



Aggregate stability of a crusted soil: differences between crust and sub-crust material, and consequences for interrill erodibility assessment. An example from the Loess Plateau of China

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1 **Aggregate stability of a crusted soil: differences between crust and**
2 **sub-crust material, and consequences for interrill erodibility**
3 **assessment. An example from the Loess Plateau of China**

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22 | *Running title: Aggregate stability of a crusted soil*

23 **Summary**

24

25 Soil interrill erodibility is a key component of soil erosion models. However,
26 when using aggregate stability to assess soil erodibility, samples are usually collected
27 from the plough layer, while soil erosion occurs at the soil surface. Hence, the
28 potential changes in erodibility caused by crusting are ignored. Moreover, soil interrill
29 erodibility is still difficult to predict accurately. This lack of prediction means that
30 current erosion models use a constant erodibility value for a given soil, and thus do
31 not consider potential heterogeneity of erodibility. This study was conducted (i) to
32 assess the heterogeneity of aggregate stability for a crusted soil and (ii) to relate this
33 heterogeneity to the aggregate stability of the underlying material (sub-crust) and to
34 standard soil properties. A field study was conducted in a small area of the Loess
35 Plateau in China in which the crust and the sub-crust were sampled. Standard soil
36 properties (organic matter content, sand content, silt content, clay content, cation-
37 exchange capacity, pH in water, and water content at the time of sampling) were
38 measured as potential explanatory factors of aggregate stability. The results showed a
39 large heterogeneity in aggregate stability among the sites, even though the sites had
40 the same soil type. The mean weight diameter (MWD) of the crust varied between
41 0.33 and 2.04 mm while the MWD of the sub-crust varied between 0.23 and 1.42 mm.
42 Soil texture and pH were very homogeneous among the sampling sites, whereas water
43 content, organic matter content and CEC varied more. Even though some correlations
44 existed (for example $r = 0.57$ between the MWD for slow wetting test and organic
45 matter content), none of the standard soil properties was able to predict aggregate
46 stability accurately. The aggregate stability of the crust was significantly greater than
47 that of the sub-crust. The large differences in aggregate stability imply large

48 differences in soil interrill erodibility. Because a single soil type was investigated, this
49 finding proves that erodibility can vary greatly in space even for a given soil type.
50 Soil interrill erodibility should be estimated from the exact material actually exposed
51 to erosive forces, the soil surface material. Using the sub-crust would have led to
52 greatly over-estimated erodibility and thus to a marked bias in erosion model
53 predictions.

54

55 **Résumé**

56

57 L'érodabilité inter-rigole est un paramètre clef des modèles d'érosion du sol.
58 Cependant, lorsque des tests de stabilité structurale sont utilisés pour évaluer
59 l'érodabilité, les mesures sont habituellement réalisées sur des échantillons prélevés
60 dans l'horizon labouré alors que l'érosion a lieu à la surface du sol. Ainsi, les
61 changements potentiels d'érodabilité causés par la formation de croûte sont ignorés.
62 De plus, l'érodabilité inter-rigole reste encore difficile à prédire avec précision. Ces
63 difficultés conduisent les modèles d'érosion à utiliser une érodabilité constante pour
64 un type de sol donné, et donc à ne pas considérer l'hétérogénéité potentielle de
65 l'érodabilité. Cette étude a été conduite pour (i) évaluer l'hétérogénéité de la stabilité
66 structurale pour un sol encroûté et (ii) relier cette hétérogénéité à la stabilité
67 structurale du matériau sous-jacent (sous-croûte) et aux propriétés standards du sol.
68 Une étude de terrain a été réalisée sur un secteur de surface limitée du Plateau de
69 Lœss (Chine). Des échantillons provenant de la croûte et de la sous-croûte ont été
70 collectés. Les propriétés standards (teneur en carbone organique, teneurs en sable,
71 limon et argile, CEC, pH, et teneur en eau au prélèvement), ont été mesurées en tant
72 que facteurs explicatifs potentiels de la stabilité structurale. Les résultats ont montré

une grande hétérogénéité de la stabilité structurale entre les différents sites alors que ces derniers présentaient le même type de sol. Le MWD de la croûte variait entre 0,33 et 2,04 mm tandis que le MWD de la sous-croûte variait entre 0,23 et 1,42 mm. La texture du sol et le pH étaient très homogènes entre les sites étudiés, tandis que la teneur en eau, la teneur en matière organique et la CEC variaient plus fortement. Bien que certaines corrélations aient été identifiées (par exemple $r=0.57$ entre le MWD du test à l'humectation lente et la teneur en carbone organique), aucune de ces propriétés n'a permis de prédire précisément la stabilité structurale. La stabilité structurale de la croûte était significativement supérieure à celle de la sous-croûte. Les grandes différences de stabilité structurale mesurées impliquent des érodabilités très contrastées. Comme un seul type de sol a été étudié, ce résultat prouve que l'érodabilité peut être très variable spatialement pour un type de sol donné. L'érodabilité inter-rigole du sol devrait être mesurée sur le matériau exact qui subit l'érosion, c'est-à-dire le matériau de surface. L'utilisation du matériau sous-jacent aurait engendré une forte surestimation de l'érodabilité et donc un biais important dans les prédictions d'un modèle d'érosion.

89

90 **Introduction**

91

In the context of soil erosion by water, interrill erodibility corresponds to the sensitivity of the surface material to detachment and transport by raindrop impacts and by sheet flow. Accordingly, interrill erodibility is a key component in erosion models (Gumiere et al., 2009; Wang et al., 2013). Currently, there is no unified definition of erodibility and those proposed are qualitative: there is thus a need for quantitative methods (Wang et al., 2013).

98 Interrill erodibility can be estimated from standard soil properties such as soil
99 texture or carbon content and using statistical functions (Alberts *et al.*, 1995; Renard
100 *et al.*, 1997). Although such estimations are easy to carry out once the statistical
101 function has been established, they postulate that samples with similar standard soil
102 properties have similar erodibilities. Moreover, the ranges of validity of the statistical
103 functions (the textures and carbon contents for which these functions can be used) are
104 often limited and poorly known. Finally, erosion models typically use a single
105 erodibility value for a given soil, hence postulating a small spatial heterogeneity of the
106 erodibility (Renard *et al.*, 1997; Jetten *et al.*, 2003).

