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A Review of Visual Soil Evaluation Techniques for Soil

Structure

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Running Title: Rev. of soil structure VSE Techniques

26 **Summary**

27

28 Soil structure forms a key component of soil quality and its assessment by semi-
29 quantitative Visual Soil Evaluation (VSE) techniques can help scientists, advisors and
30 farmers make decisions regarding sampling and soil management. VSE techniques
31 require inexpensive equipment and generate immediate results that correlate well with
32 quantitative measurements of physical and biochemical properties, highlighting their
33 potential utility. We reviewed published VSE techniques and found that soils of certain
34 textures present problems and a lack of research into the influence of soil moisture
35 content on VSE criteria. Generally, profile methods evaluate process interactions at the
36 point scale, exploring both intrinsic aspects and anthropic impacts. Spade methods
37 focus on anthropogenic characteristics, providing rapid synopses of soil structure over
38 wider areas. Despite a focus on structural form, some methods include criteria related
39 to stability and resiliency. Further work is needed to improve existing methods
40 regarding texture influences, on-farm sampling procedures and more holistic
41 assessments of soil structure.

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43 **Keywords:** visual soil examination, soil quality, soil structure

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52 **Introduction**

53

54 Soil structure is a key component of soil quality (Askari *et al.*, 2015; Mueller *et al.*,
55 2013), influencing and influenced by soil chemical and biological properties (daSilva
56 *et al.*, 2014; Askari *et al.*, 2015). Current concerns over soil resource degradation
57 (Koch *et al.*, 2013), emphasise the importance of assessing soil structure (Mueller *et*
58 *al.*, 2013). Semi-quantitative procedures for structure evaluation using visual and
59 tactile assessment are receiving increased attention (Ball *et al.*, 2013) notably
60 regarding impacts of current agricultural practices (Batey, 2009), reduced tillage
61 strategies (Giarola *et al.*, 2013) and agri-environmental considerations (Newell-Price *et*
62 *al.*, 2012). Soil has been visually assessed for millennia (Batey, 2000) and Visual Soil
63 Evaluation (VSE) techniques (Ball and Munkholm, 2015) offer repeatable procedures
64 for examining structural morphology for soil quality assessment (Mueller *et al.*, 2013).
65 Correlations between VSE techniques and quantitative soil measurements have been
66 widely described (McKenzie, 2001; Mueller *et al.*, 2009; Pulido Moncada *et al.*,
67 2014a) including indicators of soil physical quality (Guimarães *et al.*, 2013; Pulido
68 Moncada *et al.*, 2014b) and bio-chemical quality (Askari *et al.*, 2015; daSilva *et al.*,
69 2014). Compared to quantitative measurements, VSE techniques provide rapid easily
70 interpreted results using inexpensive equipment, making them widely accessible
71 (Guimarães *et al.*, 2013; Ball *et al.*, 2007; Batey, 2000).

72

73 Due to increased interest in VSE techniques and the numerous methods in use, this
74 review will outline the in-field procedures most widely described (according to
75 published, English language literature from 1940 onwards), discuss VSE methodology

76 and synthesise strengths, weaknesses and complimentary aspects between specific
77 procedures, thus identifying improvements.

78

79 **An outline of in-field methods**

80

81 VSE techniques can be categorised into spade (Tables 1 and 2) and profile methods
82 (Boizard *et al.*, 2005; Mueller *et al.* 2009). The former require soil sample blocks to be
83 examined after extraction by spade (Tables 1 and 2), evaluating structural state up to
84 50cm depth, over wide areas. The latter, founded on soil survey principles (McKeague
85 *et al.*, 1986; Batey, 2000), require examination of soil profiles to $\approx 1.5\text{m}$ in soil pits,
86 generally excavated mechanically (Table 3), providing detailed information at point
87 scale.

88

89 *Spade methods*

90 Görbing's (1947) Spade Diagnosis, the first published technique, focuses on anthropic
91 impacts on structure and crop growth, qualitatively assessing soil structure, rooting and
92 moisture content. The Peerlkamp (1959) method, the first semi-quantitative single-
93 score procedure, together with Görbing's method, formed the foundation of more
94 recent procedures. The Peerlkamp method focuses on anthropic impacts on structure
95 (Boizard *et al.*, 2005). A sample block extracted to 15cm is rapidly scored between 1
96 and 10 considering aggregate shape, size and porosity, particle cohesion and root
97 development. Layers can be assessed separately (Peerlkamp, 1967). The Werner
98 Method (Werner and Thämert 1989) examines soil physical state in terms of crop
99 growth, assessing individual layers up to 50cm. Properties including aggregate size,
100 shape, intra-aggregate fissures, aggregate face width and bio-pores each receive a score

101 (Mueller *et al.*, 2009). All three methods require the manual break-up of sample blocks
102 to expose aggregates, a key process in all spade methods.

