



HAL
open science

A comparative framework for broad-scale plot-based vegetation classification

Miquel de Cáceres, Milan Chytrý, Emiliano Agrillo, Fabio Attorre, Zoltán Botta-Dukát, Jorge Capelo, Bálint Czúcz, Jürgen Dengler, Jörg Ewald, Don Faber-Langendoen, et al.

► **To cite this version:**

Miquel de Cáceres, Milan Chytrý, Emiliano Agrillo, Fabio Attorre, Zoltán Botta-Dukát, et al.. A comparative framework for broad-scale plot-based vegetation classification. *Applied Vegetation Science*, 2015, 18 (4), pp.543-560. 10.1111/avsc.12179 . hal-01211250

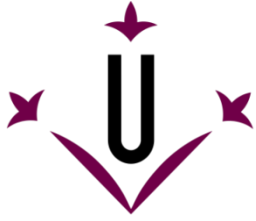
HAL Id: hal-01211250

<https://hal.science/hal-01211250>

Submitted on 25 Jun 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Universitat de Lleida

Document downloaded from:

<http://hdl.handle.net/10459.1/69891>

The final publication is available at:

<https://doi.org/10.1111/avsc.12179>

Copyright

(c) International Association for Vegetation Science, 2015

1 This manuscript is contextually identical with the following published paper:
2 Miquel De Cáceres, Milan Chytrý, Emiliano Agrillo, Fabio Attorre, Zoltán Botta-Dukát,
3 Jorge Capelo, Bálint Czúcz, Jürgen Dengler, Jörg Ewald, Don Faber-Langendoen, Enrico
4 Feoli, Scott B. Franklin, Rosario Gavilán, François Gillet, Florian Jansen, Borja Jiménez-
5 Alfaro, Pavel Krestov, Flavia Landucci, Attila Lengyel, Javier Loidi, Ladislav Mucina,
6 Robert K. Peet, David W. Roberts, Jan Roleček, Joop H.J. Schaminée, Sebastian
7 Schmidtlein, Jean-Paul Theurillat, Lubomír Tichý, Donald A. Walker, Otto Wildi,
8 Wolfgang Willner & Susan K. Wiser (2015) A comparative framework for broad-scale
9 plot-based vegetation classification. APPLIED VEGETATION SCIENCE, 18(4): pp. 543-
10 560.DOI: 10.1111/avsc.12179
11 The original published pdf available in this website:
12 <http://onlinelibrary.wiley.com/doi/10.1111/avsc.12179/abstract>

13

14 **A comparative framework for broad-scale plot-based vegetation** 15 **classification**

16

17 Miquel De Cáceres, Milan Chytrý, Emiliano Agrillo, Fabio Attorre, Zoltán Botta-Dukát,
18 Jorge Capelo, Bálint Czúcz, Jürgen Dengler, Jörg Ewald, Don Faber-Langendoen, Enrico
19 Feoli, Scott B. Franklin, Rosario Gavilán, François Gillet, Florian Jansen, Borja Jiménez-
20 Alfaro, Pavel Krestov, Flavia Landucci, Attila Lengyel, Javier Loidi, Ladislav Mucina,
21 Robert K. Peet, David W. Roberts, Jan Roleček, Joop H.J. Schaminée, Sebastian Schmidtlein,
22 Jean-Paul Theurillat, Lubomír Tichý, Donald A. Walker, Otto Wildi, Wolfgang Willner &
23 Susan K. Wiser 2015)

24 **De Cáceres, M.** (corresponding author, miquelcaceres@gmail.com): Forest Science Center
25 of Catalonia. Ctra. antiga St Llorenç km 2, 25280 Solsona, Spain.

26 **Chytrý, M.** (chytry@sci.muni.cz), **Jiménez-Alfaro, B.** (borja@sci.muni.cz), **Landucci, F.**
27 (flavia.landucci@gmail.com), **Tichý, L.** (tichy@sci.muni.cz): Department of Botany and
28 Zoology, Masaryk University, Kotlářská 2, 611 37 Brno, Czech Republic.

29 **Agrillo, E.** (emiliano.agrillo@uniroma1.it): Department of Environmental Biology,
30 University of Roma "La Sapienza", Largo Cristina di Svezia 24, 00165 Roma, Italy.

31 **Attorre, F.** (fabio.attorre@uniroma1.it): Department of Environmental Biology, University
32 of Roma "La Sapienza", P.le Aldo Moro 5, 00185 Roma, Italy.

33 **Botta-Dukát, Z.** (botta-dukát.zoltan@okologia.mta.hu), **Czúcz, B.**

34 (balint.czucz@okologia.mta.hu), **Lengyel, A.** (lengyel.attila@okologia.mta.hu): Institute of
35 Ecology and Botany, MTA Centre for Ecological Research, Alkotmány 2-4, H-2163
36 Vácraátót, Hungary.

37 **Capelo, J.** (jorge.capelo@iniav.pt): Instituto Nacional de Investigação Agrária e Veterinária,
38 Herbarium, Av. da República, Nova Oeiras, 2784-505 Oeiras, Portugal.

39 **Dengler, J.** (juergen.dengler@uni-bayreuth.de): Plant Ecology, Bayreuth Center of Ecology
40 and Environmental Research (BayCEER), University of Bayreuth, Universitätsstr. 30, 95447

41 Bayreuth, Germany & Synthesis Centre (sDiv), German Centre for Integrative Biodiversity
42 Research (iDiv) Halle-Jena-Leipzig, Deutscher Platz 5e, 04103 Leipzig, Germany.
43 **Ewald, J.** (joerg.ewald@hswt.de): Faculty of Forestry, University of Applied Sciences
44 Weihenstephan-Triesdorf, Hans-Carl-von-Carlowitz-Platz 3, 85354 Freising, Germany.
45 **Faber-Langendoen, D.** (don_faber-langendoen@natureserve.org): Conservation Science
46 Division, NatureServe, 4600 North Fairfax Drive, 7th Floor, Arlington, VA 22203, USA.
47 **Feoli, E.** (feoli@units.it) Department of Life Sciences, University of Trieste, Via Giorgieri
48 10, TS 34127 Trieste, Italy.
49 **Franklin, S.B.** (scott.franklin@unco.edu): School of Biological Sciences, University of
50 Northern Colorado, 501 20th St., Greeley, CO 80639, USA.
51 **Gavilán, R.G.** (rgavilan@ucm.es): Departamento de Biología Vegetal II, Facultad de
52 Farmacia, Universidad Complutense, E-28040 Madrid, Spain.
53 **Gillet, F.** (francois.gillet@univ-fcomte.fr): UMR 6249 Chrono-environnement, University of
54 Franche-Comté – CNRS, 16 route de Gray, 25030 Besançon cedex, France.
55 **Jansen, F.** (jansen@uni-greifswald.de): Institute of Botany and Landscape Ecology,
56 University of Greifswald, Soldmannstr. 15, 17489 Greifswald, Germany.
57 **Krestov, P.V.** (pavel.krestov@icloud.com): Botanical Garden-Institute of the Far Eastern
58 Branch of the Russian Academy of Sciences, Vladivostok, 690024, Russia.
59 **Loidi, J.** (javier.loidi@ehu.es): Department of Plant Biology and Ecology, University of the
60 Basque Country (UPV/EHU). Ap. 644. 48080-Bilbao, Spain.
61 **Mucina, L.** (Laco.Mucina@uwa.edu.au): School of Plant Biology, The University of
62 Western Australia, 35 Stirling Hwy, Crawley, WA 6009, Perth, Australia.
63 **Peet, R.K.** (peet@unc.edu): Department of Biology, University of North Carolina, Chapel
64 Hill, NC 27599-3280, USA.
65 **Roberts, D.W.** (droberts@montana.edu): Ecology Department, Montana State University,
66 Bozeman, MT 59717-3460, USA.
67 **Roleček, J.** (honza.rolecek@centrum.cz): Department of Vegetation Ecology, Institute of
68 Botany, Lidická 25/27, CZ-602 00 Brno, Czech Republic.
69 **Schaminée, J.H.J.** (joop.schaminee@wur.nl): Alterra WUR and Radboud University
70 Nijmegen, P.O. Box 47, 6700 AA Wageningen, the Netherlands.
71 **Schmidtlein, S.** (schmidtlein@kit.edu): Institute of Geography and Geoecology, Karlsruhe
72 Institute of Technology (KIT), Kaiserstr. 12, 76131 Karlsruhe, Germany.
73 **Theurillat, J.-P.** (jean-paul.theurillat@unige.ch): Fondation J.-M. Aubert, Case postale 71,
74 938 Champex-Lac, Switzerland. & Section de Biologie, Université de Genève, Case postale
75 60, CH-1292 Chambésy, Switzerland.
76 **Walker, D.A.** (dawalker@alaska.edu): Institute of Arctic Biology and Department of
77 Biology and Wildlife, University of Alaska Fairbanks, Fairbanks, AK, 99775 USA.
78 **Wildi, O.** (otto.wildi@wsl.ch): Biodiversity and Conservation Ecology. WSL Swiss Federal
79 Institute of Forest, Snow and Landscape Research, 8903 Birmensdorf, Switzerland.
80 **Willner, W.** (wolfgang.willner@vinca.at): Vienna Institute for Nature Conservation and
81 Analyses, Giessergasse 6/7, 1090 Vienna, Austria.
82 **Wiser, S.K.** (wisers@landcareresearch.co.nz): Landcare Research, PO Box 69040, Lincoln
83 7640, New Zealand.

84
85 DOI:10.1111/avsc.12179

86 **ABSTRACT**

87 **Aims:** Classification of vegetation is an essential tool to describe, understand, predict and
88 manage biodiversity. Given the multiplicity of approaches to classify vegetation, it is
89 important to develop international consensus around a set of general guidelines and purpose-
90 specific standard protocols. Before these goals can be achieved, however, it is necessary to
91 identify and understand the different choices that are made during the process of classifying
92 vegetation. This paper presents a framework to facilitate comparisons between broad-scale
93 plot-based classification approaches.

94 **Results:** Our framework is based on the distinction of four structural elements (plot record,
95 vegetation type, consistent classification section and classification system) and two
96 procedural elements (classification protocol and classification approach). For each element
97 we describe essential properties that can be used for comparisons. We also review alternative
98 choices regarding critical decisions of classification approaches; with a special focus on the
99 procedures used to define vegetation types from plot records. We illustrate our comparative
100 framework by applying it to different broad-scale classification approaches.

101 **Conclusions:** Our framework will be useful for understanding and comparing plot-based
102 vegetation classification approaches, as well as for integrating classification systems and their
103 sections.

104 **Keywords:** Assignment rule; Braun-Blanquet approach; Consistent classification section;
105 Classification system; EcoVeg approach; Phytosociology; Vegetation continuum;
106 Vegetation-plot database; Vegetation type.

107 **Abbreviations:** CCS = consistent classification section

108 **Running head:** A framework for vegetation classification

109

110 I. INTRODUCTION

111 Humans have an inherent need to classify in order to make sense of the world around them.
112 The term *classification* can refer to either the activity of defining classes of objects or the
113 outcome of such activity (Everitt et al. 2011). Vegetation classification aims to summarize
114 the spatial and temporal variation of vegetation using a limited number of abstract entities.
115 These are often called *vegetation types*, and we will follow this convention here. The
116 typologies produced by vegetation classification are useful for multiple purposes (Dengler et
117 al. 2008), including: (1) communication about complex vegetation patterns; (2) formulation
118 of hypotheses about the ecological and evolutionary processes shaping these patterns; (3)
119 creation of maps to display the spatial variation of vegetation and related ecosystem
120 properties and services; (4) surveying, monitoring and reporting plant and animal
121 populations, communities and their habitats; and (5) development of coherent management
122 and conservation strategies.

