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► **To cite this version:**

Baptiste Algayer, Yves Le Bissonnais, Frédéric Darboux. Short-term dynamics of soil aggregate stability in the field. *Soil Science Society of America Journal*, 2014, 78 (4), pp.1168-1176. 10.2136/sssaj2014.01.0009 . hal-01061537

**HAL Id: hal-01061537**

**<https://hal.science/hal-01061537>**

Submitted on 27 May 2020

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## 1 **Short-term dynamics of soil aggregate stability in the field**

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3 April 3, 2014

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8

### 9 **Abstract**

10 Aggregate stability is a key property affecting the movement and storage of water, seedling  
11 emergence and soil sensitivity to erosion. Many studies have shown that aggregate stability  
12 changes through time. Field monitoring studies performed with a relatively large (monthly)  
13 time step showed seasonal trend of aggregate stability. But shorter time step monitoring are  
14 required to explore dynamics of aggregate stability at short term. For now, biological  
15 activity was recognized to be the main factor of aggregate stability dynamic. But previous  
16 studies were currently based on the external stimulation of aggregate stability. The  
17 objectives of the study were to assess variations in aggregate stability at short time steps in  
18 the field and to identify the factors controlling these variations of stability. A six months  
19 field monitoring was performed at short time step (two to five days) on a bare field on

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20 Luvisol without organic amendment. Aggregate stability was measured for both on surface  
21 and subsurface materials by the ISO/DIS 10930 method. Rain amount and intensity, air  
22 temperature and humidity, soil temperature, water content and hydric history, soil water  
23 repellency were measured as explanatory factors. The results showed that aggregate  
24 stability varied greatly (up to 40%) over a few days for both surface and subsurface. Short  
25 term dynamics of aggregate stability were already shown by laboratory experiments, but  
26 such dynamics was never observed in the field for a bare soil without external stimulation  
27 of biological activity. For the surface, short time step variations of surface aggregate  
28 stability were primarily controlled by soil water content ( $WC_0$  and  $WC_{1/2}$ ), hydric history  
29 ( $\Delta WC_4$  and API) and rain intensity. While large changes in aggregate stability were found  
30 for the subsurface, explanatory factors remain to be found.

## 31 **Introduction**

32 Aggregate stability corresponds to the capacity of a soil aggregate to keep its cohesion  
33 and not to break up into smaller fragments when it is submitted to the effect of water. The  
34 stability of soil aggregates is a key property since it affects the movement and storage of  
35 water, soil aeration, biological activity, seedling emergence, and root penetration (Gallardo-  
36 Carrera et al., 2007). It also affects soil sensitivity to erosion and crusting (Le Bissonnais,  
37 1996; Bajracharya et al., 1998; Wang et al., 2013).

38 It is well-established that aggregate stability is a time dependent variable (e.g.  
39 Bullock et al. 1988; Caron et al., 1992; Bajracharya et al., 1998; Denef et al., 2001). For  
40 now, numerous field monitoring studies have identified a seasonal pattern, with the largest  
41 aggregate stabilities recorded in summer and the lowest values in winter (Bullock et al.  
42 1988; Blackman, 1992; Chan et al. 1994; Dimoyiannis, 2009). Such studies have shown  
43 that the temporal variability of the aggregate stability, as measured at monthly time steps  
44 over a year, varied between 20% and 30%, depending upon the study. If seasonal trends of

45 aggregate stability variation are well identified, there is a lack of knowledge concerning the  
46 temporal dynamic of aggregate stability at shorter time step (few days).

47 Laboratory studies performed at short-term explored the mechanisms of aggregate  
48 stability variation and the influence of various factors: the biological activity, the wetting  
49 and drying cycles, the rain intensity and the freezing-thawing cycles. Such studies showed  
50 that aggregate stability increased when the biological activity was stimulated by organic  
51 amendment (e.g. Tisdall and Oades, 1982, Le Guillou et al., 2012), underlining that  
52 microbial activity has a positive effect on aggregate stability (e.g., Tisdall and Oades,  
53 1982; Chenu et al. 2000). Soil temperature affects aggregate stability directly through  
54 freezing (Bullock et al. 1988) and indirectly through the stimulation of microbial activity.  
55 Rain affects aggregate stability of the soil surface through several processes, including the  
56 kinetic energy of raindrop impact and slaking (Shainberg et al., 2003). Soil water content at  
57 the time of sampling was found negatively correlated with aggregate stability (Perfect et al.  
58 1990; Caron et al., 1992). Soil hydric history affects aggregate stability through physico-  
59 chemical processes (Utomo and Dexter, 1982; Kemper and Rosenau, 1984) and through its  
60 influence on microbial activity (Denef et al., 2001). Water repellency was shown to affect  
61 aggregate stability by decreasing the aggregates wetting rate, limiting the effect of slaking  
62 and microcracks formation (Piccolo and Mbagwu, 1999; Cosentino et al. 2006). According  
63 to this literature (e.g. Perfect et al. 1990; Blackman 1992; Suwardji and Eberbach, 1998;  
64 Denef et al., 2001; Cosentino et al., 2006), temporal dynamics of aggregate stability should  
65 be primarily controlled by biological activity. However, such studies have generally been  
66 based on either the external stimulation of biological activity by organic amendments  
67 (amended soils compared to non-amended soils) (e.g., Cosentino et al., 2006; Abiven et al.,  
68 2007; Le Guillou et al., 2012) or the comparison of soils with highly contrasting organic  
69 matter contents or management practices (e.g., Blackman 1992; Suwardji and Eberbach,