107 Another approach to characterize soil interrill erodibility is to measure aggregate
108 stability in the laboratory (Le Bissonnais, 1996; Barthès & Roose, 2002). Aggregate
109 stability corresponds to the ability of an aggregate not to break up into smaller
110 fragments. A large aggregate stability of the top-soil induces a strong resistance of the
111 surface aggregates against breakdown, and thus induces less particle detachment and
112 transport by raindrop impacts and by sheet flow (Le Bissonnais, 1996; Bajracharya &
113 Lal, 1998). Hence, even though a few models use this soil property currently (LISEM,
114 De Roo *et al.*, 1996), aggregate stability is considered as a proxy of soil interrill
115 erodibility, with a poor aggregate stability corresponding to a large potential
116 erodibility and *vice versa* (Barthès & Roose, 2002; Gumiere *et al.*, 2009).

117 The properties of a given soil may change over a period of a few weeks or months
118 because of crust development (Poesen, 1981; Bryan *et al.*, 1989). In an agricultural
119 context, the soil surface evolves from a seedbed (loose surface layer composed of
120 clods and macro-aggregates) to successive stages of crusting that correspond to
121 different types of crust (Bresson & Boiffin, 1990). The structural crust corresponds to
122 a thin surface layer where the micro-aggregates resulting from the breakdown of

123 surface clods are sealed together, and the sedimentary crust corresponds to a compact
124 surface layer where the surface pores and micro-depressions are filled by small
125 fragments resulting from the erosion and sedimentation processes. The presence of a
126 crust can induce marked differences between the properties of the plough-layer and
127 the soil surface. Numerous studies show that the infiltration capacities can be very
128 different between the crust and the underlying material (e.g. Morin & Van Winkel,
129 1996). However, only a few studies have addressed the effect of a crust on erodibility
130 (McIntyre, 1958; Poesen, 1981; Darboux & Le Bissonnais, 2007). Most of the studies
131 using aggregate stability to assess erodibility are made with samples collected within
132 the plough layer (Bullock et al., 1988; Bajracharya & Lal, 1998; Barthès & Roose,
133 2002; Legout et al., 2005), notwithstanding that interrill erosion occurs at the soil
134 surface and thus depends directly on the erodibility of the crust and not on the
135 erodibility of the plough layer material. For a clay loam soil, Darboux & Le
136 Bissonnais (2007) did not find significant differences in aggregate stability between a
137 structural crust and the seedbed material (without crust); but there were notable
138 differences in aggregate stability between a sedimentary crust and the seedbed
139 material (without crust). This finding led these researchers to conclude that
140 estimations of erodibility for material collected from the plough layer may be invalid
141 for the crust, resulting in a potential bias in the estimated erodibility. However, the
142 results of this laboratory experiment had limited application, and did not attempt to
143 assess the factors responsible for differences in aggregate stability, even though
144 numerous factors have previously been identified (Amézqueta, 1999). In the present
145 work, a field study was conducted in a small area (7.5 km radius) of the Loess Plateau
146 of China. The crust and the underlying materials were sampled in areas designated for
147 different land uses. Aggregate stability was measured as a proxy of soil erodibility,

148 along with standard soil properties known to be related to aggregate stability. We
149 wished to test the hypotheses that crusts developed from a given soil type show
150 different aggregate stabilities depending on the aggregate stability of the underlying
151 material and on the standard soil properties. The research objectives were (i) to assess
152 the heterogeneity of aggregate stability of crusted Luvisols within an area presenting a
153 small spatial extent and (ii) to relate this heterogeneity to the aggregate stability of the
154 underlying material and to the standard soil properties. The consequences for
155 erodibility assessment and erosion modeling are discussed.

156

157 **Materials and methods**

158

159 *Sampling sites*

160 The Chinese Loess Plateau (northwest China) is recognized as the largest deposit of
161 loess in the world. Silt particles resulting from wind erosion at the Tibetan Plateau and
162 the Gobi desert have accumulated to an average thickness of 150 m. The silt loam
163 soils that developed on this substrate are very homogeneous in both texture and
164 chemical properties and are recognized to be very sensitive to erosion (Zheng, 2005).
165 The experimental area was located in the Ziwuling area, in the hilly-gully region of
166 the Loess Plateau (Figure 1). Altitude of the sampling sites varied between 1100 and
167 1300 m with an average annual temperature of 9° C and average annual precipitation
168 of 577 mm. Soil samples were collected on seven field sites, selected in order to
169 present the same soil type (silt loam Luvisols, *WRB*, developed on loessial material)
170 but with different land uses, erosion conditions and environmental conditions such as
171 altitude, slope position and orientation (Table 1). The sites (A, B, C and D) were
172 geographically close together (located within a 7.5 km radius) (Figure 1). There were

four sub-sites at D (D1, D2, D3 and D4) which were located along a 200-m long eroded hill slope. Table 1 provides details of the various land uses and locations.

Sampling method

Sampling was performed in September 2009 over a period of three consecutive days, beginning four days after the last previous rain event. For each site (A, B, C, D1, D2, D3 and D4), five plots (one square meter each) were defined to collect samples in order to take into account the spatial heterogeneity within each site. Prior to sampling, the soil surface was described, and the crust type was identified (Bresson & Boiffin, 1990; Belnap *et al.*, 2008). The soil surfaces had no obvious mosses or lichens and had a light colour, indicating little cyanobacterial development (Belnap *et al.*, 2008).

Paired samples (crust and underlying material) were collected from each plot at each site so that the crust was collected separately from the underlying material (hereafter referred to as 'sub-crust'). All of the sites had a structural crust, but only site C had both structural and sedimentary crust. Therefore, only structural crust is considered hereafter. Because the lower depth of the structural crust was indistinct, a thickness of approximately 5 mm was considered to be the limit. The sub-crust was defined as the soil material between -1 and -5 cm from the soil surface. In all cases, three-to-five cm samples were collected using a sharp knife to cut through the material without affecting its structure. Soil samples from the crust and sub-crust were divided into five sub-samples in order to measure aggregate stability, organic matter content, CEC, pH and soil texture.

Measurements

197 *Aggregate stability* Samples were oven-dried at 40° C over two days and stored in a
198 cold room at 4° C for fifteen days before measurements. Aggregate stability was
199 measured using a slightly modified version of Le Bissonnais' method (Le Bissonnais,
200 1996; ISO/DIS 10930, 2012), where air-dried samples from both crust and sub-crust
201 were cut into 2–5 mm fragments with a sharp knife.

202 The three stability tests of Le Bissonnais (1996) (fast wetting, slow wetting and
203 stirring) were designed to reproduce the processes involved in crust formation and
204 interrill erosion (slaking, differential clay swelling and mechanical breakdown).
205 Results of each test can be investigated separately to analyse the resistance of the
206 material against each process. Because the three processes occur often
207 simultaneously: the three MWD resulting from the three tests are commonly
208 averaged.

