugia, A., Grigulis, K., Kernéis, E., Lavorel, S., Louault, F.,  
981 Loucougaray, G., Mesléard, F., Yaverkowski, N., Kazakou, E., 2014. Plant trait-digestibility  
982 relationships across management and climate gradients in French permanent grasslands.  
983 *Journal of Applied Ecology* 51, 1207-1217.

984 Gasc, J.P., 2004. *Atlas of amphibians and reptiles in Europe*. Societas Europaea  
985 Herpetologica, Paris.

986 Gedney, N., Cox, P.M., Betts, R.A., Boucher, O., Huntingford, C., Stott, P.A., 2006. Detection  
987 of a direct carbon dioxide effect in continental river runoff records. *Nature* 439, 835-838.

988 Grêt-Regamey, A., Bebi, P., Bishop, I.D., Schmid, W.A., 2008. Linking GIS-based models to  
989 value ecosystem services in an Alpine region. *Journal of Environmental Management* 89,  
990 197-208.

991 Grêt-Regamey, A., Brunner, S.H., Altwegg, J., Bebi, P., 2013. Facing uncertainty in  
992 ecosystem services-based resource management. *Journal of Environmental Management*  
993 127, Supplement, S145-S154.

994 Grêt-Regamey, A., Rabe, S.-E., Crespo, R., Lautenbach, S., Ryffel, A., Schlup, B., 2014. On  
995 the importance of non-linear relationships between landscape patterns and the sustainable  
996 provision of ecosystem services. *Landscape Ecology* 29, 201-212.

997 Grêt-Regamey, A., Weibel, B., Bagstad, K.J., Ferrari, M., Geneletti, D., Klug, H., Schirpke,  
998 U., Tappeiner, U., 2014. On the Effects of Scale for Ecosystem Services Mapping. PLoS  
999 ONE 9, e112601.

1000 Grêt-Regamey, A., Weibel, B., Kienast, F., Rabe, S.-E., Zilian, G., 2015. A tiered approach  
1001 for mapping ecosystem services. *Ecosystem Services* 13, 16-27.

1002 Grigulis, K., Lavorel, S., Krainer, U., Legay, N., Baxendale, C., Dumont, M., Kastl, E., Arnoldi,  
1003 C., Bardgett, R., Poly, F., Pommier, T., Schloter, M., Tappeiner, U., Bahn, M., Clément, J.-C.,  
1004 2013. Combined influence of plant and microbial functional traits on ecosystem processes in  
1005 mountain grasslands *Journal of Ecology* 101, 47-57.

1006 Gritti, E.S., Duputié, A., Massol, F., Chuine, I., 2013. Estimating consensus and associated  
1007 uncertainty between inherently different species distribution models. *Methods in Ecology and*  
1008 *Evolution* 4, 442-452.

1009 Gudmundsson, L., Wagener, T., Tallaksen, L.M., Engeland, K., 2012. Evaluation of nine  
1010 large-scale hydrological models with respect to the seasonal runoff climatology in Europe.  
1011 *Water Resources Research* 48, W11504.

1012 Guerry, A.D., Ruckelshaus, M.H., Plummer, M.L., Holland, D., 2012. Modeling benefits from  
1013 nature: using ecosystem services to inform coastal and marine spatial planning. *International*  
1014 *Journal of Biodiversity Science, Ecosystem Services & Management* 8, 14.

1015 Guisan, A., Thuiller, W., 2005. Predicting species distribution: offering more than simple  
1016 habitat models. *Ecology Letters* 8, 993-1009.

1017 Hagemeyer, W.J.M., Blair, M.J., Turnhout, C., van Bekhuis, J., Bijlsma, R., 1997. EBCC atlas  
1018 of European breeding birds : their distribution and abundance. Poyser, London.

1019 Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A.,  
1020 Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L.,  
1021 Justice, C.O., Townshend, J.R.G., 2013. High-Resolution Global Maps of 21st-Century  
1022 Forest Cover Change. *Science* 342, 850-853.

1023 Harald, K.M.B., 1996. A Simplified Forest Model to Study Species Composition Along  
1024 Climate Gradients. *Ecology* 77, 2055-2074.

1025 Hickler, T., Vohland, K., Feehan, J., Miller, P.A., Smith, B., Costa, L., Giesecke, T., Fronzek,  
1026 S., Carter, T.R., Cramer, W., Kühn, I., Sykes, M.T., 2012. Projecting the future distribution of  
1027 European potential natural vegetation zones with a generalized, tree species-based dynamic  
1028 vegetation model. *Global Ecology and Biogeography, (Global Ecol. Biogeogr.)* (2012) 21,  
1029 50–63 21, 50-63.

1030 Homolová, L., Malenovský, Z., Clevers, J.G.P.W., García-Santos, G., Schaepman, M.E.,  
1031 2013. Review of optical-based remote sensing for plant trait mapping. *Ecological Complexity*  
1032 15, 1-16.

1033 Hou, Y., Burkhard, B., Müller, F., 2013. Uncertainties in landscape analysis and ecosystem  
1034 service assessment. *Journal of Environmental Management* 127, S117-S131.

1035 Huntingford, C., Cox, P.M., Mercado, L.M., Sitch, S., Bellouin, N., Boucher, O., Gedney, N.,  
1036 2011. Highly contrasting effects of different climate forcing agents on terrestrial ecosystem  
1037 services. *Philosophical Transactions of the Royal Society A*. 369, 2026–2037.

1038 Hurtt, G.C., Chini, L.P., Frolking, S., Betts, R.A., Feddema, J., Fischer, G., Fisk, J.P.,  
1039 Hibbard, K., Houghton, R.A., Janetos, A., Jones, C.D., Kindermann, G., Kinoshita, T., Klein  
1040 Goldewijk, K., Riahi, K., Shevliakova, E., Smith, S., Stehfest, E., Thomson, A., Thornton, P.,  
1041 van Vuuren, D.P., Wang, Y.P., 2011. Harmonization of land-use scenarios for the period  
1042 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and  
1043 resulting secondary lands. *Climatic Change* 109, 117-161.

1044 Hutchison, J., Manica, A., Swetnam, R., Balmford, A., Spalding, M., 2014. Predicting Global  
1045 Patterns in Mangrove Forest Biomass. *Conservation Letters* 7, 233-240.

1046 Ibanez, S., 2012. Optimizing size thresholds in a plant–pollinator interaction web: towards a  
1047 mechanistic understanding of ecological networks. *Oecologia* 170, 233-242.

1048 Ibanez, S., Manneville, O., Miquel, C., Taberlet, P., Valentini, A., Aubert, S., Coissac, E.,  
1049 Colace, M.-P., Duparc, Q., Lavorel, S., Moretti, M., 2013. Plant functional traits reveal the  
1050 relative contribution of habitat and food preferences to the diet of four subalpine  
1051 grasshoppers. *Oecologia* 173, 1459-1470.

1052 Jakeman, A., Letcher, R., Norton, J., 2006. Ten iterative steps in development and  
1053 evaluation of environmental models. *Environmental Modelling & Software* 21, 602-614.

1054 Jardine, S.L., Siikamaeki, J.V., 2014. A global predictive model of carbon in mangrove soils.  
1055 *Environmental Research Letters* 9, 104013.

1056 Jones, K.E., Bielby, J., Cardillo, M., Fritz, S.A., O'Dell, J., Orme, C.D.L., Safi, K., Sechrest,  
1057 W., Boakes, E.H., Carbone, C., Connolly, C., Cutts, M.J., Foster, J.K., Grenyer, R., Habib,  
1058 M., Plaster, C.A., Price, S.A., Rigby, E.A., Rist, J., Teacher, A., Bininda-Emonds, O.R.P.,  
1059 Gittleman, J.L., Mace, G.M., Purvis, A., Michener, W.K., 2009. PanTHERIA: a species-level  
1060 database of life history, ecology, and geography of extant and recently extinct mammals.  
1061 *Ecology* 90, 2648-2648.

1062 Jordan, S.J., O'Higgins, T., Dittmar, J.A., 2012. Ecosystem Services of Coastal Habitats and  
1063 Fisheries: Multiscale Ecological and Economic Models in Support of Ecosystem-Based  
1064 Management. *Marine and Coastal Fisheries* 4, 573-586.

1065 Jung, V., Albert, C.H., Violle, C., Kunstler, G., Loucougaray, G., Spiegelberger, T., 2014.  
1066 Intraspecific trait variability mediates the response of subalpine grassland communities to  
1067 extreme drought events. *Journal of Ecology* 102, 45-53.

1068 Kandziora, M., Burkhard, B., Müller, F., 2013. Mapping provisioning ecosystem services at  
1069 the local scale using data of varying spatial and temporal resolution. *Ecosystem Services* 4,  
1070 47-59.

1071 Kaplan, J.O., Krumhardt, K.M., Zimmermann, N.E., 2012. The effects of land use and climate  
1072 change on the carbon cycle of Europe over the past 500 years. *Glob. Chang. Biol.* 18, 902–  
1073 914. doi:10.1111/j.1365-2486.2011.02580.x

1074 Kattge, J., Díaz, S., Lavorel, S., Prentice, I.C., Leadley, P., BÖNisch, G., Garnier, E.,  
1075 Westoby, M., Reich, P.B., Wright, I.J., Cornelissen, J.H.C., Violle, C., Harrison, S.P., Van  
1076 Bodegom, P.M., Reichstein, M., Enquist, B.J., Soudzilovskaia, N.A., Ackerly, D.D., Anand,  
1077 M., Atkin, O., Bahn, M., Baker, T.R., Baldocchi, D., Bekker, R., Blanco, C.C., Blonder, B.,  
1078 Bond, W.J., Bradstock, R., Bunker, D.E., Casanoves, F., Cavender-Bares, J., Chambers,  
1079 J.Q., Chapin Iii, F.S., Chave, J., Coomes, D., Cornwell, W.K., Craine, J.M., Dobrin, B.H.,  
1080 Duarte, L., Durka, W., Elser, J., Esser, G., Estiarte, M., Fagan, W.F., Fang, J., Fernández-

1081 MÉNdez, F., Fidelis, A., Finegan, B., Flores, O., Ford, H., Frank, D., Freschet, G.T., Fyllas,  
1082 N.M., Gallagher, R.V., Green, W.A., Gutierrez, A.G., Hickler, T., Higgins, S.I., Hodgson, J.G.,  
1083 Jalili, A., Jansen, S., Joly, C.A., Kerkhoff, A.J., Kirkup, D., Kitajima, K., Kleyer, M., Klotz, S.,  
1084 Knops, J.M.H., Kramer, K., KÜHn, I., Kurokawa, H., Laughlin, D., Lee, T.D., Leishman, M.,  
1085 Lens, F., Lenz, T., Lewis, S.L., Lloyd, J., LlusiÀ, J., Louault, F., Ma, S., Mahecha, M.D.,  
1086 Manning, P., Massad, T., Medlyn, B.E., Messier, J., Moles, A.T., MÜLLer, S.C., Nadrowski,  
1087 K., Naeem, S., Niinemets, Ü., NÖLlert, S., NÜSke, A., Ogaya, R., Oleksyn, J., Onipchenko,  
1088 V.G., Onoda, Y., OrdoÑEz, J., Overbeck, G., Ozinga, W.A., PatiÑO, S., Paula, S., Pausas,  
1089 J.G., PeÑUelas, J., Phillips, O.L., Pillar, V., Poorter, H., Poorter, L., Poschlod, P., Prinzing,  
1090 A., Proulx, R., Rammig, A., Reinsch, S., Reu, B., Sack, L., Salgado-Negret, B., Sardans, J.,  
1091 Shiodera, S., Shipley, B., Siefert, A., Sosinski, E., Soussana, J.F., Swaine, E., Swenson, N.,  
1092 Thompson, K., Thornton, P., Waldram, M., Weiher, E., White, M., White, S., Wright, S.J.,  
1093 Yguel, B., Zaehle, S., Zanne, A.E., Wirth, C., 2011. TRY – a global database of plant traits.  
1094 *Global Change Biology* 17, 2905-2935.

1095 Kazakou, E., Violle, C., Roumet, C., Navas, M.-L., Vile, D., Kattge, J., Garnier, E., 2013. Are  
1096 trait-based species rankings consistent across data sets and spatial scales? *Journal of*  
1097 *Vegetation Science* 25, 235-247.

1098 Keeling, C., Piper, S.C., Bollenbacher, A.F., Walker, J.S., 2009. Atmospheric CO2 records  
1099 from sites in the sio air sampling network. *In Trends: A Compendium of Data on Global*  
1100 *Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S.*  
1101 *Department of Energy, Oak Ridge, Tenn., U.S.A. doi: 10.3334/CDIAC/atg.035.*

1102 Kelley, D.I., Prentice, I.C., Harrison, S.P., Wang, H., Simard, M., Fisher, J.B., Willis, K.O.,  
1103 2013. A comprehensive benchmarking system for evaluating global vegetation models.  
1104 *Biogeosciences* 10, 3313-3340.

1105 Kienast, F., Bolliger, J., Potschin, M., Groot, R.S.d., Verburg, P.H., Heller, I., Wascher, D.,  
1106 Haines-Young, R., 2009. Assessing Landscape Functions with Broad-Scale Environmental  
1107 Data: Insights Gained from a Prototype Development for Europe. *Environmental*  
1108 *Management* 44, 1099–1120.

1109 Klein Goldewijk, 2005. Three centuries of global population growth: A spatial referenced  
1110 population density database for 1700 – 2000 *Population and Environment* 26, 343-367.

1111 Klein Goldewijk, K., Beusen, A., Janssen, P., 2010. Long-term dynamic modeling of global  
1112 population and built-up area in a spatially explicit way: HYDE 3.1. *The Holocene* 20, 565–  
1113 573. doi:10.1177/0959683609356587

1114 Klein Goldewijk, K., Beusen, A., Van Drecht, G., De Vos, M., 2011. The HYDE 3.1 spatially  
1115 explicit database of human-induced global land-use change over the past 12,000 years.  
1116 *Glob. Ecol. Biogeogr.* 20, 73–86. doi:10.1111/j.1466-8238.2010.00587.x

1117 Kremen, C., Williams, N.E., Aizen, M.A., Gemmill-Herren, B., LeBuhn, G., Minckley, R.,  
1118 Packer, L., Potts, S.G., Roulston, T., Steffan-Dewenter, I., Vasquez, D.P., Winfree, R.,  
1119 Adams, L., Crone, E.E., Greenleaf, S.S., Keitt, T.H., Klein, A.-M., Regetz, J., Rickletts, T.H.,  
1120 2007. Pollination and other ecosystem services produced by mobile organisms: a conceptual  
1121 framework for the effects of land-use change. *Ecology Letters* 10, 299-314.

1122 Krinner, G., Viovy, N., Noblet-Ducoudré, N.d., Ogée, J., Polcher, J., Friedlingstein, P., Ciais,  
1123 P., Sitch, S., Prentice, I.C., 2005. A dynamic global vegetation model for studies of the

1124 coupled atmosphere-biosphere system. *Global Biogeochemical Cycles* 19, GB1015,  
1125 doi:10.1029/2003GB002199.

1126 Krysanova V., Hattermann F., Wechsung F., 2005. Development of the ecohydrological  
1127 model SWIM for regional impact studies and vulnerability assessment. *Hydrological*  
1128 *Processes* 19, 763–783, doi: 10.1002/hyp.5619

1129 Kuenzer, C., Ottinger, M., Wegmann, M., Guo, H., Wang, C., Zhang, J., Dech, S., Wikelski,  
1130 M., 2014. Earth observation satellite sensors for biodiversity monitoring: potentials and  
1131 bottlenecks. *International Journal of Remote Sensing* 35, 6599-6647.

1132 Laliberté, E., Shipley, B., 2011. Measuring functional diversity (FD) from multiple traits, and  
1133 other tools for functional ecology, R package.

1134 Laliberté, E., Tylianakis, J.M., 2012. Cascading effects of long-term land-use changes on  
1135 plant traits and ecosystem functioning. *Ecology* 93, 145-155.

