

Scotland's Rural College

Opportunities and future directions for visual soil evaluation methods in soil structure research

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25 **Abstract**

26 As the use of visual soil evaluation (VSE) methods has spread globally, they have been
27 exposed to different climatic and pedological scenarios, resulting in the need to elucidate
28 limitations, encourage refinements and open up new avenues of research. The main
29 objective of this paper is to outline the potential of VSE methods to develop novel soil
30 structure research and how this potential could be developed and integrated within existing
31 research. We provide a brief overview of VSE methods in order to summarize the soil
32 information that is obtained by VSE. More detailed VSE methods could be developed to
33 provide spatial information for soil process models, e.g. compaction models. VSE could be
34 combined with sensing techniques at the field or landscape scale for better management of
35 fields in the context of precision farming. Further work should be done to integrate plant
36 vigour, roots and soil fauna into VSE methods to provide general indicators of soil quality
37 and for estimation of environmental risk factors related to soil C storage, GHG emissions and
38 nutrient leaching, with particular reference to temporal changes. There is a great potential in
39 combining (rather than comparing) VSE with measurements of soil structure, i.e. integrating
40 VSE in soil structure and compaction research, as these methods provide spatial information
41 that is difficult to obtain with other methods.

42

43 *Keywords:* Soil management; Soil compaction; Sensing; Modelling; Soil quality

44

45 **1. Introduction**

46 Soil structure comprises the physical habitat of soil living organisms, and controls many
47 important physical, chemical and biological soil functions and associated ecosystem services.
48 Soil structure is typically defined as the spatial arrangement of soil constituents and voids
49 (i.e. soil pores), which may also be defined as the spatial distribution of soil properties
50 (Dexter, 1988). However, soil structure is more than just the physical arrangement of
51 particles and pores (that was referred to as “structural form” by Kay and Angers (2001)), and
52 includes structural stability (i.e. the ability to resist external stresses) and structural resilience
53 (i.e. the ability to recover upon stress removal) (Kay and Angers, 2001). Different methods
54 can be used to evaluate the different aspects of soil structure. For example, computed
55 tomography (CT) imaging is excellent at visualizing and quantifying the form of soil structure
56 (for an overview, see Taina et al., 2008; Peth, 2011; Wildenschild and Sheppard, 2013) and
57 can be used to study the dynamics of soil structural pore spaces (i.e. the dynamics of the
58 form of soil structure) by multiple scanning as demonstrated by Peth et al. (2013), but
59 cannot directly assess soil structure stability or resilience. Visual soil evaluation (VSE) cannot
60 reveal as much information on the geometrical arrangement of pores and constituents as CT
61 imaging does, but assesses both the structural form and the structural stability (e.g. DVWK,
62 1995a, 1997; ATV-DVWK, 2001; Boizard et al., 2007; Guimarães et al., 2011), and may reveal
63 information on the resilience through biological indicators (e.g. Boizard et al., 2016 this
64 issue). Unlike the texture of a soil that can be considered a static property, the soil structure
65 is a dynamic trait. Soil structure is influenced by both natural and anthropogenic processes.
66 The natural processes include abiotic processes induced by drying-wetting and freeze-thaw
67 phenomena, as well as biotic processes leading to the creation of new pore spaces by the
68 penetration of plant roots and burrowing fauna, soil aggregate stabilization by plant roots,

69 fungi, and soil fauna (enmeshing, excretions), and soil shrinkage due to plant water uptake
70 (Kay, 1990; Dexter, 1991; Horn et al., 1994; Horn, 2003; Hallett et al., 2013). Anthropogenic
71 influences on soil structure are primarily related to soil management including soil tillage,
72 soil compaction due to vehicle traffic, incorporation of organic fertilizers and amendments,
73 as well as crop selection and fertilization (for an overview, see Kay, 1990; Bronick and Lal,
74 2005; Kay and Munkholm, 2011). Such aspects have significant influence on structural
75 stability and resilience as well as structural form, all of which influence soil function (Horn,
76 1990; Horn et al., 1994).

77 Despite the recognized importance of soil structure for soil functioning, its
78 characterization and quantification of the complex interactions (as stated above) that drive
79 soil structure formation remain a challenge (e.g. Hallett et al., 2013; Peth et al., 2013). Visual
80 soil evaluation (VSE) methods have been developed to assess the structural state of soil (for
81 a review see Boizard et al. (2007)). Most VSE methods were developed as a practical
82 diagnostic tool in agricultural extension service. Various visual methods to assess soil
83 structure and soil quality have been developed and used for many years in different parts of
84 the world, and these have mainly been published in reports, booklets and notes (e.g.
85 Görbing, 1947, Peerlkamp, 1959; Preuschen, 1983; Gautronneau and Manichon, 1987;
86 DVWK, 1995a; Shepherd, 2000; Munkholm, 2000; McKenzie, 2001; Nievergelt et al., 2002).
87 More recently, methods have been refined, combined, and published in scientific journals
88 (for an overview see e.g. Ball et al., 2015). In the remainder of this paper, we use 'visual soil
89 evaluation (VSE) methods' as a general term for all methods, whereas specific methods (e.g.
90 'Profile Cultural'; Gautronneau and Manichon, 1987) will be referred to by their specific
91 name. Furthermore, there has been a growing interest to (re-)use VSE methods in research,
92 primarily have been used to characterize the impact of soil management on soil structure

93 and to help identify the type and location of measurements for further characterisation of
94 soil physical properties (Ball et al., 2015; this special issue).

95 Only a few studies have used VSE methods with regards to soil structure dynamics.
96 Roger-Estrade et al. (2000) used the 'Profil Cultural' method (Gautronneau and Manichon,
97 1987) to quantify the temporal evolution of soil structure under contrasting tillage systems,
98 and Boizard et al. (2013) used the same method to study recovery after compaction in a
99 reduced tillage experiment. Ball and Munkholm (2015) showed that the 'Visual Evaluation of
100 Soil Structure' (VESS) method (Guimarães et al., 2011) was able to reveal variations in soil
101 quality and recovery, over a four-year period of evaluation, when assessing compaction by
102 tractor and animal trampling. These authors also highlighted that repeating VSE
103 measurements over time enables the monitoring of soil quality evolution.