70 1998). Thus, there is a lack of information concerning the factors of aggregate stability  
71 temporal variation without external stimulation of the biological activity.

72 In the present study, a field monitoring of aggregate stability variations over time steps of a  
73 few days was conducted on a bare soil without stimulation of biological activity. The  
74 objectives were: 1) to assess how much aggregate stability can vary in the field at short  
75 time steps, and 2) to identify the factors controlling the variations of aggregate stability  
76 without stimulation of biological activity.

## 77 **Material and method**

### 78 *Sampling sites*

79 Field monitoring was performed on a site located in the southern part of the Parisian  
80 Basin (France), 15 kilometers southwest of the city of Chartres (48°21'5.12"N;  
81 1°16'0.55"E). This site was located on a cultivated field on a typic Luvisol with a gentle  
82 slope (7%) oriented to the north. The field was sown with wheat, and soil was drained by  
83 subsurface pipes. The A horizons was a silt loam (Soil Survey Division Staff, 1993), with  
84 16% clay and 2.2% organic matter. Other soil characteristics are shown in table 1.

### 85 *Monitoring and sampling setup*

86 A 50 m<sup>2</sup> rectangular plot (12 meter in length and 4 meter in width) was defined within  
87 the crop field. The plot was kept bare with herbicide (Bayer jardin, versatile weedkiller, 7  
88 g/l glyphosate) during the 6 months of monitoring to facilitate sampling and minimize the  
89 effects of vegetation on aggregate stability. The effect of glyphosate on aggregate stability  
90 has never been studied according to our knowledge. Monitoring was conducted during six  
91 months in 2011. It started just after the seedbed preparation and sowing, on 9 March and it  
92 ended on 18 August.

93 The plot was divided in one-meter-square subplots using plastic sticks. During the  
94 monitoring, each subplot was sampled only once. Sampling was carried out at two time  
95 scales: a regular monthly time step and at a shorter time step (two to five days) during the  
96 two weeks after a significant rain event (Table 2). For each monthly sampling, three  
97 distinct samples were collected on non-adjacent subplots from each 50 m<sup>2</sup> plot to assess the  
98 spatial variability of the measured variables within a plot. During the monitoring, 6 rain  
99 events were considered as significant based on their duration, rain amount and maximum  
100 intensity. Sampling at shorter time step (2 to 5 days) was performed during the inter-rain  
101 periods (Table 2).

102 From a subplot, paired samples of surface and subsurface materials were always  
103 collected separately. For the surface samples, material was carefully collected from the top  
104 5 mm using a small spatula. When the soil surface was crusted (Bresson and Boiffin,  
105 1990), large pieces (2-to-20 cm<sup>2</sup>) of the crust material were collected using a sharp knife to  
106 cut through the crust without affecting its structure. The subsurface material was defined as  
107 the material between 1 cm and 5 cm below the soil surface. It was carefully collected using  
108 a small spade. After May 5, the soil surfaces presented a structural crust, which developed  
109 into a sedimentary crust after August 2.

110 For each material (surface and subsurface), samples were divided into 5 subsamples in  
111 order to measure aggregate stability, water content at the sampling time, organic matter  
112 content, microbial biomass and water repellency. For aggregate stability, samples were  
113 dried at 40°C during 2 days and stored at 4°C before measurement. For organic matter  
114 content and microbial biomass, fresh soil samples were sieved at 5 mm and stored at 4°C  
115 before measurement. For water repellency, fresh samples were stored at 4°C.

## 116 *Measurements*

### 117 *Aggregate stability*

118 Aggregate stability was measured using a modified version of the ISO/DIS 10930  
119 (2012) method which is based on Le Bissonnais (1996). Two tests were considered: fast  
120 wetting (FW) and slow wetting (SW). 5 g sub-samples were dried at 40°C for 24 h prior to  
121 each test, and each test was replicated three times. Following each stability test, the  
122 resulting fragments were sieved in ethanol, and results are presented using the mean  
123 weighted diameter of the fragments (MWD) (Le Bissonnais, 1996). The results of each test  
124 (hereafter referred as  $MWD_{FW}$  and  $MWD_{SW}$ ) were considered separately to analyze the  
125 resistance of the material against specific processes (slaking for the fast wetting test and  
126 differential clay swelling for the slow wetting test). Each MWD value corresponds to one  
127 of five classes of stability: MWD above 2 mm corresponds to very stable material,  
128 between 2 and 1.3 mm corresponds to stable material, between 1.3 and 0.8 mm  
129 corresponds to median stability, between 0.8 and 0.4 mm corresponds to unstable material,  
130 and lower than 0.4 mm corresponds to very low stability (Le Bissonnais, 1996).

