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Citation for published version:

Villoslada, M, Bunce, RGH, Sepp, K, Jongman, RHG, Metzger, MJ, Kull, T, Raet, J, Kuusemets, V, Kull, A & Leito, A 2016, 'A framework for habitat monitoring and climate change modelling: construction and validation of the Environmental Stratification of Estonia', *Regional Environmental Change*.
<https://doi.org/10.1007/s10113-016-1002-7>

Digital Object Identifier (DOI):

[10.1007/s10113-016-1002-7](https://doi.org/10.1007/s10113-016-1002-7)

Link:

[Link to publication record in Edinburgh Research Explorer](#)

Document Version:

Peer reviewed version

Published In:

Regional Environmental Change

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1 **A framework for habitat monitoring and climate change modelling: construction and validation of the**
2 **Environmental Stratification of Estonia.**

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5 Miguel Villoslada¹, Robert G.H. Bunce¹, Kalev Sepp¹, Robert H.G. Jongman², Marc J. Metzger³, Tiiu Kull¹,
6 Janar Raet¹, Valdo Kuusemets¹, Ain Kull⁴ and Aivar Leito¹
7
8
9

10 (1) Estonian University of Life Sciences, Kreutzwaldi 5, 51014 Tartu, Estonia

11 (2) Alterra, Wageningen UR, Droevendaalsesteeg 3, 6708 PB Wageningen, The Netherlands

12 (3) School of GeoSciences, The University of Edinburgh, Drummond Street, Edinburgh EH8 9XP, UK

13 (4) University of Tartu, Vanemuise 46, 51014 Tartu, Estonia
14

15 Robert G.H. Bunce
16 robert.bunce@emu.ee
17

18 Kalev Sepp
19 kalev.sepp@emu.ee
20

21 Robert H.G. Jongman
22 rob.jongman@wur.nl
23

24 Marc J. Metzger
25 marc.metzger@ed.ac.uk
26

27 Tiiu Kull
28 tiiu.kull@emu.ee
29

30 Janar Raet
31 janar.raet@emu.ee
32

33 Valdo Kuusemets
34 valdo.kuusemets@emu.ee
35

36 Ain Kull
37 ain.kull@ut.ee
38

39 Aivar Leito
40 aivar.leito@emu.ee
41
42
43

44 Corresponding author: Miguel Villoslada
45 E-mail: mpecina@emu.ee
46 Phone: (+372) 56890255
47 Address: Kreutzwaldi 5, room 2C18, 51014 Tartu, Estonia
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55 **Abstract**

56 Environmental stratifications provide the framework for efficient surveillance and monitoring of biodiversity and
57 ecological resources, as well as modelling exercises. An obstacle for agricultural landscape monitoring in
58 Estonia has been the lack of a framework for the objective selection of monitoring sites. This paper describes the
59 construction and testing of the Environmental Stratification of Estonia (ESE). Principal components analysis
60 (PCA) was used to select the variables that capture the most amount of variation. Seven climate variables and
61 topography were selected and subsequently subjected to the ISODATA clustering routine in order to produce
62 relatively homogeneous environmental strata. The ESE contains eight strata, which have been described in terms
63 of soil, land cover and climatic parameters. In order to assess the reliability of the stratification procedure for the
64 selection of monitoring sites, the ESE was compared with the previous map of Landscape Regions of Estonia
65 and correlated with five environmental datasets. All correlations were significant. The stratification has therefore
66 already been used to extend the current series of samples in agricultural landscapes into a more statistically
67 robust series of monitoring sites. The potential for applying climate change scenarios to assess the shifts in the
68 strata and associated ecological impacts is also examined.