123 Vegetation changes over time and space as a result of ecological processes acting on
124 plant populations and communities at different temporal and spatial scales. In addition, the
125 quality and quantity of information available about vegetation patterns changes as new
126 vegetation data become available. These two facts have important implications for the
127 stability of classifications. Far from being static or finished products, vegetation
128 classifications need to be continually updated and refined in order to appropriately integrate
129 and summarize all available information (Mucina 1997; Peet & Roberts 2013; Wiser & De
130 Cáceres 2013). In other cases, the need to update vegetation classifications arises from
131 changes in the taxonomy of the plants that sustain the classification. This dynamic
132 perspective contrasts with the need to maintain descriptions and access to the vegetation
133 types already in use (in vegetation maps, biodiversity reports, etc.), a requirement that is
134 especially important for the conservation of habitats (e.g., Jennings et al. 2009; European
135 Commission 2013; Neldner et al. 2012). Hence, a vegetation classification may be
136 understood as a set of vegetation types where new types may be added if needed, but where
137 previously defined types may be modified or discarded only after careful reflection (Jennings
138 et al. 2009; Peet & Roberts 2013).

139 The beginnings of vegetation classification can be traced to the 19th century, with the
140 pioneering, mainly qualitative, works of early plant geographers (e.g., von Humboldt 1807;
141 Grisebach 1838; De Candolle 1855). However, the majority of conceptual and

142 methodological developments were made during the 20th century. Different traditions were
143 developed and pursued during this period (see Whittaker 1978a; Mucina 1997), including the
144 spread of numerical approaches in the 1960s and 1970s (Mucina & van der Maarel 1989).
145 The long history of vegetation classification has resulted in an extensive literature, with
146 different approaches emphasizing different characteristics and often adopting different
147 classification procedures (Mueller-Dombois & Ellenberg 1974; Whittaker 1978c; Dierschke
148 1994; Dengler et al. 2008; Kent 2012; Peet & Roberts 2013). Moreover, vegetation
149 classifications, although often following similar principles, have usually evolved quite
150 idiosyncratically and without reporting clear formal procedures regarding how to extend or
151 modify them.

152 Recently, there has been a renewed interest in vegetation classification worldwide and
153 efforts have been made at the national and international level to develop new classification
154 systems using standardized procedures (e.g., Schaminée et al. 1995; Rodwell 1991-2000;
155 ESCAVI 2003; Jennings et al. 2009; Faber-Langendoen et al. 2014). Moreover, there is
156 growing interest in harmonizing approaches worldwide and standardizing the information
157 content of classifications that serve similar purposes. This interest is motivated by the need to
158 both increase the usefulness of vegetation typologies and to enhance the acceptance of their
159 scientific underpinnings. In order to advance toward classification practices that enjoy broad
160 international acceptance, it is first necessary to develop a general framework in which the
161 concepts and criteria of classification approaches can be appropriately described and
162 compared. Such a framework would be useful to those trying to integrate existing
163 classifications and to those initiating new vegetation classification projects. This paper aims
164 at developing such a framework and represents an attempt towards crafting a global
165 consensus perspective in this subject.

166 Because our framework cannot encompass all possible ways to classify vegetation, we
167 focus on approaches dealing with data in the form of vegetation records, each of them
168 describing a plant community occurring in a small and delimited area – a *vegetation plot* – at
169 a given time. Moreover, our framework is mainly directed towards extensive regional,
170 national or international classification initiatives, which are referred to here as *broad-scale*
171 classification projects. These typically involve conducting many classification exercises, each
172 focusing on a particular kind of vegetation, and integrating their results into a single
173 classification system. In the following we first present the main conceptual elements of our
174 framework, where we distinguish between structural and procedural elements and describe

175 those element properties that are essential for comparisons (section II). We then review
 176 critical decisions and alternative choices regarding classification approaches (section III);
 177 with a special emphasis on the procedures used to define vegetation types from plot records
 178 (section IV). After that, we illustrate our comparative framework by using it to briefly
 179 describe several classification approaches (section V). We conclude with highlighting what
 180 we see as the most important future development needs in this field.

181 II. COMPARATIVE FRAMEWORK

182 Structural and procedural elements

183 In our comparative framework we distinguish between *procedural* and *structural* elements of
 184 plot-based classification of vegetation (Table 1). Two structural elements, ***vegetation-plot***
 185 ***record*** and ***vegetation type***, are well known to vegetation scientists. The most comprehensive
 186 structural element is the ***classification system***, which we define as *an organized set of*
 187 *vegetation types used to describe the variation of vegetation within given spatial, temporal*
 188 *and ecological scopes*. Examples of classification systems are the British National Vegetation
 189 Classification (Rodwell 1991–2000), the US National Vegetation Classification (USFGDC
 190 2008), or the Vegetation of the Czech Republic (Chytrý 2007–2013). Classification systems
 191 are often hierarchical, meaning that vegetation types are organized in hierarchical
 192 classification levels and qualified using ranks (e.g., association or alliance). In addition,
 193 hierarchical systems usually include nested relationships between vegetation types of
 194 different ranks.

195 **Table 1.** Structural and procedural elements in plot-based classification of vegetation. For
 196 each element we indicate a set of properties (defined in Table 2) that are essential for
 197 comparisons.

Structural element	Definition	Properties
Vegetation-plot record	The set of observations and measurements made on the plant community (and its environmental context) occurring in a given area at a given time.	<ul style="list-style-type: none"> • Spatial location and time of survey • Vegetation attributes • Environmental attributes
Vegetation type (also called <i>vegetation unit</i> or <i>plant community type</i>)	An abstract entity that describes and represents a subset of vegetation variation.	<ul style="list-style-type: none"> • Extensive class definition • Intensive class definition • Characterization (primary/secondary/spatial/temporal)

Consistent classification section (CCS)	A subset of a classification system where vegetation types are defined using the same classification protocol.	<ul style="list-style-type: none"> • Spatial, temporal and ecological (thematic) scopes • Set of vegetation types (incl. nested relationships) • Classification levels • Assignment rules
Classification system	An organized set of vegetation types used to describe the variation of vegetation within given spatial, temporal and ecological scopes.	<ul style="list-style-type: none"> • Spatial, temporal and ecological (thematic) scopes • Classification levels • Set of consistent classification sections and their relationships

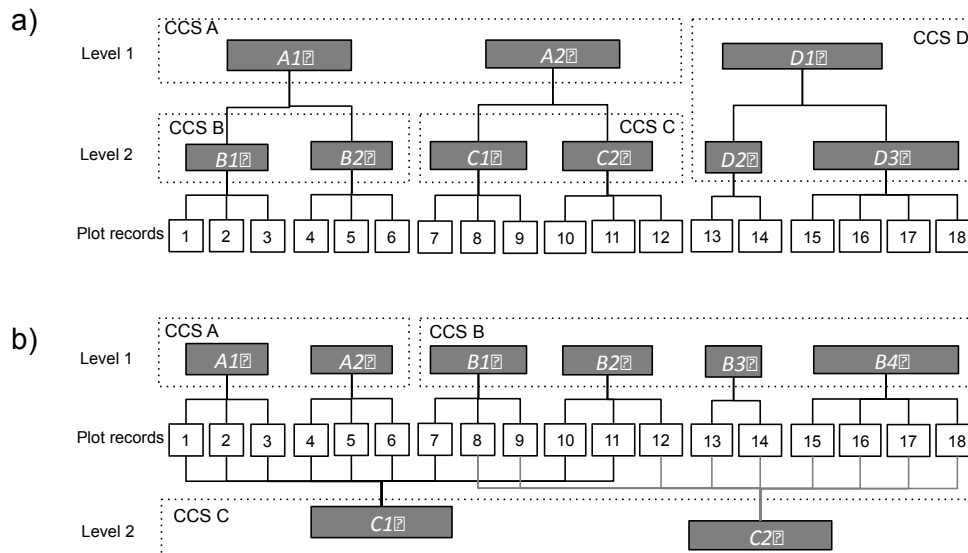
Procedural element	Definition	Properties
Classification protocol	The set of criteria and procedures that underlie the creation or modification of a consistent classification section.	<ul style="list-style-type: none"> • Ecological (or thematic) scope • Typological resolution • Spatial and temporal grains • Primary vegetation attributes • Secondary (incl. constraining) attributes • Class-definition procedures
Classification approach	The set of concepts, criteria and procedures that underlie the creation or modification of a classification system.	<ul style="list-style-type: none"> • Purpose and general requirements • Ecological (or thematic) scope • Structural requirements • Set of classification protocols

198

199 Broad-scale classification systems often involve sets of vegetation types defined based
200 on varying classification criteria. To account for this variation explicitly, we introduce a new
201 concept called *consistent classification section* (CCS) and define it as *a subset of a*
202 *classification system where vegetation types are defined using the same criteria and*
203 *procedures* (i.e., using the same classification protocol; see below). For example, the
204 vegetation types of a CCS may broadly summarize the woody vegetation of a given area on
205 the basis of physiognomy, whereas another may classify the same vegetation based on
206 detailed floristic composition; in this example, the set of vegetation types of each CCS might
207 be placed at different hierarchical levels within the same classification system (e.g., CCSs A
208 and B in Fig. 1a). Classification systems may allow vegetation types of the same hierarchical
209 level, but corresponding to very different kinds of vegetation, to be defined using different
210 criteria. For example, a classification system may allow forest associations to be defined
211 based on the dominant species of the tree layer and species composition of the herb layer,
212 while aquatic associations are defined focusing on the dominant species and its position in
213 the water column; these will represent different CCSs of the same hierarchical level (e.g.,
214 CCSs B and C in Fig. 1a; or CCSs A and B in Fig. 1b).

215 **Fig. 1.** Examples of two hypothetical classification systems. Vegetation types and plot
216 records are indicated using shaded and empty boxes, respectively. Classification system (a)

217 has two hierarchical levels, nested relationships between types and four consistent
 218 classification sections (CCS A-D). Classification system (b) has two classification levels and
 219 three CCSs (A-C). In system (b) nested relationships between types are not always possible.



220

221 Now we turn our attention to procedural elements. We define *classification protocol* as
 222 *the set of criteria and procedures that underlie the creation or modification of a consistent*
 223 *classification section*. For example, the protocol for a set of floristically-based vegetation
 224 types may include specifications of field sampling design, plot size, taxonomic resolution,
 225 taxon abundance measure, plot resemblance measure, clustering algorithm, etc. Although the
 226 focus of our framework is on plot-based classification, we do not require all vegetation types
 227 to be defined directly as groups of plot records. Vegetation types of a given hierarchical rank
 228 may be explicitly defined as groups of vegetation types of a lower rank (e.g., CCS A in Fig.
 229 1a). For example, one may define floristically-based alliances after grouping the constancy
 230 columns of a synoptic table of associations. Classification protocols of this kind will be
 231 qualified as *type-based*, whereas those dealing with plot records directly will be qualified as
 232 *plot-based*. The CCSs and vegetation types resulting from the application of classification
 233 protocols will also be qualified as *type-based* or *plot-based*, accordingly. We will use the
 234 term *classification exercise* to denote the application of a classification protocol to a
 235 particular subset of the vegetation continuum.