1136 Lamarque, J.F., Bond, T.C., Eyring, V., Granier, C., Heil, A., Klimont, Z., Lee, D., Liousse, C.,  
1137 Mieville, A., Owen, B., Schultz, M.G., Shindell, D., Smith, S.J., Stehfest, E., Van Aardenne,  
1138 J., Cooper, O.R., Kainuma, M., Mahowald, N., McConnell, J.R., Naik, V., Riahi, K., Van  
1139 Vuuren, D.P., 2010. Historical (1850-2000) gridded anthropogenic and biomass burning  
1140 emissions of reactive gases and aerosols: Methodology and application. *Atmos. Chem.*  
1141 *Phys.* 10, 7017–7039. doi:10.5194/acp-10-7017-2010

1142 Lamarque, J.-F., Kyle, G.P., Meinshausen, M., Riahi, K., Smith, S.J., van Vuuren, D.P.,  
1143 Conley, A.J., Vitt, F., 2011. Global and regional evolution of short-lived radiatively-active  
1144 gases and aerosols in the Representative Concentration Pathways. *Clim. Change* 109, 191–  
1145 212. doi:10.1007/s10584-011-0155-0

1146 Lamarque, P., Lavorel, S., Mouchet, M., Quétier, F., 2014. Plant trait-based models identify  
1147 direct and indirect effects of climate change on bundles of grassland ecosystem services.  
1148 *Proceedings of the National Academy of Sciences* 111, 13751-13756.

1149 Laniak, G.F., Olchin, G., Goodall, J., Voinov, A., Hill, M., Glynn, P., Whelan, G., Geller, G.,  
1150 Quinn, N., Blind, M., Peckham, S., Reaney, S., Gaber, N., Kennedy, R., Hughes, A., 2013.  
1151 Integrated environmental modeling: A vision and roadmap for the future. *Environmental*  
1152 *Modelling & Software* 39, 3-23.

1153 Lasseur, R., Vannier, C., Lefèbvre, J., Longaretti, P.-Y., Lavorel, S., submitted. Incorporating  
1154 interannual variability in agricultural practices for modelling the crop production ecosystem  
1155 service. *Ecological Indicators*.

1156 Lautenbach, S., Kugel, C., Lausch, A., Seppelt, R., 2011. Analysis of historic changes in  
1157 regional ecosystem service provisioning using land use data. *Ecological Indicators* 11, 676-  
1158 687.

1159 Lautenbach, S., Maes, J., Kattwinkel, M., Seppelt, R., Strauch, M., Scholz, M., Schulz-  
1160 Zunkel, C., Volk, M., Weinert, J., Dormann, C.F., 2012. Mapping water quality-related  
1161 ecosystem services: concepts and applications for nitrogen retention and pesticide risk  
1162 reduction. *International Journal of Biodiversity Science, Ecosystem Services & Management*  
1163 8, 35-49.

1164 Lautenbach, S., Mupepele, A.-C., Dormann, C.F., Lee, H., Schmidt, S., Scholte, S.S.K.,  
1165 Seppelt, R., Teeffelen, A.J.A.v., Verhagen, W., Volk, M., 2015. Blind spots in ecosystem  
1166 services research and implementation. *BioRxiv*.

1167 Lautenbach, S., Seppelt, R., Liebscher, J., Dormann, C.F., 2012. Spatial and Temporal  
1168 Trends of Global Pollination Benefit. *PLoS ONE* 7, e35954.

1169 Lautenbach, S., Volk, M., Strauch, M., Whittaker, G., Seppelt, R., 2013. Optimization-based  
1170 trade-off analysis of biodiesel crop production for managing an agricultural catchment.  
1171 *Environmental Modelling & Software* 48, 98-112.

1172 Lavorel, S., 2013. Plant functional effects on ecosystem services. *Journal of Ecology* 101, 4-  
1173 8.

1174 Lavorel, S., Diaz, S., Cornelissen, J.H.C., Garnier, E., Harrison, S.P., McIntyre, S., Pausas,  
1175 J., Pérez-Harguindeguy, N., Roumet, C., Urcelay, C., 2007. Plant functional types : are we  
1176 getting any closer to the Holy Grail ?, in: Canadell, J., Pitelka, L.F., Pataki, D. (Eds.),  
1177 *Terrestrial Ecosystems in a Changing World*. Springer-Verlag, pp. 171-186.

1178 Lavorel, S., Garnier, E., 2002. Predicting the effects of environmental changes on plant  
1179 community composition and ecosystem functioning: revisiting the Holy Grail. *Functional*  
1180 *Ecology* 16, 545-556.

1181 Lavorel, S., Grigulis, K., 2012. How fundamental plant functional trait relationships scale-up  
1182 to trade-offs and synergies in ecosystem services. *Journal of Ecology* 100, 128-140.

1183 Lavorel, S., Grigulis, K., Lamarque, P., Colace, M.-P., Garden, D., Girel, J., Douzet, R.,  
1184 Pellet, G., 2011. Using plant functional traits to understand the landscape-scale distribution  
1185 of multiple ecosystem services. *Journal of Ecology* 99, 135-147.

1186 Lavorel, S., Storkey, J., Bardgett, R.D., Bello, F.d., Berg, M.P., Roux, X.L., Moretti, M.,  
1187 Mulder, C., Díaz, S., Harrington, R., 2013. Linking functional traits of plants and other trophic  
1188 levels for the quantification of ecosystem services. *Journal of Vegetation Science* 24, 942-  
1189 948.

1190 Lavorel, S., Zupan, L., Thuiller, W., 2013. CONNECT Deliverable 1.1 Meta-database with  
1191 documentation for the synthesis of relationships between taxonomic, phylogenetic and  
1192 functional diversity.

1193 Legay, N., Baxendale, C., Krainer, U., Lavorel, S., Grigulis, K., Dumont, M., Kastl, E., Arnoldi,  
1194 C., Bardgett, R., Poly, F., Pommier, T., Schloter, M., Tappeiner, U., Bahn, M., Clément, J.-C.,  
1195 2014. The relative importance of above-ground and below-ground plant traits as drivers of  
1196 microbial properties in grasslands. *Annals of Botany* 114, 1011-1021.

1197 Lienin, P., Kleyer, M., 2012. Plant trait responses to the environment and effects on multiple  
1198 ecosystem properties. *Basic and Applied Ecology* 13, 301-311.

1199 Lindeskog, M., Arneeth, A., Bondeau, A., Waha, K., Seaquist, J., Olin, S., Smith, B., 2013.  
1200 Implications of accounting for land use in simulations of ecosystem carbon cycling in Africa.  
1201 *Earth System Dynamics* 4, 385-407.

1202 Liqueste, C., Zulian, G., Delgado, I., Stips, A., Maes, J., 2013. Assessment of coastal  
1203 protection as an ecosystem service in Europe. *Ecological Indicators* 30, 205-217.

1204 Litchman, E., Klausmeier, C.A., 2008. Trait-based community ecology of phytoplankton.  
1205 *Annual Review of Ecology and Systematics* 39, 615-639.

1206 Lloret, F., Pausas, J.G., Vilà, M., 2003. Mediterranean vegetation response to different fire  
1207 regimes in Garraf Natural Park (Catalonia, Spain): field observations and modelling  
1208 predictions. *Plant Ecology* 167, 223-236.

1209 Logsdon, R.a., Chaubey, I., 2013. A quantitative approach to evaluating ecosystem services.  
1210 *Ecological Modelling* 257, 57-65.

1211 Luck, G.W., Harrington, R., Harrison, P.A., Kremen, C., Berry, P.M., Bugter, R., Dawson,  
1212 T.P., de Bello, F., Díaz, S., Feld, C.K., Haslett, J., Hering, D., Kontogianni, A., Lavorel, S.,  
1213 Rounsevell, M., Samways, M.J., Sandin, L., Settele, J., Sykes, M.T., van den Hove, S.,  
1214 Vandewalle, M., Zobel, M., 2009. Quantifying the contribution of organisms to the provision  
1215 of ecosystem services. *Bioscience* 59, 223-236.

1216 Luck, G.W., Lavorel, S., McIntyre, S., Lumb, K., 2012. Extending trait-based frameworks to  
1217 vertebrates and improving their application to the study of ecosystem services. *Journal of*  
1218 *Animal Ecology* 81, 1065-1076.

1219 Maes, J., Egoh, B., Willemen, L., Liqueste, C., Vihervaara, P., SchÅgner, J.P., Grizzetti, B.,  
1220 Drakou, E.G., Notte, A.L., Zulian, G., Bouraoui, F., Luisa Paracchini, M., Braat, L., Bidoglio,  
1221 G., 2012. Mapping ecosystem services for policy support and decision making in the  
1222 European Union. *Ecosystem Services* 1, 31-39.

1223 Maes, J., Liqueste, C., Teller, A., Erhard, M., Paracchini, M.L., Barredo, J.I., Grizzetti, B.,  
1224 Cardoso, A., Somma, F., Petersen, J.-E., Meiner, A., Gelabert, E.R., Zal, N., Kristensen, P.,  
1225 Bastrup-Birk, A., Biala, K., Piroddi, C., Egoh, B., Degeorges, P., Fiorina, C., Santos-Martín,  
1226 F., Naruševičius, V., Verboven, J., Pereira, H.M., Bengtsson, J., Gocheva, K., Marta-  
1227 Pedroso, C., Snäll, T., Estreguil, C., San-Miguel-Ayanz, J., Pérez-Soba, M., Grêt-Regamey,  
1228 A., Lillebø, A.I., Malak, D.A., Condé, S., Moen, J., Czúcz, B., Drakou, E.G., Zulian, G.,  
1229 Laval, C., 2016. An indicator framework for assessing ecosystem services in support of the  
1230 EU Biodiversity Strategy to 2020. *Ecosystem Services* 17, 14-23.

1231 Maes, J., Paracchini, M.L., Zulian, G., 2011. A European assessment of the provision of  
1232 ecosystem services. *Towards an atlas of ecosystem services*. JRC, Ispra, Italy, p. 88.

1233 Maes, J., Teller, A., Erhard, M., al., e., 2014. Mapping and Assessment of Ecosystems and  
1234 their Services: Indicators for ecosystem assessments under Action 5 of the EU Biodiversity  
1235 Strategy to 2020, in: *Environment, E.C.D.* (Ed.).

1236 Maiorano, L., Amori, G., Capula, M., Falcucci, A., Masi, M., Montemaggiori, A., Pottier, J.,  
1237 Psomas, A., Rondinini, C., Russo, D., 2013. Threats from Climate Change to Terrestrial  
1238 Vertebrate Hotspots in Europe. *PloS one* 8, e74989.

1239 Martinez-Harms, M.J., Balvanera, P., 2012. Methods for mapping ecosystem service supply:  
1240 a review. *International Journal of Biodiversity Science, Ecosystem Services & Management*  
1241 8, 17-25.

1242 Martinez-Harms, M.J., Bryan, B.A., Balvanera, P., Law, E.A., Rhodes, J.R., Possingham,  
1243 H.P., Wilson, K.A., 2015. Making decisions for managing ecosystem services. *Biological*  
1244 *Conservation* 184, 229-238.

1245 McLeod, E., Chmura, G.L., Bouillon, S., Salm, R., Bjork, M., Duarte, C.M., Lovelock, C.E.,  
1246 Schlesinger, W.H., Silliman, B.R., 2011. A blueprint for blue carbon: toward an improved  
1247 understanding of the role of vegetated coastal habitats in sequestering CO<sub>2</sub>. *Frontiers in*  
1248 *Ecology and the Environment* 9, 552-560.



1249 Mellbrand, K., Lavery, P.S., Hyndes, G., Hambäck., P.A., 2011. Linking Land and Sea:  
1250 Different Pathways for Marine Subsidies. *Ecosystems* 14, 732-744.

1251 Metzger, M.J., Schroter, D., Leemans, R., Cramer, W., 2008. A spatially explicit and  
1252 quantitative vulnerability assessment of ecosystem service change in Europe. *Regional*  
1253 *Environmental Change* 8, 91-107.

1254 Midgley, G.F., Davies, I.D., Albert, C.H., Altwegg, R., Hannah, L., Hughes, G.O., O'Halloran,  
1255 L.R., Seo, C., Thorne, J.H., Thuiller, W., 2010. BioMove - an integrated platform simulating  
1256 the dynamic response of species to environmental change. *Ecography* 33, 1-5.

1257 Mitchell, M.G.E., Suarez-Castro, A.F., Martinez-Harms, M., Maron, M., McAlpine, C., Gaston,  
1258 K.J., Johansen, K., Rhodes, J.R., 2015. Reframing landscape fragmentation's effects on  
1259 ecosystem services. *Trends in Ecology & Evolution* 30, 190-198.

1260 Mitchell, T.D., Jones, P.D., 2005. An improved method of constructing a database of monthly  
1261 climate observations and associated high-resolution grids. *Int. J. Climatol.* 25, 693–712.  
1262 doi:10.1002/joc.1181

1263 Mitchell-Jones, A.J., Amori, G., Bogdanowicz, W., Krystufek, B., Reijnders, P.J.H.,  
1264 Spitzenberger, F., Stubbe, M., Thissen, J.B.M., Vohralik, V., Zima, J., 1999. *The Atlas of*  
1265 *European Mammals*. 250p.

1266 Mokany, K., Ash, J., Roxburgh, S., 2008. Functional identity is more important than diversity  
1267 in influencing ecosystem processes in a temperate native grassland. *Journal of Ecology* 96,  
1268 884-893.

1269 Moore, G.E., Gilmer, B.F., Schill, S.R., 2015. Distribution of Mangrove Habitats of Grenada  
1270 and the Grenadines. *Journal of Coastal Research*, 155-162.

1271 Moretti, M., Bello, F.d., Ibanez, S., Fontana, S., Pezzatti, G.B., Dziock, F., Rixen, C., Lavorel,  
1272 S., 2013. Linking traits between plants and invertebrate herbivores to track functional effects  
1273 of environmental changes. *Journal of Vegetation Science* 24, 949-962.

1274 Morin, X., Thuiller, W., 2009. Comparing niche- and process-based models to reduce  
1275 prediction uncertainty in species range shifts under climate change. *Ecology* 90, 1301-1313.

1276 Mouchet, M.A., Villéger, S., Mason, N.W.H., Mouillot, D., 2010. Functional diversity  
1277 measures: an overview of their redundancy and their ability to discriminate community  
1278 assembly rules. *Functional Ecology* 24, 867-876.

1279 Mouillot, D., Villéger, S., Scherer-Lorenzen, M., Mason, N.W.H., 2011. Functional Structure  
1280 of Biological Communities Predicts Ecosystem Multifunctionality. *PLoS One* 6, e17476.

1281 Mulder, C., Ahrestani, F.S., Bahn, M., Bohan, D.A., Bonkowski, M., Griffithsk, B.S.,  
1282 Guicharnaud, R.A., Kattge, J., Krogh, P.H., Lavorel, S., Lewis, O.T., Mancinelli, G., Naeem,  
1283 S., Peñuelas, J., Poorter, H., Reich, P.B., Rossi, L., Rusch, G.M., Sardans, J., Wright, I.J.,  
1284 2013. Connecting the Green and Brown Worlds: Allometric and Stoichiometric Predictability  
1285 of Above- and Below-Ground Networks. *Advances in Ecological Research* 49, 69-175.

1286 Müller, C., Waha, K., Bondeau, A., Heinke, J., 2014. Hotspots of climate change impacts in  
1287 sub-Saharan Africa and implications for adaptation and development. *Global Change Biology*  
1288 20, 2505-2517.

1289 Nagendra, H., Reyers, B., Lavorel, S., 2013. Impacts of land change on biodiversity: making  
1290 the link to ecosystem services. *Current Opinion in Environmental Sustainability* 5, 1-6.  
1291 <http://dx.doi.org/10.1016/j.cosust.2013.1005.1010>.

1292 Naidoo, R., Balmford, A., Costanza, R., Fisher, B., Green, R.E., Lehner, B., Malcolm, T.R.,  
1293 Ricketts, T.H., 2008. Global mapping of ecosystem services and conservation priorities.  
1294 *Proceedings of the National Academy of Sciences of the United States of America* 105,  
1295 9495-9500.

1296 Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., 2005. Soil and Water Assessment  
1297 Tool - Documentation, Version 2005.

1298 O'Connor, B., Secades, C., Penner, J., Sonnenschein, R., Skidmore, A., Burgess, N.D.,  
1299 Hutton, J.M., 2015. Earth observation as a tool for tracking progress towards the Aichi  
1300 Biodiversity Targets. *Remote Sensing in Ecology and Conservation* 1, 19-28.

1301 Ondiviela, B., Losada, I.J., Lara, J.L., Maza, M., Galván, C., Bouma, T.J., van Belzen, J.,  
1302 2014. The role of seagrasses in coastal protection in a changing climate. *Coastal*  
1303 *Engineering* 87, 158-168.