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71 **Key words: climate, geomorphology, clustering algorithm, monitoring, stratified random sampling**

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73 **Length of the manuscript**

74 Number of words: 5434 words

75 Figures and tables: 13

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91 **Introduction**

92 Environmental stratification is the process that applies multivariate statistical analysis to divide the
93 environmental gradients of a given region into relatively homogeneous units, which can then be used as a
94 framework for sampling both socio-economic and ecological features. Tried-and-tested statistical procedures are
95 used to ensure that the environmental strata are independent of personal bias (Metzger et al. 2005). Commonly,
96 climatic and topographic parameters are used as input variables in the clustering procedure. The resulting
97 environmental strata are relatively homogeneous in terms of the climatic and environmental variables (Klijn and
98 de Haes 1994). These units help in the interpretation of climatic and environmental patterns and thus lead to a
99 better understanding of underlying ecological processes (Jongman et al. 2006).

100 At present, environmental stratifications have been developed at several levels: global (Metzger et al. 2012,
101 Metzger et al. 2013), continental e.g. Europe (Metzger et al. 2005; Jongman et al. 2006), national e.g. Great
102 Britain (Bunce et al. 1996), Northern Ireland (Cooper 2000), Spain (Elena-Roselló 1997; Regato et al. 1999),
103 Norway (Bakkestuen et al. 2008), Sweden (Ståhl et al. 2011) and the Czech Republic (Fňukalová and Romportl
104 2014) and regional e.g. Bunce & Smith (1978). The original methodology was published in 1975 (Bunce et al.
105 1975) and has undergone progressive development since then, as described by Sheail and Bunce (2003).
106 Environmental stratification has primarily been applied in strategic ecological survey projects by using the strata
107 to select statistically representative random samples for surveillance and subsequent monitoring of biodiversity.
108 Environmental stratification has also been used for climate change modelling (Metzger et al. 2008).

109 National level stratifications have usually been carried out regularly in regions characterized by considerable
110 environmental variability. The main aim of this paper is to demonstrate that it is also feasible to implement
111 environmental stratifications in regions or countries without pronounced topographic and climatic variability.
112 The data required to construct regional level environmental stratifications are usually in more detail than those
113 used at the continental level. This paper describes the construction of the Environmental Stratification of Estonia
114 (ESE) and therefore provides an example of regional level classification. An important step in this process was
115 to explore the data required to cluster the environmental variability of the country into interpretable strata. The
116 suitability of the ESE for modelling possible future ecological changes according to climate change scenarios is
117 also discussed.

118 Estonia covers 45227 km² in the Baltic region of north-eastern Europe between Finland, Russia and Latvia, as
119 shown in Fig. 1. According to the European Environmental Stratification (EnS) (Metzger et al. 2005), Western

120 Estonia belongs to two classes of the Nemoral Zone, whereas Eastern Estonia is situated in the least cold of the
121 eight classes of the Boreal Zone. Therefore, although a small country, Estonia is located on the boundary
122 between two of the largest EnS classes. According to the Intergovernmental Panel on Climate Change (IPCC)
123 climate change scenarios (Nakicenovic et al. 2000), the border between these zones is likely to shift by 2050. In
124 addition, the Atlantic North Zone may extend into Western Estonia by 2080, as modelled by Metzger et al
125 (2008). The EnS partitions climate variation in Europe, but is not suitable for modelling changes in smaller
126 regions due to the insufficient regional detail of the climate datasets used and because the number of strata
127 produced is not adequate for capturing local environmental gradients. The availability of detailed physiographic
128 and climatic datasets in Estonia facilitates the construction of finer divisions at the national level, as compared to
129 the coarser resolution of the European Zones previously described by Metzger et al. (2005). It has already been
130 recognised that subdivisions of the EnS are needed for local studies. For example, Jongman et al. (2006)
131 subdivided one of the European Environmental Strata in Portugal on the basis of soil types. The existing
132 classification of Estonian landscapes (Arold 2005) was based on the interpretation of geomorphological and soil
133 patterns. The boundaries between the landscape units were descriptive and defined according to expert
134 knowledge, whereas an objective regional classification is required as a framework for landscape and
135 biodiversity monitoring strategies based on a stratified random sampling design. Statistical clustering of the
136 environmental variability into homogeneous units allows deriving reliable estimates on biodiversity, habitats and
137 land cover (Jongman et al. 2006). In this regard, Estonia lacks a robust statistical framework for the selection of
138 biodiversity and vegetation sampling and monitoring plots. The Environmental Stratification of Estonia (ESE)
139 provides the structure needed for such assessment and monitoring strategy, thus the statistical validity of these
140 strata is also examined in this paper.