209 Five-g sub-samples were dried at 40° C for 24 hours before the application of a
210 test, and each test was replicated twice (instead of three times as in the original
211 method). After the tests, the resulting fragments were sieved in ethanol. The results
212 are presented using the mean weighted diameter (MWD). Each MWD corresponds to
213 one of five classes of stability: MWD >2 mm corresponds to very stable material
214 (very weak erodibility), between 2 and 1.3 mm corresponds to stable material (weak
215 erodibility), between 1.3 and 0.8 mm corresponds to median stability (median
216 erodibility), between 0.8 and 0.4 mm corresponds to unstable material (strong
217 erodibility), and <0.4 mm corresponds to very weak stability (very strong erodibility)
218 (Le Bissonnais, 1996).

219

220 *Standard soil properties* Standard soil properties were measured to explain
221 differences in aggregate stability between the sites and between the crust and sub-

222 crust. These were gravimetric water content, organic matter content, clay content, silt
223 content, sand content, CEC and pH. Relationships between these variables and
224 aggregate stability have frequently been reported in the literature (Wischmeier &
225 Mannering, 1969; Tisdall & Oades, 1982; Amézketa, 1999; Zhang & Horn, 2001).
226 Hence, these variables could be assumed to be suitable explanatory factors for the
227 differences in aggregate stability between the crust and sub-crust materials of a given
228 site and also between sites.

229 Clay, silt and sand contents were measured by laser diffraction granulometry,
230 (Loizeau *et al.*,1994), with a Mastersizer 2000 (Malvern Instruments Ltd, Malvern,
231 UK). Soil organic matter content was measured with the Walkey & Black (1934)
232 method, cation-exchange capacity (CEC) with the ammonium rapid method
233 (Mackenzie, 1951), and pH with a 1:2.5 soil:water ratio and a pH meter. Gravimetric
234 water content was measured at the time of sampling: 10-g sub-samples were dried at
235 105° C over 48 hours. Measurements were performed on soil bulk samples for both
236 crust and sub-crust materials. Each measurement was replicated twice.

237

238 ***Statistical analyses***

239 Statistical analyses were performed using version 2.9.2 of software R (R Development
240 Core Team, 2011). To avoid the assumption of normality of samples required for the
241 use of parametric tests, a non-parametric test (Wilcoxon test) was used to compare the
242 MWD and the standard soil properties of crust and sub-crust samples. We considered
243 a significant threshold of 5%. The heterogeneity (dispersion) of the soil properties was
244 quantified using the coefficient of variation, which is a normalized measure of
245 dispersion. Linear correlation analyses (Pearson's coefficient) were performed to
246 quantify the relationships between the standard soil properties and aggregate stability.

247 To model MWD according to the soil properties, in other words to quantify the
248 proportion of MWD (dependent variable) variability which is explained by
249 independent variables, multiple regression analyses were conducted.

250

251 **Results**

252

253 *Heterogeneity of the aggregate stability* For all the sampling sites, and for both crust
254 and sub-crust, MWD was the largest for the slow wetting test (1.47 and 0.97 mm for
255 the crust and sub-crust, respectively) and the least for the fast wetting test (0.98 and
256 0.36 mm for the crust and sub-crust, respectively) (Table 2).

257 When the mean of the three stability tests is considered, the MWD of the crust varied
258 among the sites between 0.33 and 2.04 mm, with a coefficient of variation of 0.37
259 (Table 2). For crust material and for each stability tests, sites A (cultivated maize
260 field) and D1 (Ziwuling experimental station, interrill area) had the largest MWD
261 while site C (cultivated radish) had the smallest (Figure 2).

262 With the sub-crust, and again considering the mean of the three stability tests, the
263 MWD varied between 0.23 and 1.42 mm, with a coefficient of variation of 0.47
264 (Table 2). For all the stability tests on these samples, site D1 had the largest MWD
265 and site C had the smallest (Figure 2). Among the sites, the coefficients of variations
266 were larger for the sub-crust samples than for the crust samples, except for the stirring
267 test which had the same coefficient of variation (Table 2). For each site, samples were
268 collected from five plots to consider intra-site heterogeneity. Considering the mean of
269 the three stability tests, the intra-site coefficient of variations for the five plots taken at
270 each site were larger for the sub-crust than for the corresponding crust samples for
271 sites A, D1, D2, D3 and D4.

272

273 *Comparison of aggregate stability for paired crust and sub-crust samples*

274 The aggregate stability of the crust was significantly different from that of the
275 underlying material ($P = 2.10^{-10}$ for the mean of the three stability tests). For most of
276 the paired samples, the aggregate stability of the crust was greater than that of the
277 corresponding sub-crust, and the sub-crust samples were never more stable than their
278 corresponding crust (Figure 2). The difference in aggregate stability between crust and
279 sub-crust varied with the stability test. The fast wetting test had the the largest
280 differences in MWD between crust and sub-crust (0.62 mm, Table 3). In order to
281 study the relationships between the MWD of the crust and the MWD of the sub-crust
282 material, a correlation analysis was undertaken for each aggregate stability test and for
283 the mean of the three tests. The largest correlation coefficient ($r = 0.69$, $P = 5.10^{-6}$
284 significant) was found between the MWD of the crust and that of the sub-crust for the
285 slow wetting test. The correlation coefficients were 0.43 for the fast wetting test ($P =$
286 0.009, significant), 0.48 for the stirring test ($P = 0.003$, significant) and 0.59 for the
287 mean of the three tests ($P = 2.10^{-4}$, significant). However, these correlation
288 coefficients were greatly influenced by the very small MWD of site C. Without site C,
289 the correlation coefficients were only 0.52 for the slow wetting ($P = 0.003$,
290 significant), 0.20 for the fast wetting ($P = 0.30$), -0.06 for the stirring test ($P = 0.75$)
291 and 0.28 for the mean of the three tests ($P = 0.14$). The difference in aggregate
292 stability between a crust and its sub-crust showed the crust was always more stable.
293 The amplitude of this difference varied greatly both for a given site and among the
294 sites (Table 3). For example, for the mean of the three tests, the inter-site coefficient
295 of variation was 0.60 (Table 3a), whereas it ranged from 0.16 (site D4) to 0.90
296 (site D1) (Table 3b).