103

104 Drop tests, which involve dropping sample blocks from a defined height onto a hard
105 surface to expose aggregates, are also used. The Diez method (see Mueller *et al.*,
106 2009), first described in the late 1990's, incorporates a drop test from \approx 1m. Exposed
107 aggregates are then assessed by hand. The method can assess anthropic impacts to
108 40cm (Diez *et al.*, 2012). Soil surface condition, topsoil and subsoil structure along
109 with rooting, redox morphology, organic matter decomposition, macro-porosity and
110 the transition layer between topsoil and subsoil are assessed with reference to a
111 manual, with the option of generating a single summarising score (R. Brandhuber,
112 personal communication).

113

114 Beste (1999) developed an extended version of Görbing's Spade Diagnosis, which
115 assesses structure for rooting and soil biota requiring the manual aggregate exposure. It
116 incorporates a scoring system while also assessing aggregate water stability and
117 includes quantitative measures. Layers are assessed with an emphasis on surface crust
118 formation, silting and presence of worm casts (0-1cm depth), aggregate shape and
119 quantity of granular or angular aggregates (0-15cm and 15-30cm depth) along with
120 aggregate shape and inter-aggregate porosity (30-40cm depth).

121

122 Munkholm's (2000) Spade Diagnosis was founded on Preuschen's and Sobelius'
123 Spade Diagnosis, both modified versions of Görbing's (1947) method. Layers within a
124 sample block taken to 30cm are examined. Boundaries, texture, aggregate type, size
125 and grade, rupture resistance, porosity, rooting, soil fauna and organic matter

126 decomposition, are described in detail to support soil management. A drop test is
127 included to determine the degree of aggregation, but most of the assessment is by
128 manual manipulation (Table 2).

129

130 The Visual Soil Assessment (VSA) method (Shepherd 2000; 2009) captures intrinsic
131 quality factors and anthropic impacts on soil structure. Plant and soil indicators are
132 included and treated separately. For the main soil structure indicator, a drop test on an
133 8,000cm³ sample block, generally extracted from the topsoil. Exposed aggregates are
134 arranged by size on a flat surface for visual estimation of aggregate size distribution by
135 comparison with reference photographs included in a field manual. Additional visual
136 procedures are included for potential carbon sequestration and nutrient loss through
137 leaching, run-off and gaseous emissions (Shepherd 2010a). For soil quality the “VS
138 score” is the sum of individual weighted indicator scores for soil texture, structure,
139 colour and smell, mottling, macro-porosity, the presence of earthworms, potential
140 rooting depth, surface ponding, surface crusting and cover, and erosion.

141

142 The Soil Quality Scoring method (Ball and Douglas, 2003) is based on Munkholm’s
143 (2000) diagnostic principles along with Beste’s (1999) scoring criteria, assesses soil
144 physical fertility to 30cm through manual exposure of aggregates. Focusing on
145 anthropic impacts, surface condition, soil structure (by layer) and crop rooting are
146 assessed with reference to explanatory notes. The structure score is summed and
147 weighted by layer depth.

148

149 The FAL Method (Hasinger *et al.*, 2004) includes a drop test on individual layers from
150 the upper 45 cm (Boizard *et al.*, 2005). With an emphasis on anthropic impacts on

151 structure, aggregate size distribution is determined manually with smaller aggregates
152 sieved from 20mm to 0.2mm. With reference to images and a coding key, aggregates
153 are classified and the mean weight diameter and mean weight score are determined for
154 each soil layer (Boizard *et al.*, 2005).

155

156 In 2007, three spade methods were published. The Visual Soil Structure Quality
157 Assessment (VSSQA) described by Ball *et al.* (2007), was based on the Peerlkamp
158 method and subsequently renamed Visual Evaluation of Soil Structure (VESS)
159 following refinement (Guimarães *et al.*, 2011). VESS examines anthropic impacts on
160 structure and is accessible to non-experts. From the top 25cm depth, the size, shape
161 and visible porosity of aggregates are evaluated using an illustrated scoring key applied
162 to individual layers. The weighted average gives an overall “*S_q*” score, similar to the
163 system devised by Ball and Douglas (2003).