236 Finally, we define *classification approach* as *the set of concepts, criteria and*
 237 *procedures that underlie the creation or modification of a classification system*. Examples of
 238 classification approaches are the Braun-Blanquet approach (Braun-Blanquet 1964; Westhoff
 239 & van der Maarel 1973), the Integrated Synusial approach (Gillet et al. 1991; Gillet &

240 Gallandat 1996), or the EcoVeg approach (Jennings et al. 2009; Faber-Langendoen et al.
241 2014). Analogously to classification exercises, we will use the term *classification project* to
242 denote the application of a classification approach to a particular subset of the vegetation
243 continuum, an activity that creates or modifies a classification system.

244 **Properties of structural and procedural elements**

245 We provide definitions for the properties of structural and procedural elements in Table 2.
246 These properties are meant to organize the comparison of classifications. For the sake of
247 brevity, we omitted properties of plot records and other properties, such as nomenclatural
248 rules, that are not essential for comparisons. In the following we detail the most important
249 ones.

250 The *primary vegetation attributes* of a plot-based classification protocol are the
251 attributes consistently used to determine whether plot records are members of the same or
252 different vegetation types. Analogously, the primary vegetation attributes of a type-based
253 protocol are the attributes consistently used to determine which vegetation types of a lower
254 rank are grouped to form a vegetation type of a higher rank. In both cases, these are attributes
255 of the vegetation itself and not of its environment. Vegetation classifications are often
256 required to describe, reflect or indicate other vegetation characteristics not included in the set
257 of primary attributes, or external factors, such as climatic or edaphic conditions,
258 anthropogenic disturbance regime or biogeographic history. We use *secondary attributes* to
259 collectively refer to all those attributes (whether of vegetation or not) that are not primary
260 vegetation attributes. A special situation arises when a subset of secondary attributes, without
261 being explicitly used to determine membership, are used to constrain the definition of
262 vegetation types. We refer to these as *constraining attributes* of the classification protocol.
263 For example, although ‘classes’ of the Braun-Blanquet approach are defined using floristic
264 composition, a specific subset of plant taxa may be selected as primary attributes in order to
265 make classes distinct in terms of environmental conditions and biogeographic context (e.g.,
266 Pignatti et al. 1995). The presence or absence of those taxa is the only information needed to
267 consistently determine membership, but climatic and biogeographic factors have indirectly
268 influenced the definition of vegetation types.

269 **Table 2.** Properties of structural and procedural elements (the order of properties follows
270 their appearance in Table 1).

Properties of structural elements	Definition
Extensive class definition	List of the plot records (or vegetation types of lower rank) that are members of the vegetation type.
Intensive class definition	The primary attribute values that are required to be a member of the vegetation type.
Primary characterization	All statements about the primary attributes of the vegetation type (includes intensive definition).
Secondary characterization	All statements about the secondary attributes of the vegetation type (e.g., altitudinal range).
Spatial characterization	All statements about the spatial dimensions of the vegetation type (e.g., spatial distribution).
Temporal characterization	Statements about the temporal aspects of the vegetation type (e.g., successional relationships).
Spatial scope	Geographical area of interest of a CCS or a classification system.
Temporal scope	Time window during which the classification system (or a CCS) is intended to be comprehensively represent the vegetation in the target geographical area.
Ecological (thematic) scope	Range of ecosystems described in a classification system or a CCS. The ecological scope of a classification system (respectively, CCS) is limited by the corresponding scope of the approach (resp., protocol) used to create it.
Classification level	The set of vegetation types that are given the same qualifier within a classification system. Classification levels often are hierarchically arranged and vegetation types are qualified using ranks.
Assignment rules	Formal procedures used to determine the membership of plot records with respect to predefined vegetation types of a given CCS.
Properties of procedural elements	Definition
Ecological (thematic) scope	Range of ecosystems where a given classification approach or classification protocol is applicable (e.g., a classification system may be restricted to natural vegetation and a classification approach may be valid for aquatic vegetation only).
Typological resolution	Amount of variation that is placed between, as opposed to within, vegetation types.
Spatial resolution	Range of vegetation plot sizes that are allowed in a plot-based classification protocol.
Temporal resolution	Temporal resolution required for plot records in a plot-based classification protocol (i.e., whether temporal variation is pooled or kept separately).
Primary vegetation attributes	Set of vegetation attributes that are used to determine whether plots records are considered as members of the same or different vegetation types.
Secondary attributes	All those attributes (whether of vegetation or not) that are not primary vegetation attributes.
Constraining attributes	Set of attributes (not necessarily of vegetation) used to constrain the definition of vegetation types. Constraining attributes are a subset of secondary attributes.
Class-definition procedures	Set of procedures used to define new vegetation types, sometimes accounting for pre-existing types of the same CCS.
Purpose	Set of applications for which a given classification approach provides useful classification systems.

General requirements	Requirements to accept the usefulness of classification systems obtained from the application a given classification approach.
Structural requirements	Specifications of a classification approach regarding the number of classification levels and the relationships between types belonging to different CCSs.

271 The *extensive class definition* of a plot-based vegetation type is a list of the plot records
272 that belong to it. This list will be enlarged every time new plot records are assigned to the
273 type. Analogously, the *extensive class definition* of a type-based vegetation type is a list of
274 the vegetation types of the lower rank that belong to it. The *intensive class definition* of a
275 vegetation type is a statement about the values of primary vegetation attributes that are
276 required to be a member (either plots or vegetation types of a lower rank). A broader property
277 of a vegetation type is its *primary characterization* (or description), which includes all
278 statements about primary vegetation attributes. Whereas intensive definitions impose limits to
279 plot membership for a *single* vegetation type, they are often not sufficient to unambiguously
280 determine the membership of a plot record *among* the set of vegetation types that constitute a
281 CCS. We refer to the formal procedures used to determine the membership of new plot
282 records to the predefined vegetation types of a CCS as *assignment rules*. For example, sets of
283 assignment rules may be defined using diagnostic species or species combinations (e.g.,
284 Bruelheide 1997; Kočí et al. 2003; Willner 2011; De Cáceres et al. 2012). Because different
285 sets of assignment rules can produce different plot memberships, the definition of a CCS
286 should include a preferred set of assignment rules. To preserve consistency, such set of rules
287 should be able to reproduce the extensive class definition of vegetation types when applied to
288 the original plot records (De Cáceres & Wiser 2012). We refer to these as *consistent*
289 *assignment rules*. Additional sets of rules of a CCS are referred to as *complementary*
290 *assignment rules* in our framework. While the attributes used in the consistent rules must be
291 primary vegetation attributes, the attributes used in complementary rules may be either
292 primary or secondary.

293 **III. CRITICAL DECISIONS: CLASSIFICATION APPROACHES AND** 294 **PROTOCOLS**

295 Following the terminology presented in the previous section, here we briefly review some of
296 the most important decisions and alternative choices regarding the design of classification
297 approaches and protocols.

298 **General requirements**

299 Guiding principles of classification approaches largely depend on the expected usage of
 300 classification systems. Although each stakeholder may tend to tailor a classification approach
 301 according to his/her specific needs, we list in Table 3 a set of characteristics that users
 302 commonly require from classification approaches.

303 **Table 3.** Common requirements for vegetation classification approaches.

Requirement	Explanation
Comprehensiveness	Classification systems should include vegetation types that encompass, as much as possible, the full range of vegetation variation within their spatial, temporal and ecological extents. This includes the need to appropriately summarize transitional and rare plant species assemblages.
Consistency	A similar set of concepts and procedures should be consistently used for the definition of vegetation types. Because broad-scale classification projects may address the classification of vegetation with strikingly different features or be intended to satisfy many potential users, it is useful to explicitly define different CCSs.
Robustness	Minor changes in the input data (e.g., adding or deleting some plot records) should not considerably alter the result of plot-based class-definition procedures.
Simplicity	A vegetation classification may be difficult to understand and to apply by potential users when vegetation types do not have simple definitions or when assignment rules (or nomenclatural rules) are complex.
Distinctiveness of units	Vegetation types should be distinct with respect to the values of the primary vegetation attributes. Distinctiveness may sometimes be artificially increased by the choice of class-definition procedures (e.g., sampling design).
Identifiability of units	Vegetation types should be easy to identify in the landscape. This requires clear, reliable and simple assignment rules that may complement the possibly more complex consistent assignment rules.
Indication of context	Vegetation types should preferably reflect and be predictive with respect to its context, such as soil conditions, climatic factors, management practices or biogeographical history.
Compatibility	Vegetation types of a given classification system may be required to have clear relationships with the vegetation types of other classification systems (whether of vegetation or not) because this facilitates transferring information from one classification system to another.

304

305 **Structural requirements**

306 Depending on their purpose, classification approaches often specify several hierarchical
 307 levels, each describing vegetation using different primary attributes and/or typological
 308 resolution. To preserve nested relationships classification approaches have to constrain the
 309 definition of the vegetation types of one hierarchical level using the types of the other, either
 310 in a *bottom-up* or *top-down* direction (Willner 2011). One possibility to achieve this is to use

311 a single plot-based CCS encompassing several hierarchical levels (e.g., CCS D in Fig. 1a), for
312 example by using hierarchical agglomerative or divisive clustering. A more common
313 approach is to define the vegetation types of the lowest hierarchical level using plot-based
314 classification protocols and then to progressively aggregate them into higher levels using
315 type-based protocols (e.g., CCSs A, B and C in Fig. 1a).

316 **Primary vegetation attributes**

317 An important decision regarding the primary vegetation attributes concerns *the subset of*
318 *plants of interest*. Plant communities are usually composed of multiple organisms, not all of
319 which may be of interest (Barkman 1980). The choice of the subset of plants of interest may
320 be influenced by the ecological scope of the classification protocol or by technical
321 restrictions. For example, classifications of boreal forests, wherein vascular plant diversity is
322 typically low, often place a high importance on bryophytes and lichens, whereas
323 classifications of temperate forests are generally described in terms of vascular plants only,
324 and tropical forests are often floristically described focusing on a small subset of plants (e.g.,
325 woody plants or ferns) owing to their high taxonomic diversity. If the classification is
326 expected to be indicative of the prevailing environmental conditions, an important
327 consideration is whether all plants or plant groups in the community are sensitive to the same
328 environmental factors in the same ways. For example, some understory plants may respond to
329 the microclimatic and edaphic conditions created by canopy trees more strongly than to the
330 external climatic conditions. To deal with this problem, classification approaches have been
331 proposed that describe different *synusiae* (i.e., assemblages of plants having similar size and
332 habitat use) and classify them using independent protocols (see subsection ‘Synusial
333 approaches’).

334 Another decision concerns *the attributes of the plants*, which can be grouped into (a)
335 *structure*: the spatial (horizontal and vertical) arrangement of plants within the plot and their
336 size (e.g., height or trunk diameter), (b) *taxonomy*: the identity of plants (e.g., species or
337 genus), and (c) *morphology and function*: a set of relevant morphological, physiological or
338 phenological plant traits (e.g., life form, leaf size or reproductive strategy). Classification
339 protocols normally combine more than one group of plant attributes. For example,
340 physiognomic approaches often combine information about morphological (life form, leaf
341 type and leaf longevity) and structural components (e.g., Fosberg 1961; UNESCO 1973). A
342 focus on the taxonomy of plants has a great advantage in that it allows additional information

343 to be obtained by linking the taxonomic composition of the vegetation type with taxon
344 attributes or conservation status (e.g., Feoli 1984), hence increasing the value of the
345 classification.