297

298 *Variability of standard soil properties*

299 All samples had silt content between 65.5 and 73.1% and clay content between 10.0
300 and 14.4% (Figure 3) and thus belonged to the silt loam texture class (Soil Survey
301 Division Staff, 1993). Clay content had little variability between the sampling sites.
302 Silt content and sand content presented larger differences between sites, but their
303 inter-site variability was small.

304 There were large differences in gravimetric water contents between crust and sub-
305 crust. The water content of sub-crust was larger than that of crust whatever the site.
306 Crust water content varied between 0.8% (site C) and 11.7% (site D4) while sub-crust
307 water content varied between 10.8% (site D2) and 14.9% (site D4) (Figure 4d). Crust
308 water content varied significantly between sites while sub-crust water content did not
309 differ significantly among the sites (Figure 4d).

310 The organic matter content varied between 0.7% (site D4) and 1.9% (site B)
311 (Figure 4a). The CEC varied between 16.6 cmol kg⁻¹ (site C) and 27.5 cmol kg⁻¹
312 (site A) (Figure 4b). The organic matter content and CEC varied significantly between
313 sites. The pH, which ranged between 8.3 and 8.6, did not differ significantly between
314 the sites (Figure 4c).

315 At both intra- and inter-site scales, the percentages of clay, silt and sand
316 (Figure 3), organic matter content, CEC and pH (Figure 4) did not differ significantly
317 between a crust and its corresponding sub-crust.

318

319 *Relationship between standard soil properties and aggregate stability*

320 A correlation analysis was performed between the aggregate stability (MWD) and the
321 soil properties assumed to be potential explanatory factors (Table 4). This analysis

was performed for the crust (Table 4a) and sub-crust (Table 4b) separately. In both cases, the largest correlation coefficients were found between the MWD of the slow wetting test (0.57 , $P = 3.10^{-4}$, significant) and the organic matter content (0.56 , $P = 4.10^{-4}$, significant).

Clay, silt and sand contents were not significantly correlated with any of the MWD values, either for the crust and sub-crust samples. For the crust, water content, organic matter content and CEC were significantly correlated with the MWD whatever the stability test (Table 4a). For the sub-crust, organic matter content, CEC and pH correlated significantly with MWD, except that organic matter content did not correlate significantly with MWD for the stirring test, and pH did not correlate with MWD for slow wetting test (Table 4b).

A multiple regression analysis was performed using the soil properties (organic matter content, CEC, water content and pH) which were significantly correlated to aggregate stability. For the crust, among all the combinations tested the best regression was found for the mean MWD of the three tests as the dependent variable and the organic carbon content and CEC as explanatory variables:

$$\text{MWD}_{\text{mean}}(\text{mm}) = 0.39 (\pm 0.15) \times \text{SOM} (\%) + 0.06 (\pm 0.02) \times \text{CEC} (\text{cmol.kg}^{-1}) - 0.66 (\pm 0.47). \quad (1)$$

(the number in parenthesis is the standard error).

The coefficient of determination (R^2) was 0.38 . The residual standard error for the estimated MWD was 0.36 mm at the 95% confidence interval. However, because organic matter content and CEC are significantly correlated, the relevance of the proposed relationship is questionable. When CEC is removed from the relationship, the model explained only 25% of the variance of the MWD for the mean of the three tests.

347 For the sub-crust, among all the tested combinations, the most statistically
348 meaningful regression was found between MWD of the slow wetting test and organic
349 matter content and pH:

350 $MWD_{sw}(mm) = 0.69 (\pm 0.17) \times SOM (\%) + 1.15 (\pm 0.44) \times pH - 9.62 (\pm 3.70)$. (2)
351 (the number in parenthesis is the standard error). The coefficient of determination (R^2)
352 was 0.40. The residual standard error for the estimated MWD was 0.43 mm at the
353 95% confidence interval.

354 In order to link the differences in MWD between the crust and the sub-crust
355 materials to the soil properties further, linear correlation analysis was performed
356 (Table 5). Potential explanatory factors were the soil properties as before but also the
357 difference between the crust and the sub-crust for a given soil property.

358 Generally, the differences in stability between the crust and the sub-crust materials
359 were positively correlated with (i) the crust organic matter content and the difference
360 in carbon content between crust and sub-crust, (ii) the crust and sub-crust CEC and
361 (iii) the crust water content. In addition, the differences in stability between the crust
362 and the sub-crust materials were generally negatively correlated with the crust silt
363 content. A multiple regression analysis was performed using the difference in
364 aggregate stability between the crust and sub-crust materials as dependent variable
365 and the soil properties and the differences between each property for the crust and
366 sub-crust as explanatory variables. No statistically meaningful relationship was found.

367

368 Discussion

369

370 *The aggregate stability of a crust is different from the aggregate stability of its*
371 *sub-crust*

372 To the best of our knowledge, no study has investigated differences in aggregate
373 stability between crust and its underlying material. However, differences in aggregate
374 stability as a function of the crusting stage were investigated by McIntyre (1958) and
375 more recently by Darboux & Le Bissonnais (2007). Using simulated rainfall in the
376 field, McIntyre (1958) showed that crusting decreased the splash rate on sandy loams,
377 concluding that the crust formation processes increased the resistance of soil surface
378 against the breakdown induced by the raindrop impacts. This observation concurs
379 with the results of the stirring test in the present study, where crust had larger MWD
380 than its underlying material for most of the sites (Figure 2c). The same observations
381 were found for the other stability tests (Figure 2b, 2c). Darboux & Le Bissonnais
382 (2007) showed different results in a laboratory experiment. They measured the
383 aggregate stability of a seedbed (non-crust, initial material), a structural crust and a
384 sedimentary crust, and showed that the stability of structural crust was similar to that
385 of the seedbed. In the present study, the aggregate stability of the structural crust was
386 usually very different from the aggregate stability of the sub-crust irrespective of the
387 sampling site and the stability test. The differences between the results of these two
388 studies may lie in the experimental conditions. Darboux & Le Bissonnais experiment
389 (2007) used a soil with a different texture (11% clay, 58% silt and 31% sand) and
390 well-controlled experimental conditions in a laboratory. The structural crust was
391 formed very rapidly: starting from a seedbed (non-crust material), they applied a
392 single and intense simulated rain (30 mm.h⁻¹), and obtained a structural crust after
393 only six minutes of rain. Moreover, samples were collected quickly after the rain
394 ended. In our field conditions, crust formation was probably a more gradual and
395 discontinuous process, depending on the duration and intensity of successive rainfalls.

396 The present crust samples must therefore have gone through numerous cycles of
397 wetting and drying that could lead to additional consolidation.

