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

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13

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

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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 19<sup>th</sup> 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 20<sup>th</sup> 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  |
|---|---|---|
| <b>Vegetation-plot record</b>   | 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"> <li>• Spatial location and time of survey</li> <li>• Vegetation attributes</li> <li>• Environmental attributes</li> </ul>                          |
| <b>Vegetation type</b> (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"> <li>• Extensive class definition</li> <li>• Intensive class definition</li> <li>• Characterization (primary/secondary/spatial/temporal)</li> </ul> |



|  |   |   |
|--|---|---|
| <b>Consistent classification section (CCS)</b> | A subset of a classification system where vegetation types are defined using the same classification protocol.                          | <ul style="list-style-type: none"> <li>• Spatial, temporal and ecological (thematic) scopes</li> <li>• Set of vegetation types (incl. nested relationships)</li> <li>• Classification levels</li> <li>• Assignment rules</li> </ul> |
| <b>Classification system</b>                   | 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"> <li>• Spatial, temporal and ecological (thematic) scopes</li> <li>• Classification levels</li> <li>• Set of consistent classification sections and their relationships</li> </ul>                |

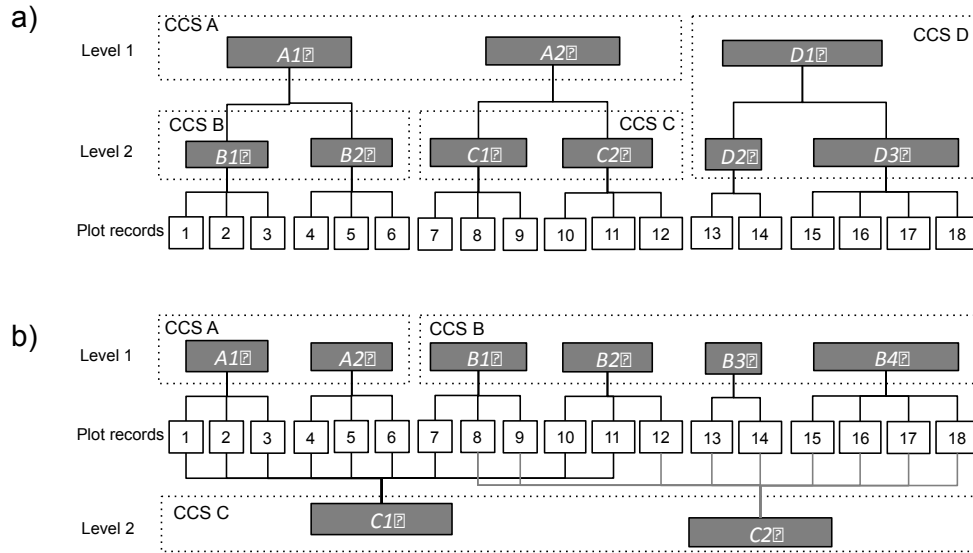
| <b>Procedural element</b>      | <b>Definition</b>   | <b>Properties</b>  |
|--------------------------------|---|--|
| <b>Classification protocol</b> | The set of criteria and procedures that underlie the creation or modification of a consistent classification section. | <ul style="list-style-type: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

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).

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

|                          |   |
|--------------------------|---|
| Environmental attributes | Average and range of climatic and soil properties<br>Canonical ordination (within the vegetation type or with respect to other types)<br>Ecological indicator values for species present in the plot records<br>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)<br>Showing the locations of vegetation plots on maps or by depicting plot densities per vegetation type in grid maps<br>Vegetation maps generated using spatial vegetation modeling techniques<br>Spatial relationships (e.g., mosaics or catenas) with other vegetation types |
| Temporal characterization | Seasonal (phenological) and non-seasonal temporal variability<br>Dynamic (e.g. successional) relationships with other vegetation types   |

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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.

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## 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  
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