346 Finally, plant attributes can be considered at different *levels of detail*. For example, the
347 horizontal structure of vegetation can be simply accounted for as open-*versus*-closed
348 vegetation, but it can also be accounted for in more detail by using the percentage of ground
349 surface covered by projection of the canopy. Similarly, different levels of resolution can be
350 used for the taxonomic identity of plants (e.g., species level or family level).

351 **Spatial and temporal resolution**

352 There are practical reasons for requiring a limited range of plot sizes, because the use of
353 records from plots of very different size and forms in a single analysis can introduce various
354 artifacts (Otýpková & Chytrý 2006; Dengler et al. 2009). In general, plot size is decided in
355 accordance with both the purpose and the scale of spatial variation of the factors that
356 determine changes in the primary vegetation attributes (Reed et al. 1993). Sometimes the
357 choice of plot size is adapted to the size of the bigger plants in the vegetation considered
358 (e.g., Barkman 1989, Peet et al. 1998; Chytrý & Otýpková 2003).

359 The temporal grain of a plot-based protocol is rarely made explicit. However, it is
360 important to define whether a given temporal variation should be addressed using different
361 plot records or not. For example, to address intra-annual (seasonal, phenological) variation of
362 vegetation features, practitioners may sample vegetation at the time of its optimal
363 phenological development only, pool observations from two or more observation dates within
364 the same year (Dierschke 1994) or separate the information from plot records collected
365 during different seasons (Vymazalová et al. 2012).

366 **Class-definition procedures**

367 An important decision is the nature of extensive class definitions to be produced. Extensive
368 class definitions can be hard or fuzzy, non-overlapping or overlapping, and some plots may
369 be left unclassified. Users of vegetation classifications have different attitudes with respect to
370 these decisions. For example, one may require every plot record to be assigned to a single
371 vegetation type at each hierarchical level and allow no plot records to remain unclassified
372 (Berg et al. 2004; Willner 2011). This strategy is needed for applications such as vegetation
373 mapping, where crisp boundaries of the mapping units are often required. Alternatively, some

374 outlying plots may be left unclassified and/or overlaps allowed (e.g., Wiser & De Cáceres
375 2013). This second approach might improve distinctiveness of vegetation types and thus help
376 users understand the concepts represented in the classification, while simultaneously
377 preserving the information on transitional or outlying character of some plots.

378 Our concept of vegetation type includes both the ideas of ‘type’ and ‘class’ (Möller
379 1993). Accordingly, there are two main perspectives regarding class-definition procedures.
380 The first emphasizes the *boundaries* between vegetation units, whereas the second
381 emphasizes central tendencies or *noda* (Poore 1955). We will refer to vegetation types of the
382 first and second kinds as *boundary-based* and *node-based*, respectively. For example, in a
383 plot-based classification protocol the boundary-based perspective would specify a range of
384 values in primary vegetation attributes, while the node-based perspective would specify the
385 values of its most typical plot records. The choice of boundary-based vs. node-based
386 classification profoundly affects the definition of vegetation types and the treatment of
387 intermediate or transitional plot records.

388 Vegetation types may be defined from expert knowledge, without an explicit use of plot
389 records and/or formal procedures to group them. For example, an expert may produce a set of
390 assignment rules in the form of dichotomous keys (e.g., Barkman 1990). In this approach, the
391 expert is responsible for consistently applying the same set of guiding principles in the
392 definition of vegetation types. In some cases, the expert defines a set of categories for each of
393 the primary vegetation attributes and intensive class definitions are produced as a result of
394 combining those categories (e.g., Dansereau 1951; Beard & Webb 1972; ESCAVI 2003;
395 Gillison 2013). Formal procedures to define vegetation types from plot records often involve
396 different steps (Peet & Roberts 2013; Lengyel & Podani 2015), including the acquisition and
397 preparation of plot data, using a manual or a computer-based algorithm to group plot records,
398 evaluating classification results and characterizing the vegetation types (see section IV).

399 Most legacy classifications include the original type definitions but they do not include
400 reports on class-definition procedures. This hinders consistency when trying to modify or
401 extend such classifications. Similarly, formal assignment rules are often not included in
402 legacy classifications, or they are poorly specified. In the latter case, calibration of new
403 assignment rules is required to enable assignments of new plot records to the original
404 vegetation types. The calibration of assignment rules from training data and subsequent
405 application of those rules for assignments is commonly referred to as *supervised*

406 *classification*. Supervised classification sometimes involves modifying the original definition
407 of vegetation types, because the assignment of the original plot records with the new
408 assignment rules usually does not allow the original extensive class definition to be
409 reproduced exactly (e.g., Kočí et al. 2003).

410 **Application of constraining attributes**

411 Restrictions coming from constraining attributes are often applied when selecting the primary
412 vegetation attributes. For example, morpho-functional classifications of vegetation are often
413 based on those morphological and physiological plant traits that are indicative of their
414 adaptations to the environment in which they live (Gillison 2013). In the case of plot-based
415 classification protocol, restrictions coming from constraining attributes may also be applied
416 at different stages of the class-definition procedures (see section IV). First, a restriction may
417 be implemented by the sampling design. For example, if a set of plot records is collected to
418 reflect some environmental gradient, the classification based on these data will tend to reflect
419 this gradient (Knollová et al. 2005; Cooper et al. 2006). Second, the restriction can be
420 implemented at the stage of grouping plot records, as in constraining groups of plot records to
421 have similar environmental characteristics (e.g., Carleton et al. 1996). Finally, using
422 additional attributes to evaluate the validity of the classification may also constrain the
423 definition of vegetation types. For example, one might examine whether vegetation types can
424 be separated in environmental space (Orlóci 1978; Hakes 1994; Willner 2006).

425 **IV. CRITICAL DECISIONS: PLOT-BASED CLASS-DEFINITION PROCEDURES**

426 **Acquisition of plot data**

427 Plot records can be obtained by conducting field surveys, which requires deciding a sampling
428 design, or by drawing them from available vegetation-plot databases (Dengler et al. 2011). In
429 both cases one has to specify a sampling design (or a re-sampling design in the case of using
430 databases; De Gruijter et al. 2006). The advantages and drawbacks of different sampling (and
431 re-sampling) designs for vegetation-plot data have been extensively discussed elsewhere
432 (e.g., Kenkel et al. 1989; Knollová et al. 2005; Botta-Dukát et al. 2007; Roleček et al. 2007;
433 Lengyel et al. 2011); we only give a brief summary in Table 4.

434 In practice, sampling (and re-sampling) designs may combine elements of different
435 approaches (Roleček et al. 2007; Peet & Roberts 2013). It is important to emphasize that the
436 statistical procedures used to group plot records are descriptive rather than inferential (i.e.,

437 they do not involve inference with respect to a larger population). This calls for ensuring
 438 comprehensiveness of the sample (i.e., that the selected plot records encompass the full range
 439 of vegetation variation within the scope of the classification), a less demanding requirement
 440 than ensuring its representativeness (i.e., that the proportions of plot records corresponding to
 441 distinct types are in concordance with their frequency in geographical/ecological space).

442 **Table 4.** Summary of advantages and drawbacks of sampling (or resampling) designs.

Sampling/resampling	Description	Advantages	Drawbacks
Random sampling	Plot locations randomly chosen over the study area	Suitable for statistical inference (once accounting for autocorrelation)	Tends to miss rare habitats
Systematic sampling	Equally-spaced sampling points over the study area	Optimizes representation across geographic space; delivers optimal estimates with respect to area	Tends to miss rare habitats
Preferential sampling	The observer decides the location of plots after exploring the area of interest and subjectively perceiving vegetation or habitat units	Optimizes representation across ecological space; allows describing rare habitats	Hard to formalize; tends to suffer from preconceived ideas of vegetation types
Stratified random sampling	Plot locations are randomly chosen within strata defined using spatial layers of environmental factors	Optimizes representation across both geographic and ecological spaces	Requires relevant environmental data at fine spatial resolution; is biased by the selection of strata
Resemblance-based re-sampling (from databases)	Selection of plot records that are dissimilar according to some resemblance measure	Avoids the necessity to choose environmental factors	Not applicable for field surveys; limited by the representativeness of the database

443

444 **Preparation of plot data**

445 Broad-scale classification often involves the compilation of plot records from very different
 446 sources. This may lead to inconsistencies between plot records included in the data set (see
 447 Table 5). Consequently, decisions have to be made to remove, or at least reduce, their effect
 448 on the classification (Peet & Roberts 2013).

449 **Table 5.** Common sources of inconsistency when pooling plot data of different origin.

Source of inconsistency	Explanation
Spatial grain	Plot size affects species richness, within-plot homogeneity, species constancy and therefore comparisons of community composition and structure.
Sampling season	The structure and composition of some plant communities can show strong seasonal variation.

Subset of plants considered	When pooling plot records of different origin, one should check that the same subsets of plants have been considered in all of them. For example, non-vascular plants or tree seedlings may have been recorded in some plot records but not in others.
Taxonomic nomenclature	Pooling plot records of different origin often results in different names for the same entity or identical names for different entities, depending on the taxonomic concepts and determination literature used in a particular region or period.
Taxonomic resolution	The amount of detail in the taxonomic identification may vary within or across plot records, especially in regions where the flora is not completely known or where plants are difficult to identify down to the species level.
Plant abundance scales	The lack of common measurement scale is problematic for procedures requiring plant abundance measurements.
Vegetation layers	The lack of common definition of vegetation layers may be problematic for procedures requiring information about the vertical structure.
Functional attributes	Class-definition procedures explicitly using morphological or functional attributes will require common measurement scales.
Observer bias	Differences in plot records can partly result also from variation in sampling accuracy among field observers (e.g., overlooked or misidentified species, biased cover estimates).

450

451 **Grouping plot records**

452 Plot-grouping algorithms produce extensive class definitions from plot records. When no
 453 prior information is used regarding membership, plot-grouping algorithms are commonly
 454 referred to as *unsupervised classification* or *clustering* (Everitt et al. 2011). There are
 455 different ways to introduce previous information on the membership of plot records into
 456 clustering procedures, an approach that can be called *semi-supervised classification* (Tichý et
 457 al. 2014). For example, one can fix the membership of some objects to certain pre-defined
 458 classes (or define which objects should belong to the same or different classes) while new
 459 classes are defined using clustering (De Cáceres et al. 2010; Tichý et al. 2014).

460 Many plot-grouping algorithms require a resemblance coefficient to be chosen to
 461 quantify the similarity or dissimilarity in primary vegetation attributes between plot records,
 462 and the consequences of this decision should be understood. This choice will be partly
 463 constrained by previous choices of the primary vegetation attributes selected, the field
 464 measuring protocols used or abundance scales unified during data preparation. However,
 465 additional decisions are still required, such as the appropriateness of applying variable
 466 transformations, standardizations or variable weights; or the selection of a resemblance
 467 coefficient (e.g., Faith et al. 1987; Shaukat 1989; Legendre & De Cáceres 2013). Finally,
 468 resemblances between plot records may be transformed before clustering (e.g., De'ath 1999;
 469 Schmidtlein et al. 2010).