1304 Ooba, M., Fujita, T., Mizuochi, M., Murakami, S., Wang, Q., Kohata, K., 2012.  
1305 Biogeochemical model (BGC-ES) and its basin-level application for evaluating ecosystem  
1306 services under forest management practices. *Procedia Environmental Sciences* 13, 274-287.

1307 Orth, R., Staudinger, M., Seneviratne, S.I., Seibert, J., Zappa, M., 2015. Does model  
1308 performance improve with complexity? A case study with three hydrological models. *Journal*  
1309 *of Hydrology* 523, 147-159.

1310 Outeiro, L., Häussermann, V., Viddi, F., Hucke-Gaete, R., Försterra, G., Oyarzo, H., Kosiel,  
1311 K., Villasante, S., 2015. Using ecosystem services mapping for marine spatial planning in  
1312 southern Chile under scenario assessment. *Ecosystem Services* 16, 341-353.

1313 Pakeman, R.J., Stockan, J., 2013. Using plant functional traits as a link between land use  
1314 and bee foraging abundance. *Acta Oecologica* 50, 32-39.

1315 Pearman, P.B., Lavergne, S., Roquet, C., Wüest, R., Zimmermann, N.E., Thuiller, W., 2014.  
1316 Phylogenetic patterns of climatic, habitat and trophic niches in a European avian  
1317 assemblage. *Global Ecology and Biogeography* 23, 414-424.

1318 Perrin, C., Michel, C., Andréassian, V., 2001. Does a large number of parameters enhance  
1319 model performance? Comparative assessment of common catchment model structures on  
1320 429 catchments. *Journal of Hydrology* 242, 275-301.

1321 Pettorelli, N., Laurance, W.F., O'Brien, T.G., Wegmann, M., Nagendra, H., Turner, W., 2014.  
1322 Satellite remote sensing for applied ecologists: opportunities and challenges. *Journal of*  
1323 *Applied Ecology* 51, 839-848.

1324 Plant, R., Ryan, P., 2013. Ecosystem services as a practicable concept for natural resource  
1325 management: some lessons from Australia. *International Journal of Biodiversity Science,*  
1326 *Ecosystem Services & Management* 9, 44-53.

1327 Potter, C.S., Randerson, J.T., Field, C.B., Matson, P.A., Vitousek, P.M., Mooney, H.A.,  
1328 Klooster, S.A., 1993. Terrestrial ecosystem production: A process model based on global  
1329 satellite and surface data. *Global Biogeochemical Cycles* 7, 811-841.

1330 Prentice, I., Cowling, S., 2013. Encyclopedia of Biodiversity, Volume 2, 2nd ed, in: Levin,  
1331 S.A. (Ed.). Waltham, MA, Academic Press, pp. 670-689.

1332 Prentice, I.C., Bondeau, A., Cramer, W., Harrison, S., Hickler, T., Lucht, W., Sitch, S., Smith,  
1333 B., Sykes, M., 2007. Dynamic Global Vegetation Modeling: Quantifying Terrestrial  
1334 Ecosystem Responses to Large-Scale Environmental Change, in: Canadell, J.G., Pataki,  
1335 D.E., Pitelka, L.F. (Eds.). Springer Verlag, Berlin, pp. 175-192.

1336 Purtauf, T., Roschewitz, I., Dauber, J., Thies, C., Tschardt, T., Wolters, V., 2005.  
1337 Landscape context of organic and conventional farms: Influences on carabid beetle diversity.  
1338 Agriculture, Ecosystems & Environment 108, 165-174.

1339 Quétier, F., Thébault, A., Lavorel, S., 2007. Linking vegetation and ecosystem response to  
1340 complex past and present land use changes using plant traits and a multiple stable state  
1341 framework. Ecological Monographs 77, 33-52.

1342 Ramankutty, N., Foley, J.A., 1999. Estimating historical changes in global land cover:  
1343 Croplands from 1700 to 1992. Global Biogeochemical Cycles 13, 997-1027.

1344 Randerson, J.T., Hoffman, F.M., Thornton, P.E., Mahowald, N.M., Lindsay, K., Lee, Y.-H.,  
1345 Nevison, C.D., Doney, S.C., Bonan, G., Stöckli, R., Covey, C., Running, S.W., Fung, I.Y.,  
1346 2009. Systematic assessment of terrestrial biogeochemistry in coupled climate–carbon  
1347 models. Global Change Biology 15, 2462-2484.

1348 Reu, B., Proulx, R., Bohn, K., Dyke, J.G., Kleidon, A., Pavlick, R., Schmidlein, S., 2011. The  
1349 role of climate and plant functional trade-offs in shaping global biome and biodiversity  
1350 patterns. Global Ecology and Biogeography 20, 570-581.

1351 Reyers, B., Biggs, R., Cumming, G.S., Elmquist, T., Hejnowicz, A.P., Polasky, S., 2013.  
1352 Getting the measure of ecosystem services: a social–ecological approach. Frontiers in  
1353 Ecology and the Environment 11, 268-273.

1354 Ricketts, T.H., Regetz, J., Steffan, I., Cunningham, S.A., Kremen, C., Bogdanski, A.,  
1355 Gemmill-Herren, B., Greenleaf, S.S., Klein, A.M., Mayfield, M.M., Morandin, L.A., Ochieng,  
1356 A., Viana, B.F., 2008. Landscape effects on crop pollination services: are there general  
1357 patterns? Ecology Letters 11, 499-515.

1358 Rudolf B, Becker A, Schneider U, Meyer-Christoffer A, Ziese M. 2010. The new “GPCC Full  
1359 Data Reanalysis Version 5” providing high-quality gridded monthly precipitation data for the  
1360 global land- surface is public available since December 2010. GPCC Status Report  
1361 December 2010. Available at <http://gpcc.dwd.de>.

1362 Sakschewski, B., von Bloh, W., Boit, A., Rammig, A., Kattge, J., Poorter, L., Peñuelas, J.,  
1363 Thonicke, K., 2015. Leaf and stem economics spectra drive diversity of functional plant traits  
1364 in a dynamic global vegetation model. Global Change Biology 21, 2711-2725.

1365 Salmon-Monviola J., Durand P., Ferchaud F., Oehler F., Sorel L., 2012. Modelling spatial  
1366 dynamics of cropping systems to assess agricultural practices at the catchment scale.  
1367 Computers and Electronics in Agriculture 81, 1-13. doi:10.1016/j.compag.2011.10.020

1368 Salmon, S., Ponge, J.F., Gachet, S., Deharveng, L., Lefebvre, N., Delabrosse, F., 2014.  
1369 Linking species, traits and habitat characteristics of Collembola at European scale. Soil  
1370 Biology and Biochemistry 75, 73-85.

1371 Scheiter, S., Higgins, S.I., 2009. Impacts of climate change on the vegetation of Africa: an  
1372 adaptive dynamic vegetation modelling approach (aDGVM). *Global Change Biology* 15,  
1373 2224-2246.

1374 Schirpke, U., Leitinger, G., Tasser, E., Schermer, M., Steinbacher, M., Tappeiner, U., 2013.  
1375 Multiple ecosystem services of a changing Alpine landscape: past, present and future.  
1376 *International Journal of Biodiversity Science, Ecosystem Services & Management* 9, 123-  
1377 135.

1378 Schmidtlein, S., Feilhauer, H., Bruehlheide, H., 2012. Mapping plant strategy types using  
1379 remote sensing. *Journal of Vegetation Science* 23, 395-405.

1380 Schulp, C.J.E., Burkhard, B., Maes, J., Van Vliet, J., Verburg, P.H., 2014. Uncertainties in  
1381 Ecosystem Service Maps: A Comparison on the European Scale. *PLoS ONE* 9, e109643.

1382 Schulp, C.J.E., Lautenbach, S., Verburg, P.H., 2014. Quantifying and mapping ecosystem  
1383 services: Demand and supply of pollination in the European Union. *Ecological Indicators* 36,  
1384 131-141.

1385 Schulp, C.J.E., Nabuurs, G.-J., Verburg, P.H., 2008. Future carbon sequestration in  
1386 Europe—Effects of land use change. *Agriculture, Ecosystems & Environment* 127, 251-264.

1387 Schulp, C.J.E., Thuiller, W., Verburg, P.H., 2014. Wild food in Europe: a synthesis of  
1388 knowledge and data of terrestrial wild food as an ecosystem service. *Ecological Economics*  
1389 105, 292-305.

1390 Seppelt, R., Dormann, C.F., Eppink, F.V., Lautenbach, S., Schmidt, S., 2011. A quantitative  
1391 review of ecosystem service studies: approaches, shortcomings and the road ahead. *Journal*  
1392 *of Applied Ecology* 48, 630-636.

1393 Shapiro, A.C., Trettin, C.C., Kuechly, H., Alavinapanah, S., Bandeira, S., 2015. The  
1394 Mangroves of the Zambezi Delta: Increase in Extent Observed via Satellite from 1994 to  
1395 2013. *Remote Sensing* 7, 16504-16518.

1396 Sibyll, S., Ursula, H., Sebastian, O., Dieter, G., Jens, H., Wolfgang, L., 2013. Contribution of  
1397 permafrost soils to the global carbon budget. *Environmental Research Letters* 8, 014026.

1398 Sitch, S., Friedlingstein, P., Gruber, N., Jones, S.D., Murray-Tortarolo, G., Ahlström, A.,  
1399 Doney, S.C., Graven, H., Heinze, C., Huntingford, C., Levis, S., Levy, P.E., Lomas, M.,  
1400 Poulter, B., Viovy, N., Zaehle, S., Zeng, N., Arneth, A., Bonan, G., Bopp, L., Canadell, J.G.,  
1401 Chevallier, F., Ciais, P., Ellis, R., Gloor, M., Peylin, P., Piao, S., Le Quéré, C., Smith, B., Zhu,  
1402 Z., Myneni, R., 2013. Trends and drivers of regional sources and sinks of carbon dioxide  
1403 over the past two decades. *Biogeosciences Discussions* 10, 20113-20177.

1404 Sitch, S., Smith, B., Prentice, I.C., Arneth, A., Bondeau, A., Cramer, W., Kaplan, J.O., Levis,  
1405 S., Lucht, W., Sykes, M.T., Thonicke, K., Venevsky, S., 2003. Evaluation of ecosystem  
1406 dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global  
1407 vegetation model. *Global Change Biology* 9, 161-185.

1408 Smith, B., Prentice, I.C., Sykes, M.T., 2001. Representation of vegetation dynamics in the  
1409 modelling of terrestrial ecosystems: comparing two contrasting approaches within European  
1410 climate space. *Global Ecology & Biogeography* (2001) 10, 621– 637 10, 621-637.

1411 Soussana, J.-F., Fereres, E., Long, S.P., Mohren, F.G.M.J., Pandya-Lorch, R., Peltonen-  
1412 Sainio, P., Porter, J.R., Rosswall, T., von Braun, J., 2012. A European science plan to

1413 sustainably increase food security under climate change. *Global Change Biology* 18, 3269-  
1414 3271.

1415 Stürck, J., Poortinga, A., Verburg, P.H., 2014. Mapping ecosystem services: The supply and  
1416 demand of flood regulation services in Europe. *Ecological Indicators* 38, 198-211.

1417 Suding, K.N., Lavorel, S., Chapin III, F.S., Diaz, S., Garnier, E., Goldberg, D., Hooper, D.U.,  
1418 Jackson, S.T., Navas, M.L., 2008. Scaling environmental change from traits to communities  
1419 to ecosystems: the challenge of intermediate-level complexity. *Global Change Biology* 14,  
1420 1125-1140.

1421 Sunny, L.J., Juha, V.S., 2014. A global predictive model of carbon in mangrove soils.  
1422 *Environmental Research Letters* 9, 104013.

1423 Nicole K. M. Vieira, N. LeRoy Poff, Daren M. Carlisle, Stephen R. Moulton II, Marci L. Koski,  
1424 and Boris C. Kondratief, 2006, A Database of Lotic Invertebrate Traits for North America.  
1425 U.S. Geological Survey Data Series 187.

1426 Taylor, KE, Stouffer, RJ, Meehl, GA., 2012. An Overview of CMIP5 and the Experiment  
1427 Design. *Bulletin of the American Meteorological Society* 93, 485–98. doi: 10.1175/BAMS-D-  
1428 11-00094.1

1429 Temperli, C., Bugmann, H., Elkin, C., 2012. Adaptive management for competing forest  
1430 goods and services under climate change. *Ecological Applications* 22, 2065-2077.

1431 Thuiller, W., Lafourcade, B., Engler, R., Araújo, M.B., 2009. BIOMOD – a platform for  
1432 ensemble forecasting of species distributions. *Ecography* 32, 369-373.

1433 Thuiller, W., Lavergne, S., Roquet, C., Boulangeat, I., Lafourcade, B., Araujo, M.B., 2011.  
1434 Consequences of climate change on the tree of life in Europe. *Nature* 470, 531-534.

1435 Townsend, M., Thrush, S.F., Lohrer, A.M., Hewitt, J.E., Lundquist, C.J., Carbines, M.,  
1436 Felsing, M., 2014. Overcoming the challenges of data scarcity in mapping marine ecosystem  
1437 service potential. *Ecosystem Services* 8, 44-55.

1438 Tucker, G., Allen, B., Conway, M., Dickie, I., Hart, K., Rayment, M., Schulp, C.J.E., van  
1439 Teeffelen, A.J.A., 2014. Policy Options for an EU No Net Loss Initiative, Report to the  
1440 European Commission. Institute for European Environmental Policy, London, pp. 1-319.

1441 Turner, D.P., Ollinger, S.V., Kimball, J.S., 2004. Integrating Remote Sensing and Ecosystem  
1442 Process Models for Landscape- to Regional-Scale Analysis of the Carbon Cycle. *BioScience*  
1443 54, 573-584.

1444 van Berkel, D.B., Verburg, P.H., 2011. Sensitising rural policy: Assessing spatial variation in  
1445 rural development options for Europe. *Land Use Policy* 28, 447-459.

1446 van der Zanden, E.H., Verburg, P.H., Múcher, C.A., 2013. Modelling the spatial distribution of  
1447 linear landscape elements in Europe. *Ecological Indicators* 27, 125-136.

1448 van Zanten, B.T., van Beukering, P.J.H., Wagtendonk, A.J., 2014. Coastal protection by  
1449 coral reefs: A framework for spatial assessment and economic valuation. *Ocean & Coastal*  
1450 *Management* 96, 94-103.

1451 Verhagen, W., Van Teeffelen, A.J.A., Baggio Compagnucci, A., Poggio, L., Gimona, A.,  
1452 Verburg, P.H., 2016. Effects of landscape configuration on mapping ecosystem service  
1453 capacity: a review of evidence and a case study in Scotland. *Landscape Ecology*, 1-23.

1454 Verheijen, L.M., Brovkin, V., Aerts, R., Bönisch, G., Cornelissen, J.H.C., Kattge, J., Reich,  
1455 P.B., Wright, I.J., van Bodegom, P.M., 2013. Impacts of trait variation through observed trait–  
1456 climate relationships on performance of an Earth system model: a conceptual analysis.  
1457 *Biogeosciences* 10, 5497-5515.

1458 Viglizzo, E.F., Jobbágy, E.G., Ricard, M.F., Paruelo, J.M., 2016. Partition of some key  
1459 regulating services in terrestrial ecosystems: Meta-analysis and review. *Science of The Total*  
1460 *Environment* 562, 47-60.

1461 Vihervaara, P., Kumpula, T., Tanskanen, A., Burkhard, B., 2010. Ecosystem services-A tool  
1462 for sustainable management of human-environment systems. Case study Finnish Forest  
1463 Lapland. *Ecological Complexity* 7, 410-420.

1464 Vilà, M., Vayreda, J., Comas, L., Ibáñez, J.J., Mata, T., Obón, B., 2007. Species richness  
1465 and wood production: a positive association in Mediterranean forests. *Ecology Letters* 10,  
1466 241-250.

1467 Villamagna, A.M., Angermeier, P.L., Bennett, E.M., 2013. Capacity, pressure, demand, and  
1468 flow: A conceptual framework for analyzing ecosystem service provision and delivery.  
1469 *Ecological Complexity* 15, 114-121.

1470 Violle, C., Choler, P., Borgy, B., Garnier, E., Amiaud, B., Debarros, G., Diquelou, S., Gachet,  
1471 S., Jolivet, C., Kattge, J., Lavorel, S., Lemauviel-Lavenant, S., Loranger, J., Mikolajczak, A.,  
1472 Munoz, F., Olivier, J., Viovy, N., 2015. Vegetation Ecology meets Ecosystem Science:  
1473 permanent grasslands as a functional biogeography case study. *Science of the Total*  
1474 *Environment* 534, 43-51.