164

165 The ‘Thinksoils’ manual, developed by the United Kingdom’s Environment Agency
166 (2007), includes instructions on conducting in-field assessment, emphasising erosion
167 and runoff risk. Soil surface, topsoil and subsoil structure, macro-porosity, aggregate
168 type and packing density along with plant and root growth are qualitatively examined.
169 (Environment Agency, 2010). The M-SQR method (Mueller *et al.*, 2007) explores
170 intrinsic soil quality and anthropic impacts to assess long-term soil quality for cropping
171 or grazing. It is not exclusively an in-field procedure (therefore omitted from Tables 1
172 and 2), as regional climatic and soil survey data are incorporated (Mueller *et al.*, 2013).
173 An overall “*SQ* score” of between 1 and 100 is generated from structural evaluation
174 along with assessment of inherent soil properties that limit productivity (e.g. stoniness)
175 and identifying “hazard” factors that limit soil quality (e.g. salinization).

176 *Profile methods*

177 Le Profil Cultural, originally developed by Hénin *et al.* (1960) and described by
178 Manichon (1987), evaluates anthropic impacts (Roger-Estrade *et al.*, 2004; Peigné *et*
179 *al.*, 2013). A soil pit the width of a seed drill ($\approx 3\text{m} \times 1.5\text{m}$) is excavated perpendicular
180 to tillage. Areas of different structure are identified in relation to horizontal layers
181 formed by successive cultivations and lateral variation from wheels. Structure is
182 described first by size and distribution of clods and from intra-clod porosity of clods
183 $>2\text{mm}$. Le Profil Cultural not only includes structural unit morphology, but also the
184 spatial variation of overall structure. Peigné *et al.* (2013) described further steps for
185 assessing a compact transition layer between topsoil and subsoil and biotic activity.

186

187 The Whole Profile Method developed by Batey (2000) offers a holistic procedure for
188 describing intrinsic soil quality and anthropic impacts on structure. The size and shape
189 of aggregates, presence of pans, structural stability, clay mineralogy and evidence of
190 compaction are evaluated (Batey, 2000). If required, Batey (2000) suggests the use of
191 scoring systems described by Peerlkamp (1967) or McKenzie (1998). Principles
192 developed by Batey form the basis of SOILpak, focused on structural characteristics
193 associated with compaction and cotton growth (McKenzie, 1998). A soil pit, 1.5m
194 deep and 4m long, perpendicular to tillage is recommended, from which five, 343cm^3
195 samples are extracted. Scores are assigned by firmness with clod size, shape, rupture
196 resistance, aggregation within clods and intra-clod porosity examined. If structural
197 scores are poor, overriding factors including interconnecting porosity, smeared layers
198 or textural changes are visually assessed. Visual assessment of aggregate stability in
199 water is scored from a dispersion test (Field *et al.*, 1997). The SOILpak procedure has

200 been extended for a range of cropping systems and soils (Anderson *et al.*, 1998;
201 McMullen, 2000).
202
203 SubVESS is an adapted version of VESS for subsoil assessment (Ball *et al.*, 2015)
204 with an emphasis on identifying anthropic impacts on transition layers or compacted
205 pans. Using a soil pit to 1.4m, soil layers are identified and assessed separately for
206 mottling, strength, porosity, rooting and aggregate characteristics. “*Ssq* scores” are
207 assigned for each layer using the SubVESS Flowchart, which provides a descriptive
208 key and reference images. An overall *Ssq* score for the profile is expressed as a
209 sequence of *Ssq* scores for individual layers from which any transition layer can be
210 identified.

211

212 **VSE Methodology**

213

214 *Evaluation criteria*

215 All methods examine anthropogenic impacts on structure with some, mainly profile
216 methods (Boizard *et al.*, 2005) additionally exploring intrinsic aspects. Aggregation
217 (type, size and shape) and porosity form diagnostic criteria in almost all methods.
218 Classification of the former generally assumes increased incidences of large (>5cm -
219 >10cm), angular aggregates with higher rupture resistance, indicates poor structural
220 quality (McKenzie, 1998; Guimarães *et al.*, 2011). Where desirable, differentiating
221 anthropic impacts from intrinsic influences may be problematic.

