

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<sup>3</sup>), 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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539 **References**

540

541 Aldana-Jague, E., Heckrath, G., Macdonald, A., van Wesemael, B., Van Oost, K., 2016. UAS-  
542 based soil carbon mapping using VIS-NIR (480-1000 nm) multi-spectral imaging:  
543 potential and limitations. *Geoderma* 275, 55-66.

544 Askari, M.S., Cui, J., O'Rourke, S.M., Holden, N.M., 2015. Evaluation of soil structural quality  
545 using VIS-NIR spectra. *Soil Till. Res.*, 134, 1-10

546 Atterberg, A., 1911. Über die physikalische Bodenuntersuchung und über die Plastizität der  
547 Tone. *Internationale Mitteilungen für Bodenkunde* 1, 10-43.



548 ATV-DVWK, 2001. Gefügestabilität ackerbaulich genutzter Mineralböden Teil III: Methoden  
549 für eine nachhaltige Bodenbewirtschaftung, ATV-DVWK-M 901 (ISBN-10: 3935669704),  
550 27 p.

551 Azéma, E., Radjai F., Saussine, G., 2009. Quasistatic rheology, force transmission and fabric  
552 properties of a packing of irregular polyhedral particles. *Mech. Mater.* 41, 729-741.

553 Babel, U., Benecke, P., Hartge, K.H., Horn, R., Wiechmann, H., 1995. Determination of soil  
554 structure at various scales. In: Hartge, K.H., Stewart, B.A. (Eds.), *Soil Structure – its*  
555 *Development and Function. Advances in Soil Science*, CRC Press, ISBN: 1-56670-173-2,  
556 pp. 1-10.

557 Ball, B.C., Batey, T., Munkholm, L.J., 2007. Field assessment of soil structural quality - a  
558 development of the Peerlkamp test. *Soil Use Manage.* 23, 329-337.

559 Ball, B.C., Batey, T., Munkholm, L.J., Guimarães, R.M.L., Boizard, H., McKenzie, D.C., Peigné,  
560 J., Tormena, C.A., Hargreaves, P., 2015. The numeric visual evaluation of subsoil  
561 structure (SubVESS) under agricultural production. *Soil Till. Res.* 148, 85-96.

562 Ball, B.C., Guimarães, R.M.L, Cloy, J.M., Hargreaves, P., Shepherd., T.G., McKenzie, B.M.,  
563 2016. Visual soil evaluation: a summary of some applications and potential  
564 developments for agriculture. *Soil Till. Res.* (This issue).

565 Ball, B.C., Munkholm, L.J., 2015. The expanding discipline and role of visual soil evaluation.  
566 In: Ball, B.C., Munkholm, L.J. (Eds.), *Visual Soil Evaluation: Realizing Potential Crop*  
567 *Production with Minimum Environmental Impact*. CAB International, Wallingford, pp.  
568 142-154.

569 Ball, B.C., Munkholm, L.J., Batey, T. (Eds.), 2012. Applications of visual soil evaluation. *Soil*  
570 *Till. Res.* 127, 1-99.

571 Ball, B.C., O'Sullivan, M.F., Hunter, R., 1988. Gas diffusion, fluid flow and derived pore  
572 continuity indices in relation to vehicle traffic and tillage. *J. Soil Sci.* 39, 327-339.

573 Batey, T., Guimarães, R.M., Peigné, J., Boizard, H., Ball, B., Munkholm, L., 2015. Assessing  
574 Structural Quality for Crop Performance and for Agronomy (VESS, VSA, SOILpak, Profil  
575 Cultural, SubVESS). In: Ball, B.C., Munkholm, L.J. (Eds.), *Visual Soil Evaluation: Realizing  
576 Potential Crop Production with Minimum Environmental Impact*. CAB International,  
577 Wallingford, pp. 15-30.

578 Ben-Dor, E., Chabrillat, S., Demattê, J.A.M., Taylor, G.R., Hill, J., Whiting, M.L., Sommer, S.  
579 2009. Using Imaging Spectroscopy to study soil properties. *Remote Sens. Environ.* 113,  
580 38-555.

581 Ben-Dor, E., Inbar, Y., Chen, Y., 1997. The reflectance spectra of organic matter in the visible  
582 near-infrared and short wave infrared region (400-2500 nm) during a controlled  
583 decomposition process. *Remote Sens. Environ.* 61, 1-15.

584 Benjamin, J.G., Blaylock, A.D., Brown, H.J., Cruse, R.M., 1990. Ridge tillage effects on  
585 simulated water and heat transport. *Soil Till. Res.* 18, 167-180.

586 Besson, A., Cousin, I., Samouëlian, A., Boizard, H., Richard, G., 2004. Structural heterogeneity  
587 of the soil tilled layer as characterized by 2D electrical resistivity surveying. *Soil Till.  
588 Res.* 79, 239-249.