141 The present study was initiated in the frame of a multidisciplinary project within the Estonian University of Life
142 Sciences concerning national ecotones and boundaries. A key module in the project is the assessment of the
143 impact of climate change on vegetation and habitats. The aim of the present study is therefore to describe the
144 construction and validation of the Environmental Stratification of Estonia (ESE), which will be used as a basis
145 for the selection of representative sampling sites for recording data on habitats and vegetation. Moreover, the
146 ESE will provide the statistical framework required to upgrade the current Agricultural Landscape Monitoring
147 programme in Estonia. The collected data will then be used in modelling the potential impacts of climate change
148 on the stock and change of biodiversity (Berry et al. 2003; Thuiller et al. 2008). Modelling exercises will also

149 include determining the shifts in the distribution of the strata under different climate change scenarios. The ESE
150 will also be used as a framework to determine the provision of ecosystem services throughout Estonia.

151 **Materials and Methods**

152 Based on previous experience, it was initially decided to examine the potential use of climatic, geomorphological
153 and soil data as input variables to generate the ESE. The data flow was organized in successive steps, as shown
154 in Fig.2. The input variables used in the stratification (Table 1) were selected based on the conceptual model
155 described by Klijn and de Haes (1994), Bunce et al. (1996) and Metzger et al. (2005). The concept is based on a
156 regression model between the environmental strata and the observed ecological parameters. In the functional
157 hierarchy described by Klijn and de Haes (1994), lower components (e.g. vegetation) are dependent on
158 parameters at a higher level (e.g. climate and geomorphology). This hierarchical framework has been recognized
159 by other authors (Godron 1994; Breckle and Walter 2002; Ferrier 2002). At the landscape scale, the variability of
160 environmental conditions is relatively high and the interrelationships between factors that determine this
161 heterogeneity are complex. However, ecosystem patterns and habitat distributions can be analysed using this
162 model even at the national scale.

163 **Climate data**

164 The climate data were interpolated from 26 Estonian meteorological stations, covering a period of 30 years. The
165 data were obtained over the period 1971-2000, which is used nationally as the official period for climate
166 reporting and analysis. In addition, the recording methodology at weather stations in Estonia has been
167 standardized only from 1971 onward. The daily observations at meteorological stations were provided by the
168 Estonian Weather Service. Latvian, Russian and Finnish weather stations were also included in the climate
169 dataset to expand the coverage of the environmental model and provide a more accurate interpretation of the
170 climate in border regions. The climate variables corresponding to the Latvian, Russian and Finnish weather
171 stations were obtained from the E-OBS dataset (Haylock et al. 2008). In order to avoid high correlations and
172 give equal weight to the climate variables, Principal Components Analysis (PCA) was used to generate a subset
173 from a climate dataset composed of 16 parameters (King and Jackson 1999). PCA is a variable reduction
174 procedure that extracts independent components from a large set of variables. PCA identifies the variables that
175 capture the most amount of variation, as well as those that are redundant (Jolliffe 1972; Krzanowski 1987;
176 McCabe 1984). A threshold of 90% of variance explained was used to select the first four components.
177 Subsequently, the two variables with the highest positive and negative loadings were selected from each

178 component. A total of seven climate variables were selected from the initial dataset, as shown in Table 1. This
179 variable selection method has been previously used by Saxon et al. (2005) to generate homogenous climate
180 domains of the continental sector of the United States of America.

181 The environmental stratification clustering process requires gridded raster layers as input variables. Therefore,
182 the climate data obtained from the weather stations were interpolated into 1x1km raster climate surfaces using
183 the Spline function in ArcGIS 10.1. As a result, seven climate raster grids were produced (Fig. 3). An analogous
184 interpolation procedure has been used by Hijmans et al. (2005) and New et al. (2002).