222

223 Mueller *et al.* (2009) found that methods based on aggregation generated similar
224 results, with strong correlations with measures of soil physical quality including bulk

225 density (ρ_b) (Newell-Price *et al.*, 2013; Guimarães *et al.*, 2013; Mueller *et al.*, 2009),
226 penetration resistance (Newell-Price *et al.*, 2013; Guimarães *et al.*, 2013) and air
227 capacity (Mueller *et al.*, 2009). Additionally, VESS, largely dependent on aggregation
228 diagnosis (Cui *et al.*, 2014), was related to soil respiration and enzyme activity (Cui *et*
229 *al.*, 2015) along with chemical properties including, total carbon, soil organic carbon
230 and total nitrogen (Askari *et al.* 2015).

231

232 Regarding aggregate determination, drop tests offer standardised, reproducible
233 procedures of exposure. However, grass roots enmeshing aggregates (Pulido Moncada
234 *et al.*, 2014a) and soils with high clay contents (Sonneveld *et al.*, 2014) were found to
235 influence drop test results. Guimarães *et al.* (2011) found the manual exposure of
236 aggregates generated the same overall results as drop-tests, despite being suggested as
237 subjective (Ball *et al.*, 2007). Unless preformed on individual layers as the FAL
238 method (Boizard *et al.*, 2005), drop tests do not allow the examination of aggregation
239 within layers - a possible limitation (Giarola *et al.*, 2010; Guimarães *et al.*, 2011;
240 Newell-Price *et al.*, 2013; Guimarães *et al.*, 2013). The delimitation of layers not only
241 indicates potential soil functioning, but contextualises aggregation indicating anthropic
242 influences. The evaluation of *in-situ* spatial arrangement, as employed by Le Profil
243 Cultural, thoroughly indicates mechanisms or morphology of aggregation (Roger-
244 Estrade *et al.*, 2004).

245

246 Both visual inter- (Shepherd 2000, Werner and Thämert 1989) and intra- (Guimarães
247 *et al.*, 2011) aggregate porosity are examined. Exploring profile faces with a knife
248 reveals macro-pores (Ball *et al.*, 2015), which can be highlighted with diluted paint
249 (McKenzie, 1998). The quantification of earthworm burrows is also employed

250 (Munkholm, 2000; Peigné *et al.*, 2013). Mueller *et al.* (2009) found the VSA inter-
251 aggregate porosity classification, assessed by examining an exposed face of a spade
252 slice sample, correlated with dry ρ_b . VESS S_q scores, for which assessment of intra-
253 aggregate porosity on exposed aggregate faces is required, corresponded with porosity
254 determined by CT imagery (Munkholm *et al.* 2013; Garbout *et al.* 2013). The
255 classification of clods described in Le Profil Cultural, based on intra-aggregate
256 porosity (Peigné *et al.*, 2013), was justified with oedometer or consolidometer tests and
257 significant differences between void ratios were reported (Roger-Estrade *et al.*, 2004).
258 Le Profil Cultural modified for tropical soils (Neves *et al.* 2003) was found to relate to
259 microbial biomass carbon (daSilva *et al.*, 2014).
260
261 Other criteria used include colour, redox morphology, smell and biological properties.
262 However, techniques that include numerous, different criteria may generate the same
263 overall result (Newel-Price *et al.*, 2013) suggesting that on certain soils, indicators
264 additional to those centred on aggregation and porosity may be redundant. Mueller *et*
265 *al.* (2009) suggested that where variation between structural states or evidence of
266 compaction is not pronounced, procedures incorporating more diverse criteria
267 (Shepherd *et al.*, 2000; Werner and Thämert, 1989) are desirable to achieve usable
268 resolution. Relationships between diverse criteria and quantitative measurements were
269 found. Pulido Moncada *et al.* (2014a) found the SQSP rooting criteria (Ball and
270 Douglas 2003) correlated with ρ_b , soil organic carbon (SOC) and saturated hydraulic
271 conductivity (K_{sat}), along with the VSA soil colour criteria (Shepherd, 2009) with SOC
272 and K_{sat} . However, the site-specific nature of such relationships is emphasised (Mueller
273 *et al.*, 2009). Indeed VSE indicates overall structural state (Munkholm, 2000; Newel-

274 Price *et al.*, 2013). Universal correlation between particular quantitative measurements
275 and VSE criteria is not necessarily expected or desirable.