398 The amplitude of the difference in aggregate stability between crust and sub-crust
399 varied according to the stability test (Table 3a). The fast wetting test was designed to
400 reproduce the processes of slaking: during rapid wetting, the compression of air
401 entrapped inside the aggregate ruptures the inter-particle bonds within the aggregate
402 and producing small fragments leading to a small MWD (Le Bissonnais, 1996). Sub-
403 crust material was very sensitive to slaking, leading to the smallest MWD, and to the
404 largest differences in MWD between crust and sub-crust (Figure 2a). The amplitudes
405 of difference were least for the differential swelling process involved in the slow
406 wetting test and for the kinetic energy involved in the stirring test (Table 3a, Figure 2).
407 Thus, the fast wetting test was the best discriminator between the crust and sub-crust
408 MWD.

409 For a given site, water content at the time of sampling was the only variable
410 showing significative differences between crust and sub-crust (Figure 4). However,
411 none of the measured standard soil properties was able to explain the differences in
412 aggregate stability between crust and sub-crust. The crust is directly exposed to
413 atmospheric conditions and may be submitted to a larger amplitude of wetting and
414 drying cycles than the sub-crust. As wetting and drying cycles are an important factor
415 of aggregate stability variation (Cosentino *et al.*, 2006), we can hypothesize that
416 difference in hydric history between crust and sub-crust may explain some of the
417 difference in aggregate stability between these materials. Water content at the time of
418 sampling did not give information about the hydric history of the soil, and thus, could
419 not explain the differences in aggregate stability between crust and sub-crust. The
420 differences may be explained by other variables. Because the crust and sub-crust

421 originated from the same initial material (a seedbed for the cultivated fields), the
422 differences in stability result necessarily from the crust formation processes. In
423 addition, the presence of carbonates and their crystallization through wetting and
424 drying cycles may also play a role in the crust reinforcement (Fernandez-Ugalde *et*
425 *al.*, 2011). Those possibilities indicate a need for a time-monitoring of aggregate
426 stability and other variables in both the crust and sub-crust.

427

428 *Aggregate stability varied greatly even for sites located on the same soil type within a*
429 *small area*

430 In the present study, standard soil properties were not dominant factors controlling
431 aggregate stability. Water content, organic matter content and CEC varied
432 significantly among the sites (Figure 4). Because these variables are known to be
433 related to aggregate stability (Wischmeier & Mannering, 1969; Tisdall & Oades,
434 1982; Amézketa, 1999; Zhang & Horn, 2001), it might have been expected that the
435 variability in aggregate stability could be explained by these properties. None of these
436 variables (or their combination) was able to satisfactorily predict the aggregate
437 stability of the crust or sub-crust. At best, only 40% of the variability could be
438 explained and this had a residual standard error of approximately 0.4 mm. Hence, the
439 predicted MWD could be wrong by as much as two stability classes (out of five
440 stability classes) (Figure 2). Consequently, these relationships have no practical use
441 for prediction, and their use would probably lead to large flaws in the interpretations.

442 Land use and site environmental conditions may have caused the differences in
443 stability among the sites without affecting the standard soil properties. Variables
444 known to affect aggregate stability, but not commonly noted, include tillage, crop
445 management or mulching through their effect on microbial activity and soil water

446 content (Amézketa, 1999). Altitude, slope position and orientation influence local
447 climate which can affect aggregate stability through soil hydric history (Amézketa,
448 1999; Cosentino *et al.*, 2006). The current experimental design did not allow us to
449 study precisely the influence of topography or location. However, we can note that
450 sites A and D1 that had the largest MWD for both crust and sub-crust were located on
451 the lowest slopes. Even more than hydric history, topography can affect flow and
452 transport history of the material which in return affects aggregate stability (Amézkéta,
453 1999). In future studies, variables such as the organic matter quality, microbial
454 activity, wetting-drying cycles and topography may need to be considered.

455 The heterogeneity of the aggregate stability measured in the crust samples was
456 less than that measured in the sub-crust samples. This finding was consistent in the
457 inter-site comparison and often observed in the intra-site comparison. The crust had
458 larger MWD on average and larger standard deviation than the sub-crust (Table 2). As
459 the observed aggregate system is physically constrained by full dispersion of the
460 particles (the MWD of a fully dispersed loamy soil may be around 0.2 mm), it may
461 have been expected that CV values would decrease with increasing MWD. However,
462 our analysis did not identify correlations between the standard deviation and the mean
463 MWD, nor negative correlations between the mean MWD and the CV. Hence, the
464 smaller heterogeneity of crust aggregate stability than of that of the sub-crust may not
465 be related to the CV calculation. The development of the crust could have decreased
466 the spatial heterogeneity of aggregate stability. This assumption has to be examined in
467 future studies.

468

469 *Consequences for erodibility assessment and erosion modelling*

470 When used for erodibility assessment, aggregate stability is usually measured in the
471 sub-crust material (Bullock *et al.*, 1988; Bajracharya & Lal, 1998; Barthès & Roose,
472 2002; Legout *et al.*, 2005). The finding that the crust is generally less erodible than
473 the sub-crust strongly suggests that erodibility should be assessed on the material
474 actually exposed to erosive forces: the soil surface. The common practice of using the
475 underlying material, instead of the crust, would cause an over-estimate by at least one
476 erodibility class in 60% of cases and by at least two erodibility classes in 30% of
477 cases of our soil (Figure 2).

478 In erosion models, erodibility can be assessed with soil standard properties such as
479 soil texture and organic matter content through statistical functions (Alberts *et al.*,
480 1995; Renard *et al.*, 1997). Such an approach assumes that samples collected from the
481 same soil type have similar erodibilities (Gumiere *et al.*, 2009). Because a single soil
482 type was investigated in the present study, a similar erodibility would have been
483 expected. This was clearly not the case. This finding underlines the large uncertainty
484 in the prediction of erodibility when assessed using standard soil properties. Currently,
485 parameterization of erosion models sets a single erodibility value for a given soil and
486 thus does not consider the variability of erodibility within a given soil. This over-
487 simplification could explain part of the large inaccuracy in the predicted results of
488 erosion models (Jetten *et al.*, 2003). Comparisons between the seven sites showed that
489 the heterogeneity of the crust was less than that of the sub-crust. Using crust samples
490 for erodibility assessment, would decrease the heterogeneity of the mapped erodibility
491 (although this heterogeneity would remain large).