1475 Violle, C., Enquist, B.J., McGill, B.J., Jiang, L., Albert, C.H., Hulshof, C., Jung, V., Messier, J.,  
1476 2012. The return of the variance: intraspecific variability in community ecology. *Trends in*  
1477 *Ecology & Evolution* 27, 244-252.

1478 von Essen, M., 2015. Cork before cattle: Quantifying Ecosystem Services in the Portuguese  
1479 Montado and Questioning Ecosystem Service Mapping. Lund University Centre for  
1480 Sustainability Studies.

1481 von Haaren, C., Albert, C., 2011. Integrating ecosystem services and environmental  
1482 planning: limitations and synergies. *International Journal of Biodiversity Science, Ecosystem*  
1483 *Services & Management* 7, 150-167.

1484 Watanabe, M.D.B., Ortega, E., 2014. Dynamic emergy accounting of water and carbon  
1485 ecosystem services: A model to simulate the impacts of land-use change. *Ecological*  
1486 *Modelling* 271, 113-131.

1487 Weedon, G.P., Gomes, S., Viterbo, P., Shuttleworth, W.J., Blyth, E., Österle, H., Adam, J.C.,  
1488 Bellouin, N., Boucher, O., Best, M., 2011. Creation of the WATCH Forcing Data and Its Use  
1489 to Assess Global and Regional Reference Crop Evaporation over Land during the Twentieth  
1490 Century. *Journal of Hydrometeorology* 12, 823-848.

1491 Wicaksono, P., Danoedoro, P., Hartono, Nehren, U., 2016. Mangrove biomass carbon stock  
1492 mapping of the Karimunjawa Islands using multispectral remote sensing. *International*  
1493 *Journal of Remote Sensing* 37, 26-52.

1494 Wischmeier, W.H., Smith, D.D., 1978. Predicting rainfall erosion losses – a guide to  
1495 conservation planning. US Department of Agriculture, Washington, D.C.

1496 Wolff, S., Schulp, C.J.E., Verburg, P., 2015. Mapping ecosystem services demand: A review  
1497 of current research and future perspectives. *Ecological Indicators* 55, 159-171.

1498 Woodward, F.I., Cramer, W., 1996. Plant functional types and climatic change: Introduction.  
1499 *Journal of Vegetation Science* 7, 306-308.

1500 Wullschleger, S.D., Epstein, H.E., Box, E.O., Euskirchen, E.S., Goswami, S., Iversen, C.M.,  
1501 Kattge, J., Norby, R.J., van Bodegom, P.M., Xu, X., 2014. Plant functional types in Earth  
1502 system models: past experiences and future directions for application of dynamic vegetation  
1503 models in high-latitude ecosystems. *Annals of Botany* 114, 1-16.

1504 Yee, S.H., Dittmar, J.A., Oliver, L.M., 2014. Comparison of methods for quantifying reef  
1505 ecosystem services: A case study mapping services for St. Croix, USVI. *Ecosystem Services*  
1506 8, 1-15.

1507 Yee, T.W., Mitchell, N.D., 1991. Generalized additive models in plant ecology. *Journal of*  
1508 *Vegetation Science* 2, 587-602.

1509 Zaehle, S., Ciais, P., Friend, A.D., Prieur, V., 2011. Carbon benefits of anthropogenic  
1510 reactive nitrogen offset by nitrous oxide emissions. *Nature Geoscience* 4, 601–605.  
1511 doi:10.1038/ngeo1207

1512 Zaehle, S., Friend, A.D., 2010. Carbon and nitrogen cycle dynamics in the O-CN land  
1513 surface model: 1. Model description, site-scale evaluation, and sensitivity to parameter  
1514 estimates. *Global Biogeochem. Cycles* 24, GB1005.

1515 Zupan, L., Cabeza, M., Maiorano, L., Roquet, C., Devictor, V., Lavergne, S., Mouillot, D.,  
1516 Mouquet, N., Renaud, J., Thuiller, W., 2014. Spatial mismatch of phylogenetic diversity  
1517 across three vertebrate groups and protected areas in Europe. *Diversity and Distributions* 20,  
1518 674-685.

1519 Zurell, D., Thuiller, W., Pagel, J., Cabral, J.S., Münkemüller, T., Gravel, D., Dullinger, S.,  
1520 Normand, S., Schiffers, K.H., Moore, K.A., Zimmermann, N.E., 2016. Benchmarking novel  
1521 approaches for modelling species range dynamics. *Global Change Biology* 22, 2651-2664.

1522

1523

<b>Model type</b>	<b>MAES Tier</b>	<b>Ecosystem Service Provider representation</b>	<b>Scales</b>	<b>Skill needs</b>	<b>Data needs</b>	<b>Validation</b>	<b>Transferability in space and time</b>
<b>Proxy</b>	1	Land cover / use or vegetation type	All	Low Tools: GIS application	Low-medium	Rare	Large uncertainty if local or past / future conditions exceed those of model development and validation
<b>Phenomenological</b>	2	Landscape pattern and processes	Mainly Local-regional	Low Tools: GIS application	Low-medium	Rare	Large uncertainty if local or past / future conditions exceed those of model development and validation
<b>Niche-based</b>	2-3	Species geographic distributions	Regional - continental	Medium Tools : Maxent (Elith et al., 2011), BIOMOD (Thuiller et al., 2009)	Medium Constrained by availability of modelled species distribution or of species distribution data.	Well developed	Designed for scenario projections Current limitations: lack species interactions, demographic and evolutionary processes
<b>Trait-based</b>	3	Trait effects on ecosystem functioning, and possibly spatial trait distributions	Local – regional Extension to continental scale through remote sensing	Medium-High Lack of readily available (or validated) models. Standardized packages for calculation of trait-based indices (Casanoves et al., 2011; Laliberté and Shipley, 2011).	Medium-High Constrained by availability of trait data and environmental layers (e.g. soils)	Easy but requires local data collection	Well-adapted for scenario projections. Risk of exceeding conditions / parameter space of model development and validation
<b>Full process – large scale</b>	3	Plant Functional Types Also possibly : individual species, traits	Regional - continental - global	High Tools : Complex computer models	High Long-term climate data, information on land use/cover change and N input	Well developed using spatial databases derived from remote sensing observations or from sampling	Designed for scenario projections Risk of exceeding conditions / parameter space of model development and validation



<b>Full process – local- landscape scale</b>	3	Plant Functional Types to individual species	Local - landscape – regional	High Tools : Complex computer models	High Long-term climate data, information on land use/cover change and N input	Well developed using spatial databases derived from remote sensing observations or from sampling	Depending on data availability
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Table 1 – Strengths and weaknesses of different model types for practice. Maes tiers refer to levels of model complexity (Grêt-Regamey et al., 2015). Criteria were rated according to expert opinion and synthesis of published studies.

Model type	Primary data sources for Europe	Remote sensing data
<b>Proxy</b>	<p>Land cover maps</p> <p>Vegetation data bases (Chytrý et al., 2011). European Vegetation Archive (EVA)</p> <p>Global Index of Vegetation-Plot Databases (<a href="http://www.givd.info">http://www.givd.info</a>) (Dengler et al., 2011)</p> <p>Potential lack of data layers (e.g. soils)</p>	<p>Mapping thematic variables like Land Use/Land Cover, Vegetation, Forest, Wetland, Water, Burnt area, etc.</p> <p>Regional scale (for mapping landscape units), medium spatial resolution data like multitemporal MODIS, Spot Vegetation or MeteoSat data to follow vegetation dynamic.</p> <p>Local scale (for mapping precise thematic variables): high spatial resolution Landsat8 or Sentinelle-2 (for passive RS data), RadarSat or TerraSar (for active RS data).</p> <p>(Ayanu et al., 2012 ; Burkhard et al., 2012; Kuenzer et al., 2014 ; Pettorelli et al., 2014)</p>
<b>Phenomenological</b>	<p>Maps or proxy of landscape elements (van der Zanden et al., 2013)</p> <p>Topographic information including Digital Elevation Models: road networks, river networks (Lehner et al., 2004), coastlines (USGS HYDRO1K, 2015)</p> <p>Biophysical data including soil data (European Soil database see Panagos et al., 2012)</p>	<p>As for proxy models</p>
<b>Niche-based</b>	<p>Occurrence data for all European terrestrial vertebrate species: 187 mammals (Mitchell-Jones et al., 1999), 445 breeding birds (Hagemeijer et al., 1997), and 149 amphibians and reptiles (Gasc, 2004).</p> <p>Refined data for 275 mammals, 429 birds and 102 amphibians across the Palearctic at 300 m resolution by incorporating 46 GlobCover land use/land cover classes (Maiorano et al., 2013). Clustering at 10' by (Zupan et al., 2014).</p> <p>Extensive distribution data available for 1280 higher plants; digitized Atlas Flora Europea. Trees: exhaustive data at 1 km<sup>2</sup> resolution (<a href="http://www.efi.int/portal/virtual_library/information_services/mapping_services/tree_species_maps_for_european_forests/">http://www.efi.int/portal/virtual_library/information_services/mapping_services/tree_species_maps_for_european_forests/</a>).</p> <p>More comprehensive species distribution data available on a country per country basis, and for specific regions within a same country.</p> <p>Availability of phylogenies currently increasing, especially in Europe. Mega-phylogenies for higher plants, mammals and birds for Europe (Thuiller et al., 2011), with further complements for the Palearctic and amphibians by (Zupan</p>	<p>Texture variables like object size and shape, compactness, homogeneity/heterogeneity, neighborhood relationships, fragmentation, connectivity, relevant for plant type specification and habitats characterization.</p> <p>Global scale, Meteosat or SpotVegetation.</p> <p>Regional scale, medium spatial resolution data like multitemporal MODIS; can characterize vegetation dynamics.</p> <p>(Ayanu et al., 2012 ; Burkhard et al., 2012; Kuenzer et al., 2014 ; Pettorelli et al., 2014)</p>

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et al., 2014).

Trait data for functional diversity: see trait-based models

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### Trait-based

Community composition data – locally measured or from vegetation data bases as for proxy-based models. There are currently no public community composition data bases for animals

Site-level measurements following standard methods (Cornelissen et al., 2003).

Communal plant trait data bases, e.g. TRY (Kattge et al., 2011). More easily measurable traits such as plant size (e.g. vegetative height), leaf size, structural (e.g. Specific Leaf Area, Leaf Dry Matter Content) or chemical (e.g. C, N, P) concentrations, wood density or seed size available for many species globally. Traits requiring more time-consuming, expensive, or technically-demanding measurements, and especially root traits poorly available.

Trait data bases for birds (Pearman et al., 2014), mammals (PanTHERIA (Jones et al., 2009)), amphibians (<http://amphibiaweb.org/>), fish (FishBase (Froese and Pauly)), phytoplankton (Litchman and Klausmeier, 2008), lotic invertebrates (Nicole et al., 2006), soil invertebrates (e.g. (Salmon et al., 2014) for Collembola).

Plant/Canopy height using laser scanning (LiDAR).

Leaf phenology: satellite multi-temporal data or timelaps cameras (class by spatial resolution from coarse to fine) : AVHRR NDVI time series, MODIS, Sentinelle-2, RadarSat-2, Pleiades ; or aerial photos/hyperspectral data using airborne sensor.

Using Radiative Transfer Models (RTM), leaf mass per area (for Specific Leaf Area SLA estimation), leaf water content using RTM and/or SWIR wavelengths of RS data (for leaf dry matter content), chlorophyll content (for leaf nitrogen concentration estimation).

Methods operational at individual/population/community/ecosystem scales depending on RS data source.

(Homolová et al., 2013; Kuenzer et al., 2014)

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### Full process – large-scale

Climate forcing from observations (e.g. Mitchell and Jones, 2005, Rudolf *et al.*, 2010, Weedon *et al.*, 2011) or from a suite of climate models (e.g. CMIP5, Taylor et al., 2012)

Atmospheric CO<sub>2</sub> concentration from observations for the past and models for the future RCPs (e.g. Keeling et al., 2009).

Land-use data historical reconstructions and future scenarios (e.g., Fader et al., 2010, 2015, Hurtt et al., 2011, Kaplan et al., 2012, Klein Goldewijk et al., 2011, 2010, Ramankutty and Foley 1999).

Highly generalized classes of soil texture (e.g. by FAO/IIASA/ISRIC/ISSCAS/JRC, 2012).

Drainage direction map (e.g. Döll and Lehner, 2002) for models that apply a river routine scheme allowing for studying ecosystem services related to water flows

Global N deposition (e.g. Lamarque et al., 2010; 2011) and N fertilization of croplands (e.g. by Zaehle et al., 2011) for models accounting for C-N

1) RS data provide model inputs, 2) RS data for calibrating model parameters, 3) RS data for evaluation of models output. Models that are run for scenario studies obviously must be prognostic models that are not fed by RS data.

Frequent terrestrial indicators that are derived from RS data are e.g. Land use / Land cover, topography, phenology, gross primary production, evapotranspiration, but see the reviews in Turner et al. (2004), Andrew et al. (2014). At the global scale, the often used satellite instruments are Landsat, Meteosat, Spot-Vegetation, NOAA-AVHRR, ATSR, MISR, SeaWiFS (e.g. Ayanu et al. 2012, Kelley et al., 2013, Randerson et al., 2009).

Remote Sensing derived land use data (e.g. Hansen et al., 2013 for forest extent, loss, and gain from 2000 to 2012) are typical model inputs. Seasonal fraction of absorbed photosynthetically active radiation (fPAR) can be used as input by process-models (Potter et al., 1993), but they are also useful tools for the validation of full process-models that simulate the fPAR based on the modelling of biophysical processes (Bondeau et al., 2007; Lindeskog et al., 2013).

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	<p>interactions</p> <p>Population density maps (Klein Goldewijk, 2005; Klein Goldewijk et al. 2010) when this is required by fire disturbance modelling</p> <p>Communal plant trait data bases for PFT parameterisation, e.g. TRY (Kattge et al., 2011).</p>	
<b>Full process – local-landscape-scale</b>	<p>Input data (historical and scenarios) as for large-scale process-based models with the additional possibility for local-landscape scale data</p> <p>Climate forcing from observations (e.g. UKCP09)</p> <p>Land-use / land management data: Fuchs et al. 2013, CORINE land cover (EEA, 2012), Salmon-Monviola et al., 2012</p> <p>Detailed DEM and soil quality maps (Krysanova et al., 2005)</p>	<p>The same distinction as above between remote-sensing data for model input data or for model calibration/validation can be made.</p> <p>For vegetation mapping (like thematic variables) at the local or very local scale use of RS satellite data at 1 to 5 m spatial resolution (Worldview, Pleiades, Spot 6-7, Rapid-Eye, Quickbird, ...).</p> <p>For vegetation and soil characterization (plant diversity, heterogeneity, soil roughness, compaction, etc.), use of airborne RS data like NIR aerial photos, hyperspectral data or full-waveform LiDAR. (Feng et al., 2010)</p>

Table 2 – Data sources for parameterisation of different types of ecosystem service mapping methods, with specific reference to Europe. (a) Terrestrial ecosystems

<b>Model type</b>	<b>Primary data sources for Europe</b>	<b>Remote sensing data</b>
<b>Proxy</b>	<ul style="list-style-type: none"> <li>- Data on bathymetry, topography, slope, geomorphology, submarine habitats, emerged habitats, wave regime, tidal range, relative sea level, storm surge, population density, infrastructures, artificial surface, main cultural sites (Liquete et al., 2013)</li> <li>- Data on fishing fleet and fishing grounds distribution, value of landings, harvest rate information, price of harvested products (Guerry et al., 2012)</li> <li>- Data on stored C, rate of C accumulation in sediments, market and non-market valuation of C (Guerry et al., 2012)</li> </ul>	<ul style="list-style-type: none"> <li>LandSat images from US Geological Survey Landsat (Shapiro et al., 2015)</li> <li>EU Corinne Land Cover (Liquete et al., 2013)</li> <li>Modelled seabed habitat maps (Liquete et al., 2013)</li> <li>ALOS AVNIR-2 (Advanced Land Observation Satellite Advanced Visible and Near Infrared Radiometer type 2) (Wicaksono et al., 2016)</li> </ul>
<b>Phenomenological</b>	<ul style="list-style-type: none"> <li>- Sediment and bathymetry charts, point source contaminant data, tidal model outputs, seabed shear stress and expert information (Townsend et al., 2014)</li> </ul>	
<b>Niche-based</b>	<ul style="list-style-type: none"> <li>- WorldClim Bioclim data (Jardine and Siikamaeki, 2014)</li> <li>- Fisheries landings, effort data, habitat GIS coverages, survival rates for habitat types, salinity (Jordan et al., 2012)</li> </ul>	
<b>Trait-based</b>	<ul style="list-style-type: none"> <li>- Seagrass patch growth, patch survival in seagrass planting projects, estimates of seagrass CO<sub>2</sub> sequestration per unit area (Duarte et al., 2013)</li> </ul>	
<b>Full process – large-scale</b>	<ul style="list-style-type: none"> <li>- Submarine habitat cover (Yee et al., 2014)</li> </ul>	
<b>Full process – local-landscape-scale</b>	<ul style="list-style-type: none"> <li>- Use of biogeochemical model; Dissolved Organic Carbon; Particulated Organic Carbon; nutrients; carbonates; zooplankton; microzooplankton; phytoplankton (Canu et al., 2015)</li> </ul>	