104 All VSE methods are mainly used within an agronomic context, with the purpose of
105 assessing soil management effects and providing soil management recommendations. Thus,
106 it is important that VSE scores have veracity and are nearly reproducible. Therefore, soil
107 structure is systematically evaluated according to manuals and instruction videos to reduce
108 operator dependence for most VSE methods. In general, different operators typically find
109 very similar scores (e.g Ball et al., 2007; Guimarães et al., 2011). Subjectivity is, however, still
110 considered a modest limitation to VSE methods, e.g. in relation to the isolation of structural
111 units and the assessment of their properties and efforts to further reduce this limitation
112 continue. Other limitations include possibly confusing soil moisture effects on soil strength
113 with those of compaction and difficulty in use in soils of extreme textures and insufficient
114 emphasis on porosity, particularly with spade methods (Ball and Munkholm, 2015;
115 Munkholm and Holden, 2015). Scale is also an important aspect to take account for any soil
116 structure description method. Babel et al. (1995) proposed an initial description of soil

117 structure (shape and surface of the structural units, geometrical arrangement, aggregate
118 strength, bioturbation, etc.) at a given scale, and then to reproduce observations at various
119 scales applicable across land uses and across scientific disciplines.

120 VSE methods yield information on the vertical thickness and depth of natural and
121 anthropogenic soil layers, and on the spatial arrangement of structural features (profile
122 methods) or the size distribution of soil fragments (spade methods). Such information is not
123 available, for example, from sampling at discrete (pre-defined) depths with small volumes
124 (e.g. undisturbed cylindrical soil cores that may have a typical volume of 100 cm^3), which are
125 typically used in soil structure research. Several studies have demonstrated significant
126 correlations between the various structural features (as e.g. obtained by VSE methods) and a
127 range of soil properties (mainly soil physical properties such as, bulk density, penetration
128 resistance, saturated hydraulic conductivity, among others; see e.g. Horn, 1990; Shepherd,
129 2003; Dörner and Horn, 2009; Guimarães et al., 2013; Moncada et al., 2014; Ball et al., 2016
130 this issue). Moreover, the shape of the fragments and an estimate of the tensile strength of
131 the fragments is obtainable from VSE methods. The 'Profil Cultural' reports detailed
132 information regarding the spatial arrangement and distribution of soil properties (e.g.
133 aggregates, pores, roots, organic residues), whereas other methods such as VESS (Guimarães
134 et al., 2011), the Visual Soil Assessment (VSA) method (Shepherd et al., 2009) and SOILpak
135 (McKenzie et al., 1998), for example, combine this information into a score or soil quality
136 index, either for each layer or for a whole soil profile. The reason for combining this
137 information into a single index is that such an index will be useful for assessing the overall
138 physical quality of a soil, for comparing soil quality across soils, and for providing soil
139 management recommendations. However, valuable information on soil structure can be lost
140 through the combination process. We will argue in this paper that this information could be

141 useful in research aiming at better understanding the impact of soil structure on soil
142 functioning (including plant growth) and better understanding of soil structure dynamics.

143 A joint workshop of the two ISTRO working groups on Visual Soil Examination and
144 Evaluation (VSEE) and Subsoil Compaction held in May 2014 brought together scientists
145 dealing with characterisation of soil structure and its dynamics with a focus on soil
146 management impacts (soil tillage, soil degradation by compaction). A main aim of the
147 workshop was to jointly discuss and possibly outline (i) research needs of visual soil
148 evaluation methods, new approaches (ii) to combine VSE methods with “traditional” soil
149 physical methods and analysis as well as with remote and proximal sensing techniques, and
150 (iii) to integrate VSE in soil structure research for better quantification of soil structure and
151 better understanding of soil structure dynamics caused by soil management. This article
152 summarises and synthesizes the discussions from the workshop. Although the workshop had
153 an emphasis on tropical conditions, most of the discussions were relevant to all soils.

154 The main objectives of this paper are to outline (i) research needs for improvement of
155 VSE methods, and (ii) the opportunities of VSE methods in soil structure research. We will
156 provide a brief overview of VSE methods, in order to summarize the soil information that is
157 obtained by VSE. We will describe research needs for further development of VSE methods
158 and their better integration in soil structure research. Finally, we propose ways of using and
159 integrating the spatial information obtained by VSE in research on soil structure dynamics
160 and soil compaction.

161

162

163 **2. Brief overview of visual soil assessment methods**

164 *2.1 General approach of visual soil evaluation methods*

165 Many visual soil evaluation (VSE) methods have been developed worldwide to evaluate
166 the soil structural quality of topsoils and whole soil profiles. As mentioned above, many
167 different methods have been developed and used in various parts of the world, but
168 description of many methods may not be readily available for the international scientific
169 community because they are often published in institutional reports, notes or as booklets.
170 However, most methods share similar soil quality assessment criteria related to visible soil
171 porosity as well as the size, shape and strength of aggregates. Please consult Boizard et al.
172 (2007) for an overview of 10 different methods presented at the ISTRO 2005 workshop at
173 Péronne, France. The methods generally divide into topsoil-focused spade methods and
174 topsoil and subsoil focused profile methods. The most commonly used spade methods in
175 research are the VSA method (Shepherd et al., 2009) and the VESS method developed from
176 the Peerlkamp method (Ball et al., 2007; Guimarães et al., 2011) (Munkholm and Holden,
177 2015). Among the soil profile methods, 'Profil Cultural' (Gautronneau and Manichon, 1987;
178 Peigné et al., 2013), SOILpak (McKenzie et al., 1998) and, most recently, the numeric visual
179 evaluation of subsoil structure methods (SubVESS) (Ball et al., 2015) are used in research
180 (Munkholm and Holden, 2015). These five spade and profile methods are described in detail
181 by Batey et al. (2015). It is also important to mention methods that integrate information
182 from different methods into an overall soil quality rating such as the Muencheberg Soil
183 Quality Rating system (Mueller et al., 2013).