589 Boizard, H., Batey, T., McKenzie, D.C., Richard, G., Roger-Estrade, J., Ball, B.C., Bradley, I.,  
590 Cattle, S., Hasinger, G., Munkholm, L.J., Niewergelt, J., Peigné, J., Shepherd, G., 2007.  
591 Field meeting "Visual Soil Structure Assessment" held at the INRA Research Station,  
592 Estrées-Mons, France, 25-2 May 2005, 34 pp.

593 Boizard, H., Peigné, J., Sasal, M.C., Guimarães, M.F., Piron, D., Tomis, V., Vian, J.F., Cadoux,  
594 S., Ralisch R., Tavares Filho, J., Heddadj, D., Battista, J., Duparque, A., Franchini, J.C.,

595 Roger-Estrade, J., 2016. Developments in the “profil cultural” method for an improved  
596 assessment of soil structure under no-till. *Soil Till. Res.* (This issue).

597 Boizard, H., Yoon, S.W., Leonard, J., Lheureux, S., Cousin, I., Roger-Estrade, J., Richard, G.,  
598 2013. Using a morphological approach to evaluate the effect of traffic and weather  
599 conditions on the structure of a loamy soil in reduced tillage. *Soil Till. Res.* 127, 26-33.

600 Boussinesq, J., 1885. Application des Potentiels à l'étude de l'équilibre et du Mouvement des  
601 Solides Élastiques. Gauthier-Villars, Paris, pp. 30.

602 Bronick, C.J., Lal, R., 2005. Soil structure and management: a review. *Geoderma* 124, 3-22.

603 Chun, H.C., Gimenez, D., Yoon, S.W., 2008. Morphology, lacunarity and entropy of intra-  
604 aggregate pores: Aggregate size and soil management effects. *Geoderma* 146, 83-93.

605 Cloy, J.M., Ball, B.C., Shepherd, T.G., 2015. Evaluating land quality for carbon storage,  
606 greenhouse gas emissions and nutrient leaching. In: Ball, B.C., Munkholm, L. R. (Eds),  
607 Visual Soil Evaluation: Realising Potential Crop Production with Minimum  
608 Environmental Impact. CABI, Wallingford, UK, pp. 103-121.

609 Coutadeur, C., Coquet, Y., Roger-Estrade, J., 2002. Variation of hydraulic conductivity in a  
610 tilled soil. *Eur. J. Soil Sci.* 53, 1-10.

611 Dewitte, O., Jones, A., Elbelrhiti, H., Hor ion, S., Montanarella, L., 2012. Satellite remote  
612 sensing for soil mapping in Africa: An overview. *Prog. Phys. Geogr.* 36, 514 -538.

613 Dexter, A.R., 1991. Amelioration of soil by natural processes. *Soil Till. Res.* 20, 87-100.

614 Dexter, A.R., Bird, N.R.A., 2001. Methods for predicting the optimum and the range of soil  
615 water contents for tillage based on the water retention curve. *Soil Till. Res.* 57, 203-  
616 212.

617 Dörner, J., Horn, R., 2009. Direction-dependent behaviour of hydraulic and mechanical  
618 properties in structured soils under conventional and conservation tillage. *Soil Till. Res.*  
619 102, 225-232.

620 DVWK, 1995a. Bodenkundliche Untersuchungen im Felde zur Ermittlung von Kennwerten zur  
621 Standortcharakterisierung. Teil I: Ansprache der Böden. DVWK-Regel 129/1995 (ISBN  
622 3-89554-024-2).

623 DVWK, 1995b. Gefügestabilität ackerbaulich genutzter Mineralböden. Teil 1: Mechanische  
624 Belastbarkeit. DVWK Merkblatt 234, ATV-DVWK, Hennef.

625 DVWK, 1997. Gefügestabilität ackerbaulich genutzter Mineralböden. Teil 2: Auflastabhängige  
626 Veränderung von bodenphysikalischen Kennwerten. DVWK Merkblatt 235, ATV-DVWK,  
627 Hennef.

628 DVWK, 1999. Bodenkundliche Untersuchungen im Felde zur Ermittlung von Kennwerten zur  
629 Standortcharakterisierung. Teil II: Ableitungen zu Wasser- und Lufthaushalt von Böden.  
630 DVWK-Regel 136/1999 (ISBN 3-935067-55-0).

631 Etana, A., Larsbo, M., Keller, T., Arvidsson, J., Schjønning, P., Forkman, J., Jarvis, N., 2013.  
632 Persistent subsoil compaction and its effects on preferential flow patterns in a loamy  
633 till soil. *Geoderma* 192, 430-436.

634 Franco, A.L.C., Cherubin, M.R., Cerri, C.E.P., Guimarães, R.M.L., Cerri, C.C., 2016. Relating the  
635 visual soil structure status and the abundance of soil engineering invertebrates across  
636 land use change. *Soil Till. Res.* (This issue).

637 Gautronneau, Y., Manichon, H., 1987. Guide méthodique du profil cultural. GEARA et CEREF,  
638 1987. Mimeografado.

639 Görbing, J. 1947. Die Grundlagen der Gare im praktischen Ackerbau (Band I und II), Landbuch  
640 Verlag GMBH, Hannover.