276

277 In addition to structural form, surface sealing (Shepherd, 2009; Ball and Douglas 2003)
278 or dispersion tests (Beste, 1999; McKenzie, 1998) can indicate stability, while organic
279 matter contents, soil texture, cracking, rooting and earthworm populations (Shepherd,
280 2009; McKenzie, 1998) indicate resiliency, thus holistically assessing structure (Kay,
281 1990).

282

283 *Spatial, textural and moisture variation*

284 Profile methods are efficient at distinguishing localised variation (Roger-Estrade *et al.*,
285 2004; McKenzie, 2001). Spade methods being quick, though less comprehensive
286 (Boizard *et al.*, 2013), generate accuracy through replication over wide areas. At a field
287 scale, sampling strategies vary (Cui *et al.*, 2014; Munkholm, 2000) and further
288 attention to on-farm procedures (Askari *et al.*, 2013) regarding survey objectives is
289 required. Recommended minimum numbers of samples range from four for VSA
290 (Shepherd, 2010b) to ten for VESS (Ball *et al.*, 2007) with the avoidance of damaged
291 areas, depending on objectives (Batey, 2000). Profile method soil pit excavation is
292 perpendicular to tillage and sufficiently long to capture damaged areas and micro-
293 variation (McKenzie, 1998; Peigné *et al.*, 2013). Additionally, pits can be located in
294 two contrasting areas, capturing extremes of spatial variation within a field (Ball *et al.*,
295 2015; McKenzie, 1998). Sampling strategies at farm scale (Sonneveld *et al.*, 2014)
296 have received limited attention.

297

298 Texture can influence diagnostic criteria, reducing precision. Batey and McKenzie
299 (2006) mentioned differences in cracking and rupture resistance associated with
300 cohesive, sandy and peaty soils. Texture can be dealt with by modifying the procedure
301 or within classification systems. A modified VSA dropt test requires sandy and loam
302 soil samples to be dropped from 0.5m instead of 1m (Shepherd 2009). Peerlkamp
303 (1959) described different classification systems, with the poorest class featuring
304 dense, smooth faced aggregates on clay and loam soils, and single-grain structure on
305 sandy soils. However, consideration must be given to agricultural management
306 capacity, as single-grain soils when irrigated, may be highly productive. Similar
307 classification differences were outlined by Diez *et al.* (2012), McKenzie (1998) and
308 Ball and Douglas (2003). The latter emphasised macro-porosity and soil colour
309 assessment in fine-textured soils, as opposed to solely aggregation.

310

311 Relationships between moisture content and VSA, SOILpak (Murphy *et al.*, 2013) and
312 VESS (Cui *et al.* 2014) have been described. Techniques recommend deployment on
313 moist soils (Ball *et al.*, 2007; Boizard *et al.*, 2005; Ball and Douglas, 2003, Batey,
314 2000), with scientific studies conducted at near Field Capacity (Abdollahi *et al.*, 2015;
315 Pulido Moncada *et al.*, 2014b). Clearly criteria such as rupture resistance will be
316 affected by moisture content, Munkholm (2000) and McKenzie (1998) include
317 different diagnostic descriptions for wet and dry soils. Some older methods described
318 by de Boodt *et al.* (1967) also include procedures for dealing with moisture content.
319 Research on the impact of moisture content on VSE criteria and deployment is limited.

320

321

322

323 *VSE output*

324 Batey (2000) emphasised the importance of describing structure rather than measuring
325 it. Qualitative outputs, generally associated with profile methods (Peigné *et al.*, 2013;
326 Batey, 2000) - reflecting their soil survey origin, provide detailed site-specific
327 descriptive information, potentially lost when applying numeric scores. Qualitative
328 descriptions may not be universally comparable (Batey, 2000) though this may not be
329 desirable. Le Profil Cultural explores point specific morphology and causes (Roger-
330 Estrade *et al.*, 2004) not necessarily applicable elsewhere. When summarising
331 structural state, numeric scoring systems are regarded as important (Ball *et al.*, 2015;
332 Ball *et al.*, 2013) as they quantify structural condition, are universally comparable and
333 allow statistical analysis (Newell-Price *et al.*, 2013; Munkholm, *et al.*, 2013). Mueller
334 *et al.* (2009) differentiated between techniques involving the assessment of properties
335 either, concurrently or separately. The latter (Shepherd, 2000) might enhance
336 reliability and objectivity (Mueller *et al.*, 2009) though may not to produce a
337 summarising score (Ball and Douglas, 2003; Munkholm, 2000; Beste, 1999; Werner
338 and Thämert 1989).