### 131 *Organic matter content and microbial biomass*

132 As soil was kept bare and no organic amendment was incorporated, biological activity  
133 was not expected to change much during the monitoring. Organic matter content and  
134 microbial biomass were measured, as control measurements, to characterize the biological  
135 activity. Organic matter content was measured using the sulfochromic oxidation method  
136 (ISO 14235, 1998), microbial biomass using the fumigation method (ISO 14240-2, 1997).

137 *Potential explanatory variables*

138 Air relative humidity and temperature, rain amount and intensity, soil water content and  
139 hydric history, and water repellency of the aggregates, were considered as potential  
140 explanatory factors of aggregate stability variations.

141 The air relative humidity and temperature were recorded hourly (Vaisala, HMP45C) at  
142 1.5 m above ground.

143 Rain amount was measured hourly using a rain gauge (Campbell Scientific, ARG 100).  
144 Average rain intensity and maximum rain intensity was calculated for each rain event. To  
145 characterize the amount of rainfall in the days preceding a sampling date, an antecedent  
146 precipitation index (API) was calculated from the rainfall data using a 7-day duration as:

147  $P_i$

148 where  $i$  is the  $i^{\text{th}}$  day before sampling and  $P_i$  (in mm) is the total precipitation height on  
149 the  $i^{\text{th}}$  day.

150 Soil water content was measured at each sampling time by the gravimetric method  
151 carried out on the surface and subsurface samples. Volumetric soil water content and soil  
152 temperature were measured hourly using TDR and thermistor probes (Decagon Devices,  
153 soil moisture sensor 5TE) at two depths (1 cm and 5 cm) and at two different locations in  
154 each plot (4 probes per plot) for the whole monitoring duration. According to their design  
155 principle, TDR probes are known to show approximate data for very top soils. A  
156 preliminary analysis was performed to compare gravimetric water content data and  
157 volumetric water content data for the 19 sampling times. Results showed that these  
158 measurements were significantly correlated and showed similar results ( $r^2= 0.79$ ).

159 To characterize the hydric history of the soil, two indices were calculated from the  
160 water content data: the mean of water content for a duration  $t$  (in days) prior sampling  
161 ( $WC_t$ ) and the difference in water content between the beginning and the end of that period

162 ( $\Delta WC_t$ ). A preliminary analysis based on a correlation analysis was performed to identify  
163 the duration of both hydric history indices that was the most relevant to aggregate stability  
164 changes. For both indices, durations ranging from 0.25 to 8 days were tested. Results  
165 showed that the most-significant durations were half day for water content ( $WC_{1/2}$ ) and 4  
166 days for the difference in water content ( $\Delta WC_4$ ).

167 Subcritical water repellency was measured with the intrinsic sorptivity method  
168 (Tillman et al., 1989). The experimental design described by Hallett and Young (1999) was  
169 used. Measurements were performed on 1-cm-diameter aggregates, on surface samples  
170 only. Samples were dried at 40°C during the 48 h prior to measurements. When the soil  
171 surface was crusted, measurements were made on the top of 1 cm<sup>2</sup> crust fragments.  
172 Subcritical water repellency was expressed as the water repellency index R defined by  
173 Tillman et al. (1989). The given R value corresponds to the mean of 10 replicates. A higher  
174 R value means a larger water repellency. An R index equal to 1.0 corresponds to a  
175 completely non-repellent material, an R index between 1.0 and 1.95 corresponds to a non-  
176 repellent material and an R index higher than 1.95 corresponds to a subcritical water  
177 repellent material (Tillman et al., 1989).

## 178 **Statistical analysis**

179 Statistical analysis were completed using R software version 2.9.2 (R Development  
180 Core Team, 2011). The short time step variability was considered as significant when its  
181 coefficient of variation (CV) was significantly larger than the CV of the spatial variability  
182 measured at the monthly time step. Throughout the whole study, a 5% significance level  
183 was considered. Linear correlation analysis (Pearson's coefficient) were used to identify  
184 relationships between the MWD and the other factors. This analysis was carried out for the  
185 surface and subsurface datasets separately. In order to classify the identified factors, and to

186 measure their combined effect on aggregate stability (MWD), simple and multiple  
187 regression analysis were carried out.