641 Govaerts, B., Sayre, K., Deckers, J., 2006. A minimum data set for soil quality assessment  
642 of wheat and maize cropping in the highlands of Mexico. *Soil Till. Res.* 87, 163–174.

643 Guimarães, R.M.L., Ball, B.C., Tormena, C.A., 2011. Improvements in the visual evaluation of  
644 soil structure. *Soil Use Manage.* 27, 395-403.

645 Guimarães, R.M.L., Ball, B.C., Tormena, C.A., Giarola, N.F.B., da Silva, A.P., 2013. Relating  
646 visual evaluation of soil structure to other physical properties in soils of contrasting  
647 texture and management. *Soil Till. Res.* 127, 92–99.

648 Guimarães, R.M.L., Fenton, O., Murphy, B., Tormena, C.A., 2015. Soil structure under  
649 adverse weather/climate conditions. In: Ball, B.C., Munkholm, L.J. (Eds.), *Visual Soil*  
650 *Evaluation: Realizing Potential Crop Production with Minimum Environmental Impact.*  
651 CAB International, Wallingford, pp. 15-30.

652 Hallett, P.D., Karim, K.H., Bengough, A.G., Otten, W., 2013. Biophysics of the vadose zone:  
653 from reality to model systems and back again. *Vadose Zone J.* 12,  
654 doi:10.2136/vzj2013.05.0090.

655 Han, E., Kautz, T., Perkons, U., Uteau, D., Peth, S., Huang, N., Horn, R., Köpke, U., 2015. Root  
656 growth dynamics inside and outside of soil biopores as affected by crop sequence  
657 determined with the profile wall method. *Biol. Fertil. Soils* 51, 847-856.

658 Hartmann, A., Gräsle, W., Horn, R., 1998. Cation exchange processes in structured soils at  
659 various hydraulic properties. *Soil Till. Res.* 47,67-72.

660 Horn R., Taubner H., Wuttke M., Baumgartl, T. 1994. Soil physical properties and processes  
661 related to soil structure. *Soil Till. Res.* 30, 187-216.

662 Horn, R. 2003. Stress–strain effects in structured unsaturated soils on coupled mechanical  
663 and hydraulic processes. *Geoderma* 116, 77-88.

664 Horn, R., 1990. Aggregate characterization as compared to soil bulk properties. *Soil Till. Res.*  
665 17, 265-289.

666 Horn R., Peng X., Fleige H. & Dörner J. 2014. Pore rigidity in structured soils—only a  
667 theoretical boundary condition for hydraulic properties? *Soil Sci. Plant Nutr.* 60, 3-14.

668 Kautz, T., Amelung, W., Ewert, F., Gaiser, T., Horn, R., Jahn, R., Javaux, M., Kemna, A.,  
669 Kuzyakov, Y., Munch, J., Pätzold, S., Peth, S., Scherer, H., Schloter, M., Schneider, H.,  
670 Vanderborght, J., Vetterlein, D., Walter, A., Wiesenberg, G., Köpke, U., 2013. Nutrient  
671 acquisition from arable subsoils in temperate climates: a review. *Soil Biol. Biochem.* 57,  
672 1003-1022.

673 Kay, B.D., Angers, D.A., 2001. Soil structure. In: Sumner, M. E. (Ed.), *Handbook of Soil*  
674 *Science*. CRC Press, Boca Raton. p. 229-276.

675 Kay, B.V., 1990. Rates of change of soil structure under different cropping systems. *Adv. Soil*  
676 *Sci.* 12, 1-52.

677 Kay, B.V., Munkholm, L.J., 2011. Managing the Interactions between Soil Biota and their  
678 Physical Habitat in Agroecosystems. In: Ritz, K., Young, I. (Eds.), *The Architecture and*  
679 *Biology of Soils: Life in Inner Space*, CAB International, pp. 170-195.

680 Keller, T., Lamandé, M., Arvidsson, J., Berli, M., Ruiz, S., Schjønning, P., Selvadurai A.P.S.,  
681 2014. Transmission of vertical soil stress under agricultural tyres: comparing  
682 measurements with simulations. *Soil Till. Res.* 140, 106-117.

683 Kramer, L.F.M. , Tormena, C.A., Guimarães, R.M.L., Muller, M.M.L., Michalovicz, L., Moreira,  
684 W.H., 2015. Avaliação qualitativa e quantitativa da qualidade estrutural do solo em  
685 mata nativa e sob cultivo. In: IV Reunião Paranaense de Ciência do Solo, 2015, Cascavel  
686 (Conference abstract).

687 Lynch, J.M., 1984. Interactions between biological processes, cultivation and soil structure.  
688 Plant Soil 76, 307-318.

689 McKenzie, D., 1998. SOILpak for cotton growers, 3<sup>rd</sup> Edition. Orange, New South Wales,  
690 Australia.

691 McKenzie, D.C., 2001. Rapid assessment of soil compaction damage, I. The SOILpak score, a  
692 semi-quantitative measure of soil structural form. Austr. J. Soil Res. 39, 117-125.