339

340 The Peerlkamp method, a concurrent type system, generated the same overall
341 diagnosis as a complex multi-component system (Newell-Price *et al.*, 2013). However,
342 its ten-point scoring system is criticised as being too broad, with a five-point index
343 identified as optimal (Ball *et al.*, 2007). This can consist of three exclusive and two
344 intermediate classifications (Beste, 1999), or five exclusive classifications, with non-
345 integer intermediates possible (Guimarães *et al.*, 2011). In the case of VESS, the use of
346 integer values can limit sensitivity and interpretation (Askari *et al.*, 2013), but deci-
347 metric scores, derived by calculation from integer values requires expert diagnosis.

348 Additionally, integer values can be grouped into a simple “traffic-light” colour scheme
349 (Ball *et al.*, 2007; McKenzie, 2013), clearly indicating structural state and potential
350 remediation requirements.

351

352 **Strengths, Weaknesses and Complimentary Aspects**

353 In this section, only the most widely utilised methods are discussed.

354

355 *Strengths and weaknesses*

356 VSA includes a range of intrinsic characteristics of soil quality and of structural
357 resiliency. The VSA drop test offers a clearly defined procedure for aggregate
358 exposure, useful for non-experts, the later modifications of which account for texture
359 variation (Shepherd 2009), originally found to be problematic (Newell-Price *et al.*,
360 2013; Giarola *et al.*, 2010). However, VSA does not delimit layers. VESS considers
361 layers and focuses on anthropic impacts, relying on the manual exposure of aggregates.
362 This requires some experience but still is suitable for non-expert use (Ball *et al.*, 2007).
363 Despite being reported as not dependent on texture (Cui *et al.*, 2014; Guimarães *et al.*,
364 2013; Giarola *et al.*, 2013; Guimarães *et al.*, 2011), VESS was problematic with fine
365 textured soils (Askari *et al.*, 2013), an issue that Ball *et al.* (2007) originally identified
366 (Askari *et al.*, 2015). However, Pulido Moncada *et al.* (2014a) demonstrated that
367 VESS generated similar results to VSA while taking less time.

368

369 SOILpak examines intrinsic soil quality along with structural stability and resiliency -
370 notably vertical porosity highlighted with paint (McKenzie, 1998). Although possibly
371 problematic on sandier soils (Boizard *et al.*, 2005), SOILpak not only includes
372 different scoring procedures for different textures, but also descriptions of criteria at

373 different moisture contents (McKenzie, 1998) while being suitable for non-expert use.
374 In contrast, Le Profil Cultural, only applicable to arable soils, requires expertise
375 (Roger-Estrade *et al.*, 2004) and is time consuming (Boizard *et al.*, 2005). However, it
376 provides a comprehensive evaluation of structural morphology, notably impacts of
377 tillage. Later descriptions (Peigné *et al.*, 2013) include criteria such as texture,
378 cracking, and earthworm activity exploring vertical porosity, intrinsic quality,
379 structural stability and resiliency. The analysis of clod morphology may indicate the
380 latter (Boizard *et al.*, 2002). SubVESS, suitable for non-expert use, generates a
381 relatively rapid evaluation of management below tillage depth. Issues may arise when
382 differentiating anthropogenic from intrinsic features and when used on stony soils
383 (Ball *et al.*, 2015).

384

385 *Complimentary aspects*

386 Profile methods examine point specific structural variation, assessing intrinsic quality
387 and anthropic impacts, thus process interactions. VSA and VESS allow wider spatial
388 evaluation and indicate structural state without thoroughly exploring mechanisms.
389 Both approaches can be used together. SubVESS examines from 30cm depth and so
390 should be used with VESS (Ball *et al.*, 2015). Specific technique methodology differs
391 and can be complimentary. As Mueller *et al.* (2009) noted, where structural variation
392 over wide areas is minimal, multi-component systems such as VSA, may be preferable
393 over concurrent systems such as VESS. SubVESS, which places emphasis on
394 aggregation and anthropic impacts (Ball *et al.*, 2015) worked well on a range of soil
395 types, apart from a stony fine soil that was classified as *Ssq* 1 (good structural quality)
396 despite being agronomically poor as indicated by Le Profil Cultural which considers
397 intrinsic properties (Peigné *et al.*, 2013).