184 The five different VSE methods mentioned above all include assessment of size, shape
185 and strength of soil aggregates and of visible porosity (Batey et al., 2015). These features
186 yield information on the quality of soil as plant growth medium, habitat for soil biology and
187 on conditions for nutrient cycling, and water and gas storage and transport. Other
188 commonly evaluated features are soil colour (e.g. VESS, SubVESS and VSA), earthworms in

189 terms of numbers, sizes, species and burrows (e.g. VSA and Munkholm spade method
190 (Munkholm, 2000)), rooting in terms of proliferation and architecture, depth, and distortion
191 (e.g. VESS, VSA, SOILpak and SubVESS), porosity (all methods) and water stable aggregates
192 (SOILpak). Most methods include an evaluation of distinct soil layers or zones but often
193 evaluation scores are assessed across different layers. The importance of specific evaluation
194 of limiting layers such as hardpans is highlighted in the profile methods (SOILpak, SubVESS
195 and 'Profil Cultural') and in some spade methods (VESS, Guimarães et al., 2011). The VSE
196 methods differ markedly in terms of the level of details regarding the evaluation. The more
197 detailed the analysis (as for 'Profil Cultural') the longer it takes to complete an evaluation. In
198 general the simple spade methods such as VESS are fastest (5-15 min per sample) and the
199 detailed profile methods take the longest time (1-3 hours) (Boizard et al., 2007; Batey et al.,
200 2015). The fast and easy to use spade methods make it possible to do many replicates at the
201 same time as it takes to do one detailed profile evaluation. Thereby, a larger area and more
202 treatments can be covered within the same time interval. On the other hand this may be at
203 the expense of more detailed understanding of specific land use or management effects on
204 soil structure. In many cases a combination of fast and simple methods with a few more
205 detailed evaluations may be beneficial in order to obtain both general knowledge on spatial
206 differences and in depth knowledge of the impact of specific land use or soil management.
207 Please consult Batey et al. (2015) for more details on similarities and differences between
208 the commonly used methods.

209

210 *2.2. Application of visual methods in practice*

211 VSE methods are used in many countries by agricultural advisors, teachers, and
212 farmers, even though detailed knowledge of the use of the VSE methods in practice is often

213 lacking. More detailed VSE methods will require specialized soil knowledge for successful
214 application, while simple spade methods only require some methodological training for
215 successful application by students or farmers, for example. We expect that the methods are
216 most widely used in Western Europe, Australia, New Zealand and Brazil, where most of
217 today's known methods have been developed. To illustrate the interest in VSE methods in
218 practice, the VESS manual has been translated into a number of languages, including
219 Spanish, French, Portuguese, Norwegian and Danish, primarily by advisors.

220

221 *2.3 Application of visual methods in soil research*

222 The VSE methods are increasingly being used in soil research to evaluate effects of
223 land use and soil management, primarily. Munkholm and Holden (2015) listed 29 VSE papers
224 on arable soil and 10 VSE papers on grassland soils in a recent review and most of them had
225 been published since 2010. In general, VSE methods have been useful to detect effects of
226 land use and management on soil structure. Most VSE papers also include comparative
227 quantitative soil structure data e.g. soil pore characteristics, bulk density, soil strength, soil
228 structural stability and hydraulic conductivity. Strong correlations have been found in many
229 cases as outlined by e.g. Batey et al. (2015). Significant correlations with crop yield have also
230 been shown in some studies (Mueller et al., 2009; Munkholm et al., 2013).

231 The VSE methods have primarily been used for comparative studies where effects of
232 land use and management has been investigated at a specific time. In a few cases the VSE
233 methods have been applied to study soil structure dynamics, i.e. spatio-temporal changes in
234 soil structure after e.g. animal or field traffic induced soil compaction (Ball and Munkholm,
235 2015; Boizard et al. 2013). Boizard et al. (2013) showed that the "Profil Cultural" was a useful
236 tool to assess soil recovery after heavy compaction. They detected the development of a

237 platy structure layer in the years after a heavy compaction treatment. The above mentioned
238 studies suggest that there is a great potential for more widespread application of VSE
239 methods in studies of soil structure dynamics. However, VSE methods are destructive by
240 nature and this has to be taken into account when choosing VSE as a tool to study temporal
241 evolution of soil structure, especially within field experiments.

242

243

244 **3. Research needs for further development of visual soil assessment methods**

245 *3.1 Improving the quality of scoring by including the impact of soil moisture content at* 246 *sampling*

247 Soil aggregate fragmentation is an integral component of many visual evaluation
248 methods (see previous section). However, fragmentation is strongly affected by the soil
249 moisture (for an overview, see e.g. Dexter and Bird, 2001; Munkholm, 2011), and hence the
250 soil moisture, measured in terms of water content or in terms of matric potential, at the
251 time of assessment can influence the result of the test (Fig. 1). Water strongly affects the
252 consistency and the strength of soil (e.g. Atterberg, 1911; Horn, 2003), consequently, a drier
253 soil is generally harder and more difficult to break up, and therefore, extra pressure is
254 required to fragment dry aggregates. Especially, it is important that the soil is not dried to
255 conditions drier than it has ever experience before, as this is associated with irreversible soil
256 structural changes, when smaller aggregates may break up due to pore weakening (Horn et
257 al. 2014). This may not be a problem under many conditions, but could be crucial when
258 evaluating subsoils in temperate climates. A wet soil is weak, and beyond a certain moisture
259 content soil no longer break-up, instead the aggregates plastically deform when a pressure is
260 applied. Both, a too dry and a too wet soil may result in a false interpretation of its structure.