492

493 **Conclusions**

494

Crust showed a greater aggregate stability than its underlying material. This finding emphasizes the importance of estimating soil interrill erodibility on the soil surface material. On a crusted soil, the use of material collected from the plough layer may lead to greatly over-estimated erodibility and thus bias the results of the erosion models. The large heterogeneity in aggregate stability among sites proves that erodibility can greatly vary in space, even when considering a small test area and a single soil type. From the present study, we conclude that interrill erodibility assessment should ideally be performed with a large sampling density, which could be impractical, leaving the construction of a sound erodibility map currently unattainable. The fact that standard soil properties were not able to accurately predict the observed differences in aggregate stability lead us to suggest investigating other variables such as (i) the soil hydric history linked to local climatic conditions, (ii) environmental factors such as topography and (iii) the physical processes involved in crust formation. Factors that affect the erodibility of the soil surface should be better understood so that reliable erodibility maps can be produced from a reasonably small set of measurements.

511

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513

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518

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Site	Geographic location (latitude; longitude)	Land use and slope position	Altitude / m	Orientation	Slope gradient (field scale)
A	36°03.888' N; 109°12.621' E	Cultivated maize field, upslope	1053	E	5° - 10°
B	36°03.874' N; 109°12.675' E	Apple orchard, shoulder of a terrace	1118	SW	5° - 30°
C	36°04.227' N; 109°11.226' E	Cultivated radish crop, middle slope, sampling in ridges and furrows	1206	SE	5° - 13°
D1	36°05.149' N; 109°8.958' E	Ziwuling experimental station, bare soil, upslope, interrill area	1270	SW	5° - 10°
D2	36°05.431' N; 109°8.951' E	Ziwuling experimental station, bare soil, mid-slope, rill area	1245	SW	30° - 35°
D3	36°05.450' N; 109°8.947' E	Ziwuling experimental station, bare soil, 20 m from foot slope, ephemeral gully area	1180	SW	25° - 35°
D4	36°05.460' N; 109°8.884' E	Ziwuling experimental station, bare soil, 10 m from foot slope, gully area	1154	SW	35° - 40°

Table 2 Heterogeneity of the mean weighted diameter among the sampling sites (inter-site heterogeneity) for the fast wetting test, the slow wetting test, the stirring test and the mean of the three tests. Mean of the MWD corresponds to the mean of five

Stability test	MWD of the crust					MWD of the sub-crust				
	Min. /mm	Max. / mm	Mean / mm	σ^a / m)	CV ^b	Min. / mm	Max. / mm	Mean / mm	σ / mm	CV
Fast wetting	0.20	1.62	0.98	0.41	0.42	0.13	0.95	0.36	0.18	0.51
Slow wetting	0.41	2.22	1.47	0.52	0.36	0.22	1.93	0.97	0.52	0.54
Stirring	0.29	1.77	1.14	0.41	0.39	0.23	1.23	0.69	0.27	0.39
Mean of the 3 tests	0.33	2.04	1.20	0.44	0.37	0.23	1.42	0.68	0.32	0.47

plots with two replicates each, n=10.

603 ^a σ : standard deviation; ^bCV: coefficient of variation.

Table 3 Heterogeneity of the difference in mean weighted diameter between crust and sub-crust (a) among the sampling sites (inter-site heterogeneity) for all stability tests, and (b) for each site (intra-site heterogeneity) for the mean of the three stability tests. Mean of the MWD corresponds to the mean of five plots with two replicates each, n=10.

(a)

Difference in MWD between crust and sub-crust					
Stability test	Min. / mm	Max. / mm	Mean / mm	σ / mm	CV
Fast wetting	0.10	1.04	0.62	0.35	0.56
Slow wetting	0.24	1.03	0.50	0.30	0.60
Stirring	0.00	0.81	0.45	0.32	0.71
Mean of the 3 tests	0.16	0.93	0.46	0.28	0.60

^a σ : standard deviation; ^bCV: coefficient of variation.

(b)

Difference in MWD between crust and sub-crust					
Site	Min. / mm	Max. / mm	Mean / mm	σ / mm	CV
A	0.61	0.90	0.80	0.12	0.22
B	0.44	1.24	0.77	0.30	0.39
C	0.09	0.27	0.16	0.07	0.45
D1	0.08	1.25	0.52	0.47	0.90
D2	0.08	0.59	0.31	0.27	0.87
D3	0.05	0.40	0.18	0.14	0.76
D4	0.83	1.13	0.93	0.15	0.16

^a σ : standard deviation; ^bCV: coefficient of variation.

613 **Table 4** Correlations (Pearson's coefficient) between aggregate stability and standard
 614 soil properties (a) for the crust and (b) for the sub-crust.

615 (a)

MWD	Water content	Organic matter	CEC	pH	Clay content	Silt content	Sand content
Fast wetting	0.35	0.50	0.50	0.11	0.08	-0.31	0.21
Slow wetting	0.32	0.57	0.46	0.22	0.09	-0.18	0.11
Stirring	0.45	0.42	0.56	0.20	0.14	-0.16	0.06
Mean of the three tests	0.36	0.52	0.52	0.18	-0.10	-0.22	0.13

616 n= 35; $\alpha=5\%$: $r = 0.32$

617 bold = significant at the 5% level

618 (b)

MWD	Water content	Organic matter	CEC	pH	Clay content	Silt content	Sand content
Fast wetting	-0.11	0.51	0.44	0.19	0.12	0.09	-0.07
Slow wetting	-0.17	0.56	0.44	0.41	0.04	-0.12	0.11
Stirring	-0.05	0.22	0.46	0.47	0.28	0.29	-0.29
Mean of the three tests	-0.13	0.49	0.48	0.41	0.13	0.03	-0.04

619 N = 35; $\alpha = 5\%$: $r = 0.32$

bold = significant at the 5% level

620 **Table 5** Correlations (Pearson's coefficient) between the differences in aggregate stability between crust and sub-crust and the standard soil
621 properties.