## 188 **Results**

### 189 **Temporal variation of aggregate stability**

190  $MWD_{FW}$  and  $MWD_{SW}$  were significantly correlated ( $r=0.82$ ,  $p$ -value  $<0.001$ ). Because  
191 the slow wetting test exhibited the largest temporal dynamics, only this test is detailed in  
192 the present section (Figures 1 and 2).

193 Based on the monthly samples, the largest spatial variability of the  $MWD_{SW}$  at a given  
194 time was 9% for the surface and 12% for the subsurface (Figure 1a). As it was explained  
195 previously, variations above this threshold were considered as significant. During the  
196 monitoring period, aggregate stability varied greatly for both the surface and the  
197 subsurface. The surface  $MWD_{SW}$  ranged from 0.34 mm (very unstable) to 0.99 mm  
198 (medium stability), with a mean of 0.68 mm, a variance of 0.04 mm<sup>2</sup> and a CV of 29%.  
199 The subsurface  $MWD_{SW}$  ranged from 0.39 mm (very unstable) to 1.08 mm (medium  
200 stability), with a mean of 0.60 mm, a variance of 0.04 mm<sup>2</sup> and a CV of 32%. Such  
201 dynamics in time are considered significant because there are larger than the spatial  
202 variability assessed at a given time by the monthly sampling (Figure 1a).

203 Considering the monthly time step only (Figure 1a), the CV of aggregate stability was  
204 29% for the surface and 32% for the subsurface. Considering the short time step, aggregate  
205 stability also varied greatly for both surface and subsurface: the same CV were found for  
206 both surface and subsurface. Variance of the aggregate stability was similar between the  
207 monthly time step and the short time step monitoring ( $p$ -value = 0.8 for both surface and  
208 subsurface).

209 Short time step sampling periods showed various trends in aggregate stability (Figure  
210 2). During the May short-time monitoring period (Figure 2a), the variance of surface

211 MWD<sub>SW</sub> was 0.01 mm<sup>2</sup> for both surface (CV=9%) and subsurface (CV=17%). The surface  
212 MWD<sub>SW</sub> decreased significantly immediately after rain 1, but did not changed after R2.  
213 Subsurface MWD<sub>SW</sub> did not varied significantly after both rain events. During June short-  
214 time monitoring period (Figure 2b), the surface MWD<sub>SW</sub> showed a variance of 0.05 mm<sup>2</sup>  
215 with a CV of 42%, while the subsurface MWD<sub>SW</sub> was much more stable (variance = 0.01  
216 mm<sup>2</sup> and CV=15%). The surface MWD<sub>SW</sub> decreased significantly after R3 and R4,  
217 showing its largest decrease after R4: from 0.78 mm (10 June, prior rainfall 4) to 0.38 mm  
218 (14 June). Inter-rain periods 3 and 4 showed a significant increase of the MWD<sub>SW</sub>, the  
219 largest increase of the MWD<sub>SW</sub> occurring during the inter-rain period 3: from 0.34 mm (8  
220 June) to 0.78 mm (10 June). During August short-time step monitoring (Figure 2c), the  
221 variance of MWD<sub>SW</sub> was 0.02 mm<sup>2</sup> for the surface (CV=20%) and 0.05 mm<sup>2</sup> for the  
222 subsurface (CV=30%). Both surface and subsurface MWD<sub>SW</sub> kept stable after R5 but  
223 decreased significantly after R6. Inter-rain periods 5 and 6 showed significant increase of  
224 MWD<sub>SW</sub> for both surface and subsurface.

## 225 Explanatory variables

226 Results of the temporal dynamics of the explanatory variables are presented in Tables  
227 3 and 4 and in Figures 3 and 4. Organic matter content varied between 1.8% and 1.4% ,  
228 with a variance of 0.01 %<sup>2</sup> and a CV of 6% for both surface and subsurface (Figure 3a).  
229 Microbial biomass showed a larger variability: a variance of 1609 and a CV of 26% for the  
230 surface and a variance of 2767 and a CV of 43% for the subsurface (Figure 3b).

231 The R index of the surface was often larger than 1.95, indicating that the samples  
232 could present a subcritical hydrophobicity. Water repellency showed a large temporal  
233 variability with a CV of 50% (Table 3, Figure 3c).

234 Air temperature varied between 1.6°C and 36.1°C. Air temperature was always  
235 positive during the monitoring period, hence no freezing occurred. Soil surface  
236 temperature varied between 4.8°C and 31.2°C with a CV of 32%, while subsurface  
237 temperature varied between 9.7°C and 30.4°C with a CV of 19% (Figure 4a and 4b). The  
238 studied site exhibited a cumulated rain of 219 mm. Among the 6 rain event considered, R3  
239 (June 4) presented the highest rain amount (26.2 mm in 7 hours) and a maximum intensity  
240 of 16.8 mm h<sup>-1</sup> (table 4b). The dynamic of the soil water content was very different between  
241 the surface and the subsurface. Surface water content showed a variance of 10.3 %<sup>2</sup> and a  
242 CV of 28% while subsurface water content remained very stable (variance = 0.06 %<sup>2</sup> and  
243 CV=4%) (Table 3c; Figure 4c).