Table 2 – Data sources for parameterisation of different types of ecosystem service mapping methods, with specific reference to Europe. (b) Marine ecosystems



## Figures

Figure 1 - Biodiversity components incorporated into different categories of models of ecosystem service supply

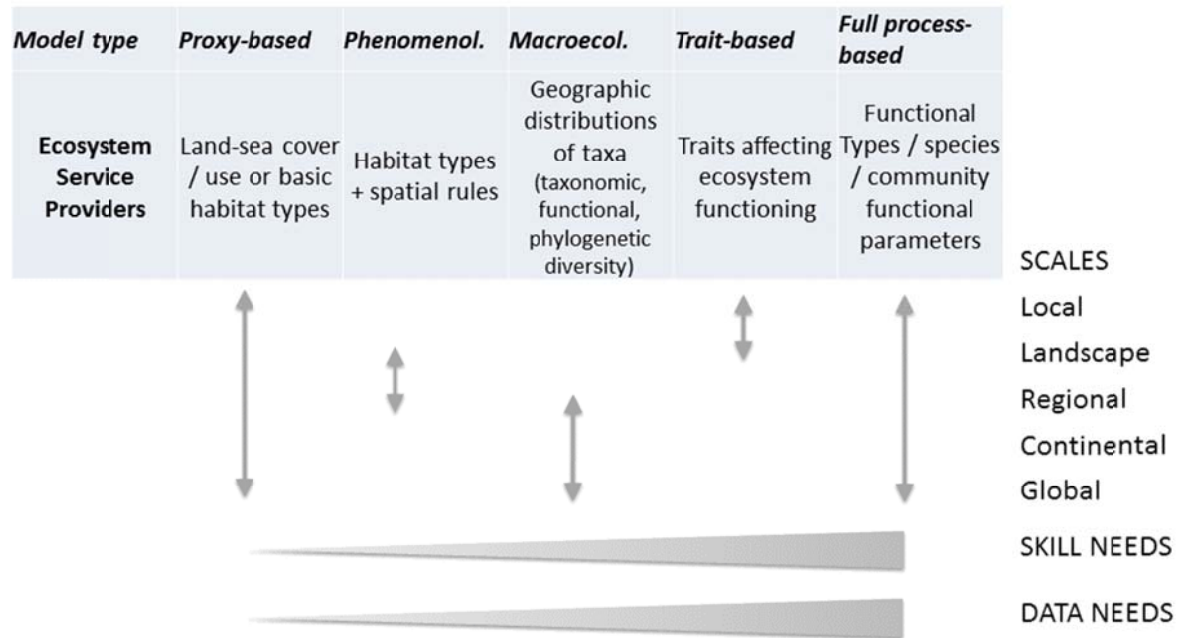


Figure 2 – Proxy-based spatial modelling of five-year average crop production (energy equivalent MG/ha) (2008-2012) for the Grenoble urban area (France). Schematic method identifying crop succession over 5 years at parcel scale using MODIS data for determining winter / spring crops based on phenology of photosynthetically active biomass. Adapted from Lasseur et al. in review.



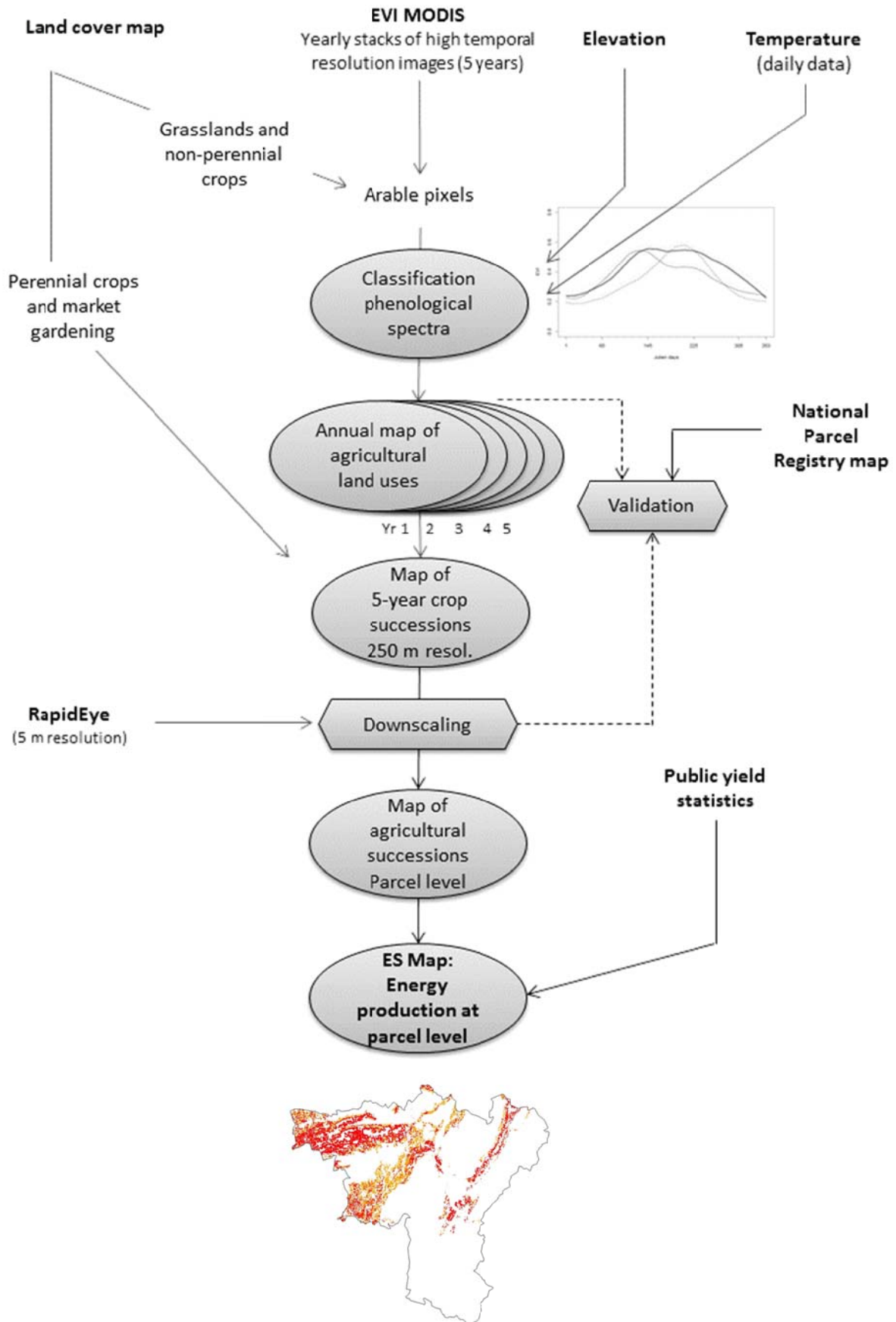


Figure 3 - Phenomenological model development for mapping marine ecosystem services based marine ecological principles. Adapted from Townsend et al., 2014.

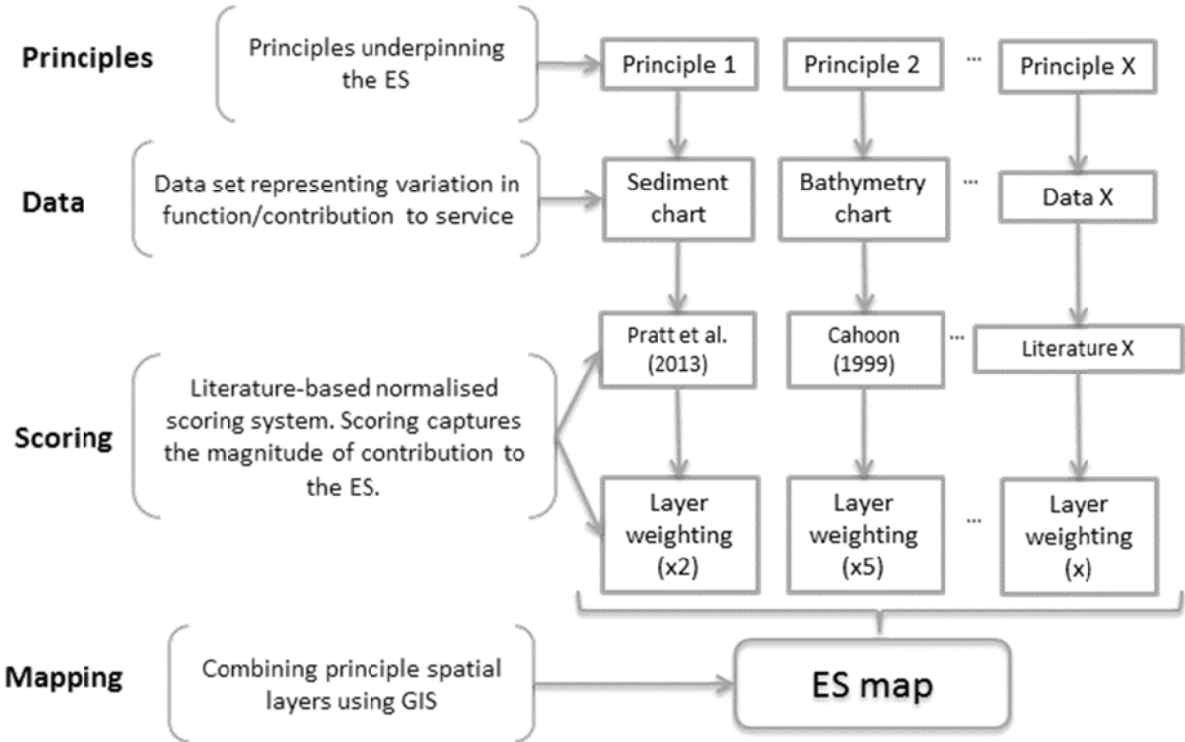


Figure 4 – Macro-ecological models of ecosystem service supply potential. ESP: ecosystem service provider; SDM: species distribution modelling. Here the final map uses richness of vertebrate predators of rodents as an indicator for potential capacity to control rodents in Europe (from Civantos et al. 2012).

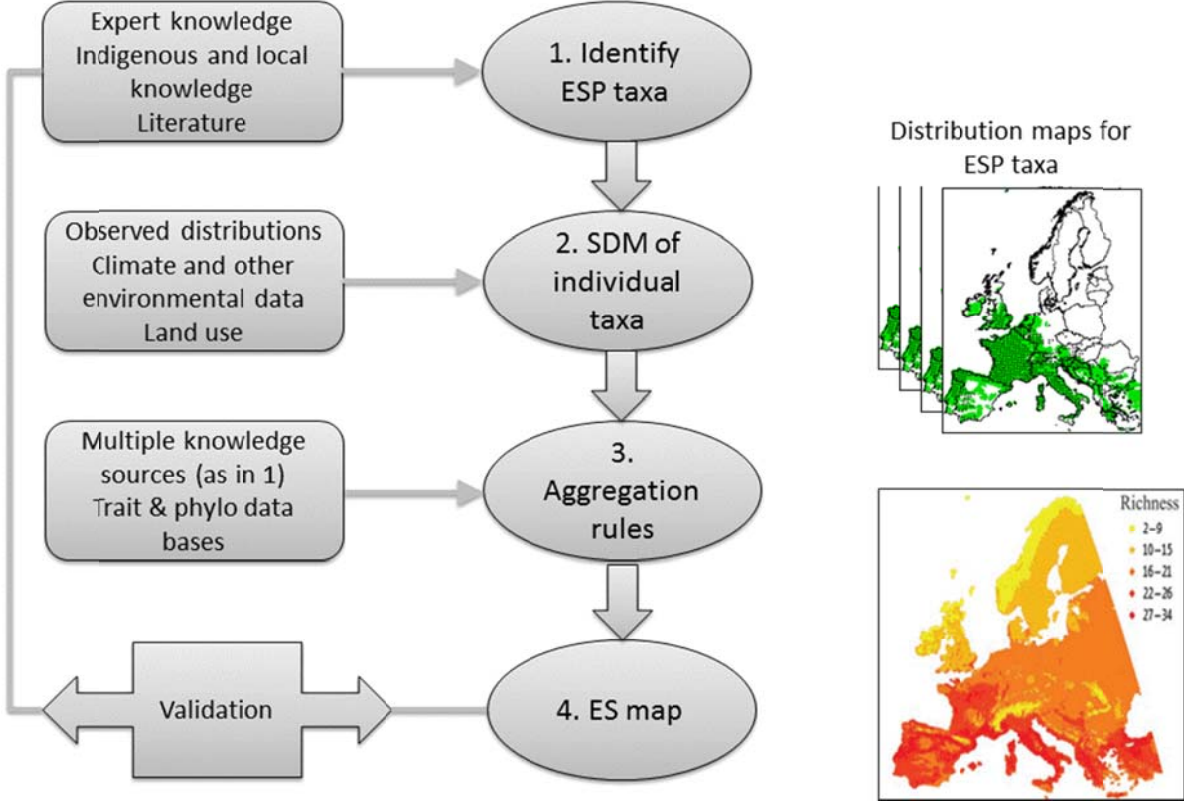


Figure 5 – Trait-based modelling of ecosystem service supply potential for mountain grasslands. Schematic summary of modelling steps based on cascading effects from land use and environmental variables, to community mean plant traits and to ES, illustrated here in the case of fodder production by mountain grasslands (adapted from (Lavorel *et al.*, 2011) and (Lavorel & Grigulis, 2012)). N: nitrogen, P: phosphorus.