Difference in MWD	Water content			Organic matter			CEC			pH			Clay content			Silt Content			Sand content		
	C	U	C-U	C	U	C-U	C	U	C-U	C	U	C-U	C	U	C-U	C	U	C-U	C	U	C-U
Fast wetting	0.40	0.29	0.30	0.40	0.27	0.29	0.45	0.45	-0.16	0.04	0.16	0.09	-0.07	0.20	-0.21	-0.46	-0.26	-0.23	0.37	0.16	0.23
Slow wetting	0.32	0.42	0.09	0.18	-0.01	0.42	0.12	0.15	-0.10	-0.19	-0.07	-0.11	-0.21	0.25	-0.35	-0.22	-0.04	-0.25	0.23	-0.06	0.36
Stirring	0.40	0.26	0.32	0.40	0.29	0.29	0.35	0.33	-0.07	-0.01	-0.28	-0.06	-0.19	0.09	-0.21	-0.48	-0.32	-0.16	0.42	0.23	0.19
Mean of the 3tests	0.36	0.30	0.26	0.34	0.19	0.37	0.33	0.33	-0.12	-0.06	0.05	-0.10	-0.17	0.20	-0.28	-0.41	0.22	-0.23	0.36	0.11	0.28

622
623 C=crust; U=sub-crust; C-U=difference in soil property value between the crust and the sub-crust. N = 35; $\alpha = 5\%$; $r = 0.32$

624 Bold = significant at the 5%.

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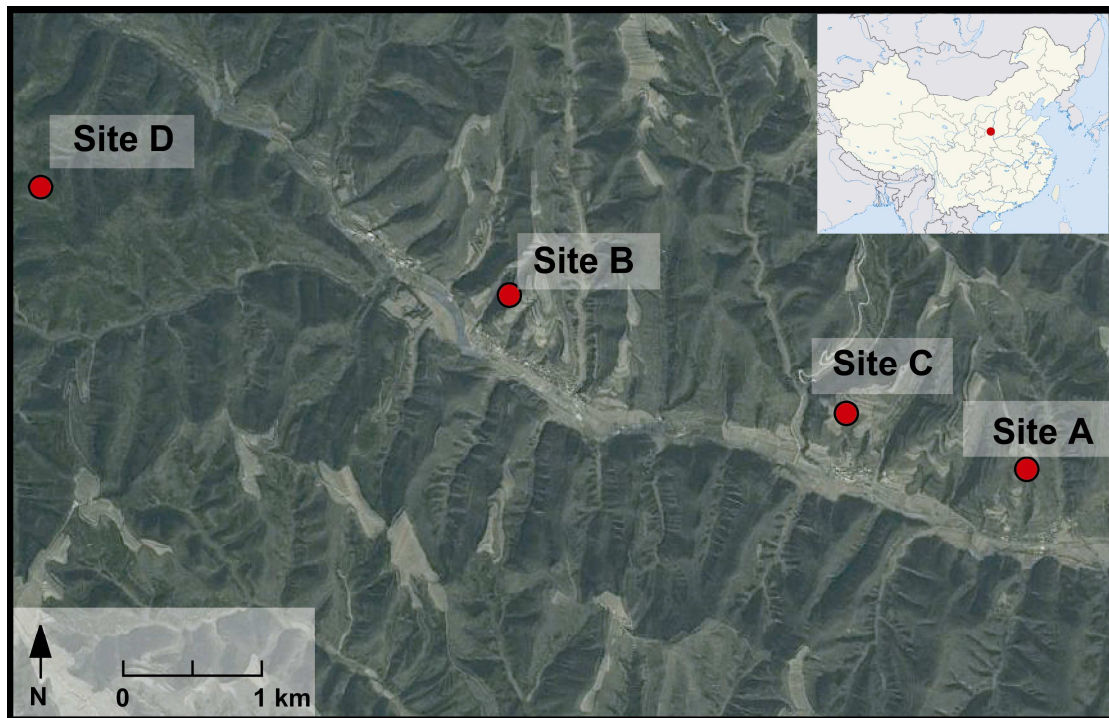
631 Small letters above the bars correspond to paired comparisons between crust and sub-
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635 **Figure 3** Crust and sub-crust contents in (a) clay, (b) silt, and (c) sand for all sites.

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640 **Figure 4** Crust and sub-crust values for (a) organic matter content, (b) CEC and
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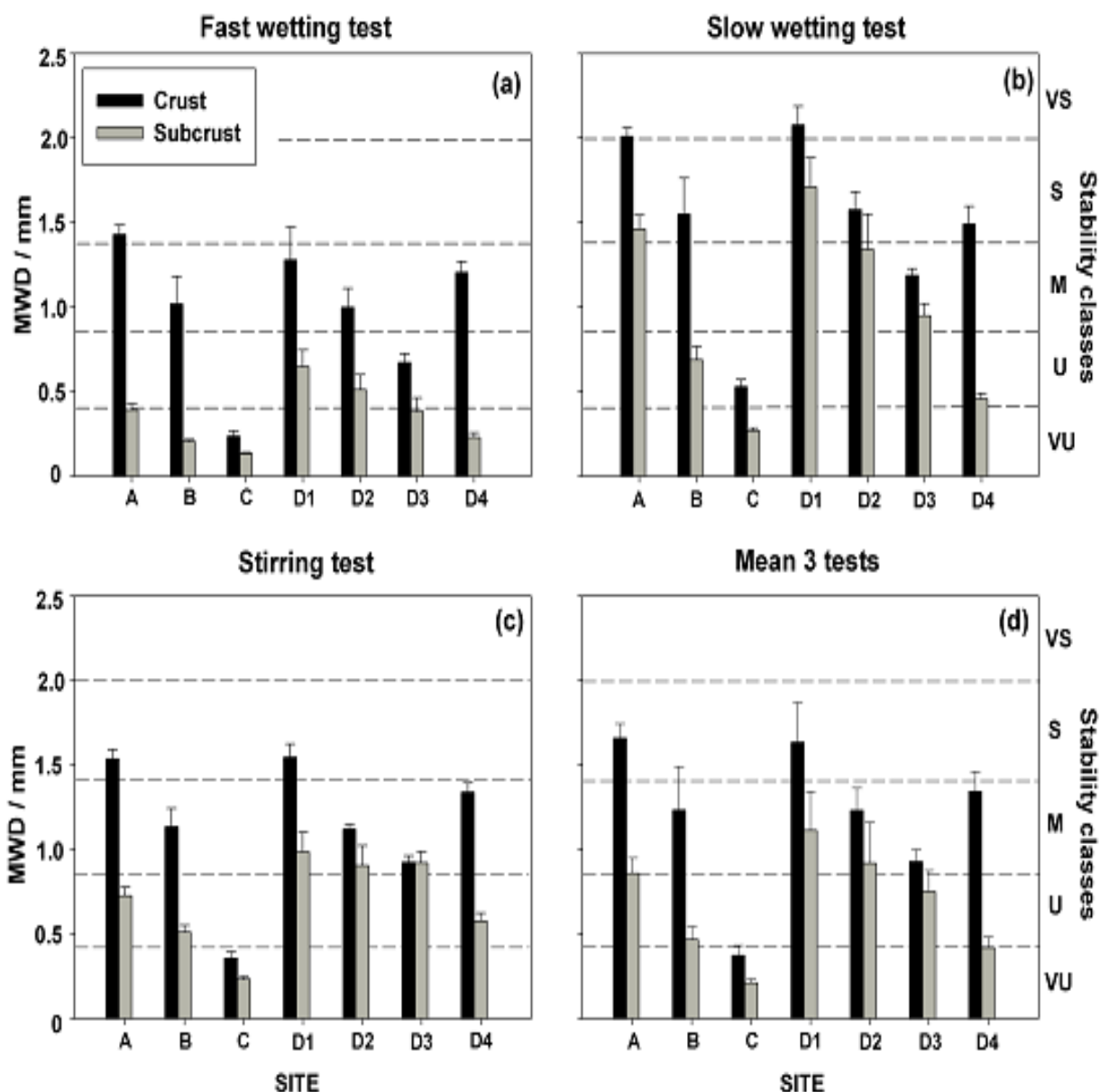