#### 244 **Relationships between aggregate stability and explanatory variables**

245 Aggregate stability did not significantly correlated with microbial biomass, organic  
246 matter and water repellency whatever the stability test (Table 5). The same results were  
247 found between MWD and air temperature, soil temperature or air humidity (not shown).

248 A correlation analysis was performed to test the influence of the rain characteristic on  
249 aggregate stability. For the 6 considered rain events, correlation coefficient were calculated  
250 between rain amount, mean intensity and maximum intensity, and the MWD value  
251 measured immediately after the rain event. The best correlation coefficient was found  
252 between the maximum intensity of the rain event and the surface MWD measured  
253 immediately after the rain event ( $r = -0.77$  for  $MWD_{FW}$  and  $-0.83$  for  $MWD_{SW}$ ). Mean rain  
254 intensity and total rain amount did not correlate significantly with aggregate stability.  
255 Subsurface MWD did not correlate with rain event characteristics. The same analysis was  
256 performed between rain characteristics and the difference between MWD before and after  
257 the rain event. Here also, the best correlation coefficient was found between the maximum  
258 intensity of the rain event and the difference between MWD before and after the rain event

259 ( $r = 0.82$  for  $MWD_{FW}$  and  $0.80$  for  $MWD_{SW}$ ). Considering the soil water content and hydric  
260 history, for the surface, the MWD was significantly and negatively correlated with the  
261  $WC_0$ ,  $WC_{1/2}$ ,  $\Delta WC_4$  and API for both stability tests (Table 6). For the subsurface, no  
262 significant correlation were found between any of the MWD and the variables linked to  
263 hydric history (API,  $WC_0$ ,  $WC_{1/2}$  and  $\Delta WC_4$ ), except for the  $MWD_{SW}$  that significantly and  
264 negatively correlated with  $WC_0$  ( $r = -0.57$ ) (table 6).

265 In order to classify the influence of each variable found to be significantly correlated  
266 with aggregate stability, and to measure the combined effect of these variables, regression  
267 analysis were done. The considered variables were:  $WC_0$ ,  $WC_{1/2}$ , API and  $\Delta WC_4$  for the  
268 surface, and  $WC_0$  for the subsurface. At first, simple regression analysis was conducted  
269 (Table 7). For the subsurface, none of the simple regression models were significant,  
270 regardless of the aggregate stability test. Considering the surface  $MWD_{FW}$ , the best simple  
271 regression model was with  $WC_{1/2}$  (54% of  $MWD_{FW}$  variation). Models with  $WC_0$  or API  
272 were also statistically significant ( $r^2 = 51\%$  and  $37\%$ , respectively). For the slow wetting  
273 test, all four models were significant, with  $r^2$  between 39% and 50% (Table 7). The  
274 variables found to be significant during this simple regression analysis were combined in  
275 multiple regression models (except  $WC_0$ ,  $WC_{1/2}$ , and API, which were not independent).  
276 Among all combinations, the only valid multiple regression models were found for the  
277 surface.  $WC_{1/2}$  and  $\Delta WC_4$  together accounted for 59% of the  $MWD_{SW}$ , and the combination  
278 of  $WC_0$  and  $\Delta WC_4$  accounted for 57% of the  $MWD_{SW}$ .

## 279 Discussion

### 280 Aggregate stability varied significantly at short time step

281 The results show that the aggregate stability in the field varied greatly at short time  
282 steps (of a few days). Variations up to 32% were measured for both surface and subsurface  
283 materials. Short term dynamics of aggregate stability was already observed during

284 laboratory experiments (e.g. Utomo and Dexter, 1982; Deneff et al., 2001; Cosentino et al.,  
285 2006), but, according to our knowledge, only one study observed it in the field (Caron et  
286 al., 1992). Moreover, the variability of aggregate stability was never observed by field  
287 measurements for a bare soil without any external stimulation of biological activity.

288 Up to now, most field monitoring studies used monthly samplings to assess aggregate  
289 stability dynamics (Blackman, 1992; Bajracharya et al., 1998; Suwardji and Eberbach,  
290 1998; Dimoyiannis, 2009). Such studies showed that during the year, aggregate stability  
291 could vary between 20% up to 30%. The present study showed that same variability of  
292 aggregate stability was occurring at a much smaller time scale. Moreover, for specific  
293 periods, aggregate stability can show a larger variability at short time step than at monthly  
294 time step. It was the case for the June monitoring period when surface aggregate stability  
295 varied up to 46% over a 7-day period, proving that large changes in aggregate stability are  
296 occurring over a few days. In some cases, variations in aggregate stability at short time  
297 steps induced changes of up to two stability classes. Such large changes would affect soil  
298 properties, such as storage of water, root penetration (Gallardo-Carrera et al., 2007) or soil  
299 sensitivity to erosion (Le Bissonnais, 1996; Bajracharya et al., 1998; Wang et al., 2013), and  
300 thus, should not be ignored by future studies.