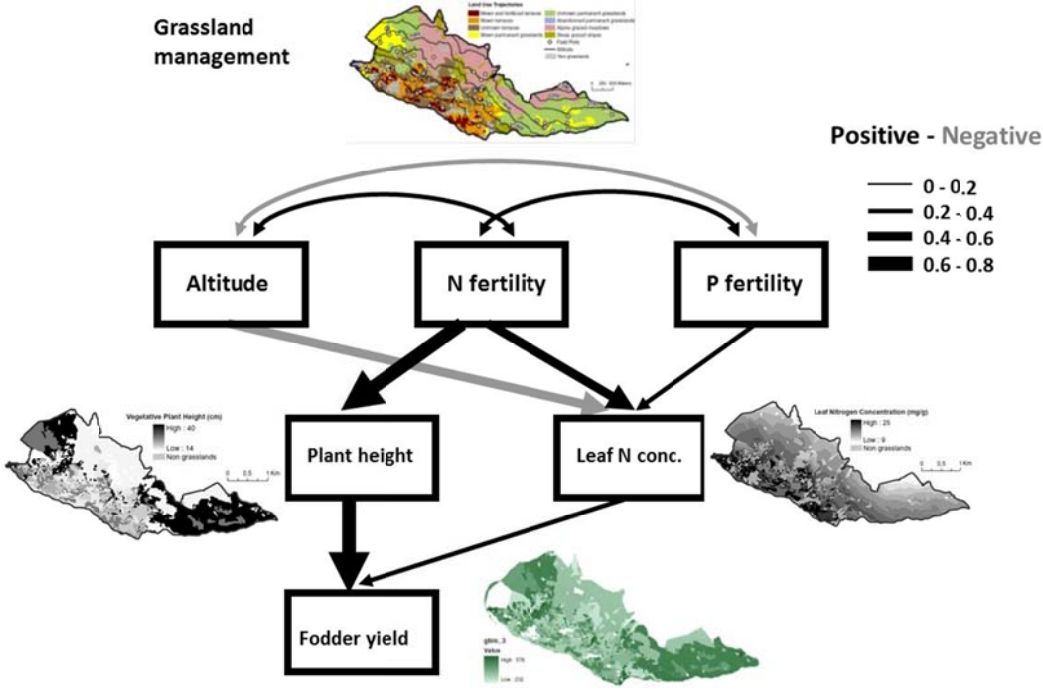
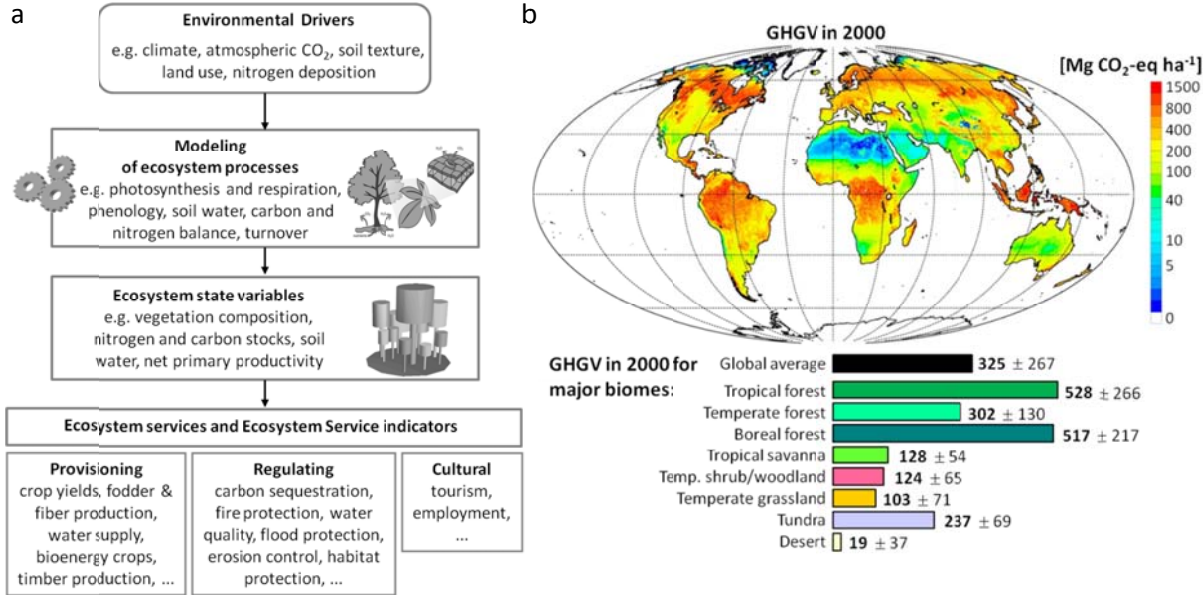


Figure 6 – Workflow typical for process-based models (a). Selected provisioning and regulating services are most often directly linked to simulated ecosystem state variables while cultural services may only be derived from suitable indicators. Example application of a process-based model for the quantification of an ES metric accounting for the full biogeochemical implications of carbon sequestration by estimating contribution of CO<sub>2</sub> to the Greenhouse Gas Value (GHGV) (b) (Figure after Bayer et al., 2015).



## Appendix 1

Appendix 1 - Table 1a - Part 1 - Terrestrial Model Variables

<b>Model name</b>	<b>Ecosystem service</b>	<b>Model type</b>	<b>Scale(s) of applicability</b>	<b>Land cover</b>
	(CICES terminology)		local / regional / continental...	classification and data source
<b>IVM-carbon</b> <b>(Schulp et al., 2008)</b>	Global climate regulation	Phenomenological	continental (EU)	CLUE
<b>IVM-pollination</b> <b>(Schulp et al., 2014)</b>	Pollination	Phenomenological	applied at continental (EU) (NUTS2-regions). Model run on 250x250 LC data CORINE	CORINE and additional linear element dataset (van der Zanden et al., 2013)
<b>IVM-tourism</b> <b>(van Berkel and Verburg, 2011)</b>	Physical use of land-/seascapes	Phenomenological	continental (EU)	CORINE land cover
<b>Biocontrol</b> <b>(Civantos et al., 2012)</b>	Biocontrol	Niche-based	regional - continental (EU)	CORINE land cover 2000 - although any data base is suitable in principle
<b>Trait-based models of grassland ES</b> <b>(Grigulis et al., 2013; Lavorel et al., 2011)</b>	Grassland forage quantity, forage quality, soil organic matter, leached nitrates, soil fertility, soil stability	Trait-based	landscape	grassland management types

<b>LPJ-GUESS</b> (Sitch et al., 2003; Smith et al., 2001).	Global climate regulation, surface water supply (non-drinking), cultivated crops, fodder; tested: timber, energy crops, soil formation, etc.	Process-based	regional/global	Historical and land-use fractions according to (Hurt et al., 2011), crop species according to MIRCA2000 (Portmann et al., 2010). Usage of CLUMondo tested
<b>LPJmL</b> (Bondeau et al., 2007)	Provisioning (cultivated crops, fodder grass, fibres, timber, energy plants, non-drinking surface water), Regulation and maintenance (vegetation cover protecting, hydrological cycle and water flow maintenance, soil formation, global and regional climate regulation)	Process-based	regional / global	1) specifically adapted LPJmL historical land use data set (Fader et al. 2010), derived from the combination of MIRCA 2000 (Portmann et al., 2010), cropland and pasture fractions (Ramankutty et al., 2008), and historical land cover (Klein Goldewijk et al., 2007). Spatial resolution: 0.5° global, 0.25° regional, finer if needed. 2) for the future: published land use projections or simulated land use from the bio-economic MAgPIE model fed by LPJmL (Lotze-Campen et al., 2008; Lotze-Campen et al., 2010)
<b>IVM-FloodRegulation</b> (Stürck et al., 2014)	Flood protection	Process-based	continental (EU)	CORINE land cover 2000

<b>SWAT</b> <b>(Lautenbach et al., 2012)</b>	Cultivated crops, fibres and other materials from crops for direct use or processing (biofuel), Hydrological cycle and water flow maintenance, Mass stabilisation and control of erosion rates, Chemical condition of freshwaters, surface water for drinking, ground water for drinking, surface water for non-drinking purposes, ground water for non-drinking purposes	Process-based	regional	Any classification is suitable, it needs to be linked to the entries in the crop type database which contains generic land use classes and individual crops
<b>HILLFLOW</b> <b>(Leitinger et al., 2015)</b>	Soil moisture, deep water seepage	Process-based	landscape	grassland management types



Appendix 1 - Table 1a - Part 2 - Terrestrial Model Variables

Model name	Abiotic variables			
	<i>climate</i>	<i>soil</i>	<i>landscape pattern</i>	<i>others</i>
<b>IVM-carbon</b> (Schulp et al, 2008)		emission factors: Map with emission factor for each land use type as 1x1 km grids (see calculation rules) (Janssens et al., 2004) & Forest emission factors for soil and biomass from EFISCEN simulations		Map of forest biomass carbon content per EFISCEN region
<b>IVM-pollination</b> (Schulp et al, 2014)				
<b>IVM-tourism</b> (Van Berkel & Verburg, 2011)			Classification of the landscape relief within a 10km radius	tourist infrastructure; accesibility; policy instruments; tourist attractions; local cooperative networks; NGO operation and cooperation
<b>Biocontrol</b> (Civantos et al. 2012)	monthly precipitation, temperature (min, max, mean), ETP, aridity index. Data from alternative data bases or climate scenarios (variable spatial resolution)			

<b>Trait-based models of grassland ES</b> <b>(Lavorel et al. 2011, Grigulis et al. 2013)</b>		soil texture (calculation of water holding capacity), soil depth, soil C, soil N	DEM: altitude
<b>LPJ-GUESS</b> <b>(Smith et al. 2001, Sitch et al. 2003).</b>	Daily or monthly average air surface temperature, precipitation (daily precipitation or monthly precipitation and wet days), incoming shortwave radiation (or sunshine hours per day). Various sources depending on scale and considered time frame, e.g. 0.5° from CRU TS 3.1 (Mitchell and Jones 2005), usually in combination with CMIP5 scenario climate data (e.g. MPI-ES-LR after Giorgetta et al., 2013).	global soil map (FAO, 1991)	atmospheric CO2 concentration
<b>LPJmL (Bondeau et al. 2007)</b>	Daily or monthly average air surface temperature, daily precipitation (or monthly precipitation and wet days), cloudiness or shortwave and longwave radiation. Various sources depending on the scale, e.g. 0.5° from CRU TS 3.1 (Mitchell and Jones 2005) and GPCC (Rudolf et al 2010), 0.25° from WATCH Forcing Data (Weedon et al. 2011) and ERA-Interim (ECMWF).	Harmonized World Soil Database (version 1.2) (2012) aggregated to 0.5° resolution and classified according to the USDA soil texture classification ( <a href="http://edis.ifas.ufl.edu/ss169">http://edis.ifas.ufl.edu/ss169</a> ).	atmospheric CO2 concentration

<b>IWM-FloodRegulation (Stürck et al, 2014)</b>	precipitation regime (Haylock et al., 2008)	soil water holding capacity classification (FAO, 2009)	DEM and forest and agricultural management variables
<b>SWAT (Lautenbach et al. 2012)</b>	precipitation, temperature (min and max), solar radiation, wind speed, humidity, potential evapotranspiration, daily resolution, spatial resolution: climate stations. Depending on the method used to calculate evapotranspiration. Values can also be estimated using a weather generator.	number and thickness of layers, hydrologic soil class, soil porosity, saturated hydraulic conductivity, porosity, field capacity, water content at wilting point, clay/silt/sand content, organic matter content, bulk density,... available resolution of soil together with land cover resolution defines the achievable resolution	terrain (slope)
<b>HILLFLOW (Leitinger et al. 2015)</b>	precipitation, temperature (min and max), solar radiation, wind speed, humidity, potential evapotranspiration, daily resolution, spatial resolution: climate stations.	soil texture, saturated water content, field capacity, residual soil water content, saturated hydraulic conductivity, soil depth, macropores	DEM: altitude, slope, aspect

Appendix 1 - Table 1a - Part 3 - Terrestrial Model Variables

Model name	Biotic variables					
	<i>individual species</i>	<i>species diversity indices</i>	<i>Plant Functional Types</i>	<i>Plant Funct. Traits</i>	<i>functional diversity indices</i>	<i>others</i>
<b>IVM-carbon</b> (Schulp et al, 2008)						forest age
<b>IVM-pollination</b> (Schulp et al, 2014)						pollination dependency index per crop; Habitat suitability for bees
<b>IVM-tourism</b> (Van Berkel & Verburg, 2011)						biophysical characteristics (e.g., presence of sea, beach); presence of N2000 areas, HNV farmland, and UNESCO natural monuments
<b>Biocontrol</b> (Civantos et al. 2012)	vertebrate species known as predators of vertebrate or invertebrate pests					
<b>Trait-based models of grassland ES</b> (Lavorel et al. 2011, Grigulis et al. 2013)		plant Shannon diversity			plant community mean vegetative height, leaf N concentration, leaf dry matter content, rooting architecture	microbial functional diversity parameters calculated from plant traits and soil N and WHC

<p><b>LPJ-GUESS</b> (Smith et al. 2001, Sitch et al. 2003).</p>	<p>11 PFTs e.g. according to (Ahlström et al., 2012); 11 CFTs (Lindeskog et al., 2013)</p>	
<p><b>LPJmL (Bondeau et al. 2007)</b></p>	<p>9 PFTs (Sitch et al., 2003), 12/14 annual CFTs, 2 types of managed grass, 3 types of bioenergy plants. 7 perennial crops (Mediterranean version).</p>	
<p><b>IVM-FloodRegulation (Stürck et al, 2014)</b></p>		<p>tree species, as part of the forest management variables at 1km scale (Brus et al., 2012)</p>
<p><b>SWAT (Lautenbach et al. 2012)</b></p>		<p>The crop.dat we use contains currently 17 generic land use types with vegetation cover (such as pasture, rangeland, deciduous forest), 81 agricultural crops. But this list has been extended e.g. for applications in the tropics.</p>

**HILLFLOW (Leitinger et al. 2015)**

community mean  
root depth,  
evapo-  
transpiration,  
canopy  
interception

Appendix 1 - Table 1b - Part 1 - Terrestrial Model Applications

<b>Model name</b>	<b>Ecosystem service</b> (CICES terminology)	<b>Model type</b>	<b>Brief description of model logics</b>
<b>IVM-carbon</b> <b>(Schulp et al, 2008)</b>	Global climate regulation	Phenomenologica I	The carbon sequestration effect of land use change scenarios is tested at the EU scale. Each land cover category is assigned an annual average effect on carbon sequestration per country. For forest carbon sequestration is weighted by calculation of forest age, for agriculture a SOC map is used to weigh the effects of agriculture on carbon sequestration
<b>IVM-pollination</b> <b>(Schulp et al, 2014)</b>	Pollination	Phenomenologica I	potential supply of pollination is mapped based on habitat suitability of different land covers. Visitation probability is then calculated based on distance from landscape elements providing habitat using a distance decay function. Demand for pollination is mapped based on pollination dependency of crops. In the last step actual supply is then determined based on an overlay of pollination potential supply and pollination demand.
<b>IVM-tourism</b> <b>(Van Berkel &amp; Verburg, 2011)</b>	Physical use of land- /seascapes	Phenomenologica I	expert based assessment of rural development options in Europe including rural tourism. Rural tourism is assessed based on suitability for summer tourism, winter tourism and nature tourism. These three factors are weighted by a factor for symbolic capital.
<b>Biocontrol</b> <b>(Civantos et al. 2012)</b>	Biocontrol	Niche-based	niche-based model of the distribution of vertebrates that exert predation on vertebrate or invertebrate pests

<b>Trait-based models of grassland ES</b> (Lavorel et al. 2011, Grigulis et al. 2013)	grassland forage quantity, forage quality, soil organic matter, leached nitrates, soil fertility, soil stability	Trait-based	statistical models of ecosystem properties depending on soil parameters, plant traits and their variations in response to soil and altitude
<b>LPJ-GUESS</b> (Smith et al. 2001, Sitch et al. 2003)	Global / regional climate regulation, surface water supply (non-drinking), cultivated crops; tested: timber, energy crops, soil formation, etc.	Process-based	LPJ-GUESS DGVM simulates development of land vegetation and biogeochemical cycles. Output variables are used to derive current state of selected Ecosystem Services and their historical and future transitions, e.g. carbon, nitrogen and water cycles, potential crop yields, that are translated into various Ecosystem Services
<b>LPJmL</b> (Bondeau et al. 2007)	Provisioning (cultivated crops, fodder grass, fibres, timber, energy plants, non-drinking surface water), Regulation and maintenance (vegetation cover protecting, hydrological cycle and water flow maintenance, soil formation, global and regional climate regulation)	Process-based	Process-based agro-ecosystem model: simulates the distribution of the potential natural vegetation, carbon stocks, carbon and water cycles, crop yields, harvested biomass. Climate- and management-driven outputs translate into a range of Ecosystem Services.
<b>IVM-FloodRegulation</b> (Stürck et al, 2014)	Flood protection	Process-based	The STREAM hydrological model is applied to several catchments across the EU. Precipitation data is linked to soil and land cover classes across the catchments resulting in a flood regulation supply index. The flood regulation supply is compared between current and potential vegetation (based on (Ramankutty and Foley, 1999)) to determine target areas where vegetation could



			enhance flood regulation supply
<b>SWAT</b> <b>(Lautenbach et al. 2012)</b>	Cultivated crops, fibres and other materials from crops for direct use or processing (biofuel), Hydrological cycle and water flow maintenance, Mass stabilisation and control of erosion rates, Chemical condition of freshwaters, surface water for drinking, ground water for drinking, surface water for non-drinking purposes, ground water for non-drinking purposes	Process-based	SWAT is a physically-based, conceptual, continuous-time river basin model with spatially semi-distributed parameters operating on a daily time step. It was designed to simulate broader scale patterns of discharge and water quality in the spatial and temporal domain (Neitsch et al., 2005). The model integrates all relevant processes for watershed modeling including water flow, nutrient transport and turnover, vegetation growth, land use, and water management at the sub-basin scale. It considers five different pools of nitrogen in the soils (Neitsch et al., 2005): two inorganic (ammonium and nitrate) and three organic (fresh organic nitrogen and active and stable organic nitrogen). Nitrogen is added to the soil by fertilizer, manure or residue application, fixation by bacteria, and atmospheric deposition. Nitrogen losses occur by plant uptake, leaching, volatilization, denitrification and erosion.
<b>HILLFLOW</b> <b>(Leitinger et al. 2015)</b>	Soil moisture, deep water seepage	Process-based	Mechanistic model of water evaporation, lateral flow and deep seepage depending on vegetation demand, soil properties and terrain