185 **Geomorphology data**

186 The influence of geographical factors in the distribution and coverage of plant species, even in lowland regions
187 such as Estonia has already been described (Kull et al. 2002; Palo et al. 2008). In order to provide sufficiently
188 detailed information at the local scale in the stratification, geomorphological data were also included by
189 incorporating a digital elevation model, derived from the Estonian LIDAR database. Mean elevation data were
190 calculated within each 1x 1km climate grid cell.

191 **Soil data**

192 At the initial stage of the modelling process, two soil databases were considered for analysis: the Soil Map of
193 Estonia (1:10.000) and the European Soil Database (1:1.000.000) (European Commission 2004). The Soil Map
194 of Estonia proved impractical because of inconsistencies in the definitions of the classes. Before any data could
195 be used, extensive pre-processing would have been required in order to ensure that the classes were consistent
196 throughout the country. In contrast, the coarse resolution of the European Soil Database (ESDB) does not
197 capture the necessary detail required at the regional scale. Moreover, soil information is expressed as categorical
198 classes, which are not compatible with the climate and geomorphology variables expressed as continuous
199 gridded raster layers. Although a transformation of categorical soil data into a continuous grid is possible, the
200 large amount of soil classes in combination with the coarse resolution of the ESDB unbalanced the clustering
201 process, and lead to certain strata being defined exclusively by a unique soil class. The soil data were therefore
202 not included.

203 The input variables are measured in different units, and some also have large variances which can in turn, have
204 an undesired effect on the resulting clusters. The variables were therefore standardized to zero mean and unit
205 standard deviation.

206 The variables were subsequently subjected to the ISODATA clustering algorithm to generate the environmental
207 strata. This procedure has been used in comparable studies by Metzger et al. (2005) and Tou and Gonzalez
208 (1974). ISODATA is an iterative algorithm that uses minimum Euclidean distances between each pixel and the
209 closest cluster in the multi-dimensional feature space of the selected variables. The process starts with arbitrary
210 means being assigned to a pre-defined number of clusters. Each raster cell is then assigned to the cluster of
211 which the mean is the closest. The process repeats itself, each raster cell being progressively assigned to the
212 closest cluster in the multidimensional space until no more grid cells are reassigned. The Runtime software
213 program ArcGIS 10.1 was used to perform the analysis. As stated by Memarsadeghi et al. (2007), the main
214 advantage of ISODATA over other clustering procedures is the ability of the algorithm to split large diffuse
215 clusters and to merge small clusters whose centres are closer than a certain threshold. The clustering operation
216 reduces the overall environmental variation into groups with comparable variation around a mean. The number
217 of strata is arbitrary, but each stratum is distinctive and interpretable in terms of its environmental characteristics.
218 The number of strata at which the clustering procedure was stopped was eight. This was considered an
219 interpretable division of Estonia: while reflecting the well-known division between East and West (Lippmaa
220 1935), the main geomorphological features and contrast between Upland and Lowland regions is appropriately
221 captured by eight strata. In addition, it was observed that the ISODATA algorithm failed to produce clusters
222 when the number was set at ten and above. This could be explained by the fact that the algorithm was not able to
223 create distinguishable clusters above a certain limit. Given the size of Estonia and the main aim of the present
224 study, eight strata is thus considered a practical number for scientific and policy objectives, as well as an
225 adequate reflection of the variation in the environment of the country.

226 At the last stage of the process, isolated pixels and scattered regions smaller than 15 km² were assigned to the
227 closest stratum. In relatively flat regions such as Estonia, these scattered pixels are statistical artefacts of the
228 clustering algorithm, rather than real local features, and the spatial integrity of classes was therefore considered
229 to be the overriding factor (Metzger et al. 2005).