693 Moncada, M.P., Penning, L.H., Timm, L.C., Gabriels, D., Cornelis, W.M., 2014. Visual  
694 examinations and soil physical and hydraulic properties for assessing soil structural  
695 quality of soils with contrasting textures and land uses. Soil Till. Res. 140, 20-28.

696 Mueller, L., Kay, B.D., Hu, C., Li, Y., Schindler, U., Behrendt, A., Shepherd, T.G., Ball, B.C.,  
697 2009. Visual assessment of soil structure: evaluation of methodologies on sites in  
698 Canada, China and Germany. Part I: Comparing visual methods and linking them with  
699 soil physical data and grain yield of cereals. Soil Till. Res. 103, 178–187.

700 Mueller, L., Saporov, A., Lischeid, G., 2014. Novel Management and Assessment Tools for  
701 Monitoring and Management of Land and Water Resources in Agricultural Landscapes  
702 of Central Asia. Springer International, Switzerland, pp.115-142.

703 Mueller, L., Shepherd, G., Schindler, U., Ball, B.C., Munkholm, L.J., Hennings, V.,  
704 Smolentseva, E., Rukhovic, O., Lukin, S., Hu, C., 2013. Evaluation of soil structure in the  
705 framework of an overall soil quality rating. Soil Till. Res. 127, 74-84.

706 Mulder, V. L., deBruin, S., Schaepman, M. E., Mayr, T.R., 2011. The use of remote sensing in  
707 soil and terrain mapping - A review. Geoderma 162, 1 -19.

708 Munkholm, L.J., 2000. The spade analysis - a modification of the qualitative spade diagnosis  
709 for scientific use, Tjele, Denmark, pp. 1-40.

710 Munkholm, L.J., 2011. Soil friability: A review of the concept, assessment and effects of soil  
711 properties and management. *Geoderma* 167-168, 236-246.

712 Munkholm, L.J., Heck, R.J., Deen, B., 2013. Long-term rotation and tillage effects on soil  
713 structure and crop yield. *Soil Till. Res.* 127, 85–91

714 Munkholm, L.J., Holden, N.M., 2015. Visual evaluation of grassland and arable management  
715 impacts on soil quality. In: Ball, B.C., Munkholm, L.J. (Eds.), *Visual Soil Evaluation:  
716 Realizing Potential Crop Production with Minimum Environmental Impact*. CAB  
717 International, Wallingford, pp. 49-65.

718 Murphy, B.W., Crawford, M.H., Duncan, D.A., McKenzie, D.C., Koen, T.B., 2013. The use of  
719 visual soil assessment schemes to evaluate surface structure in a soil monitoring  
720 program. *Soil Till. Res.* 127, 3-12.

721 Naderi-Boldaji, M., Sharifi, A., Hemmat, A., Alimardani, R., Keller, T., 2014. Feasibility study  
722 on the potential of electrical conductivity sensor Veris® 3100 for field mapping of  
723 topsoil strength. *Biosyst. Eng.* 126, 1-11.

724 Naveed, M., Schjønning, P., Keller, T., de Jonge, L.W., Moldrup, P., Lamandé, M., 2016.  
725 Quantifying vertical stress transmission and compaction-induced soil structure using  
726 sensor mat and X-ray computed tomography. *Soil Till. Res.* 158, 110-122.

727 Nawaz, M.F., Bourrié, G., Trolard, F., 2013. Soil compaction impact and modelling. A review.  
728 *Agron. Sust. Dev.* 33, 291–309.

729 Ndiaye, B., Molénat, J., Hallaire, V., Gascuel, C., Hamon, Y., 2007. Effects of agricultural  
730 practices on hydraulic properties and water movement in soils in Brittany (France). *Soil  
731 Till. Res.* 93, 251-263.

732 Nievergelt, J., Petrasek, M., Weisskopf, P., 2002. *Bodengefüge: Ansprechen und Beurteilen  
733 mit visuellen Mitteln*. Schriftenreihe der FAL 41 (ISBN 3-905608-62-6), 94 p.



734 Pagenkemper, S.K., Athmann, M., Uteau, D., Kautz, T., Peth, S., Horn, R. 2015. The effect of  
735 earthworm activity on soil bioporosity – Investigated with X-ray computed tomography  
736 and endoscopy. *Soil Till. Res.* 146 A, 79-88.

737 Paradelo, M., Hermansen C., Knadel, M., Moldrup, P., Greve, M.H., de Jonge, L.W., 2016.  
738 Field-scale predictions of soil contaminant sorption using visible-near infrared  
739 spectroscopy. *J. Near Infrared Spectrosc.* 24, 281-291.

740 Peerlkamp, P.K., 1959. A visual method of soil structure evaluation. *Meded. v.d.*  
741 *Landbouwhogeschool en Opzoekingsstations van de Staat te Gent.* XXIV No. 24, pp.  
742 216-221.

743 Peigné, J., Vian, J.F., Cannavacciuolo, M., Lefevre, V., Gautronneau, Y., Boizard, H., 2013.  
744 Assessment of soil structure in the transition layer between topsoil and subsoil using  
745 the profil cultural method. *Soil Till. Res.* 127, 13-25.