261 Soil friability describes the tendency of a soil to break down into fragments of desired sizes
262 upon application of a stress (Utomo and Dexter, 1981). A range of water contents can be
263 defined within which soil friability is satisfactorily (see Munkholm, 2011). The upper (i.e.
264 wet) limit of this range is typically defined from soil consistency and often assumed at $w = PL$
265 (lower plastic limit). A shortcoming of using PL as a limit is that it is determined on
266 remoulded soils, and natural soil may behave differently. The lower (i.e. dry) limit is less well
267 defined but related to energy requirement for fragmentation. Soil friability is maximum at
268 intermediate soil water contents, with the maximum friability at a water content, w , at
269 around $0.9 \times PL$, see Munkholm (2011). Similarly, we can define a range of suitable water
270 contents for visual soil evaluation (Fig. 1). It may be assumed that the range of water
271 contents for satisfactory friability and satisfactory visual soil evaluation coincide. For this
272 reason, it is generally recommended that visual tests are conducted while the soil is within
273 the friable range (Ball et al., 2016 – this issue), to avoid misinterpretation of the sample. The
274 ease of fragmenting an aggregate is one of the key factors evaluated by VESS. We suggest
275 that the optimum range of water contents for visual soil evaluation could be investigated in
276 future research. The range of suitable water contents may be affected by climatic conditions
277 (e.g. rainfall patterns) and soil type (e.g. different for sand soils vs clay soils). The latter
278 problem may be overcome by specifying a range in matric potentials rather than in water
279 content. Another strategy could be to develop methods to normalize VSE results to a
280 standardized water content (e.g. by using w/PL) or matric potential. This would require that
281 the water content and/or matric potential at the time of VSE is measured, as suggested by
282 Babel et al. (1995). Furthermore, it could be interesting to perform VSE at various water
283 contents/potentials. We hypothesize that the change in soil quality (e.g. score) as assessed

284 by VSE as a function of soil water status may carry some information on the resilience of a
285 certain soil (structure).

286

287 *3.2 Extending the scope of VSE by integrating biological indicators*

288 Macrofauna and root activity, which are also assessed in VSE methods, play a major
289 role in soil structural quality, mainly by improving macroporosity, by promoting aggregation,
290 and by stabilizing structures (e.g. Lynch, 1984; Kay, 1990; Dexter, 1991; Uteau et al., 2013;
291 Han et al., 2015; Pagenkemper et al., 2015). Some methods, such as the VSA, include the
292 number of earthworms as an indicator of soil quality (Shepherd, 2009), while Munkholm
293 (2000) uses the number of earthworm holes as another quality aspect to be evaluated.
294 Munkholm (2000) highlights the difficulty of evaluating soil macrofauna as it can be difficult
295 to observe the fauna before they escape the soil block extracted for evaluation. VESS does
296 not currently include faunal presence as part of its evaluation, however, the presence of
297 distinct biopores (resulting from earthworm and root activity) is a criterion for attributing a
298 score and counting of earthworms within the block is proposed as an extension of the
299 method. Franco et al. (2016, this issue) showed positive correlations between VESS and
300 reduction in *Isoptera* and *Coleoptera* abundance, while earthworm activity has been shown
301 to have an important impact on soil structural quality (Piron et al., 2012). Therefore, the
302 improvement and incorporation of faunal assessments in visual methods and the evidence
303 of their action in soil structure dynamics should be a future research goal, as also highlighted
304 by Boizard et al. (2007) and Munkholm and Holden (2015).

305

306 *3.3 Combining visual soil assessment methods with remote and proximal sensing and* 307 *interactive tools for mobile devices*

308 Remote sensing techniques can be used to show diagnostic indicators of soil
309 properties, such as soil texture (Peng et al., 2014), organic matter content (Viscarra Rossel
310 and Hicks, 2015; Aldan-Jague et al., 2016), organic matter quality (Ben-Dor et al., 1997), iron
311 content, soil texture or particle size distribution, clay mineralogy, water content, soil
312 contamination (Peng et al., 2016), cation exchange capacity and calcium carbonate content
313 through imaging spectroscopy (Ben-Dor et al., 2009; Stenberg et al., 2010; Soriano-Disla et
314 al., 2014) and soil moisture through RADAR sensing (Zribi et al., 2011). Estimates of these
315 properties by means of remote sensing typically rely on relationships established from
316 standard measurements on pre-treated and remoulded soil samples in the laboratory.
317 However, actual in situ properties of structured soils may differ from apparent properties
318 measured on homogenised samples. Therefore, there is a risk of misinterpretation of data.
319 For example, Hartmann et al. (1998) showed that there is a difference in the observed cation
320 exchange when comparing homogenized samples with in situ structured soil. Multispectral
321 sensing can be used to estimate land cover and use, vegetation indices and degradation
322 (Dewitte et al., 2012; Mulder et al., 2011). Here we differentiate remote sensing that is
323 airborne or satellite based at the large scale from proximal sensing that is ground-based for
324 finer scales (Wulf et al., 2014).

325 Proximal sensors utilize a variety of electromagnetic radiations to infer information on
326 salinity, organic composition, mineralogy, moisture content, topsoil thickness and clay
327 content (Samouelian et al., 2005; Viscarra Rossel et al., 2006). These and other sensing
328 techniques can be used to differentiate the landscape or plot into scaled units of sensory
329 output that can be related to site properties through field sampling (Paradelo et al., 2016).
330 Good correlations have been observed between the results of remote or proximal sensing
331 and soil variables such as bulk density, penetration resistance, soil organic carbon and soil

332 moisture and, for VIS-NIR sensing of soil quality, has been related to visual quality scores for
333 VESS (Askari et al., 2015).

334 A promising area of future study is the correlation of electromagnetic spectrum
335 sensing results with visual evaluation scores as it would allow the interpolation of a limited
336 number of Sq scores (from VESS) over the sensed areas, reducing the burden of sampling.
337 This would be of particular relevance in precision farming where inputs are related to soil
338 variables. Aerial photography, now available at low cost using Unmanned Aerial Vehicle
339 (UAV/drone) technology, could be used to identify areas of compacted or degraded soil for
340 further investigation via VSE. Combining techniques of remote and ground-based sensing
341 and yield mapping could be used to delineate areas with similar soil properties and/or
342 adverse yield productivity (Fig. 2), and thereby assist in selecting locations for more detailed
343 investigation using VSE. In addition, use of handheld devices with various sensors (e.g. NIR to
344 detect moisture content) could complement VSE and make soil quality scoring more robust
345 (cf. Section 3.1).

346 Another promising area of developing technology is the use of interactive tools for
347 mobile devices, such as smart phones and tablets, that include instructional help videos,
348 methodologies and scoring applications, which allow field observations to be related to
349 reference photographic guides, to make soil quality scoring more relevant or for easy
350 transmission to experts available online. This would allow more information to be available
351 than from a chart or field guide, reducing errors and the influence of the operator.