Appendix 1 - Table 1b - Part 2 - Terrestrial Model Applications

Model name	Main strengths	Limitations
<p><b>IVM-carbon</b> <b>(Schulp et al, 2008)</b></p>	<p>able to detect changes in carbon sequestration following land use change at coarse levels; applicable across many EU countries;</p>	<p>use of country level averages per land cover class; focused on mapping changes and not necessarily state; only applicable at country or coarser level; only applicable in the EU four countries incorporated in study Janssens et al. (2005)</p>
<p><b>IVM-pollination (Schulp et al, 2014)</b></p>	<p>incorporation of both mapping demand and supply; applicable across many regions; level of detail can be enhanced by parameterizing the model for individual species</p>	<p>difficult to validate results, assumption of habitat uniformity, variation in timing of pollination demand and supply within a year not accounted for</p>

<b>IVM-tourism (Van Berkel &amp; Verburg, 2011)</b>	Applicable across the EU; using easy accessible datasets	Only applicable at this scale; expert based approach makes it inherently subjective; preferences and suitable indicators might change over time; dos not generate reliable results in all regions
<b>Biocontrol (Civantos et al. 2012)</b>	Climate- and land use-based distributions of service providing species. Easy to project given scenarios. Contribution of individual species may be combined with different weights e.g. depending on diets (although currently even weights)	Usual limits of species distribution modelling
<b>Trait-based models of grassland ES (Lavorel et al. 2011, Grigulis et al. 2013)</b>	Mechanistic understanding of ES supply; functional understanding of ES trade-offs / bundles. Easy to project given scenarios.	Generic nature of models under checking (inter-site comparison). May need adaptation for different bioclimatic regions

<b>LPJ-GUESS (Smith et al. 2001, Sitch et al. 2003)</b>	Global quantification; historical and future transitions; high detail in representation of vegetation dynamics (age cohorts and gap dynamics), closed carbon and nitrogen cycles	Limitations in resolution (0.5°x0.5°), applicable up to contry/regional level (i.e. Downscaling aspired in Scottish Exemplar)
<b>LPJmL (Bondeau et al. 2007)</b>	Closed carbon cycle, consistent representation of the biogeochemical processes bewteen the different plant types.	Currently no nitrogen cycle
<b>IVM-FloodRegulation (Stürck et al, 2014)</b>	Combination of flood regulation demand and supply to identify priority areas where flood regulation can be enhanced using natural vegetation.	Extrapolation of estimates for relation between land cover, soils and flood regulation from single catchments to the entire EU. Method is difficult to apply at smaller scales

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<b>SWAT</b> <b>(Lautenbach et al., 2012)</b>	Detailed representation of crop management; high number of management options implemented	Limited for the modelling of forests - focus is on the modelling of agricultural systems. Suitable for the regional scale (watersheds > ~ 50 sqkm), not suitable for small watersheds.
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<b>HILLFLOW (Leitinger et al. 2015)</b>	Mechanistic understanding of ES supply depending on vegetation functioning	Not a detailed hydrological model; requires heavy site measurements for parameterisation
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Appendix 1 - Table 2a - Part 1 - Marine Model Variables

<b>Model name</b>	<b>Ecosystem service</b>	<b>Model type</b>	<b>scale(s) of applicability</b>	<b>Land cover</b>
	(CICES terminology)		local / regional / continental...	classification and data source
<b>Ecosim/EcoPath (Alcamo et al, 2005)</b>	Provisioning, nutrition, biomass (fish production)	Niche-based	regional	NA
<b>Mercury sequestration (Anastacio et al 2013)</b>	Mediation of waste, toxics and other nuisances	Process-based	regional	NA
<b>Spatial model of coastal ecosystem services (Barbier 2012)</b>	mediation of flows (storm protection) & fish density	NA	local	NA
<b>Hydrodynamic model (Temmerman et al 2012)</b>	Mediation of flows (flood protection)	Phenomenological	local	NA
<b>Hydrodynamic model (Shepherd et al 2007)</b>	Maintenance of physical, chemical and biological conditions (nutrient removal and carbon sequestration)	Phenomenological	local	NA
<b>Mangrove's wind protection (Das et al, 2013)</b>	Mediation of flows (wind protection)	Phenomenological	regional	NA
<b>CO<sub>2</sub> capture potential of seagrass restoration (Duarte et al, 2013)</b>	Maintenance of physical, chemical and biological conditions (carbon sequestration)	Trait-based	local	NA

<b>Multiscale ecological and economic models salmon, shrimp &amp; blue crab (Jordan et al 2012)</b>	Provisioning, nutrition, biomass (food production)	Phenomenological	local & regional	NA
<b>Coastal protection (Liquete et al 2013)</b>	coastal protection	Spatial proxy-based	continental (EU)	Three data sources: EU Corine Land Cover (CLC) dataset v.15 from the year 2000 with a resolution of 100 m (EEA 2011); and modelled seabed habitat maps (MESH 2010; EUSeaMap JNCC 2010)
<b>Role of eelgrass in ES, food web modeling (Plummer et al 2013)</b>	multiple ES (provisioning, cultural, supporting)	Spatial proxy-based	local	NA
<b>InVEST Marine carbon storage &amp; sequestration (Guerry et al 2012)</b>	Carbon storage & sequestration	Spatial proxy-based	local / regional / continental	NA
<b>InVEST Food provision (Guerry et al 2012)</b>	Food provision	Spatial proxy-based	local / regional / continental	NA
<b>InVEST Marine renewable energy (Guerry et al 2012)</b>	Energy	Spatial proxy-based	local / regional / continental	NA



<b>InVEST Recreation (Guerry et al 2012)</b>	Recreation	Spatial proxy-based	local / regional / continental
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Appendix 1 - Table 2a - Part 2 - Marine Model Variables

Model name	Abiotic variables			
	<i>climate</i>	<i>soil</i>	<i>landscape pattern</i>	<i>others</i>
<b>Ecosim/EcoPath (Alcamo et al, 2005)</b>	x			Economic development, greenhouse emissions, air pollution emission, risk of acidification and excess nitrogen emissions, climate change, sea level rise, nitrogen loading to coastal marine systems
<b>Mercury sequestration (Anastacio et al 2013)</b>				Hg in biomass (several variables, Hg in belowground biomass, Hg exiting biomass, incorporation 365 days ago...), temperature, salinity, cloud cover
<b>Spatial model of coastal ecosystem services (Barbier 2012)</b>				Distance to the ecosystem, distance from seaward edge
<b>Hydrodynamic model (Temmerman et al 2012)</b>	x		x	
<b>Hydrodynamic model (Shepherd et al 2007)</b>		x	x	Elevation; management variables;
<b>Mangrove's wind protection (Das et al, 2013)</b>	x			% damaged houses, impact of the storm, wind velocity, velocity of the storm surge, surge height, distance from the coast
<b>CO2 capture potential of seagrass restoration (Duarte et al, 2013)</b>	x			

<p><b>Multiscale ecological and economic models salmon, shrimp &amp; blue crab</b> (Jordan et al 2012)</p>	<p>Fishery landings, effort data, habitat GIS coverages, survival rates for habitat types, salinity, economic value salmon fisheries</p>
<p><b>Coastal protection</b> (Liquete et al 2013)</p>	<p>Bathymetry, topography, slope, geomorphology, submarine habitats, emerged habitats, wave regime, tidal range, relative sea level, storm surge, population density, infrastructures, artificial surface, main cultural sites</p>
<p><b>Role of eelgrass in ES, food web modeling</b> (Plummer et al 2013)</p>	<p>No abiotic variables stated</p>
<p><b>InVEST Marine carbon storage &amp; sequestration</b> (Guerry et al 2012)</p>	<p>Carbon stored, rate of C accumulation in sediments, economic information such as market/non-market value of stored/sequestered Carbon</p>
<p><b>InVEST Food provision</b> (Guerry et al 2012)</p>	<p>Fishing fleet distribution, value of landings, fishing grounds distribution, price of harvested product, harvest rate information</p>
<p><b>InVEST Marine renewable energy</b> (Guerry et al 2012)</p>	<p>wave condition data (height, peak period, technological capabilities (e.g. Performance tables, maximum capacity)</p>
<p><b>InVEST Recreation</b> (Guerry et al 2012)</p>	<p>visitation rates, recreational activities</p>

Appendix 1 - Table 2a - Part 3 - Marine Model Variables

Model name	Biotic variables						Ecosystem type
	<i>individual species</i>	<i>species diversity indices</i>	<i>Plant Functional Types</i>	<i>Plant Functional Traits</i>	<i>Functional diversity indices</i>	<i>others</i>	
<b>Ecosim/EcoPath (Alcamo et al, 2005)</b>	x					Trophic flows, biomass, production, mortality, exports, biomass accumulation, biomass of functional groups, consumption, catch data, trophic behaviours, landings, discards, fishing effort, human population development	marine
<b>Mercury sequestration (Anastacio et al 2013)</b>							tidal wetlands
<b>Spatial model of coastal ecosystem services (Barbier 2012)</b>						Thread of ecological collapse	mangrove habitat
<b>Hydrodynamic model (Temmerman et al 2012)</b>			tidal wetlands				tidal wetlands
<b>Hydrodynamic model (Shepherd et al 2007)</b>							tidal wetlands and mudflats

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(estuary)

<b>Mangrove's wind protection (Das et al, 2013)</b>	x	mangrove forest	distance from mangrove forest, mangrove forest extent	mangrove forest
<b>CO<sub>2</sub> capture potential of seagrass restoration (Duarte et al, 2013)</b>	x	seagrass meadows	patch growth, patch survival in seagrass planting projects, estimates of seagrass CO <sub>2</sub> sequestration per unit area for five seagrass species	seagrass meadows
<b>Multiscale ecological and economic models salmon, shrimp &amp; blue crab (Jordan et al 2012)</b>	x		stock biomass, net recruitment per year, carrying capacity	marine
<b>Coastal protection (Liquete et al 2013)</b>				marine
<b>Role of eelgrass in ES, food web modeling (Plummer et al 2013)</b>			biomass, growth efficiency, consumption rates of prey, immigration rate, mortality, emigration rate, biological groups (primary producers, invertebrates, fishes, birds, marine mammals, detrital pools), commercial and recreational fisheries	marine

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<b>InVEST Marine carbon storage &amp; sequestration (Guerry et al 2012)</b>	vegetation distribution maps
<b>InVEST Food provision (Guerry et al 2012)</b>	fish distribution, fish survival, recruitment rate
<b>InVEST Marine renewable energy (Guerry et al 2012)</b>	None
<b>InVEST Recreation (Guerry et al 2012)</b>	habitat distribution

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Appendix 1 – Table 2b - Part 1 – Marine Model Application

Model name	Model Category	Ecosystem service	Brief description of model logics
		(CICES terminology)	
<b>Coastal protection (Liquete et al., 2013)</b>	Spatial proxy-based	coastal protection	Provides a conceptual and methodological approach to assess coastal protection as an ecosystem service at different spatial-temporal scales, and applies it to the entire EU coastal zone. The assessment of coastal protection incorporates 14 biophysical and socio-economic variables from both terrestrial and marine datasets. Those variables define three indicators: coastal protection capacity, coastal exposure and human demand for protection. The three indicators are then framed into the ecosystem services cascade model to estimate how coastal ecosystems provide protection, in particular describing the service function, flow and benefit.
<b>InVEST Marine carbon storage &amp; sequestration (Guerry et al., 2012)</b>	Spatial proxy-based	Carbon storage & sequestration	The marine carbon model estimates how much carbon is stored in coastal vegetation, how much carbon is sequestered in the sediments and the economic value of storage and sequestration.

<b>InVEST Coastal protection</b> <b>(Guerry et al., 2012)</b>	Spatial proxy-based	coastal protection	The InVEST Coastal Protection model quantifies the protective services provided by natural habitats of nearshore environments in terms of avoided erosion and flood mitigation. The model's profile generator prepares a 1D bathymetry transect of a shoreline, providing information about its backshore and the location of natural habitats. The transect is used to estimate the total water level and shoreline erosion in the presence and absence of nearshore marine habitats
<b>InVEST Food provision</b> <b>(Guerry et al 2012)</b>	Spatial proxy-based	Food provision	InVEST model estimates the quantity and monetary value of fish harvested by commercial fisheries. Appropriate to use for single species or groups of species with similar life stories. It estimates annual production of fish. Another section of the model can be used to analyse the production and monetary value of farmed fish and shellfish and quantify by-products of farming.
<b>InVEST Marine renewable energy</b> <b>(Guerry et al 2012)</b>	Spatial proxy-based	Energy	Models energy production from waves and models off-shore wind energy production. The model assesses potential wave power and



			energy based on wave conditions and technology-specific capabilities.
<b>InVEST Recreation (Guerry et al 2012)</b>	Spatial proxy-based	Recreation	The InVEST recreation model predicts the spread of person-days of recreation, based on the locations of natural habitats and other features that factor into people's decisions about where to recreate
<b>Hydrodynamic model (Temmerman et al., 2012)</b>	Phenomenological	Mediation of flows (flood protection)	Hydrodynamic model simulations of flood attenuation by a tidal marsh, with particular focus on the effects of spatial patterns of vegetation dieoff. Tidal marsh die-off, which may increase with ongoing global change (e.g. because sea level rise), is expected to have non-linear effects on reduced coastal protection against flood waves.
<b>Hydrodynamic model (Shepherd et al., 2007)</b>	Phenomenological	Maintenance of physical, chemical and biological conditions (nutrient removal and carbon sequestration)	Hydrodynamic model to estimate nutrient removal and carbon sequestration in a UK estuary covered with tidal wetlands and mudflats, based on sediment dynamics and composition. The model also estimates the associated value of habitat created under a scenario of extensive managed realignment. A cost

			benefit analysis of the managed realignment is conducted too.
<b>Mangrove's wind protection (Das and Crépin, 2013)</b>	Phenomenological	Mediation of flows (wind protection)	Modeling of wind attenuation and protection offered by mangroves in the event of wind-related damage during storms, specially in areas affected by tangential wind
<b>Ecosim/EcoPath (Alcamo et al., 2005)</b>	Niche-based	Provisioning, nutrition, biomass (fish production)	Fish production (landings) is estimated for three regional fisheries (Gulf of Thailand, Central North Pacific North Benguela) for 4 different scenarios. The model computes dynamic changes in selected marine ecosystems as a function of fishing efforts (Pauly et al. 2000). For its fish production estimates, the EcoSim/EcoPath model takes into account not only the future source of feed for aquaculture, but also future subsidies for the fishing industry, the management objectives of fishing (either to optimize employment or profits), and the impact of climate change on shifts in species distribution and abundance (Pauly et al. 2003). For all scenarios, fish catch (by weight) is maintained in the North Benguela fishery, not maintained in the Central North Pacific, and has

			mixed results in the Gulf of Thailand. The overall message of these results is that it is uncertain whether future demands for fish can be sustainably provided by either aquaculture or marine fisheries.
<b>Multiscale ecological and economic models salmon, shrimp &amp; blue crab (Jordan et al., 2012)</b>	Niche-based	Provisioning, nutrition, biomass (food production)	Model of the link between the production functions of critical habitats to commercial and recreational fishery values through the combination of specific research data with spatial analysis and population models
<b>CO<sub>2</sub> capture potential of seagrass restoration (Duarte et al., 2013)</b>	Trait-based	Maintenance of physical, chemical and biological conditions (carbon sequestration)	Model of the long term carbon sequestration expected for seagrass restoration programmes
<b>Role of eelgrass in ES, food web modeling (Plummer et al., 2013)</b>	Trait-based	multiple ES (provisioning, cultural, supporting)	Use of dynamic simulations in a food web model of central Puget Sound, Washington, USA developed in the Ecopath with Ecosim software, to examine how the marine community may respond to changes in coverage of native eelgrass ( <i>Zostera marina</i> ), and how these modeled responses can be assessed using an ecosystem services framework, expressing these services with economic currencies in some cases

			and biological proxies in others.
<b>Mercury sequestration (Anastácio et al., 2013)</b>	Process-based	Mediation of waste, toxics and other nuisances	Modelling of growth and mercury (HG) sequestration by <i>Bolboschoenus maritimus</i> on the most contaminated area of a temperate shallow coastal lagoon historically subjected to heavy Hg load, under gradients of climate driven variables. Simulation of <i>B. maritimus</i> mercury sequestration under different environmental scenarios involving increases and decreases in temperature, salinity and cloud cover. The largest effects were related to high salinity scenarios but all variables presented an inverse relation with Hg-sequestration
<b>Spatial model of coastal ecosystem services (Barbier, 2012)</b>	NA	mediation of flows (storm protection) & fish density	Modelling of ecological production functions that decline across a coastal landscape