746 Peng, Y., Bou Kheir, R., Adhikari, K., Malinowski, R., Greve, M.B., Knadel, Greve, M.H., 2016.  
747 Digital mapping of toxic metals in Qatari soils using remote sensing and ancillary data.  
748 *Remote Sensing* 8, 1003.

749 Peng, Y., Knadel, M., Gislum, R., Schelde, K., Thomsen, A., Greve, M.H., 2014. Quantification  
750 of SOC and clay content using visible near-infrared reflectance-mid-infrared  
751 reflectance spectroscopy with Jack-Knifing partial squares regression. *Soil Sci.* 179,  
752 325-332.

753 Perfect, E., Kay, B.D., 1994. Statistical characterization of dry aggregate strength using  
754 rupture energy. *Soil Sci. Soc. Am. J.* 58, 1804-1809.

755 Petersen, H., Rabbel, W., Horn, R., Fleige, H., 2005. Applicability of geophysical prospecting  
756 methods for mapping of soil compaction and variability of soil texture on farm land. *J.*  
757 *Plant Nutr. Soil Sci.* 168, 1-12.

758 Peth, S., 2011. Noninvasive quantification of 3D pore space structures in soils. In: Glinski, J.,  
759 Horabik, J., Lipiec, J. (Eds.), *Encyclopedia of Agrophysics*. Springer, Berlin, pp. 516-519.

760 Peth, S., Nellesen, J., Fischer, G., Tillmann, W., Horn R., 2013. Dynamics of Soil Macropore  
761 Networks in Response to Hydraulic and Mechanical Stresses Investigated by X-ray  
762 Microtomography. In: Logsdon, S., Horn, R., Berli, M. (Eds.), *Advances in Agricultural  
763 Systems Modeling 3. Quantifying and Modeling Soil Structure Dynamics*. pp. 121-153.

764 Piron, D., Pérès, G., Hallaire, V., Cluzeau, D., 2012. Morphological description of soil structure  
765 patterns produced by earthworm bioturbation at the profile scale. *Eur. J. Soil Biol.* 50,  
766 83–90.

767 Preuschen, G. 1983. Die Spatendiagnose und ihre Auswertung. In: *Root ecology and its  
768 practical application*. eds W. Böhm, L. Kutschera & E. Lichtenegger), International  
769 Symposium Gumpenstein, 1982, Bundesanstalt Gumpenstein, A-8952 Irdning, pp. 355-  
770 368.

771 Regan, J.T., 2012. The erodibility and surface runoff potential of a selection of Irish tillage  
772 soils. PhD Thesis, National University of Ireland, Galway, Ireland.

773 Richards, B.G., Baumgartl, T., Horn, R., Gräsele, W. 1997. Modelling the effects of repeated  
774 wheel loads on soil profiles. *Int. Agrophys.* 11, 177-187.

775 Richards, B.G., Peth, S. 2009. Modelling soil physical behaviour with particular reference to  
776 soil science. *Soil Till. Res.* 102, 216-224.

777 Roger-Estrade, J., Richard, G., Boizard, H., Boiffin, J., Caneill, J., Manichon, H., 2000.  
778 Modelling changes in the tilled layer structure over time as a function of cropping  
779 systems. *Eur. J. Soil Sci.* 51, 455-474.

780 Roger-Estrade, J., Richard, G., Dexter, A.R., Boizard, H., De Tourdonnet, S., Bertrand, M.,  
781 Caneill, J., 2009. Integration of soil structure variation with time and space into models  
782 for crop management. A review. *Agron. Sustain. Dev.* 29, 135-142.

783 Samouelian, A., Cousin, I., Tabbagh, A., Bruand, A., Richard, G., 2005. Electrical resistivity  
784 survey in soil science: a review. *Soil Till. Res.* 83, 173 -193.

785 Schjønning, P., Lamandé, M., Munkholm, L.J., Lyngvig, H.S., 2016. Soil precompression stress,  
786 penetration resistance and crop yields in relation to differently-trafficked, temperate-  
787 region sandy loam soils. *Soil Till. Res.* 16, 298-308.

788 Schjønning, P., van den Akker, J.J.H., Keller, T., Greve, M.H., Lamandé, M., Simojoki, A.,  
789 Stettler, M., Arvidsson, J., Breuning-Madsen, H., 2015. Driver-Pressure-State-Impact-  
790 Response (DPSIR) analysis and risk assessment for soil compaction – a European  
791 perspective. *Adv. Agron.* 133, 183-237.

792 Shepherd, T.G., 2000. Visual soil assessment. *Field Guide for Cropping and Pastoral Grazing*  
793 *on Flat to Rolling Country*, 1st edition, 1. horizons.mw & Landcare Research,  
794 Palmerston North, New Zealand.

795 Shepherd, T.G., 2003. Assessing soil quality using visual soil assessment. In: Currie, L.D.,  
796 Hanly, J.A. (Eds.), *Tools for Nutrients and Pollutant Management: Applications to*  
797 *Agriculture and Environmental Quality*. Occasional Report No. 17. Fertilizer and Lime  
798 Research Centre, Massey University, Palmerston North, pp. 153–166.