352

353 *3.4 Integrating VSE with other properties to provide more holistic estimation of soil quality*

354 The measurement of soil hydraulic properties is a useful indicator of a drainage or
355 aeration limitation of the cropping potential, however, inferring these properties via visual

356 methods can be difficult. Many soil features closely related to soil hydraulics, such as surface
357 crusting, large cloddy structure, soil colour, surface deformation, surface ponding, soil
358 erosion and surface microrelief can be scored visually using *ad hoc* keys (Murphy et al.,
359 2013; Guimarães et al., 2015, Shepherd, 2009). Including surface features in visual methods
360 could be of particular value by enabling improved inferences regarding hydraulic properties.
361 For example, recording the presence of sealing or surface crusting or platy layers could imply
362 restricted infiltration or water drainage. The development of visual assessments such as the
363 erosion toolkits that relate soil texture and slope to soil structure and thereby to risk of
364 erosion (Regan, 2012; Guimarães et al., 2015) could enable more objectivity when linking
365 surface features with soil structural quality.

366 Profile methods, such as SubVESS, “Profil Cultural” and SOILpak (topsoil and subsoil)
367 give an overall status of soil structure to a greater soil depth than the spade methods. A
368 vertical continuous pore network is important for soil functions, such as drainage and
369 aeration and as a conduit for root growth, all of which are key factors for crop productivity
370 and profile methods are suitable when tracking macropore continuity (Munkholm and
371 Holden, 2015). Identifying and distinguishing man-made from naturally compacted layers
372 will enable profile methods to be more useful for identifying subsoil layers that require
373 loosening. Munkholm and Holden (2015) reported that identifying the layer that limits plant
374 growth is crucial for subsoils, therefore, reporting evaluations for individual layers is
375 recommended by Ball et al. (2015) and McKenzie (1998).

376 Assessment of agricultural land in terms of soil quality and soil structure using quick
377 VSA and VESS techniques has been shown to provide an indication of the potential for soils
378 to store C, release GHGs and lose nutrients, and are therefore important for identifying
379 problems as well as to combat environmental change (Cloy et al., 2015). VSA and VESS were

380 also used to estimate the risk of soil emissions of nitrous oxide from pastures where
381 compaction damage was present and rates of mineral N fertilizer were high. Visual
382 assessments also have the potential to assess the risk of surface water runoff and nutrient
383 loss. Such assessments which combine detailed soil and crop visual evaluations with fertilizer
384 management history are areas for potential development. The potential role of soil colour
385 was shown for the further extension of visual evaluation techniques to a soil carbon storage
386 index. These methods show clear potential for further development and research to provide
387 validation of scored soil and crop qualities with measured properties of soil C storage, GHG
388 emissions and nutrient leaching (Cloy et al., 2015; Ball et al., 2016 – this issue).

389 Extending and combining visual methods with other simple quantitative or qualitative
390 field methods will give a more general soil quality indicator, such as in VSA and SOILpak
391 (Mueller et al., 2014; Munkholm and Holden, 2015). Govaerts et al. (2006) proposed a
392 minimum data set to assess soil quality that should take into account soil and climatic
393 conditions for the specific agro-ecological zone and their interaction with land use. Mueller
394 et al. (2014) also proposes the combination of quantitative and qualitative field based
395 methods with visual evaluation of soil methods. Combination of VSE methods with visual
396 crop evaluation may also extend the agronomic relevance of VSE for identifying limiting soil
397 conditions.

398

399

400 **4. Potential of visual soil evaluation methods to advance soil structure research**

401 *4.1. Accounting for spatial variability in soil modelling*

402 Quantification of the form of soil structure can be achieved through imaging (e.g. Peth
403 et al., 2013) or indirect measurements (i.e. water and gas transport, aggregate size

404 distribution, etc.; e.g. Ball et al., 1988). All imaging techniques and physical measurements
405 are limited to a given size of observation, which makes our understanding of soil structure
406 discontinuous and incomplete. Thus, extrapolation from measurements on soil samples to
407 soil profile or to field is uncertain (e.g. Etana et al., 2013). Usually, averaged measurements
408 on randomly sampled soil cores (10^{-2} m) are used to explain soil functioning at the profile
409 (10^0 m) or field scale (10^2 m), or to parameterize models. The issue of upscaling observations
410 at core or smaller scale to field, landscape and global scale was highlighted as one of the
411 essential challenges for soil modelling in a recent extensive review (Vereecken et al., 2016).

412 The variability of a soil property can be described using probabilistic models (Perfect
413 and Kay, 1994; Chun et al., 2008). However, simulation and evaluation of the effect of
414 agricultural practices on soil functions often need maps of the spatial organization of the
415 different structural features. Geophysical methods including electrical resistivity
416 tomography, ground penetrating radar and seismic methods can be used to obtain two- or
417 three-dimensional maps of soil physical properties that can be related to parameters
418 relevant for soil models (Besson et al., 2004; Petersen et al., 2005). Further information on
419 spatial variation of soil structural features can be readily assessed in situ by visual soil
420 evaluation methods. VESS has been used to determine the minimum sampling density of
421 VESS and of other assessments of soil quality to capture the spatial variation in a field. This
422 involved sampling at up to 16 points per ha and mapping the data sets by kriging at
423 decreasing sampling density to determine the optimum sampling density. This was $\sim 0.9 - 1$
424 per ha for the two agricultural fields assessed (Laura Thomas and Bryan Griffiths, SRUC
425 Edinburgh, personal communication). This corroborates similar result found by Rachel M.L.
426 Guimarães (unpublished data), who evaluated 36 blocks per ha and concluded that one VESS
427 evaluation per ha was the minimum sample density required to accurately represent a field's

428 soil quality via VESS, however, it is suggested that three replicates should be taken per ha for
429 statistical purposes.

430 Few studies have attempted to integrate soil structure spatial variability at the profile
431 scale as described by visual soil evaluation methods into models, but some exceptions are
432 the studies by Benjamin et al. (1990), Coutadeur et al. (2002) and Ndiaye et al. (2007). The
433 methodology was the same for all these studies: physical measurements were performed in
434 the laboratory or in the field for the different structural zones as identified on the soil profile
435 by VSE, and measured soil parameters were used to model heat or water transport in two
436 dimensions. However, none of these works took into account the temporal variation in soil
437 structure, which would need also a model of structure dynamics, e.g. 'Sisol' developed by
438 Roger-Estrade et al. (2009). For the studies mentioned above, VSE methods were used to
439 give information on the spatial distribution of different zones, but soil properties needed to
440 model the process in question (e.g. water transport) were obtained by measurements. VSE
441 methods were used to choose the position of the sampling, which might lead to an
442 overestimation of the differences between, for example, loose and compacted zones, as
443 transitions between these zones might be difficult to sample.