470 Choosing a plot-grouping algorithm entails deciding on many characteristics of the
 471 vegetation types that will be defined. Providing a comprehensive review of methodological
 472 choices in plot-grouping algorithms is beyond the scope of this paper (but see Podani 1994;
 473 Everitt et al. 2011; Kent 2012; Legendre & Legendre 2012; Peet & Roberts 2013, Wildi
 474 2013). Nevertheless, we provide a brief overview of the main advantages and disadvantages
 475 of the most commonly used algorithm families (Table 6).

476 **Table 6.** Plot-grouping algorithm families and their advantages and drawbacks.

Algorithm (examples)	Boundary- or node-based	Advantages	Drawbacks
Relevé table sorting (manual or computer-assisted)	Boundary-based or node-based	Produces diagnostic species or species groups.	Difficult to implement for large data sets.
Hierarchical agglomerative (e.g., UPGMA, beta-flexible)	Boundary-based or node-based	Produces vegetation types at different hierarchical levels; assignment rules can be created a posteriori using cluster resemblance thresholds.	Difficult to define new types without rebuilding the whole classification; low robustness to sampling variation due to agglomeration.
Hierarchical divisive (e.g., TWINSpan)	Boundary-based	Produces vegetation types at different hierarchical levels; may produce assignment rules.	Difficult to define new types without rebuilding the whole classification.
Hard partitioning (e.g., K-means, Partitioning Around Medoids)	Node-based	New types can be defined using semi-supervision; may produce assignment rules.	Requires multiple runs for different numbers of clusters to identify best solutions.
Fuzzy partitioning (e.g., Fuzzy C-means, Noise Clustering)	Node-based	New types can be defined using semi-supervision; may produce assignment rules; transitions treated explicitly.	Requires multiple runs for different numbers of clusters to identify best solutions; requires specifying fuzziness parameters.
Constrained classification (e.g., Multivariate Regression Tree)	Boundary-based	Vegetation types reflect differences in environmental conditions.	Requires both vegetation and environmental data; produces assignment rules, but these are based on environmental variables.

477

478 The number of vegetation types to define is a critical decision because it strongly
 479 influences typological resolution (e.g., a larger number of clusters leads to a finer typological
 480 resolution). Alternatively, specifying *a priori* desired resolution for the classification protocol
 481 may help determine the number of clusters to be sought. Most non-hierarchical methods
 482 require the number of clusters to be specified before executing the algorithm. In hierarchical
 483 clustering the number of clusters is either decided *a posteriori* (when cutting the hierarchy) or
 484 is a function of a stopping rule (Roleček et al. 2009; Schmidtlein et al. 2010). Although one

485 would be inclined to let the data ‘speak’ for themselves, the idea of one and only ‘natural’
 486 grouping is a myth (Dale 1988).

487 Sometimes the groups resulting from a plot-grouping algorithm are modified *a*
 488 *posteriori*, with the aim to facilitate the calibration of assignment rules and achieve
 489 consistency between these and the definition of vegetation types (e.g., Li et al. 2013). For
 490 example, when diagnostic species are calculated from the results of clustering, re-assignment
 491 of the plots might be necessary in order to achieve a consistent classification (Willner 2011;
 492 Luther-Mosebach et al. 2012).

493 **Evaluation of vegetation types**

494 Following Gauch & Whittaker (1981), we distinguish *internal* and *external* evaluation
 495 criteria (Table 7). Internal criteria evaluate the appropriateness of the vegetation types by
 496 using the primary vegetation attributes. Internal evaluation is often used to choose among
 497 alternative grouping procedures, or to choose between alternative parameterizations of a
 498 given procedure, for example to decide on the number of clusters (Tichý et al. 2010;
 499 Vendramin et al. 2010). External evaluation uses secondary attributes, or a previous
 500 classification of the same plot records, as a benchmark for comparison. In relation to the
 501 requirements of a classification (Table 3), external criteria often evaluate the ability of
 502 vegetation types to indicate external conditions (e.g. how well the site conditions or the
 503 geographic location of a plot can be predicted from its membership to a given unit).
 504 Alternatively, one may assess the degree to which vegetation types are identified using
 505 external attributes (e.g., whether plot membership can be predicted from environmental
 506 conditions).

507 **Table 7.** Evaluation criteria for plot-based classification protocols (compare to Table 3).

Criterion	Explanation
Internal criteria	
Distinctiveness of units	Evaluates how distinct vegetation types are in terms of primary vegetation attributes. For example, one can evaluate the compactness and between-cluster separation in the multivariate space (e.g., Carranza et al. 1998; Aho et al. 2008; Roberts 2015).
Similar internal heterogeneity	Evaluation of the similarity of vegetation types in their internal heterogeneity (e.g. compositional variability).
Classification stability	Evaluates whether similar units are obtained (i) in a slightly modified data set (e.g. bootstrapped, or with a few plots added, deleted or replaced, or jittering abundance values) (e.g., Tichý et al. 2011); or (ii) in parallel non-overlapping subsets, selected

randomly from the same data set or sampled independently in the same area (e.g., Botta-Dukat 2008).

Identifiability of units Evaluates the ability to easily identify the vegetation types using a subset of the primary vegetation attributes, for example with diagnostic species (Willner 2006).

External criteria

Environmental evaluation Evaluates the compactness and differentiation of vegetation units in environmental space, often by using multivariate statistics (e.g., Orłóci 1978; Hakes 1994).

Geographic evaluation Evaluates the appropriateness of the vegetation type from its spatial distribution. For example, it may be important to assess whether the geographic extent of a given vegetation unit is too small; or whether the geographical ranges of vegetation units overlap or correspond to some meaningful biogeographic regions (e.g., Loidi et al. 2010).

Evaluation by using taxon traits Evaluates the predictive value with respect to biogeography, population ecology or ecological requirements of their component taxa by examining taxon attributes such as distribution range, functional traits or life history.

Comparison with an alternative classification Evaluation by comparison to a previous classification of the same plots. For example, to determine the algorithm and parameterization that best fits the criteria used by experts in the definition of the legacy classification (e.g., Grabherr et al. 2003).

508

509 **Characterization of vegetation types**

510 Characterization should include the most important information about vegetation types that
 511 different end-users may require. Table 8 summarizes different kinds of information that the
 512 characterization of vegetation types may include. Additional information may be added to
 513 complement the characterization of vegetation types for particular applications. Examples
 514 include assessments of degree of conservation, protection status, vulnerability to invasions,
 515 animal habitat suitability, recommendations for management or ecosystem services provided
 516 (e.g., Berg et al. 2004, 2014).

517 **Table 8.** Characterization criteria for plot-based vegetation types.

Criterion	Examples
Primary characterization	
Average values or typical plot records	Mean values of the primary vegetation attributes (e.g., a species constancy column) Designation of the most typical plot record(s)
Internal heterogeneity	Range of values in primary vegetation attributes (e.g., range of cover values) Average dissimilarity in primary vegetation attributes (e.g., Jaccard or Bray-Curtis for species composition).
Relationship with other types	Diagnostic species lists Unconstrained ordination
Secondary characterization	
Additional vegetation attributes	Descriptions of physiognomy, spectra of life forms or chorological elements Descriptions of particular morphological and functional traits

Environmental attributes	Average and range of climatic and soil properties Canonical ordination (within the vegetation type or with respect to other types) Ecological indicator values for species present in the plot records Disturbance intensity and frequency (e.g. browsing, fire, mowing)
--------------------------	---

Spatial and temporal characterization

Spatial characterization	Geographic extent of the distribution extrapolated from the proportion of plot records assigned to it (for random or systematic sampling designs) Showing the locations of vegetation plots on maps or by depicting plot densities per vegetation type in grid maps Vegetation maps generated using spatial vegetation modeling techniques Spatial relationships (e.g., mosaics or catenas) with other vegetation types
Temporal characterization	Seasonal (phenological) and non-seasonal temporal variability Dynamic (e.g. successional) relationships with other vegetation types

518

519 **V. EXAMPLES**

520 The following examples have been chosen to illustrate our comparative framework. Although
521 we tried to include frequently used approaches, our selection is neither comprehensive nor is
522 meant as a recommendation of preferred approaches.

523 **Physiognomic approaches**

524 The first classification attempts ever made for large areas were physiognomic (Grisebach
525 1838). Most physiognomic classifications are not plot-based, in the sense that plot records are
526 not used to define vegetation types and classification keys (e.g., UNESCO 1973). An
527 example of a modern, plot-based, physiognomic system is that adopted for the Australian
528 National Vegetation Information System (see Beard & Webb 1972; Walker & Hopkins 1990;
529 ESCAVI 2003). This system has six hierarchical levels and is primarily physiognomic,
530 although floristic composition also plays a role. Vegetation types in each level arise as
531 combinations of predefined categories. Nested relationships between vegetation types are
532 ensured because the sets of primary vegetation attributes used at coarser levels are a subset of
533 those used at finer levels: ‘Classes’ (level I) are defined according to the dominant growth
534 form of the dominant stratum, whereas ‘structural formations’ (level II) are defined as the
535 combination of dominant growth form, cover class and height class for the dominant stratum.
536 Levels III and IV incorporate the dominant genus of the dominant stratum and of three strata,
537 respectively, as classification criterion; additional floristic criteria are considered for levels V
538 and VI. Whereas the system has a predefined set of vegetation types for the two uppermost
539 levels, the vegetation types of the remaining levels are defined when using the set of
540 predefined categories and a specific grammar to describe individual plot records, as in other
541 descriptive physiognomic approaches (e.g., Dansereau 1951). The protocols in this system

542 can be labeled as *plot-based*, but they are fundamentally distinct to floristic approaches,
543 which typically use formal procedures to group plot records.

544 **Dominant-species approaches**

545 Although species dominance has long been used as a classification criterion to informally
546 classify forest stands, there are formal classification approaches that use this as the main
547 classification criterion of low-level units. The ecological scope of dominant-species
548 approaches is often limited to floristically poor areas, because the concept of species
549 dominance is difficult to apply as a classification criterion to communities composed of large
550 numbers of species, such as lowland tropical forests.

551 One example of dominant-species approach is that proposed by Du Rietz (1930) and
552 employed in Northern Europe, where the ‘sociation’ was the basic unit of vegetation
553 classification (see Mueller-Dombois & Ellenberg 1974; Trass & Malmer 1978). The
554 protocols for sociations were plot-based and use the dominant species of each vegetation
555 layer as primary vegetation attribute. Another hierarchical level was that of ‘consociations’,
556 which were type-based classes of sociations whose uppermost layer was dominated by the
557 same species. Thus, in this case building definitions of vegetation types in the bottom-up
558 direction ensured their nestedness. Another example of species-dominance approach is the
559 one used for some time in British and North American ecology, where vegetation was
560 classified according to ‘dominance-types’ (Whittaker 1978b). Dominance-types were defined
561 by the dominance (in terms of importance values) of one or more species in the uppermost
562 layer, thus resembling the notion of consociation. In Russia, the most successful classification
563 approach, developed by Sukachev (1928), was similar to that of Du Rietz. The units from the
564 ‘association’ (close to the ‘sociation’ of Du Rietz) to the ‘formation’ levels were defined by
565 dominance criteria, while additional coarser classification levels were defined according to
566 vegetation physiognomy (Aleksandrova 1978).

567 **Floristic approaches**

568 Under this label we include classification approaches whose lowest level units are defined
569 according to the complete (or nearly so) taxonomic composition. These are often called
570 *phytosociological* approaches, although the term *phytosociology* can be also used for plot-
571 based vegetation classification in general (Dengler et al. 2008).