799 Shepherd, T.G., 2009. Visual soil assessment. Volume 1. *Field guide for pastoral grazing and*  
800 *cropping on flat to rolling country*. Second edition, Horizons Research Council,  
801 Palmerston North, New Zealand, pp. 120.

802 Soane, B.D., van Ouwerkerk, C. (Eds.), 1994. *Soil compaction in crop production*.  
803 *Developments in Agricultural Engineering* 11, 662 + xvii p.

804 Soriano-Disla, J.M., Janik, L.J., Viscarra Rossel, R.A., Macdonald, L.M., McLaughlin, M.J., 2014.  
805 The performance of visible, near-, and mid-infrared reflectance spectroscopy for  
806 prediction of soil physical, chemical, and biological properties. *Appl. Spectrosc. Rev.* 49,  
807 139-186.

808 Stenberg, B., Viscarra Rossel, R.A., Mouazen, A.M., Wetterlind, J., 2010. Visible and near  
809 infrared spectroscopy in soil science. *Adv. Agron.* 107, 163-215.

810 Taina, I. A., Heck, R.J., Elliot, T.R., 2008. Application of X-ray computed tomography to soil  
811 science: A literature review. *Can. J. Soil Sci.* 88, 1-20.

812 Uteau, D., Pagenkemper, S.K., Peth, S., Horn, R., 2013. Root and time dependent soil  
813 structure formation and its influence on gas transport in the subsoil. *Soil Till. Res.* 132,  
814 69-76.

815 Utomo, W.H., Dexter, A.R., 1981. Soil Friability. *J. Soil Sci.* 32, 203-213.

816 Vereecken, H., Schnepf, A., Hopmans, J. W., Javaux, M., Or, D., Roose, T., Vanderborght, J.,  
817 Young, M. H., Amelung, W., Aitkenhead, M., Allison, S. D., Assouline, S., Baveye, P.,  
818 Berli, M., Brüggemann, N., Finke, P., Flury, M., Gaiser, T., Govers, G., Ghezzehei, T.,  
819 Hallett, P., Hendricks Franssen, H. J., Heppell, J., Horn, R., Huisman, J. A., Jacques, D.,  
820 Jonard, F., Kollet, S., Lafolie, F., Lamorski, K., Leitner, D., McBratney, A., Minasny, B.,  
821 Montzka, C., Nowak, W., Pachepsky, Y., Padarian, J., Romano, N., Roth, K., Rothfuss, Y.,  
822 Rowe, E. C., Schwen, A., Šimůnek, J., Tiktak, A., Van Dam, J., van der Zee, S. E. A. T. M.,  
823 Vogel, H. J., Vrugt, J. A., Wöhling, T. & Young, I. M. 2016. Modeling Soil Processes:  
824 Review, Key Challenges, and New Perspectives. *Vadose Zone J.*, 15.  
825 doi:10.2136/vzj2015.09.0131

826 Viscarra Rossel, R.A., Walvoort, D.J.J., McBratney, A.B., Janik, L.J., Skjemstad, J.O., 2006.  
827 Visible, near infrared, mid infrared or combined diffuse reflectance spectroscopy for  
828 simultaneous assessment of various soil properties. *Geoderma*, 131, 59-75.

829 Voivret, C., Radjai, F., Delenne, J.-Y., El Yousoufi, M.S., 2007. Space-filling properties of  
830 polydisperse granular media. *Phys. Rev. E* 76, 021301.

831 Wildenschild, D., Sheppard, A.P., 2013. X-ray imaging and analysis techniques for quantifying  
832 pore-scale structure and processes in subsurface porous medium systems. *Adv. Water*  
833 *Resour.* 51, 217-246.

834 Wulf, H., Mulder, T., Schaepman, M. E., Keller, A., Jörg P., 2015. Remote Sensing of Soil:  
835 project report from the Federal Office of the Environment (FOEN/BAFU). University of  
836 Zurich. Available at:  
837 [http://www.geo.uzh.ch/fileadmin/files/content/abteilungen/rsl1/Remote\\_sensing\\_of\\_](http://www.geo.uzh.ch/fileadmin/files/content/abteilungen/rsl1/Remote_sensing_of_soils_BAFU_report_dpi300_v.pdf)  
838 [soils\\_BAFU\\_report\\_dpi300\\_v.pdf](http://www.geo.uzh.ch/fileadmin/files/content/abteilungen/rsl1/Remote_sensing_of_soils_BAFU_report_dpi300_v.pdf) (assessed 28.04.2016).