444 In a recent study, Moncada et al. (2014) showed that pedotransfer functions could
445 benefit from integrating a VSE score. Similarly, it was shown in the DVWK bulletins 234 and
446 235 (DVWK 1995b, 1997) that prediction of soil functions (e.g. soil strength) requires
447 knowledge of in situ soil structural features related to aggregation, in addition to intrinsic
448 soil properties (e.g. texture). All these results might be due to the more holistic approach of
449 VSE methods as compared with specific physical measurements. It is well known that soil
450 structure changes over time due to natural and anthropogenic factors. Despite of this,
451 dynamic changes in soil structure is ignored in most soil models (Vereecken et al., 2016) –

452 most likely due to lack of empirical data. VSE methods are sensitive to temporal changes
453 (Boizard et al., 2013; Ball and Munkholm, 2015) and may be used as tool to assess in situ
454 changes at aggregate to pedon scale and at different depths. Qualitative information from a
455 VSE method at different times before and after tillage could be successfully used to model
456 soil structural dynamics as affected by tillage (Roger-Estrade et al., 2000). Fig. 3 illustrates
457 how the spatial information obtained from visual soil evaluation could be used in soil
458 process modelling. The qualitative information from VSE may be supplemented with
459 quantitative data at selected times and depths, which may be used in more mechanistic soil
460 modelling.

461

462 *4.2. Improving the description of compaction propagation by including spatial description of* 463 *soil structure within the soil profile*

464 Compaction is a major soil threat due to ongoing intensification of agricultural
465 practices: farmers and contractors choose large machinery to increase efficiency of field
466 operations, and industry designs machinery that can perform on weak soils to increase
467 flexibility of field operations planning (Schjønning et al., 2015). Description of the stress-
468 strain processes during compaction of agricultural soils is typically based on geotechnical
469 frameworks using continuum mechanics (Nawaz et al., 2013). However, agricultural soils
470 present a three-dimensional organization of various components (mineral and organic
471 particles, plant residues, stones) (e.g. Horn, 1990). Although approaches from continuum
472 mechanics have been shown to produce fairly good estimations of stress transmission in
473 arable soil (Keller et al., 2014), especially tilled topsoils may rather resemble a granular
474 material (assembly of aggregates) than a continuum. Horn (1990) showed that stress
475 transmission is affected by soil aggregation, readily assessed in some VSE techniques. The

476 model described and applied by Richards et al. (1997) and Richards and Peth (2009) could
477 accommodate heterogeneity of soil properties and accounts for their evolution due to
478 mechanical and hydraulic stresses. Naveed et al. (2016) recently observed that, in topsoils,
479 stress propagation was heterogeneous and occurred through specific paths as long as the
480 macro-structures were not deformed (Fig. 4). Thus, mechanics of tilled soil layers may be
481 better described by granular matter physics than continuum physics. The mechanical
482 behaviour of granular materials largely depends on grain size distribution (Voivret et al.,
483 2007) and grain shapes (Azéma et al., 2009). By analogy, soil aggregate size distribution and
484 aggregate shapes are expected to influence soil mechanical behaviour. Fig. 5a illustrates the
485 elastic mode of stress propagation under a point load in an isotropic and continuous matter
486 as described by Boussinesq (1885), which might be enough to describe stress propagation
487 under certain soil conditions. Bulk measurements of soil physical parameters (such as
488 measurements on soil cores) average soil properties for the volume of the sample, and
489 measurements on replicated soil samples are typically averaged to represent properties at
490 the pedon scale. Using average soil properties for a collection of aggregates may lead to an
491 oversimplified description of soil properties within a profile that would result in an
492 unrealistic stress propagation (Fig. 5b). Introducing some information about the aggregate
493 properties (size distribution) and how the collection of aggregates is spatially organized
494 would improve description of stress propagation and therefore help better understanding
495 mechanical behaviour of structured soil (Fig. 5c). Therefore, information from VSE methods
496 associated with granular physics would help to better understand stress-strain relationships
497 of aggregated soil layers.

498

499

500 **5. Conclusions**

501 Since their inception VSE methods have grown to become important tools in research.
502 However, VSE methods still need better harmonization and reduction in subjectivity in
503 aggregate exposure and the influence of soil moisture content at sampling for more accurate
504 scoring. Handheld sensors and ICT devices may also help in this area. The spatial distribution
505 of structural features recorded by VSE methods is often integrated into a score or soil quality
506 index. We argue that VSE provides important information regarding spatial distribution of
507 soil structure, particularly aggregation and macro-porosity, which could be disaggregated
508 and used to better understand various soil processes, especially the process of soil
509 compaction. More detailed VSE methods, such as 'Profil Cultural', could be developed
510 (simplified, disaggregated and made more accessible) so that the spatial information is more
511 easily provided. VSE could be combined with sensing techniques at field or landscape scale
512 for better management of fields in the context of precision farming. Combining VSE methods
513 with visual crop evaluation may extend the agronomic relevance of VSE for identifying
514 limiting soil conditions. Further work should be done to integrate plant vigour, roots and soil
515 fauna into VSE methods to provide general indicators of soil quality and environmental
516 indicators of greenhouse gas emission, carbon storage and nutrient transport. For this
517 purpose more comparisons between scoring and field/laboratory measurements are
518 needed. However, we see a great potential in combining (rather than comparing) VSE with
519 measurements of soil structure, i.e. integrating VSE in soil structure research, as these
520 methods provide repeatable spatial information on large-scale aspects of soil structure that
521 are difficult to obtain with other methods.

522

523

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537

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840

841 **Figure captions**

842

843 **Fig. 1.** Schematic illustration of the suitable range of soil water contents for visual soil
844 evaluation, in analogy to the relationship between soil friability and soil water content.
845 Adapted from Munkholm (2011).