572 *Traditional Braun-Blanquet approach*

573 The Braun-Blanquet approach (Braun-Blanquet 1964) aims at producing a universal
574 classification system including vegetation of any kind. The following description is based on
575 Westhoff & van der Maarel (1973). Vegetation units in the traditional Braun-Blanquet
576 approach are arranged into four main hierarchical levels, with ‘association’ being the basic
577 one, followed by ‘alliance’, ‘order’ and ‘class’. All vegetation types (called *syntaxa*) are
578 defined by floristic composition as the primary vegetation attribute. The basic unit,
579 association, is defined by a *characteristic species combination*, which includes diagnostic
580 species (i.e., species that find their optimum within the vegetation type and/or that allow
581 differentiation between the current and closely-related types), and constant companions (i.e.,
582 species with high frequency). In contrast, primary vegetation attributes at higher hierarchical
583 levels (alliance up to class) are normally restricted to diagnostic species. In the case of
584 associations, classification protocols are plot-based and class-definition procedures include
585 preferential sampling, the rearrangement of compositional tables according to groups of
586 differentiating species and the comparison of preliminary plot groupings with the floristic
587 composition of types already defined. Uniform physiognomy and environmental conditions
588 can be regarded as validation criteria for new associations, in addition to the requirement of
589 distinct species composition. Classification protocols for vegetation types of higher rank are
590 type-based and, broadly speaking, class-definition procedures include the identification of
591 groups of species whose occurrence is restricted to a group of types of the lower rank.

592 *Modern variants of the Braun-Blanquet approach*

593 The Braun-Blanquet approach has followers in many parts of the world, although it has been
594 most extensively applied in Europe. Due to the long tradition of this approach and the lack of
595 a central coordination, many different variants have emerged and been applied in different
596 countries and *époques*. This has led to classification systems that widely differ between
597 regions and countries, which in extreme cases might share not much more than common
598 naming conventions (syntaxonomy) and a similar typological resolution. Variations can be in
599 the choice of primary vegetation attributes. In some cases, a complementary or prominent
600 role is given to dominant species. In others, vegetation structure or physiognomy is
601 considered in addition to floristic composition (e.g., Landucci et al. 2015). The use of
602 constraining attributes also differs across applications of the method, particularly regarding
603 types of high rank. Class-definition procedures are varied, ranging from expert-based
604 approaches to highly formalized node-based or boundary-based plot-grouping algorithms. In
605 fact, most of the methodological alternatives listed in section IV have been used in modern

606 applications of the Braun-Blanquet approach. The structural requirements for classification
607 hierarchies, and the role that diagnostic species play, also widely vary between different
608 variants (and are often not made explicit). Modern Braun-Blanquetian classification systems
609 with one or several explicit and detailed classification protocols include those of the
610 Netherlands (Schaminée et al. 1995 et seq.), the German state of Mecklenburg-Vorpommern
611 (Berg et al. 2004), the Czech Republic (Chytrý 2007–2013) and the woody vegetation of
612 Austria (Willner & Grabherr 2007).

613 *British National Vegetation Classification*

614 The British National Vegetation Classification (Rodwell 1991–2000) is an example of
615 classification system where a clear classification approach has been consistently followed. It
616 can be considered either as one of the modern variants of the Braun-Blanquet approach or as
617 an independent phytosociological approach. Four plot-based classification protocols can be
618 distinguished, due to variation in spatial grain: four plot sizes were used to sample different
619 vegetation types depending on the size of dominant plants. Primary vegetation attributes were
620 the complete species list, including cryptogams, with cover being recorded using the Domin
621 scale. Field sampling locations followed a preferential design; and datasets of new plots
622 sampled in the field were complemented with additional plot records from previous studies.
623 Sets of plots were grouped using the TWINSpan algorithm (Hill 1979). Vegetation types,
624 called ‘communities’, were the product of many rounds of analyses, with classification
625 stability and expert-based assessment being used as validation criteria. Primary
626 characterization included constancy classes and the range of cover values for all species.
627 Although the classification system has one main classification level, vegetation types were
628 presented in twelve major vegetation groups. Manual classification keys exist but an
629 automated assignment procedure for new plots was developed based on the similarity of these
630 plots with constancy columns of particular communities (Hill 1989).

631 *Synusial approaches*

632 The traditional Braun-Blanquet approach and its modern variants are restricted to the
633 classification of *phytocoenoses*, i.e. assemblages that include all plants (or at least all vascular
634 plants) of the community. However, other branches of phytosociology have focused on the
635 classification of *synusiae* – one-layered, ecologically homogeneous assemblages (e.g.,
636 epiphytic or epilithic communities, herbaceous communities, shrubby fringe communities) –
637 using similar classification approaches (see Barkman 1980). A modern example is the

638 Integrated Synusial approach, developed in Switzerland and France (Gillet et al. 1991; Gillet
639 & Gallandat 1996; Julve 1998-2014). This approach implies having separate plot records and
640 building separate CCSs for each category of *synusiae*, i.e. tree, shrub, herb and cryptogam
641 layers. Synusial vegetation types are called ‘elementary syntaxa’. Class-definition procedures
642 for elementary syntaxa are very similar to those of the Braun-Blanquet approach, although
643 with some notable differences in the sampling protocols (Gillet et al. 1991). After elementary
644 syntaxa are defined, a type-based CCS can be created for the classification of complete
645 *phytocoenoses*, based on their synusial composition. For this purpose, plot records are made
646 of lists of elementary syntaxa and they are subsequently compared and grouped as plot
647 records of taxa in the Braun-Blanquet approach.

648 *The EcoVeg approach*

649 EcoVeg (USFGDC 2008; Jennings et al. 2009; Faber-Langendoen et al. 2014) is an
650 integrated physiognomic-floristic-ecological classification approach that aims to
651 systematically classify all the world’s existing vegetation, preferably using vegetation plots.
652 EcoVeg has broadly distinct protocols for natural/semi-natural vs. cultural vegetation,
653 including separate eight-level hierarchies. Within each hierarchy there are somewhat distinct
654 protocols for three sets of levels (upper, mid and low levels). For natural and semi-natural
655 vegetation, the upper levels (L1: ‘Formation class’; L2: ‘Formation subclass’; L3:
656 ‘Formation’) use classification protocols based on growth forms as primary vegetation
657 attributes, the mid levels (L4: ‘Division’; L5: ‘Macrogroup’; L6: ‘Group’) use protocols
658 based on both growth forms and floristic composition, and the lower levels (L7: ‘Alliance’;
659 L8: ‘Association’) use protocols based on floristic composition only. In addition to the
660 primary vegetation attributes, protocols also include also the specification of constraining
661 attributes. For example, ‘Formation Subclasses’ (L2) of natural vegetation are defined using
662 combinations of dominant and diagnostic growth forms that are chosen to reflect specific
663 global macro-climatic factors (e.g., tropical vs. temperate) or macro-substrate factors (e.g.,
664 saltwater vs. freshwater). In all cases type definitions are boundary-based. Although not all
665 levels are plot-based, the goal of this approach is to document all types at all levels from plot
666 data, using a dynamic peer-review process. The characterization of types includes the
667 vegetation attributes, environment, dynamics, key diagnostic features, geographic range, and
668 synonymy. Levels L5–L8 of EcoVeg are similar to the ‘class’, ‘order’, ‘alliance’ and
669 ‘association’ levels of the Braun-Blanquet approach.

670 VI. CONCLUDING REMARKS

671 The development of common concepts and terminology is essential for providing a global
672 perspective to vegetation classification approaches. Working towards that end, the broad
673 international authorship of this article extensively discussed various concepts, often specific
674 to local and regional traditions, and finally was able to accept certain conventions. The
675 framework presented here will be useful for describing and comparing both new and legacy
676 classification approaches. We tried to avoid being overly prescriptive because our aim was
677 not to compare the advantages and disadvantages of the different classification approaches
678 and protocols. Nevertheless, we feel that our globalized world will sooner or later require
679 international conventions with respect to vegetation classification practices. Because a single,
680 universally valid, classification approach may not satisfy everybody, users and developers of
681 vegetation classifications should work together to seek commonalities among the different
682 approaches and, ultimately, promote a set of conventional, harmonized practices adapted for
683 different situations. For example, standard guidelines could be recommended for the
684 development of CCSs conditioned on the choices made by the user regarding the ecological
685 scope (e.g., temperate forest vegetation), primary vegetation attributes (e.g., floristic
686 composition or morpho-functional attributes) and typological resolution (e.g., associations or
687 formations). This huge task demands operative and shared definitions forming a common
688 vocabulary, and the main goal of the framework in this paper was to provide direction for this
689 process.

690 The need for broad-scale classification systems has recently driven European
691 vegetation scientists to work hard on the integration of CCSs and classification systems that
692 the application of the different variants of the Braun-Blanquet approach has produced in
693 different areas. This task is particularly challenging due to the multiplicity of approaches and
694 because the validity of diagnostic species and floristic vegetation types is inherently
695 geographically limited. Integration of CCSs is usually done at the national or regional scale
696 by compilation of national monographs or hierarchical lists of vegetation types (Jiménez-
697 Alfaro et al. 2014). Only relatively recently, CCSs have been developed for all the vegetation
698 types of whole countries or states, such as in the Netherlands (Schaminée et al. 1995 et seq.)
699 and the Czech Republic (Chytrý 2007–2013); and initiatives exist for larger areas (e.g.,
700 Dengler et al. 2013; Walker et al. 2013). Establishing plot-based CCSs for types of high
701 hierarchical rank at subcontinental to continental scales is also a relatively new development
702 (e.g., Zechmeister & Mucina 1994; Eliáš et al. 2013), and raises the question of how the types

703 in these new CCSs can be related to types of lower rank. We believe that the framework
704 presented here will be useful for this integration task, as it will contribute to the
705 understanding of the differences between the approaches employed to develop the different
706 legacy classification systems. Moreover, it will force integrated systems to be explicit about
707 the different CCSs and the protocols used in each section.

708 In addition to the promotion of standard approaches and the integration of classification
709 systems produced using similar approaches, it will be necessary to relate vegetation types
710 defined in classification systems having the same scope but produced using very different
711 approaches. Referencing across legacy classifications may facilitate their preservation and
712 avoid the problems of forcing their integration into a single framework. In the particular case
713 of classification approaches having similar protocols at fine typological resolution, as
714 happens for associations and alliances of the Braun-Blanquet and EcoVeg approaches,
715 another alternative may be the harmonization of vegetation type definitions (i.e., building
716 cross-walks) at these levels of resolution, a strategy that would ensure both the compatibility
717 of classification systems and the preservation of original classification criteria at coarser
718 levels of resolution.

719 **ACKNOWLEDGEMENTS**

720 The views expressed in this paper result from the exchange of ideas among its authors during
721 a workshop organized by the Vegetation Classification Committee of the International
722 Association for Vegetation Science (IAVS), held in Rome in April 2013, and subsequent
723 discussions. The International Association for Vegetation Science (IAVS) supported the
724 workshop leading to this contribution. Additional funding to M.D.C. came from Masaryk
725 University and from a fellowship of the Spanish Ministry of Economy and Competitiveness
726 (RYC-2012-11109). M.C. and L.T. were supported by the Czech Science Foundation
727 (P505/11/0732). R.G. was supported by REMEDINAL3-CM (S2013/MAE-2719), B.C. by
728 the Bolyai grant of the Hungarian Academy of Sciences, and L.M. acknowledges the Iluka
729 Chair (The University of Western Australia). The authors would like to thank Andy Gillison
730 for participating in the discussions around this topic.