230 In order to determine the reliability of the stratification, it was necessary to compare this method with
231 independent classifications and to assess the correlations between the clustered input variables and the
232 underlying environmental gradients using the datasets shown in Table 2. The Estonian Landscape Regions
233 classification (Arold 2005) is derived from soil and geomorphological characteristics using expert judgement.
234 Although the classes are not based on statistical reproducible criteria, it is useful to compare their distribution
235 patterns with the ESE to examine the extent of agreement. The Fuzzy Kappa statistic (Hagen 2003) was

236 therefore calculated using Map Comparison Kit v 3.0 (Visser 2004). The objective of the Fuzzy Kappa statistic is
237 to assess the degree of agreement between maps of different classes and the comparisons should thus be treated
238 as similarity coefficients rather than as measures of correlation (Bunce et al. 2002; Klotz et al. 2016).

239 In order to test the relationships between the ESE and the underlying environmental gradients, regressions were
240 calculated between a number of datasets and the ESE. According to the hierarchical framework previously
241 described, correlations should be present between higher, independent components and the dependent variables.
242 As shown in Table 2, the components derived from the variables used for clustering were correlated with five
243 environmental datasets. Bunce et al. (1996) described classical regression as the most appropriate model to
244 assess the abovementioned correlation. The complex of underlying environmental factors used to create the
245 classes and the selected environmental datasets (Table 2) are the independent and dependent variables
246 respectively. This procedure, referred to as orthogonal regression, has previously been used (Metzger et al. 2005)
247 to assess the validity of the European classification.

248 Regressions cannot be directly calculated between nominal variables such as Corine land cover and the ESE
249 clustering variables. In order to calculate a multivariate proxy of the land cover classes, the percentages of each
250 class within each stratum were calculated. The first principal component of the land cover percentages was then
251 extracted and correlated with the mean first principal component of the clustering variables within each stratum.
252 Although being directly influenced by human activity, the broad land cover distribution was expected to show a
253 strong relationship with the environmental gradients captured by the ESE. The same procedure was applied to
254 the European Soil Database soil types.

255 The distribution of plant species was also expected to show significant correlations with the ESE. Species that
256 show well defined distribution patterns in Estonia were chosen for the analysis. The whole flora could not be
257 used because the majority of species that are present throughout the country would provide much background
258 noise in the analysis. Consequently, 26 species were selected as representatives of the Estonian flora, recorded
259 from the 6'x10' grid used for the Atlas of the Estonian Flora (Kukk and Kull 2005). Binary distribution data
260 were then analyzed by Canonical Correspondence Analysis (CCA) (Ter Braak 1986). The distribution data were
261 fed into the statistical analysis software Canoco 5 to obtain CCA first axis scores for each grid square (Ter Braak
262 and Šmilauer 2012). The mean CCA scores within each stratum were subsequently calculated and then
263 correlated with the mean PCA first axis scores of the stratification for each stratum.

264 For continuous variables such as topsoil organic carbon, the regression was calculated between the mean score of
265 the first principal component of the classification variables and the mean value of the response variable within
266 each stratum. Cover Management factor is also a continuous variable, therefore the same procedure was applied.
267 Cover Management factor is one of the five factors included in the Revised Universal Soil Loss Equation
268 (RUSLE) and it accounts for the effects of land cover, crops and crop management practices in soil loss
269 (Panagos et al. 2015).

270 The next stage in the approach is to select a set of randomly located survey sites for sampling biodiversity and
271 landscape monitoring from within each stratum. The procedure used has been described by Metzger et al. (2013)
272 and Carvalho et al. (2015). The design of the sampling framework as well as the number of sampling sites
273 required depends upon the population or the area of habitat or land cover type being sampled. In the present
274 study, the use of the ESE as a framework for monitoring is exemplified by its application in the Agricultural
275 Landscape Monitoring (ALM) programme in Estonia. The number of agricultural landscape monitoring sites in
276 Estonia currently being surveyed as a basis for modelling is only 22, which is statistically unreliable. However,
277 the aim is to increase the number of sites for a long term ALM programme in order to obtain estimates on
278 agricultural land use change and landscape metrics. Stratified random sampling was chosen as the most suitable
279 strategy for the objects of the ALM (Peterseil et al. 2004; Ståhl et al. 2011). The first step of the sampling design
280 was the definition of the target population, which was restricted to all 1 km squares containing agricultural land.
281 Subsequently an agricultural raster mask layer was extracted from the Estonian Basic Map and intersected with a
282 grid of 1 km square resolution specifically created for this process. In order to set the minimum required
283 sampling size, the coefficient of variation of agricultural area within the 1 km squares was defined as the quality
284 constraint (Brus et al. 2011). For any required coefficient of variation, the minimum amount of total sampling
285 units in a stratified random sampling design is defined by Eq. 1 below (de Gruijter et al. 2006):