846

847 **Fig. 2.** Conceptual figure showing the use of remote and proximal sensing and interactive
848 tools for mobile devices together with visual soil evaluation. Remote sensing and ground-
849 based sensing can identify variations in soil properties and yield-limiting factors (e.g. soil
850 texture, nitrogen availability, soil moisture, soil compaction), while yield mapping reflects
851 the spatial variability of productivity. For example, combining areas of poor soil conditions
852 and restricted productivity reveals zones that require further evaluation by VSE in order to
853 deduce specified soil management recommendations for soil improvement. Ground-based
854 sensing photo from Naderi-Boldaji et al. (2014). Visual soil evaluation photo from Dr. Craig D.
855 Rogers

856

857 **Fig. 3.** Conceptual figure illustrating how the spatial information obtained from visual soil
858 evaluation could be used in soil process modelling. We outline two ways of incorporating
859 structural information in models, either via localization of areas of different soil properties
860 (left) or via a statistical approach (right). Detailed profile methods can be used for either
861 method, while spade methods are limited to incorporation of spatial information via
862 statistical means. Different levels of grey in the lower left picture represent different soil
863 quality scores or different values of a given soil property. Profil Cultural photo from Boizard
864 et al., (2017 this issue). VESS photo from Rachel M.L. Guimarães.

865

866 **Fig. 4.** The importance of including structure information for predicting stress propagation.

867 Stress transmission in an undisturbed soil column (0.2 m high and 0.2 m in diameter) derived

868 from X-ray computed tomography at applied stresses of 275 kPa (A) and 620 kPa (B). *Source:*

869 from Naveed et al. (2016).

870

871 **Fig. 5.** Spatial information on soil structure provided by VSE could potentially lead to a better

872 representation of stress propagation. (A) is a photoelastic view of a plate, (B) a regular

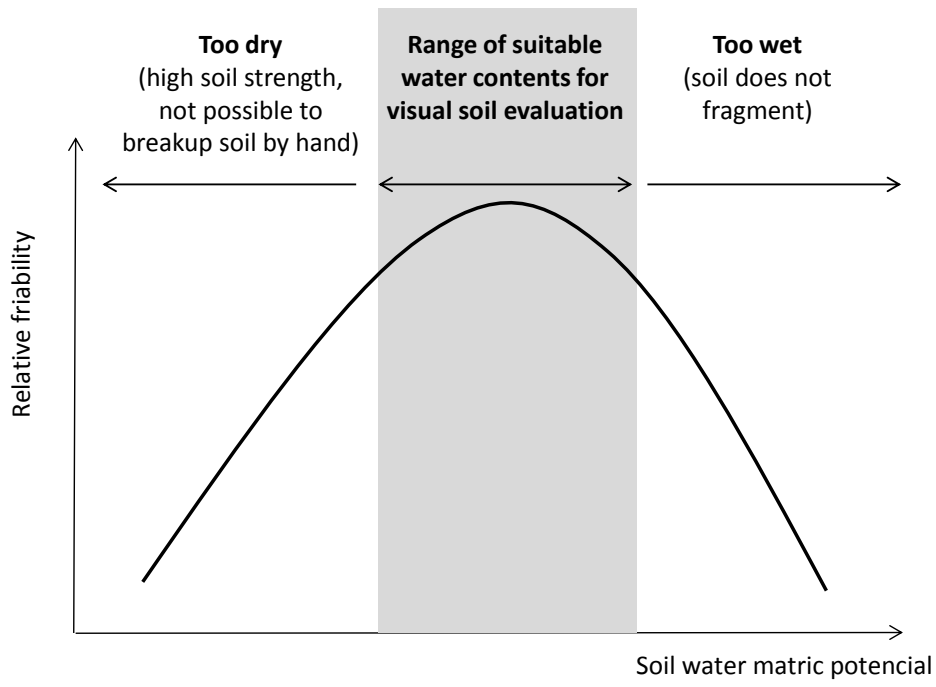
873 packing of mono-sized discs and a (C) is a random packing of discs with three different sizes.

874 All are subjected to a point load of 600 N. The plate and the discs were made of

875 polycarbonate, which has a Young's modulus of 2.0 GPa and a Poisson's ratio of 0.37.

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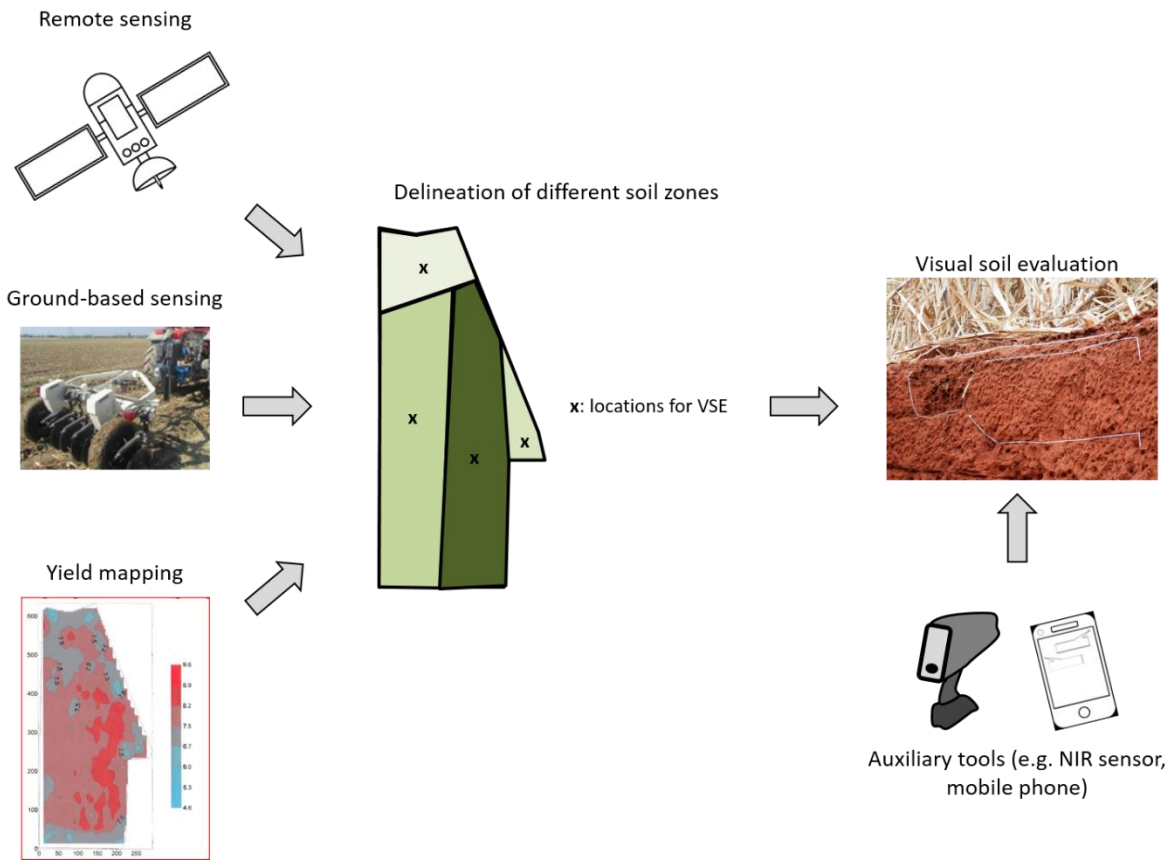