398 **Conclusion**

399

400 We show wide and growing evidence of the utility of VSE techniques. An
401 appropriate method can be selected for all situations whether research, monitoring
402 or management. Assessment objectives, the survey area and operators' level of
403 expertise will dictate method selection. Profile methods allow a more detailed
404 structural assessment than spade methods, but at the cost of coverage of within-
405 field variation due to time constraints. However, both approaches offer information
406 not attainable using quantitative measurements. Improvements required;

407

408 • The interaction between moisture content and VSE criteria appears to have
409 received limited attention, while variation in soil texture presents problems for
410 some procedures. Modified procedures or classification systems according to
411 varying textures would be of benefit, notably to VESS. Nevertheless, research
412 shows methods are robust and valuable.

413 • As the utility of VSE techniques has been established, we recommended
414 exploration of sampling strategies and analysis of spatial variation. Minimum
415 sample replication per method should be determined.

416

417 Further research is encouraged on new procedures and on less utilised existing
418 methods. The latter may offer useful approaches to improve more widely adopted
419 methods and to explore wider aspects of structure such as stability and resiliency,
420 important for an integrated and holistic assessment, notably of agricultural soils.

421

422

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424

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427

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Table 1 Outline of VSE Spade Methods (Drop Test Procedures)

Method*	Origin	Objective	Land assessed	Characteristics assessed	Criteria employed	Depth assessed	Scoring system used	Intended users	Time requirement
The Diez Method (Diez <i>et al.</i> , 2012)	Germany	To assess structure in relation to soil functioning, notably plant growth and water infiltration	Emphasis on arable	Anthropic impacts on structure	Aggregate type, size, shape, inter-aggregate porosity, rooting, redox morphology, transition layer	40 ^b cm	Score between 1 and 5 used (<i>1 = best, 5 = worst</i>)	Advisors and farmers ^b	--
Visual Soil Assessment (VSA) (Shepherd, 2000, 2009, 2010)	New Zealand	To assess soil state, plant performance and the impact of farm management	Arable and grassland	Intrinsic soil quality and anthropic impacts on structure	Texture, aggregate size distribution, macro-porosity, redox morphology surface ponding and deformation, earthworms, smell, colour, potential rooting depth	Varying depths	VS score of between 0 and 50 (<20 = <i>poor</i> , 20-35 = <i>moderate</i> , >35 = <i>good</i>)	Advisors and farmers	40 minutes
FAL Method (Hasinger <i>et al.</i> , 2004)	Switzerland	To provide an accurate evaluation of structural state at a specific point ^a	Arable and grassland	Anthropic impacts on structure	Aggregate type, size, distribution and mean weight diameter ^a	45 cm	Score between 1 and 14 used for aggregate mean score (<i>1 = worst, 14 = best</i>). Aggregate mean weight diameter is described in mm	Researchers and advisors ^a	90 minutes ^a

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*Sources provided are not necessarily the original description of methods, ^a Sourced from: Boizard *et al.* (2005), ^b Points are of the authors' opinions

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Table 2 Outline of VSE Spade Methods (Manual Aggregate Exposure Procedures)

Method*	Origin	Objective	Land assessed	Characteristics assessed	Criteria employed	Depth assessed	Scoring system used	Intended users	Time requirement
Spade Diagnosis (Görbing 1947)	Germany	To assess structure in relation to plant growth	Emphasis on arable	Anthropic impacts on structure	Aggregate size, shape, porosity and rooting	30 cm	No numeric scores used	Advisors and farmers	--
Peerlkamp Method (Peerlkamp, 1959)	The Netherlands	To assess structure in relation to fertility, summarised by a single score	Emphasis on arable	Anthropic impacts on structure	Aggregate size shape, rupture resistance, inter- and intra-porosity, rooting, surface soil dispersion	15 cm	<i>St</i> Score between 1 and 10 (<i>1 = worst, 10 = best</i>)	Researchers, advisors and farmers ^a	30 minutes for 10 assessments ^a
The Werner Method (Werner and Thämert 1989)	Germany	To assess soil physical condition in relation to plant growth	--	Anthropic impacts on structure	Layers, aggregate size, width, shape, inter-aggregate porosity, bio-pores	50 cm	Scores between 1 and 4 or 1 and 5 used to describe individual properties, resulting in a five digit nominal value score for each layer	Researchers	--
Extended Spade Diagnosis (Beste, 1999)	Germany	To assess structure with regard to rooting conditions	Emphasis on arable	Anthropic impacts on structure	Aggregate type, size, shape, along with aggregate	40 cm	Scores between 1 and 5 used for structure and between	Advisors and farmers	--