301 Considering this short term dynamics, it appears clearly that monthly measurements  
302 are not enough to assess precisely the temporal dynamic of aggregate stability. Monthly  
303 time step monitoring give information on the dynamics of aggregate stability at the  
304 seasonal scale, but monthly estimation of aggregate stability cannot be used as actual  
305 values of aggregate stability at a given time. Short time step measurements are required to  
306 reach accurate assessments of aggregate stability.

307 **Aggregate stability variation was primarily controlled by the rain intensity, soil water**  
308 **content and hydric history**

309 In the present study, soil was kept bare during all the monitoring, and no amendments  
310 were incorporated. Aggregate stability did not significantly correlated with organic matter  
311 content nor microbial biomass, for both surface and subsurface. This result leads us to  
312 conclude that a stimulation of biologic activity (i.e. organic amendment) is required to  
313 make it affect aggregate stability.

314 Water repellency of the surface aggregates varied independently from the aggregate  
315 stability. Based on previous studies (Piccolo and Mbagwu, 1999; Cosentino et al., 2006;  
316 Goebel et al., 2012) this variable was expected to influence aggregate stability. In our case,  
317 the range of measured R index (between 1.9 and 7.0) did not correspond to very contrasted  
318 water repellencies. It seems that more contrasted water repellencies are required to  
319 influence aggregate stability.

320 The result of the present study underlined the significant influence of rain events on  
321 surface aggregate stability dynamics. Aggregate stability decreased significantly after 4 of  
322 the 6 rain events. The largest decrease was observed for the rain 4 which showed the  
323 highest total rain amount and maximum rain intensity. According to the results of the  
324 correlation analysis, the maximum rain intensity appeared to be the dominant factor of  
325 aggregate stability decrease upon all the considered rain characteristics. The greater the  
326 maximum rain intensity, the greater the aggregate stability decrease. Relationships between  
327 rain amount and aggregate stability were observed in the field by monthly monitoring  
328 studies (Blackman, 1992; Bajracharya et al., 1998; Suwardji and Eberbach, 1998;  
329 Dimoyiannis, 2009). Usually, temporal patterns of precipitation are considered as an  
330 important factor in aggregate stability decrease through raindrop impact, which affects the  
331 structure of surface aggregates, and through the increase of soil water content (e.g.  
332 Shainberg et al., 2003; Dimoyiannis, 2009). The present study underlines the importance of  
333 rain intensity on the short time step aggregate stability decrease. More than the rain

334 amount, the maximum rain intensity seems to be a dominant indicator of surface aggregate  
335 stability decrease. However, as only six rain events were considered, such result must be  
336 taken carefully, and more detail studies should be conducted to confirm this observation.

337 Subsurface aggregate stability was not related to rainfall characteristics

338 The results also showed that the soil water content and its dynamics were dominant  
339 factors of surface aggregate stability. Soil water content at the time of sampling ( $WC_0$ ) and  
340 few hours before sampling ( $WC_{1/2}$ ) were significantly and negatively correlated with  
341 aggregate stability. Simple regression models with  $WC_0$  explained up to 51% of aggregate  
342 stability variation ( $MWD_{FW}$ ), while simple regression models that included  $WC_{1/2}$   
343 explained up to 54% of the aggregate stability variations ( $MWD_{FW}$ ), making  $WC_{1/2}$  the  
344 dominant explanatory factor in aggregate stability variation at short time step.

345 Previous studies (e.g., Perfect et al., 1990; Blackman, 1992; Dymoyiannis, 2009) have  
346 found negative correlations between water content and aggregate stability variation at the  
347 monthly time step. The present study found similar relationships at a short time step (a few  
348 days) but for surface aggregate stability only. In a field monitoring study performed at  
349 short time step (2 days) on a bare soil, Caron et al. (1992) did not found significant  
350 relationships between aggregate stability and  $WC_0$ . In this previous study, samplings were  
351 performed within the plowed layer (between -15 and -25 cm). Similarly, the present study  
352 did not a relationship between aggregate stability and  $WC_0$  for the plowed layer (-1 to -5  
353 cm). Such a relationship was found only for the soil surface (0 to -0.5 cm).