$$286 \quad n_{req} = \frac{1}{V_{max}} \left(\sum_{h=1}^L N_h S_h(y) \right)^2$$

287 where n_{req} is the required total sample size, V_{max} is the maximum sampling variance of the total area, N_h is the
288 number of 1km squares in stratum h , S_h is the spatial standard deviation of y within stratum h and y is the land
289 cover class or habitat being sampled. V_{max} is obtained by multiplying the required coefficient of variation by the
290 total area of the population being sampled.

291 **Results**

292 The distribution map of the strata of the ESE is shown in Fig. 4. The boundary between the Nemoral and Boreal
293 Zones (Metzger et al. 2005) is almost precisely reproduced at the border between classes 1-3 and 4-8. This result
294 confirms the significance and stability of this boundary, since the ESE and the European Environmental
295 Stratification were generated from different climate and topography datasets.

296 Names have been ascribed to the classes, which together with summary information are shown in Table 3. In
297 order to better understand the characteristics of the environmental strata, a brief description of each stratum
298 based on geomorphology, soils and land cover is presented in Table 4.

299 The ESE was compared with the landscape classification of Arold (2005) and the Fuzzy Kappa comparison
300 yielded a kappa statistic of 0.415, interpreted as “moderate strength of agreement” (Landis and Koch 1977),
301 which is indicative of similarities between the classifications.

302 The correlations between the selected environmental datasets and the ESE were significant at the 0.05 level. The
303 scatter diagram for the relationship of the Cover Management factor mean value within each stratum with the
304 first PCA axis of the environmental variables is shown in Fig. 5a and Table 2, with an r-value of .77. A summary
305 of the percentage of each soil type within each stratum is provided in Fig. 6

306 The results of the analysis of the 26 species are shown in Fig. 5b and Table 2, with an r-value of .76. This
307 analysis confirms the role of the principal environmental gradients as determinant factors in the distribution
308 patterns of the flora of Estonia, therefore validating statistically the reliability of the environmental stratification
309 procedure.

310 Fig. 5c and Table 2 show a correlation of the overall land cover pattern and the underlying environmental
311 gradients with an r-value of .67. A summary of the percentage of each Corine Land Cover class within each
312 stratum is provided in Fig. 7.

313 Based on the proposed sampling design and an initial coefficient of variation set at 0.1, a total minimum number
314 of 40 1 km monitoring squares was obtained as a basis for monitoring. The minimum required amount of
315 monitoring sites per stratum was therefore set at five, which were assigned to the smallest stratum (Northern
316 Lowlands). The allocation of monitoring sites was subsequently weighted according to stratum size, as described
317 by Haines-Young et al. (2000). This represents the most effective method for reducing the final standard errors

318 of any parameters for which estimates are required. The result was a total sample size of 100 monitoring sites
319 and a final coefficient of variation of 0.06. Further samples can be added later according to the objectives of a
320 given project (Haines-Young et al 2000). Increasing the number of samples does not usually change the total
321 figures but reduces the standard errors (Mateus 2004; Jongman et al 2006).

322 Table 5 shows the current number of agricultural landscape monitoring sites in Estonia and the number of
323 additional monitoring sites needed per stratum. Further steps in the construction of the stratified random
324 sampling design involve subdividing the strata into equal-area polygons according to the number of sampling
325 sites required per stratum as described by Metzger et al. (2013). Subsequently, a sampling 1 km square will be
326 placed at random within each equal-area polygon. A similar sampling methodology has been successfully
327 implemented in Portugal (Carvalho et al. 2015).