Appendix 1 - Table 2b – Part 2 – Marine Model Application

Model name	Main strengths	Limitations
<b>Coastal protection (Liquete et al 2013)</b>	The assessment shown in the paper could help assist the comparison between European regions and to further national or regional scale studies of ecosystem services. In Europe it can have a direct application on the EU Biodiversity Strategy, the EU Floods Directive. On an international scale, this approach could be taken by CBD (Convention on biological diversity) countries.	The continental scale of the model may oversimplify the local coastal processes, since they cannot be taken into account a the continental scale and resolution. Coastal studies generally lack the step of aggregation of data and knowledge transfer from local case studies to regional ones. Due to the lack of large scale datasets or methodologies some important factors could not be included in the model (e.g. local sediment Budget, subsidence, main direction of morphologic features with respect to wave action, coastal development and management, low vs. high coasts, health of the ecosystems, the specific non-linear response of habitats for protection among others). Further information on limitations or aspects that could improve the model are discussed in the paper.
<b>InVEST Marine carbon storage &amp; sequestration (Guerry et al 2012)</b>	Not stated in the paper	Not stated in the paper
<b>InVEST Coastal protection (Guerry et al 2012)</b>	Not stated in the paper	A primary limitation is that the Erosion Protection model assumes that all erosion leads to a loss of land. Further, the model estimates coastal protection services provided by habitats in terms of the reduction in damages due to erosion from storm waves, not surge. Some coastal habitats

		<p>have the ability to attenuate surge in addition to waves (e.g., marshes, coastal forests), while other nearshore subtidal habitats do not (e.g., eelgrass). the model has technical limitations. The first is the lack of high quality GIS data that are readily available. The theoretical limitations of the Nearshore Waves and Erosion model are more substantial. As mentioned earlier, wave evolution is modeled with a 1D model. This assumes that the bathymetry is longshore-uniform (i.e. the profile in front of the site is similar along the entirety of the stretch of shoreline). Because this is unlikely true, the model ignores any complex wave transformations that occur offshore of the site of interest</p>
<b>InVEST Food provision (Guerry et al 2012)</b>	Production of maps that identify the most important marine and coastal areas across a variety of fishing fleets	It does not model behavior , for that reason it is not well suited to the evaluation of how human uses may change in response to changes in the marine environment.
<b>InVEST Marine renewable energy (Guerry et al 2012)</b>	Not stated in the paper	Not stated in the paper
<b>InVEST Recreation (Guerry et al 2012)</b>	Not stated in the paper	The model does not presuppose that any predictor variable has an effect on visitation. Instead, the tool estimates the magnitude of each predictor's effect based on its spatial correspondence with current visitation in the area of interest. It requires the assumption that people's responses to attributes that serve as predictors in the model will not change over time.

		In other words, in the future, people will continue to be drawn to or repelled by the attributes as they are currently.
<b>Hydrodynamic model (Temmerman et al 2012)</b>	Not stated in the paper	Not stated in the paper
<b>Hydrodynamic model (Shepherd et al 2007)</b>	Cost benefit analysis (CBA) demonstrates that managed realignment provides positive economic advantages. In a wider sense the case study demonstrates how CBA of managed realignment schemes should be undertaken so that the potential social cost of realignment can be better understood	The model and CBA is based in many assumptions (e.g. sedimentation rate 1.5 or 6mm per year) and uncertainties (e.g. habitat values or nitrogen removal), however the assumptions are conservative, if anything it will have underestimated the value of the service
<b>Mangrove's wind protection (Das et al, 2013)</b>	The study found that not accounting for the role of mangroves significantly overestimates actual wind damage. Wind barriers like mangroves reduces tangential wind and contributes substantially to reduce wind-caused damage to structures	While the simplicity of the model makes it very tractable for use in empirical studies in poor regions, further model development and better data would shed more light on the particular mechanisms underlying mangrove protection from storms
<b>Ecosim/EcoPath (Alcamo 2005)</b>	Global application	Not stated in the paper
<b>Multiscale ecological and economic models salmon, shrimp &amp; blue crab (Jordan et al 2012)</b>	Ecological production functions generally are observed at fine spatial scales for brief spans of time, whereas the resulting ecosystem services and their economic values may be delivered over broad geographic and temporal scales. This paper demonstrates methods of modeling and estimation that link fishery production and its associated economic indicators to the distributions and attributes of coastal habitats across scales ranging from habitat patches to large ocean basins.	Not stated in the paper

<p><b>CO<sub>2</sub> capture potential of seagrass restoration (Duarte et al, 2013)</b></p>	<p>The model indicates that the cumulative C sequestered increases rapidly over time and with planting density. The value corresponding to this C sequestration suggests that the costs of seagrass restoration projects may be fully recovered by the total CO<sub>2</sub> captured in societies with a carbon tax in place</p>	<p>The model presented delivers rough, but conservative, estimates of the average CO<sub>2</sub> capture capacity associated with seagrass restoration projects. These estimates are conservative because they focus on the mean, whereas planting of seagrass patches for CO<sub>2</sub> capture can be managed to achieve maximum capture, which could double the estimates provided above. In addition, the model considers clonal spread alone, whereas the restored meadows would produce seeds as they develop, contributing to accelerate colonization beyond the limits imposed by clonal growth, accelerating space occupation and therefore carbon capture.</p>
<p><b>Role of eelgrass in ES, food web modeling (Plummer et al 2013)</b></p>	<p>Increased eelgrass coverage was most associated with increases in commercial and recreational fishing with some small decreases in one non-market activity, bird watching. When ES categories were considered (aggregations of individual groups of species) there was little evidence of strong tradeoffs among marine resources; that is, increasing eelgrass coverage was essentially either positive or neutral for all services examined</p>	<p>Not stated in the paper</p>
<p><b>Mercury sequestration (Anastacio et al 2013)</b></p>	<p>tool to analyze system behavior and to make projections regarding mercury sequestration. This is particularly relevant in the case of human interventions (i.e. engineering) for the optimization of this ecosystem service</p>	<p>the value calculated does not include sequestration by other plants sharing the habitat with <i>B. maritimus</i>. For this reason we should expect that the total value for mercury sequestration by wetland plants will be higher since other plant species are present in the</p>



		studied area
<b>Spatial model of coastal ecosystem services (Barbier 2012)</b>	The basic model demonstrates how spatial production of ecosystem services affects the location and extent of landscape conversion. An extension allows for the risk of ecological collapse, when the critical size of the remaining landscape that precipitates the collapse is not known. Both models are simulated using the example of spatial variation in ecosystem services across a mangrove habitat that might be converted to shrimp aquaculture.	Not stated in the paper

## References

- Ahlström, A., Schurgers, G., Arneth, A., Smith, B., 2012. Robustness and uncertainty in terrestrial ecosystem carbon response to CMIP5 climate change projections. *Environmental Research Letters* 7, 044008.
- Alcamo, J., van Vuuren, D., Ringler, C., Cramer, W., Masui, T., Alder, J., Schulze, K., 2005. Changes in nature's balance sheet: Model-based estimates of future worldwide ecosystem services. *Ecology and Society* 10, 19-19.
- Anastácio, P.M., Marques, B., Lillebø, A.I., 2013. Modeling the effect of temperature, solar radiation and salinity on *Bolboschoenus maritimus* sequestration of mercury. *Ecological Modelling* 256, 31-42.
- Barbier, E.B., 2012. Progress and Challenges in Valuing Coastal and Marine Ecosystem Services. *Review of Environmental Economics and Policy* 6, 1-+.
- Bondeau, A., Smith, P.C., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W., Gerten, D., Lotze-Campen, H., Müller, C., Reichstein, M., Smith, B., 2007. Modelling the role of agriculture for the 20th century global terrestrial carbon balance. *Global Change Biology* 13, 679-706.
- Brus, D.J., Hengeveld, G.M., Walvoort, D.J.J., Goedhart, P.W., Heidema, A.H., Nabuurs, G.J., Gunia, K., 2012. Statistical mapping of tree species over Europe. *European Journal of Forest Research* 131, 145-157.
- Civantos, E., Thuiller, W., Maiorano, L., Guisan, A., Araújo, M.B., 2012. Potential Impacts of Climate Change on Ecosystem Services in Europe: The Case of Pest Control by Vertebrates. *BioScience* 62, 658-666.
- Das, S., Crépin, A.-S., 2013. Mangroves can provide protection against wind damage during storms. *Estuarine, Coastal and Shelf Science* 134, 98-107.
- Duarte, C.M., Sintes, T., Marba, N., 2013. Assessing the CO<sub>2</sub> capture potential of seagrass restoration projects. *Journal of Applied Ecology* 50, 1341-1349.
- Grigulis, K., Lavorel, S., Krainer, U., Legay, N., Baxendale, C., Dumont, M., Kastl, E., Arnoldi, C., Bardgett, R., Poly, F., Pommier, T., Schloter, M., Tappeiner, U., Bahn, M., Clément, J.-C., 2013. Combined influence of plant and microbial functional traits on ecosystem processes in mountain grasslands *Journal of Ecology* 101, 47-57.
- Guerry, A.D., Ruckelshaus, M.H., Arkema, K.K., Bernhardt, J.R., Guannel, G., Kim, C.-K., Marsik, M., Papenfus, M., Toft, J.E., Verutes, G., Wood, S.A., Beck, M., Chan, F., Chan, K.M.A., Gelfenbaum, G., Gold, B.D., Halpern, B.S., Labiosa, W.B., Lester, S.E., Levin, P.S., McField, M., Pinsky, M.L., Plummer, M., Polasky, S., Ruggiero, P., Sutherland, D.A., Tallis, H., Day, A., Spencer, J., 2012. Modeling benefits from nature: using ecosystem services to inform coastal and marine spatial planning. *International Journal of Biodiversity Science, Ecosystem Services & Management* 8, 107-121.
- Hurt, G.C., Chini, L.P., Frothingham, S., Betts, R.A., Feddema, J., Fischer, G., Fisk, J.P., Hibbard, K., Houghton, R.A., Janetos, A., Jones, C.D., Kindermann, G., Kinoshita, T., Klein Goldewijk, K., Riahi, K., Shevliakova, E., Smith, S., Stehfest, E., Thomson, A., Thornton, P., van Vuuren, D.P., Wang, Y.P., 2011. Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands. *Climatic Change* 109, 117-161.

Janssens, I.A., Freibauer, A., Schlamadinger, B., Ceulemans, R., Ciais, P., Dolman, A.J., Heimann, M., Nabuurs, G.-J., Smith, P., Valentini, R., 2004. The carbon budget of terrestrial ecosystems at country-scale—a European case study. *Biogeosciences Discussions* 1, 167-193.

Jordan, S.J., O'Higgins, T., Dittmar, J.A., 2012. Ecosystem Services of Coastal Habitats and Fisheries: Multiscale Ecological and Economic Models in Support of Ecosystem-Based Management. *Marine and Coastal Fisheries* 4, 573-586.

Klein Goldewijk, K., Van Drecht, G., Bouwman, A.F., 2007. Mapping contemporary global cropland and grassland distributions on a 5 × 5 minute resolution. *Journal of Land Use Science* 2, 167-190.

Lautenbach, S., Maes, J., Kattwinkel, M., Seppelt, R., Strauch, M., Scholz, M., Schulz-Zunkel, C., Volk, M., Weinert, J., Dormann, C.F., 2012. Mapping water quality-related ecosystem services: concepts and applications for nitrogen retention and pesticide risk reduction. *International Journal of Biodiversity Science, Ecosystem Services & Management* 8, 35-49.

Lavorel, S., Grigulis, K., Lamarque, P., Colace, M.-P., Garden, D., Girel, J., Douzet, R., Pellet, G., 2011. Using plant functional traits to understand the landscape-scale distribution of multiple ecosystem services. *Journal of Ecology* 99, 135-147.

Leitinger, G., Ruggenthaler, R., Hammerle, A., Lavorel, S., Lamarque, P., Schirpke, U., Clément, J.C., Obojes, N., Tappeiner, U., 2015. Drought impact on water provision of managed alpine grasslands in two climatically different regions of the Alps. *Ecohydrology* in press.

Lindeskog, M., Arneeth, A., Bondeau, A., Waha, K., Seaquist, J., Olin, S., Smith, B., 2013. Implications of accounting for land use in simulations of ecosystem services and carbon cycling in Africa. *Earth System Dynamics Discussion* 4, 235-278.

Liquete, C., Zulian, G., Delgado, I., Stips, A., Maes, J., 2013. Assessment of coastal protection as an ecosystem service in Europe. *Ecological Indicators* 30, 205-217.

Lotze-Campen, H., Müller, C., Bondeau, A., Rost, S., Popp, A., Lucht, W., 2008. Global food demand, productivity growth, and the scarcity of land and water resources: a spatially explicit mathematical programming approach. *Agricultural Economics* 39, 325-338.

Lotze-Campen, H., Popp, A., Beringer, T., Müller, C., Bondeau, A., Rost, S., Lucht, W., 2010. Scenarios of global bioenergy production: The trade-offs between agricultural expansion, intensification and trade. *Ecological Modelling* 221, 2188-2196.

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., 2005. Soil and Water Assessment Tool - Documentation, Version 2005.

Plummer, M.L., Harvey, C.J., Anderson, L.E., Guerry, A.D., Ruckelshaus, M.H., 2013. The Role of Eelgrass in Marine Community Interactions and Ecosystem Services: Results from Ecosystem-Scale Food Web Models. *Ecosystems* 16, 237-251.

Portmann, F.T., Siebert, S., Döll, P., 2010. MIRCA 2000 - Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modelling. *Global Biogeochemical Cycles* 24, GB1011.

Ramankutty, N., Evan, A.T., Monfreda, C., Foley, J.A., 2008. Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. *Global Biogeochemical Cycles* 22, 1-19.

Ramankutty, N., Foley, J.A., 1999. Estimating historical changes in global land cover: Croplands from 1700 to 1992. *Global Biogeochemical Cycles* 13, 997-1027.

Schulp, C.J.E., Lautenbach, S., Verburg, P.H., 2014. Quantifying and mapping ecosystem services: Demand and supply of pollination in the European Union. *Ecological Indicators* 36, 131-141.

Schulp, C.J.E., Nabuurs, G.-J., Verburg, P.H., 2008. Future carbon sequestration in Europe - Effects of land use change. *Agriculture, Ecosystems and Environment* 127, 251-264.

- Shepherd, D., Burgess, D., Jickells, T., Andrews, J., Cave, R., Turner, R.K., Aldridge, J., Parker, E.R., Young, E., 2007. Modelling the effects and economics of managed realignment on the cycling and storage of nutrients, carbon and sediments in the Blackwater estuary UK. *Estuarine, Coastal and Shelf Science* 73, 355-367.
- Sitch, S., Smith, B., Prentice, I.C., Arneth, A., Bondeau, A., Cramer, W., Kaplan, J.O., Levis, S., Lucht, W., Sykes, M.T., Thonicke, K., Venevsky, S., 2003. Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. *Global Change Biology* 9, 161-185.
- Smith, B., Prentice, I.C., Sykes, M.T., 2001. Representation of vegetation dynamics in the modelling of terrestrial ecosystems: comparing two contrasting approaches within European climate space. *Global Ecology & Biogeography* (2001) 10, 621– 637 10, 621-637.
- Stürck, J., Poortinga, A., Verburg, P.H., 2014. Mapping ecosystem services: The supply and demand of flood regulation services in Europe. *Ecological Indicators* 38, 198-211.
- Temmerman, S., De Vries, M.B., Bouma, T.J., 2012. Coastal marsh die-off and reduced attenuation of coastal floods: A model analysis. *Global and Planetary Change* 92-93, 267-274.
- van Berkel, D.B., Verburg, P.H., 2011. Sensitising rural policy: Assessing spatial variation in rural development options for Europe. *Land Use Policy* 28, 447-459.
- van der Zanden, E.H., Verburg, P.H., Mûcher, C.A., 2013. Modelling the spatial distribution of linear landscape elements in Europe. *Ecological Indicators* 27, 125-136.