354 The soil hydric history indices  $\Delta WC_4$  and API were found to be significant factors of  
355 surface aggregate stability and were negatively correlated with aggregate stability for the  
356 soil surface. The relationship between the water content history and aggregate stability give  
357 two pieces of information. Firstly, aggregate stability decreases when the soil is getting  
358 more humid: the greater the wetting, the larger the decrease of aggregate stability. This

359 result confirms the negative influence of rain amount and intensity on aggregate stability  
360 that we previously observed. A high rain intensity provokes a rapid soil wetting with a  
361 large wetting amplitude that decreases aggregate stability (e.g. R3), while a rain event with  
362 a low rain intensity and thus a wetting with a small amplitude do not affect aggregate  
363 stability (e.g. R5). Secondly, aggregate stability increases when the soil is drying, and the  
364 more intense the drying, the larger the increase of aggregate stability: a large amplitude  
365 drying caused an increase in aggregate stability as it was the case during IR 3 and 6, while  
366 a small drying amplitude did not affect aggregate stability as for IR 1 and 2.

367 These results were previously observed by laboratory studies. They showed wetting  
368 cause a decrease of aggregate stability through physico-chemical processes such as the loss  
369 of inter-particle cohesion (Sheel et al., 2008), slaking (Zaher et al., 2005) and microcracking  
370 (Le Bissonnais, 1996). They also showed that drying increases aggregate stability by the  
371 formation of bonds between particles in relationship with clay flocculation and  
372 precipitation of soluble components (Kemper and Rosenau, 1984; Kemper et al., 1987;  
373 Dexter et al., 1988). While these relationships were only observed in laboratory  
374 experiments, the present study clearly observed similar relationships for field conditions,  
375 suggesting the same processes may be active.

## 376 **Conclusions**

377 Aggregate stability varied greatly over time steps of a few days for both surface and  
378 subsurface. Short term dynamics of aggregate stability were already shown by laboratory  
379 experiments, but such dynamics was never observed in the field for a bare soil without  
380 external stimulation of biological activity (i.e. no organic amendment). MWD variations of  
381 up to 42% were measured at short time step for specific periods proving that large changes  
382 in aggregate stability are occurring even in a few days. Such large changes are likely to  
383 affect soil properties such as storage of water and soil sensitivity to erosion, and thus,

384 should not be ignored. At the surface, short time step variations of aggregate stability were  
385 primarily related with water: Rain maximum intensity, water content at or close to the time  
386 of sampling ( $WC_0$  and  $WC_{1/2}$ ), and hydric history indices ( $\Delta WC_4$  and API) were the  
387 dominant factors influencing surface aggregate stability. While large changes in aggregate  
388 stability were found for the subsurface, explanatory factors remain to be found. These  
389 results underline the dominant effect of abiotic factors such as water content dynamics on  
390 aggregate stability variations at a short time step in the field in the absence of biological  
391 activity stimulation. To improve the prediction of aggregate stability, further research  
392 should analyze the interactions between abiotic and biotic factors at short time step in the  
393 field.

394

395

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## 475 **Figure caption**

476 **Figure 1:** Temporal variation of aggregate stability for the slow wetting test of surface and  
477 subsurface at monthly time step (a) and short time step (b).

478 MWD<sub>sw</sub> monthly time step: each MWD<sub>sw</sub> point corresponds on the mean of three samples  
479 located on the same plot (spatial variability) and 3 replicates for each measurements ( $n=9$ ).

480 Bars are standard errors.

481 MWD short time step: each MWD corresponds on the mean of three replicates ( $n=3$ ). Bars  
482 are standard error.s

483 Stable, Medium, Unstable, Very unstable, refers to the aggregate stability classes (Le  
484 Bissonnais, 1996)

485 **Figure 2:** Temporal variation of aggregate stability for the slow wetting test at short time  
486 step for (a) May , (b) June and (c) August.

487 MWD monthly time step: each MWD corresponds on the mean of three samples located on  
488 the same plot (spatial variability) and 3 replicates for each measurements ( $n=9$ ). Bars are  
489 standard errors.

490 MWD short time step: each MWD corresponds on the mean of three replicates ( $n=3$ ). Bars  
491 are standard errors.

492 R1, R2, R3, R4, R5, and R6 refer to the number of the rain event.

493 **Figure 3:** Temporal variation in (a) organic matter content, (b) microbial biomass and (c)  
494 water repellency.

495 a and b: each point is the mean of three replicates; bars are standard errors.

496 c: each point is the mean of 10 replicates; bars are standard errors.

497 **Figure 4:** Temporal dynamics of the soil variables; a) Surface soil temperature, b)  
498 subsurface soil temperature, c) Volumic soil water content for surface and subsurface.