328 **Discussion**

329 The methodology presented in this paper produced eight unbiased environmental classes for Estonia that are
330 based on explicit criteria and explain its environmental variability. The division between eastern and western
331 environmental regions in Estonia (Lippmaa 1935; Laasimer 1965) has been confirmed in the ESE and many of
332 the observed distribution limits of plant species occur along this border between Nemoral and Boreal strata,
333 which is likely to shift under climate change scenarios (Metzger et al. 2008). Consequently Estonia is an optimal
334 location for modelling the impacts of climate change.

335 The ESE differs from the previous environmental classification (Arold 2005) in having explicit statistical criteria
336 for defining the classes and is therefore independent of personal judgement. The comparison with the
337 classification of Estonian Landscapes confirms the fact that, although based on contrasting conceptual
338 frameworks and datasets, the ESE and the Estonian Landscape Regions reflect the same general environmental
339 patterns. Jones and Bunce (1985) and Metzger et al. (2005) reached the same conclusion with respect to the
340 validity of statistical classification versus intuitive and expert knowledge based procedures, proving the benefits
341 of statistically robust stratification methods. More recently Carvalho et al. (2015) confirmed the value of the
342 approach described in the present paper.

343 Several regressions were calculated between the ESE and environmental datasets. The distribution patterns of the
344 environmental strata are related to the known distribution of individual plant species, two of which are shown in
345 Fig. 8. *Myrica gale* is a north-western Atlantic species and a major contributor to vegetation cover in the bogs of

346 Western Britain and Norway. In contrast, *Chamaedaphne calyculata* is a species with affinities with continental
347 conditions, which replaces *Myrica gale*, to some extent, occupying a similar role within bog habitats. Regarding
348 land cover, many factors, such as socio-economic changes, major political decisions and cultural background,
349 have affected its distribution patterns (Mander and Palang 1994; Fuchs et al. 2013). However, the results shown
350 in Fig. 5c demonstrate that the overall pattern is still correlated with the underlying environmental gradients.

351 The number of strata that is required should be determined according to the objectives of individual projects.
352 Bunce et al. (1996) discussed the use of complex stopping rules, such as testing the variance between the classes
353 and concluded that, in order to obtain statistically reliable results, the most appropriate procedure is to define a
354 minimum size of group that is appropriate for the objectives of the particular project. The divisions made for
355 large regions such as Europe will inevitably be much coarser than for a small country such as Estonia but this
356 does not detract from their value in selection of representative sites, which will be based on the variation within
357 the given domain. The statistical procedure inside the clustering algorithm ensures that the environmental
358 gradients within a given region and the corresponding variation in the data are appropriately clustered in the
359 resulting strata. Additional divisions within a large region can be made for specific objectives. An example of
360 subdividing classes is given by Jongman et al. (2006), who partitioned three EnS strata in the Alpine South zone
361 into six substrata according to altitude in order to capture the full complexity of the Alpine zone from valley
362 floors to summits. Because climate data are continuously variable, there is rarely any natural cut-off point, as is
363 often the case in the analysis of plant taxonomic data.

364 The climate data used in the construction of the ESE were the best available at the time of analysis. However,
365 when more detailed data becomes available, it could be used to update the stratification in order to improve the
366 definition of boundaries between classes. When the boundaries are shifted, a reassessment of the existing sample
367 and an assessment of the need of additional 1 km monitoring squares are needed. Barr (2011) provides a
368 complete overview on how to proceed when monitoring sites are reallocated. However, Bunce et al. (1996)
369 showed that, in practice, only minor variations are observed through re-classification. In addition, any
370 inefficiencies in the strata will be incorporated in the standard errors of the field estimates (Metzger et al. 2005).