878

879 **Fig. 1.**

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883 **Fig. 2.**

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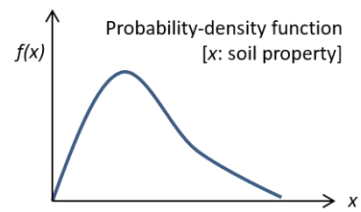
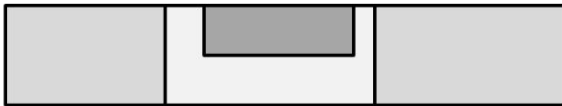
Detailed profile method, e.g. 'profil cultural'



Spade method, e.g. VESS



Discretization
(e.g. finite element method, distinct element method)



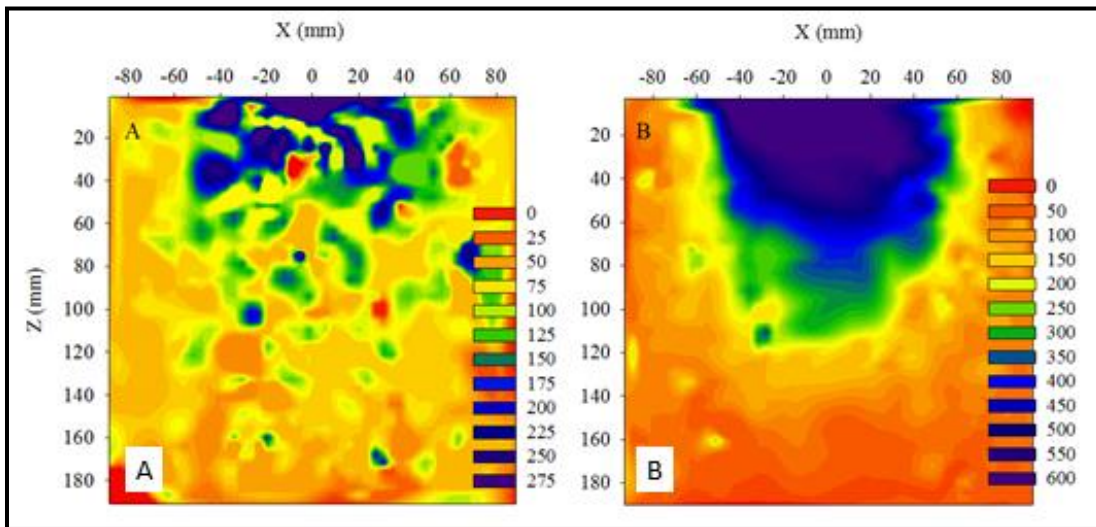
Numerical modelling (in 2-D, potentially 3-D), e.g. fluid flow, root growth, compaction, etc.

887

888 **Fig. 3.**

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890



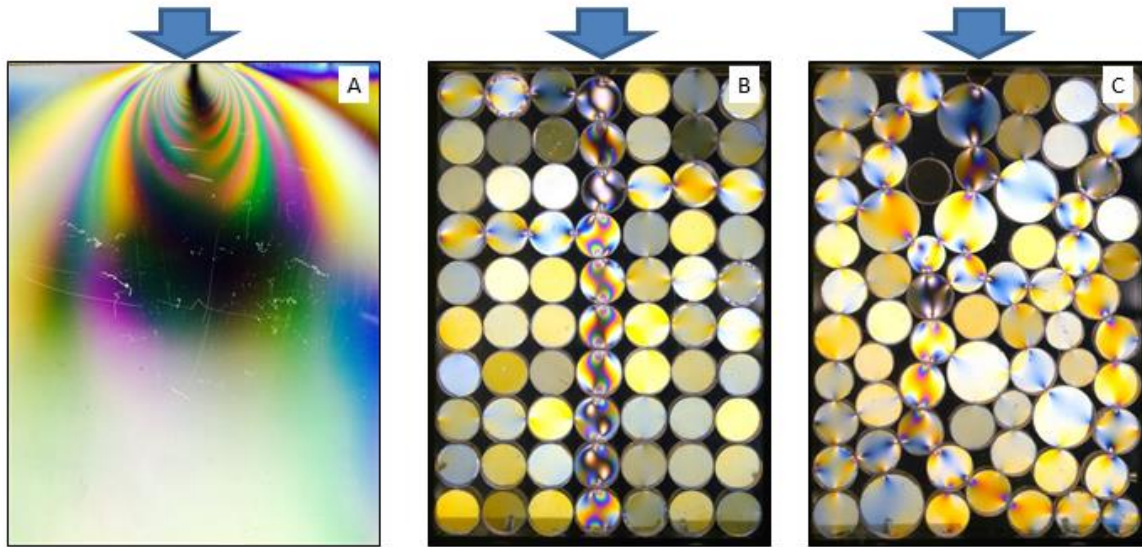
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892

893 **Fig. 4.**

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896

897 **Fig. 5.**

898