839 Zribi, M., Baghdadi, N., Nolin, M., 2011. Remote Sensing of Soil. *Appl Environ Soil Sci.* 2p.  
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

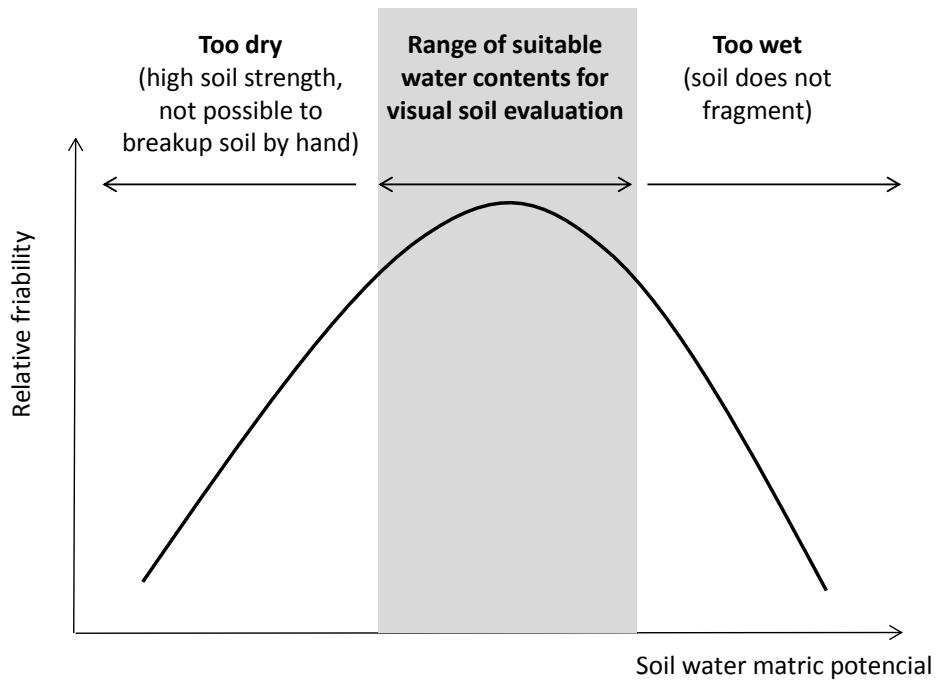
873 packing of mono-sized discs and a (C) is a random packing of discs with three different sizes.

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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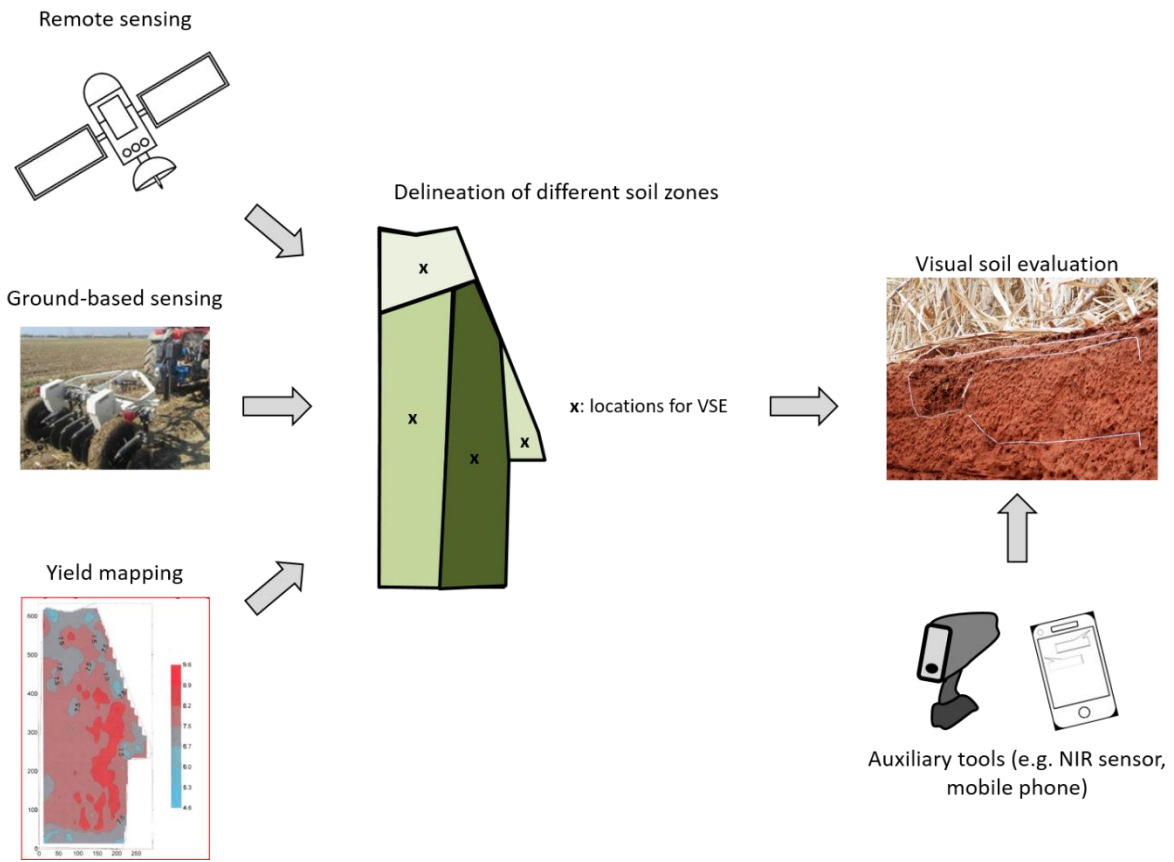
878