371 In order to make informed decisions, reliable monitoring data derived from statistically robust sampling designs
372 is required (Ortega et al. 2011). In this regard, a main shortcoming of the Agricultural Landscape Monitoring
373 methodology in Estonia has been the lack of a framework for the objective selection of monitoring sites for stock
374 and change of vegetation and habitats. The sampling efficiency is maximized when the population is stratified

375 according to the environmental gradients that define the site characteristics (Jongman et al. 2006). As described
376 in this study, the ESE has been used as a framework to optimize the ALM programme in Estonia in order to
377 obtain more reliable estimates of spatiotemporal trends of land use. The number of monitoring sites was
378 determined based on the coefficient of variation of agricultural land within the 1 km squares in Estonia. As stated
379 by Jongman et al. (2006), improvements in the sampling effort can be made in later stages, once exploratory data
380 has been collected. The results obtained from the representative set of sampling sites can subsequently be
381 extrapolated into national or regional estimates (Bunce et al. 1996; Haines-Young et al. 2000).

382 Another key objective of the ESE is providing the framework for modelling exercises. Several modelling
383 exercises have been previously performed using environmental stratifications as a framework. For example, Petit
384 et al. (2001) assessed the consequences of environmental change for biodiversity in each of the EnS. On the
385 other hand, Bugter et al. (2011) examined the likelihood of exotic species to survive according to temperature
386 zones defined by the Global Environmental Stratification (Metzger et al. 2012) and climate change models. Leito
387 et al. (2015) used the European stratification as a framework to assess the effects of climate change in wintering
388 and stopover sites of the Eurasian crane (*Grus grus*).

389 A current on-going project in ecotones and boundaries in Estonia has recently implemented the ESE to examine
390 the potential effects of climate change on habitats and groups of species. In this regard, Liivamägi et al. (2013)
391 showed the changes in the distribution of the Clouded Apollo butterfly (*Parnassius mnemosyne*). The
392 distribution of this species is strongly limited to classes four, five, seven and eight of the ESE, and further work
393 is needed to model the changes in the distribution limits based on climate change models. Moreover, the ESE is
394 currently being used for vegetation and habitat recording from dispersed random squares based on the procedure
395 described in this paper and previously defined by Metzger et al. (2013) and Carvalho et al. (2015). Further
396 applications include the assessment of the provision of certain ecosystem services, utilizing the environmental
397 strata as units for stratified random sampling.

398 The European environmental stratification has previously been used to evaluate the potential impact of climate
399 change in the provision of ecosystem services (Metzger et al. 2006). The climate change scenarios created for
400 Estonia show a range of results, depending on the General Circulation Models and IPCC storylines adopted.
401 However, mean increases of 10-20% in annual precipitation and a mean warming by 2.3–4.5°C are projected by
402 the end of the 21st Century (Jaagus and Mändla 2014). The implications for biodiversity and ecosystem services
403 provision in Estonia have yet to be determined but the ESE will make such analyses possible. Consequently,

404 further research will involve coupling climate change models (climate change simulations have already been
405 calculated in Estonia by Luhamaa et al. (2014) with the Environmental Stratification of Estonia. This approach
406 has already been tested by Metzger et al. (2008). By incorporating climate change predictions in the stratification
407 as input data, the future distribution of the strata can be quantified in terms of the direction and extent of change.
408 The results of such analyses will in due course enable the estimation of the potential changes in ecological
409 resources and the provision of ecosystem services in Estonia.

410 **Conclusions**

411 The Environmental Stratification of Estonia (ESE) was constructed using climate and geomorphological data and
412 applying standard statistical procedures. The classification has been tested and correlated with environmental
413 data sets, demonstrating that the strata are representative of the principal underlying environmental gradients.
414 Because the strata are determined statistically and independently of personal judgement, the ESE provides the
415 framework for optimizing the existing Agricultural Landscape Monitoring programme in Estonia, in order to
416 obtain statistically robust figures. Furthermore, the ESE will provide the background for modelling the effects of
417 climate change on habitats, species distribution and the provision of ecosystem services.

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653 for sites

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670 these species has been previously published (Kukk and Kull 2005)

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