731 **AUTHOR CONTRIBUTIONS**

732 M.D.C., with contributions from M.C., took the leadership in structuring and writing the
733 manuscript, whereas the remaining authors participated in the workshop discussions and

734 substantially enhanced the different versions of the manuscript by contributing with text and
735 ideas. The resulting paper reflects a consensus view of the authors.

736 REFERENCES

- 737 Aho, K., Roberts, D.W. & Weaver, T. 2008. Using geometric and non-geometric internal evaluators to compare
738 eight vegetation classification methods. *Journal of Vegetation Science* 19: 549–562.
- 739 Aleksandrova, V.D. 1978. Russian approaches to classification. In Whittaker, R.H. (ed.) *Classification of plant*
740 *communities*, pp. 167–200. Dr. W. Junk, The Hague, NL.
- 741 Barkman, J.J. 1980. Synusial approaches to classification. In Whittaker, R.H. (ed.) *Classification of plant*
742 *communities*, pp. 111–165. Dr. W. Junk, The Hague, NL.
- 743 Barkman, J.J. 1989. A critical evaluation of minimum area concepts. *Vegetatio* 85: 89–104.
- 744 Barkman, J.J. 1990. A tentative typology of European scrub and forest communities based on vegetation texture
745 and structure. *Vegetatio* 86: 131–141.
- 746 Braun-Blanquet, J. 1964. *Pflanzensoziologie. Grundzüge der Vegetationskunde*. 3. Aufl. Springer, Wien, AT.
- 747 Beard, J.S. & Webb, M.J. 1972. *The vegetation survey of Western Australia, its aims, objects and methods. Part*
748 *I of explanatory notes to Sheet 2: Great Sandy Desert. Vegetation Survey of Western Australia:*
749 *1:1,000,000 Vegetation Series*. University of Western Australia Press, Perth, AU.
- 750 Berg, C., Dengler, J., Abdank, A. & Isermann, M. (eds.) 2004. *Die Pflanzengesellschaften Mecklenburg-*
751 *Vorpommerns und ihre Gefährdung – Textband*. Weissdorn, Jena, DE.
- 752 Berg, C., Abdank, A., Isermann, M., Jansen, F., Timmermann, T. & Dengler, J. 2014. Red Lists and
753 conservation prioritization of plant communities - a methodological framework. *Applied Vegetation*
754 *Science* 17: 403–515.
- 755 Botta-Dukát, Z. 2008. Validation of hierarchical classifications by splitting dataset. *Acta Botanica Hungarica*
756 50: 73–80.
- 757 Botta-Dukát, Z., Kovács-Láng, E., Rédei, T., Kertész, M. & Garadnai, J. 2007. Statistical and biological
758 consequences of preferential sampling in phytosociology: Theoretical considerations and a case study.
759 *Folia Geobotanica* 42: 141–152.
- 760 Bruehlheide, H. 1997. Using formal logic to classify vegetation. *Folia Geobotanica* 32: 41–46.
- 761 Carleton, T., Stitt, R. & Nieppola, J. 1996. Constrained indicator species analysis (COINSPAN): an extension of
762 TWINSPAN. *Journal of Vegetation Science* 7: 125–130.
- 763 Carranza, L., Feoli, E. & Ganis, P. 1998. Analysis of vegetation structural diversity by Burnaby's similarity
764 index. *Plant Ecology* 138: 77–87.
- 765 Chytrý, M. (ed.) 2007–2013. *Vegetace České republiky*. Vol. 1–4. Academia, Praha, CZ.
- 766 Chytrý M. & Otýpková, Z. 2003. Plot sizes used for phytosociological sampling of European vegetation.
767 *Journal of Vegetation Science* 14: 563–570.
- 768 Cooper, A., McCann, T. & Bunce, R.G.H. 2006. The influence of sampling intensity on vegetation classification
769 and the implications for environmental management. *Environmental Conservation* 33: 118–127.
- 770 Dale, M. 1988. Knowing when to stop: Cluster Concept-Concept Cluster. *Coenoses* 3: 11–32.
- 771 Dansereau, P. 1951. Description and recording of vegetation upon a structural basis. *Ecology* 32: 172–229.
- 772 De'ath, G. 1999. Extended dissimilarity: a method of robust estimation of ecological distances from high beta
773 diversity data. *Plant Ecology* 144, 191–199.
- 774 De Cáceres, M. & Wiser, S.K. 2012. Towards consistency in vegetation classification. *Journal of Vegetation*
775 *Science* 23: 387–393.
- 776 De Cáceres, M., Font, X. & Oliva, F. 2010. The management of vegetation classifications with fuzzy clustering.
777 *Journal of Vegetation Science* 21: 1138–1151.
- 778 De Cáceres, M., Legendre, P., Wiser, S.K. & Brotons, L. 2012. Using species combinations in indicator value
779 analyses. *Methods in Ecology and Evolution* 3: 973–982.
- 780 De Candolle, A.P. 1855. *Géographie botanique raisonnée ou exposition des faits principaux et des lois*
781 *concernant la distribution géographique des plantes de l'époque actuelle*. Masson, Paris, FR.
- 782 De Grijter, J.J., Bierkens, M.F.P., Brus, D. J. & Knotters, M. 2006. *Sampling for Natural Resource Monitoring*.
783 Springer, Berlin, DE.
- 784 Dengler, J., Chytrý, M. & Ewald, J. 2008. Phytosociology. In: Jørgensen, S.E. & Faith, B.D. (eds.),
785 *Encyclopedia of Ecology, Volume 4*, pp. 2767–2779. Elsevier, Oxford, UK.
- 786 Dengler, J., Löbel, S. & Dolnik, C. 2009. Species constancy depends on plot size – a problem for vegetation
787 classification and how it can be solved. *Journal of Vegetation Science* 20: 754–766.
- 788 Dengler, J., Jansen, F., Glöckler, F., Peet, R.K., De Cáceres, M., Chytrý, M., Ewald, J., Oldeland, J., Lopez-
789 Gonzalez, G., (...) & Spencer, N. 2011. The Global Index of Vegetation-Plot Databases (GIVD): a new
790 resource for vegetation science. *Journal of Vegetation Science* 22: 582–597.

- 791 Dengler, J., Bergmeier, E., Willner, W. & Chytrý, M. 2013. Towards a consistent classification of European
792 grasslands. *Applied Vegetation Science* 16: 518–520.
- 793 Dierschke, H. 1994. *Pflanzensoziologie – Grundlagen und Methoden*. E. Ulmer, Stuttgart, DE.
- 794 Du Rietz, G.E. 1930. Vegetationsforschung auf soziationsanalytischer Grundlage. *Handb. Biol. Arbmeth.* 11:
795 293–480.
- 796 ESCAVI 2003. *Australian vegetation attribute manual: National Vegetation Information System, Version 6.0*.
797 Executive Steering Committee for Australian Vegetation Information Department of the Environment and
798 Heritage, Canberra, AU.
- 799 European Commission 2013. *Interpretation manual of European Union habitats. EUR 28*. European
800 Commission, Brussels, BE.
- 801 Everitt, B.S., Landau, S., Leese, M. & Stahl, D. 2011. *Cluster analysis*. J. Wiley & Sons, Chichester, UK.
- 802 Eliáš, P. jr., Sopotlieva, D., Dítě, D., Hájková, P., Apostolova, I., Senko, D., Melečková, Z. & Hájek, M.
803 2013. Vegetation diversity of salt-rich grasslands in Southeast Europe. *Applied Vegetation Science* 16:
804 521–537.
- 805 Faith, D.P., Minchin, P.R. & Belbin, L. 1987. Compositional dissimilarity as a robust measure of ecological
806 distance. *Vegetatio* 69: 57–68.
- 807 Faber-Langendoen, D., Keeler-Wolf, T., Meidinger, D., Tart, D., Hoagland, B., Josse, C., Navarro, G.,
808 Ponomarenko, S., Saucier, J.-P., Weakley, A. & Comer, P. 2014. EcoVeg: a new approach to
809 vegetation description and classification. *Ecological Monographs* 84: 533–561.
- 810 Feoli, E. 1984. Some aspects of classification and ordination of vegetation data in perspective. *Studia*
811 *Geobotanica* 4: 7–21.
- 812 Fosberg, F.R. 1961. A classification of vegetation for general purposes. *Tropical Ecology* 2: 1–28.
- 813 Gauch Jr, H.G. & Whittaker, R.H. 1981. Hierarchical classification of community data. *Journal of Ecology* 69:
814 537–557.
- 815 Gillet, F., de Foucault, B. & Julve, P. 1991. La phytosociologie synusiale intégrée: objets et concepts. *Candollea*
816 46: 315–340.
- 817 Gillet, F. & Gallandat, J.-D. 1996. Integrated synusial phytosociology: some notes on a new, multiscalar
818 approach to vegetation analysis. *Journal of Vegetation Science* 7: 13–18.
- 819 Gillison, A.N. 2013. Plant functional types and traits at the community, ecosystem and world level. In: Van der
820 Maarel, E. & Franklin, J. (eds), *Vegetation Ecology*, 2nd edn. pp 347–386. Wiley-Blackwell, Chichester,
821 U.K.
- 822 Grabherr, G., Reiter, K. & Willner, W. 2003. Towards objectivity in vegetation classification: the example of
823 the Austrian forests. *Plant Ecology* 169: 21–34.
- 824 Grisebach, A. 1838. Ueber den Einfluss des Klimas auf die Begränzung der natürlichen Floren. *Linnaea* 12:
825 159–200.
- 826 Hakes, W. 1994. On the predictive power of numerical and Braun-Blanquet classification: an example from
827 beechwoods. *Journal of Vegetation Science* 5: 153–160.
- 828 Hill, M.O. 1979. *TWINSPAN - a FORTRAN program for arranging multivariate data in an ordered two-way*
829 *table by classification of the individuals and attributes*. Cornell University, Ithaca, NY.
- 830 Hill, M.O. 1989. Computerized matching of relevés and association tables, with an application to the British
831 National Vegetation Classification. *Vegetatio* 83: 187–194.
- 832 von Humboldt, A. 1807. *Ideen zu einer Geographie der Pflanzen nebst einem Naturgemälde der Tropenländer*.
833 Cotta, Tübingen, DE.
- 834 Jennings, M.D., Faber-Langendoen, D., Loucks, O.L., Peet, R.K. & Roberts, D. 2009. Standards for associations
835 and alliances of the U.S. National Vegetation Classification. *Ecological Monographs* 79: 173–199.
- 836 Jiménez-Alfaro, B., Chytrý, M., Rejmánek, M. & Mucina, L. 2014. The number of vegetation types in European
837 countries: major determinants and extrapolation to other regions. *Journal of Vegetation Science* 25: 863–
838 872.
- 839 Julve, P. 1998–2014. Baseveg – Répertoire synonymique des unités phytosociologiques de France. Available
840 online: <http://perso.wanadoo.fr/philippe.julve/catminat.htm>
- 841 Kenkel, N.C., Juhász-Nagy, P. & Podani, J. 1989. On sampling procedures in population and community
842 ecology. *Vegetatio* 83: 195–207.
- 843 Kent, M. 2012. *Vegetation description and data analysis: A practical approach*. 2nd edn. Wiley-Blackwell,
844 Chichester, UK.
- 845 Knollová, I., Chytrý, M., Tichý, L. & Hájek, O. 2005. Stratified resampling of phytosociological databases:
846 some strategies for obtaining more representative data sets for classification studies. *Journal of Vegetation*
847 *Science* 16: 479–486.
- 848 Kočí, M., Chytrý, M. & Tichý, L. 2003. Formalized reproduction of an expert-based phytosociological
849 classification: A case study of subalpine tall-forb vegetation. *Journal of Vegetation Science* 14: 601–610.