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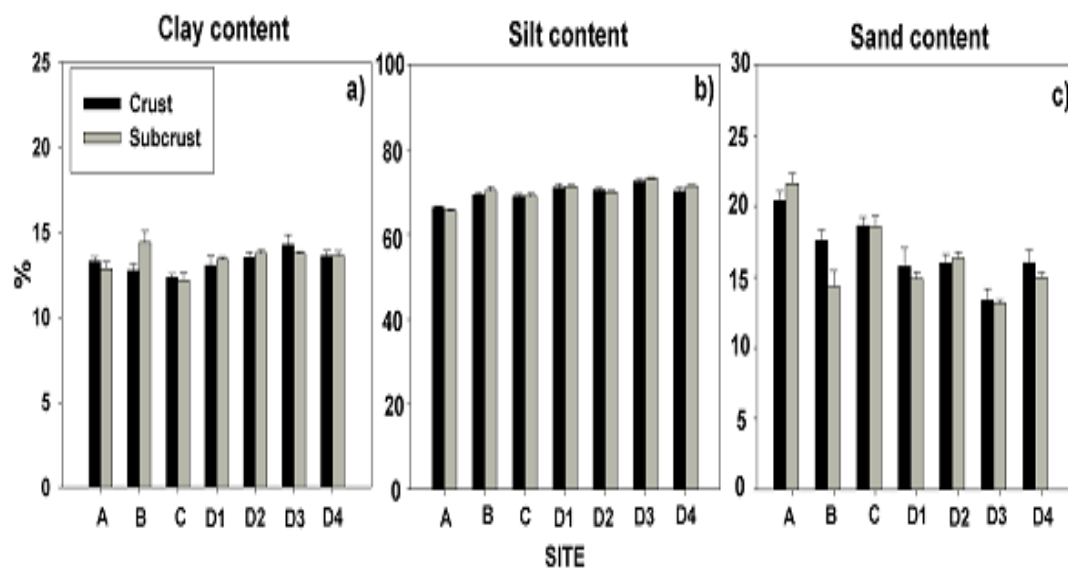
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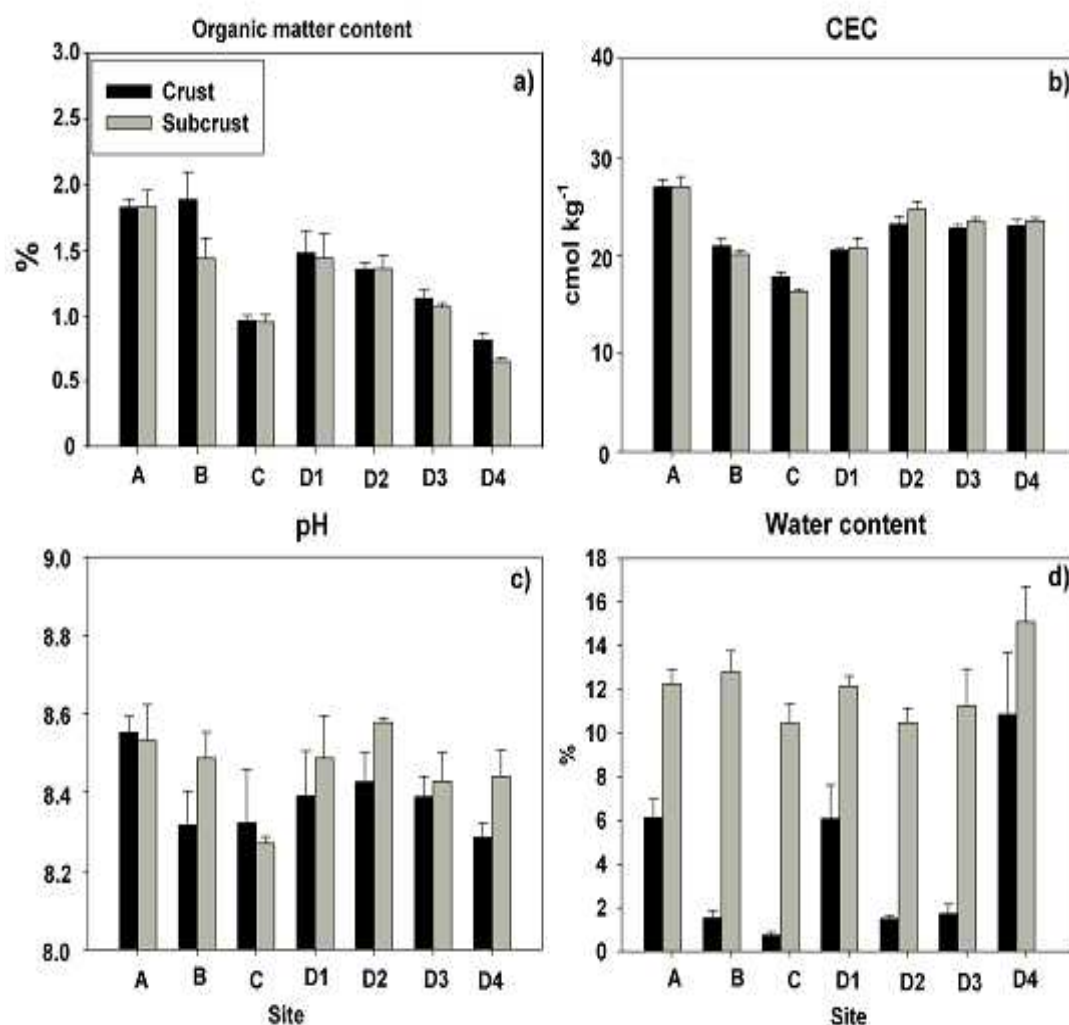
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