		and habitats for soil biota			stability		0 and 2 for silting type. Three sample layers are assessed separately		
Spade Analysis (Munkholm, 2000)	Denmark	To describe and relate soil tillage to management while aiding and evaluating soil management decisions	Emphasis on arable	Intrinsic soil quality and anthropic impacts on structure	Texture, colour, layer boundaries, aggregate size, shape, grade, soil consistence, macro-porosity, pore distribution, connectivity, orientation and rooting, OM decomposition and soil fauna	30 cm	Different scoring systems used for different properties, though no summarising numeric scores used	Researchers and advisors ^a	1 – 3 hours ^a
Soil Quality Scoring Procedure (SQSP) (Ball and Douglas, 2003)	United Kingdom	To assess physical fertility in terms of structure, rooting and soil surface conditions	Arable and grassland	Anthropic impacts on structure	Soil surface, aggregate type, size, shape, rupture resistance and rooting	30 cm	Three separate scores are assigned, each between 1 and 5 (<i>1 = worst, 5 = best</i>)	Researchers and advisors ^a	1 hour ^a
Visual Soil Structure Quality Assessment (VSSQA) –	United Kingdom	To semi-quantitatively assess soil structural quality in a	Arable and grassland	Anthropic impacts on structure	Aggregate size, shape, intra-porosity, rupture	25 cm	Sq Score between 1 and 5 (<i>1 = best, 5 = worst</i>)	Advisors and farmers	15 minutes

Visual Evaluation of Soil Structure (VESS) (Guimarães <i>et al.</i> , 2011)		manner accessible to non-experts			resistance rooting, redox-morphology				
Thinksoils Manual (Environment Agency, 2007, 2010)	United Kingdom	To assess soil structure with regard to erosion and run-off potential	Arable and grassland	Anthropic impacts on structure	Fissures and porosity, aggregate size, shape, rupture resistance, redox morphology, rooting, crop growth	40 cm	No numeric scores used	Advisors and farmers	- -

*Sources provided are not necessarily the original description of methods, ^a Sourced from: Boizard *et al.* (2005)

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Table 3 Outline of VSE Profile Methods

Method*	Origin	Objective	Land assessed	Characteristics assessed	Criteria employed	Depth assessed	Scoring system used	Intended users	Time requirement
Le Profil Cultural (Peigné <i>et al.</i> , 2013)	France	To examine the impact of tillage on soil structure features	Arable	Emphasis on anthropic impacts on structure	Soil layers, structural zones, macro-pores, aggregate/clod size, intra-porosity, redox morphology, rooting	1.5 m	No numeric score used	Researchers	1 – 3 hours ^a
Whole Profile Assessment (Batey, 2000)	United Kingdom	To assess the anthropic impact on intrinsic soil properties in relation to crop growth ^a	Arable and grassland	Intrinsic soil quality and anthropic impacts on structure	Soil layers, texture, aggregate size, shape, aggregate stability, compacted zones, soil bearing capacity, soil colour, redox morphology	1.2 - 1.5 m	No numeric score used	Researchers and consultants ^a	20 – 40 minutes ^a
SOILpak (McKenzie, 1998)	Australia	To identify and assess compaction in relation to crop growth	Emphasis on arable	Intrinsic soil quality and anthropic impacts on structure	Texture, soil surface, rooting, aggregate size, shape, rupture resistance, macro-pores, aggregate stability	1.5 m	Score between 0 and 2 used for structural (0 = worst, 2 = best) and ASWAT score	Land surveyors, advisors and farmers	25 – 90 minutes ^a

							between 0 and 16 used for aggregate stability (0 = negligible dispersion, 16 = serious dispersion)		
SubVESS Flowchart (Ball <i>et al.</i> , 2015)	United Kingdom	To assesses any anthropogenic transition layer in terms of crop growth	Emphasis on arable	Anthropic impacts on structure	Redox morphology, porosity, rooting, aggregate size, shape	1.4 m	<i>Ssq</i> scores of between 1 and 5 (1 = best, 5 = worst)	Advisors	20 minutes

*Sources provided are not necessarily the original description of methods, ^a Sourced from: Boizard *et al.* (2005)

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