- 850 Landucci, F., Tichý, L., Šumberová, K. & Chytrý, M. 2015. Formalized classification of species-poor
851 vegetation: a proposal of a consistent protocol for aquatic vegetation. *Journal of Vegetation Science*. doi:
852 10.1111/jvs.12277.
- 853 Legendre, P. & De Cáceres, M. 2013. Beta diversity as the variance of community data: dissimilarity
854 coefficients and partitioning. *Ecology Letters* 16: 951–963.
- 855 Legendre, P. & Legendre, L. 2012. *Numerical ecology*. 3rd ed. Elsevier, Amsterdam, NL.
- 856 Lengyel, A., Chytrý, M. & Tichý, L. 2011. Heterogeneity-constrained random resampling of phytosociological
857 databases. *Journal of Vegetation Science* 22: 175–183.
- 858 Lengyel, A. & Podani, J. 2015. Assessing the relative importance of methodological decisions in classifications
859 of vegetation data. *Journal of Vegetation Science*. doi: 10.1111/jvs.12268.
- 860 Li C.-F., Chytrý M., Zelený D., Chen M.-Y., Chen T.-Y., Chiou C.-R., Hsia Y.-J., Liu H.-Y., Yang S.-Z., Yeh
861 C.-L., Wang J.-C., Yu C.-F., Lai Y.-J., Chao W.-C. & Hsieh C.-F. 2013. Classification of Taiwan forest
862 vegetation. *Applied Vegetation Science* 16: 698–719.
- 863 Loidi, J., Biurrun, I., Campos, J.A., Garcia-Mijangos, I. & Herrera, M. 2010. A biogeographical analysis of the
864 European Atlantic lowland heathlands. *Journal of Vegetation Science* 21: 832–842.
- 865 Luther-Mosebach, J., Dengler, J., Schmiedel, U., Röwer, I.U., Labitzky, T. & Gröngroft, A. 2012. A first formal
866 classification of the Hardeveld vegetation in Namaqualand, South Africa. *Applied Vegetation Science* 15:
867 401–431.
- 868 Möller, H. 1993. "Pflanzengesellschaft" als Typus und als Gesamtheit von Vegetationsausschnitten. Versuch
869 einer begrifflichen Klärung. *Tuexenia* 13: 11–21.
- 870 Mucina, L. 1997. Classification of vegetation: Past, present and future. *Journal of Vegetation Science* 8: 751–
871 760.
- 872 Mucina, L. & van der Maarel, E. 1989. Twenty years of numerical syntaxonomy. *Vegetatio* 81: 1–15.
- 873 Mueller-Dombois, D. & Ellenberg, H. 1974. *Aims and methods of vegetation ecology*. J. Wiley & Sons, New
874 York, NY, US.
- 875 Neldner, V.J., Wilson, B.A., Thompson, E.J. & Dillewaard, H.A. 2012. *Methodology for Survey and Mapping*
876 *of Regional Ecosystems and Vegetation Communities in Queensland*. Version 3.2. Updated August 2012.
877 Queensland Herbarium, Queensland Department of Science, Information Technology, Innovation and the
878 Arts, Brisbane, AU.
- 879 Otýpková, Z. & Chytrý, M. 2006. Effects of plot size on the ordination of vegetation samples. *Journal of*
880 *Vegetation Science* 17: 465–472.
- 881 Orlóci, L. 1978. *Multivariate Analysis in Vegetation Research*. Dr. W. Junk, The Hague, NL.
- 882 Peet, R.K. & Roberts, D.W. 2013. Classification of natural and semi-natural vegetation. In: van der Maarel, E.
883 & Franklin, J. (eds.), *Vegetation ecology*. 2nd ed. pp. 28–70. Oxford University Press, New York, NY, US.
- 884 Peet, R.K., Wentworth, T.R. & White, P.S. 1998. A flexible, multipurpose method for recording vegetation
885 composition and structure. *Castanea* 63: 262–274.
- 886 Pignatti, S., Oberdorfer, E., Schaminée, J.H.J. & Westhoff, V. 1995. On the concept of vegetation class in
887 phytosociology. *Journal of Vegetation Science* 6: 143–152.
- 888 Podani, J. 1994. *Multivariate Data Analysis in Ecology and Systematics: A methodological guide to the SYN-*
889 *TAX 5.0 package*. SPB Academic Publishing, The Hague, NL.
- 890 Poore, M.E.D. 1955. The use of phytosociological methods in ecological investigations: I. The Braun-Blanquet
891 system. *Journal of Ecology* 43: 226–244.
- 892 Reed, R.A., Peet, R.K., Palmer, M.W. & White, P.S. 1993. Scale dependence of vegetation-environment
893 correlations: A case study of a North Carolina piedmont woodland. *Journal of Vegetation Science* 4: 329–
894 340.
- 895 Roberts, D.W. 2015. Vegetation classification by two new iterative reallocation optimization algorithms. *Plant*
896 *Ecology* 216: 741–758.
- 897 Rodwell, J.S. (ed.) 1991–2000. *British plant communities*. Vol. 1–5. Cambridge University Press, Cambridge,
898 UK.
- 899 Roleček, J., Chytrý, M., Hájek, M., Lvončík, S. & Tichý, L. 2007. Sampling design in large-scale vegetation
900 studies: do not sacrifice ecological thinking to statistical purism! *Folia Geobotanica* 42: 199–208.
- 901 Roleček, J., Tichý, L., Zelený, D. & Chytrý, M. 2009. Modified TWINSpan classification in which the
902 hierarchy respects cluster heterogeneity. *Journal of Vegetation Science* 20: 596–602.
- 903 Shaikat, S.S. 1989. A technique for species weighting and its utility in data reduction and minimization of
904 misclassification. *Coenoses* 4: 163–168.
- 905 Schaminée, J.H.J., Stortelder, A.H.F. & Weesthoff, V. (eds.) 1995. *De vegetatie van Nederland – Deel 1.*
906 *Inleiding tot de plantensociologie – grondslagen, methoden en toepassingen*. Opulus, Uppsala, SE.
- 907 Schmidtlein, S., Tichý, L., Feilhauer, H. & Faude, U. 2010. A brute-force approach to vegetation classification.
908 *Journal of Vegetation Science* 21: 1162–1171.
- 909 Sukachev, V.N. 1928. *Vegetation communities: introduction to phytosociology*. Kniga, Leningrad (in Russian).
- 910 Trass, H. & Malmer, N. 1978. North European approaches to classification. In: Whittaker, R.H. (ed.),
911 *Classification of plant communities*, pp. 203–233. Dr W. Junk, The Hague, NL.

- 912 Tichý, L., Chytrý, M., Hájek, M., Talbot, S.S. & Botta-Dukát, Z. 2010. OptimClass: Using species-to-cluster
913 fidelity to determine the optimal partition in classification of ecological communities. *Journal of*
914 *Vegetation Science* 21: 287–299.
- 915 Tichý, L., Chytrý, M. & Botta-Dukát, Z. 2014. Semi-supervised classification of vegetation: preserving the
916 good old units and searching for new ones. *Journal of Vegetation Science* 25: 1504–1512.
- 917 Tichý, L., Chytrý, M. & Šmarda, P. 2011. Evaluating the stability of the classification of community data.
918 *Ecography* 34: 807–813.
- 919 UNESCO 1973. *International classification and mapping of vegetation*, pp. 1–93. UNESCO Ecology and
920 Conservation Series 6. UNESCO, Paris, FR.
- 921 U.S. Federal Geographic Data Committee. 2008. *National Vegetation Classification Standard, Version 2.*
922 *FGDC-STD-005-2008 (Version 2).*
- 923 Vendramin, L., Campello, R.J.G.B. & Hruschka, E.R. 2010. Relative clustering validity criteria: A comparative
924 overview. *Statistical Analysis and Data Mining* 3: 209–235.
- 925 Vymazalová, M., Axmanová, I. & Tichý, L. 2012. Effect of intra-seasonal variability on vegetation data.
926 *Journal of Vegetation Science* 23: 978–984.
- 927 Walker, D., Alsos, I.G., Bay, C., Boulanger-Lapointe, N., Breen, A.L., Bültmann, H., Christensen, T.,
928 Damgaard, C., Daniëls, F.J.A., Hennekens, S., Reynolds, M.K., Le Roux, P.C., Luoto, M., Pellissier, L.,
929 Peet, R.K., Schmidt, N.M., Stewart, L., Virtanen, R., Yoccoz, N.G., & Wisz, M.S. 2013. Rescuing
930 valuable Arctic vegetation data for biodiversity models, ecosystem models and a panarctic vegetation
931 classification. *Arctic* 66: 133–137.
- 932 Walker, J. & Hopkins, M.S. 1990. Vegetation. In: McDonald, R.C., Isbell, R.F., Speight, J.G., Walker, J. &
933 Hopkins, M.S. (eds) *Australian soil and land survey. Field handbook*, pp. 1–198. 2nd ed. Inkata Press,
934 Melbourne, AU.
- 935 Westhoff, V. & van der Maarel, E. 1973. The Braun-Blanquet Approach. In Whittaker, R.H. (ed.) *Classification*
936 *and ordination of communities*, pp. 289–329. Dr W. Junk, The Hague, NL.
- 937 Whittaker, R.H. 1978a. Approaches to classifying vegetation. In: Whittaker, R.H. (ed.), *Classification of plant*
938 *communities*, pp. 1–31. Dr W. Junk, The Hague, NL.
- 939 Whittaker, R.H. 1978b. Dominance-types. In: Whittaker, R.H. (ed.) *Classification of plant communities*, pp. 67–
940 79. Dr W. Junk, The Hague, NL.
- 941 Whittaker, R.H. (ed.) 1978c. *Classification of plant communities*. Dr W. Junk, The Hague, NL.
- 942 Wildi, O. 2013. *Data analysis in vegetation ecology*. 2nd ed. Wiley-Blackwell, Chichester, UK.
- 943 Willner, W. 2006. The association concept revisited. *Phytocoenologia* 36: 67–76.
- 944 Willner, W. 2011. Unambiguous assignment of relevés to vegetation units: the example of the Festuco-
945 Brometea and Trifolio-Geranietea sanguinei. *Tuexenia* 31: 271–282.
- 946 Willner, W. & Grabherr, G. 2007. *Die Wälder und Gebüsch Österreichs – Ein Bestimmungswerk mit Tabellen.*
947 2 vols. Spektrum Akademischer Verlag, Heidelberg, DE.
- 948 Wiser, S.K. & De Cáceres, M. 2013. Updating vegetation classifications: an example with New Zealand's
949 woody vegetation. *Journal of Vegetation Science* 24: 80–93.
- 950 Zechmeister, H.G. & Mucina, L. 1994. Vegetation of European springs: High-rank syntaxa of the *Montio-*
951 *Cardaminetea*. *Journal of Vegetation Science* 5: 385–402.