879 **Fig. 1.**

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883 **Fig. 2.**

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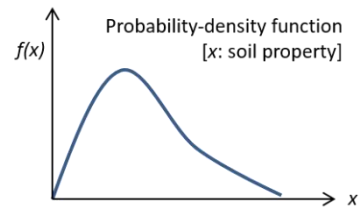
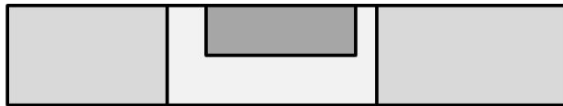
Detailed profile method, e.g. 'profil cultural'



Spade method, e.g. VESS



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



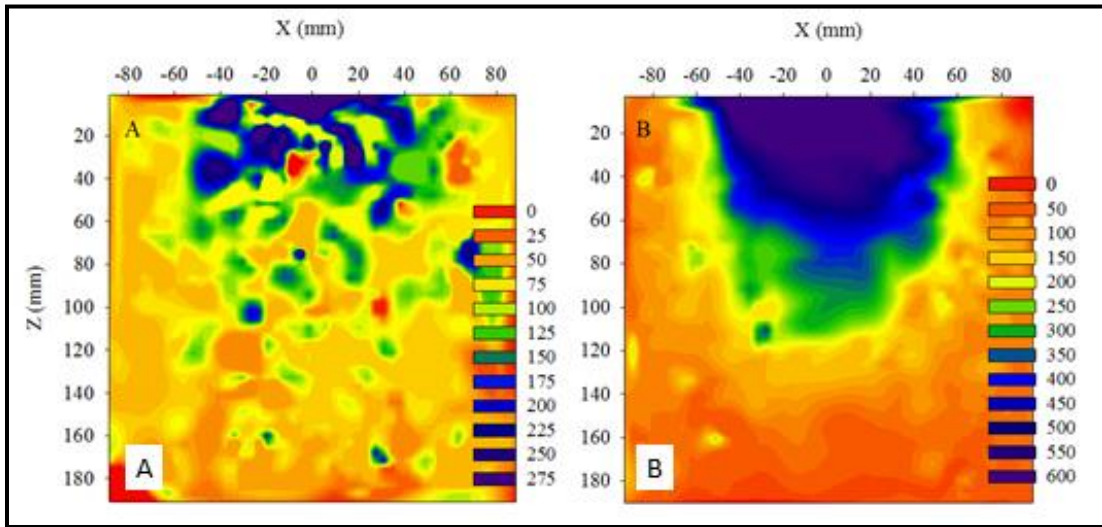
Numerical modelling (in 2-D, potentially 3-D), e.g. fluid flow, root growth, compaction, etc.

887

888 **Fig. 3.**

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890



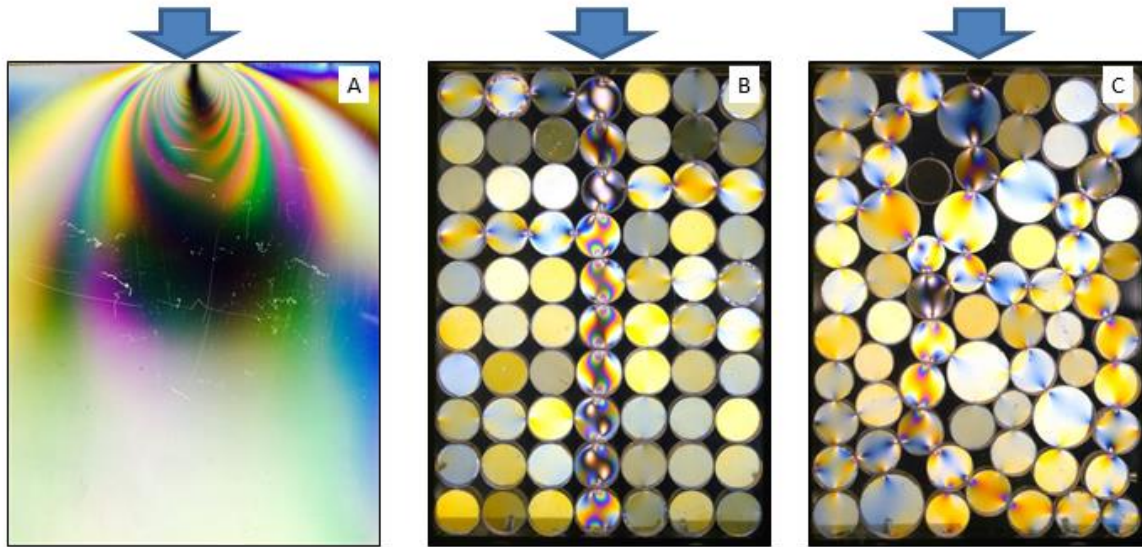
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893 **Fig. 4.**

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896

897 **Fig. 5.**

898