499 Curves are to the mean of two replicates

500

501

Table 1: Soil properties for the studied site

<b>Culture (current/ antecedent)</b>	<b>Clay</b>	<b>Silt</b>	<b>Sand</b>	<b>Organic matter</b>	<b>CEC</b>	<b>pH</b>	<b>Ca</b>	<b>Mg</b>	<b>K</b>	<b>Na</b>
	g kg <sup>-1</sup>		cmol kg <sup>-1</sup>			g kg <sup>-1</sup>				
Wheat/Maize	164	798	38	21.6	9.1	6.7	8.8	0.5	0.6	0.03

# Postprint

Version définitive du manuscrit publié dans / Final version of the manuscript published in:  
Soil Science Society of America Journal, 2014, 78(4), 1168- <http://dx.doi.org/10.2136/sssaj2014.01.0009>

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Version postprint

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Table 2: Sampling pattern and rain events during field monitoring

Date	Sampling		Rain event
	Monthly	Short term	
16/3	S0		
30/3	S1		
28/4	S2		
2/5			R1
3/5		S3	Inter-rain
5/5		S4	period 1
7/5			R2
9/5		S5	
11/5		S6	
13/5		S7	Inter-rain
16/5		S8	period 2
18/5		S9	
30/5	S10		
4/6			R3
7/6		S11	Inter-rain
8/6		S12	period 3
10/6		S13	
14/6		S14	R4
16/6		S15	Inter-rain
4/7	S16		period 4
2/8	S17		
4/8			R5
8/8		S18	Inter-rain
10/8		S19	period 5
12/8		S20	
14/8			R6
16/8		S21	Inter-rain
18/8		S22	period 6

504 S = sampling; R = rain event

505

506

507 Table 3: variability of the organic matter content, microbial biomass and water repellency

508 of aggregates

	<b>Microbial biomass</b>				<b>Water repellency</b>							
	Max	Min	Mean	CV	Max	Min	Mean	CV				
	<b>mg kg<sup>-1</sup></b>				<b>%</b>							
					<b>R index</b>							
					<b>%</b>							
Surface	1.8	1.4	1.7	6	234	72	147	26	7.4	1.2	3.3	50
Subsurface	1.8	1.5	1.7	7	256	37	117	46				

509

510

511 Table 4: variability of the a) atmospheric variables: air temperature (Air T), air humidity  
 512 (Air H) and cumulated rain, b) rain event characteristics, and c) soil variables: soil  
 513 temperature (Soil T) and soil water content (Soil WC) for the whole monitoring duration.

514 a)

Air T		Air H		Cumulated rain		mm
Max	Min	Mean	SD	Mean	SD	
°C		%				
36.1	1.6	16.1	5.3	76.8	20.5	219

515

516 b)

Rain event	Date	Duration	Rain amount	Maximum intensity
		h	mm	mm h <sup>-1</sup>
R1	2/5	5	4.0	2.0
R2	7/5	3	13.2	7.0
R3	4/6	7	26.2	16.8
R4	14/6	1	9.8	9.8
R5	4/8	8	13.5	4.0
R6	14/8	5	7.4	4.8

517

518 c)

	Soil T				Soil WC			
	Max	Min	Mean	CV	Max	Min	Mean	CV
	°C				%			
<b>surface</b>	31.2	4.8	19.1	32	22.5	6.1	11.7	28
<b>subsurface</b>	30.4	9.7	18.9	19	22.8	17.9	19.6	4

519

520 Table 5: correlations (Pearson's coefficient) between aggregate stability and organic matter

521 content, microbial biomass and water repellency.

	Surface		Subsurface		
	OM	BIOMI	WR	OM	BIOMI
<b>MWD<sub>FW</sub></b>	0.33 (ns)	0.25 (ns)	0.12 (ns)	0.34 (ns)	-0.07 (ns)
<b>MWD<sub>sw</sub></b>	0.14 (ns)	0.32 (ns)	0.24 (ns)	-0.29 (ns)	-0.06 (ns)

522 dataset:  $n=19$ ;  $df=17$ ;  $\alpha=5\%$ ;  $r=0.46$

523 ns=Not significant at the 5% level

524 OM = organic matter content

525 BIOMI = microbial biomass

526 WR=water repellency

527 Table 6: Correlations (Pearson's coefficient) between MWD and soil water indices

	Surface				Subsurface			
	$WC_0$	$WC_{1/2}$	$\Delta WC_4$	$API$	$WC_0$	$WC_{1/2}$	$\Delta WC_4$	$API$
$MWD_{FW}$	-0.73*	-0.76*	-0.54*	-0.63*	0.14(ns)	0.13(ns)	0.25(ns)	-0.18(ns)
$MWD_{SW}$	-0.69*	-0.72*	-0.70*	-0.65*	-0.57*	-0.37(ns)	-0.04(ns)	-0.25(ns)

528

529 dataset:  $n=19$ ;  $df=17$ ;  $\alpha=5\%$ ;  $r=0.46$

530 \* significant at the 5% level

531 ns = not significant at the 5% level

532  $WC_0$ : soil water content at the time of sampling

533  $WC_{1/2}$ : mean soil water content for half a day prior to sampling

534  $\Delta WC_4$ : difference between water content at the time of sampling at water content 4 days

535 prior to sampling

536  $API$ : antecedent precipitation index

537

538

Table 7: Simple regressions for MWD variations

Dataset	Df	WC <sub>0</sub>		WC <sub>1/2</sub>		API		ΔWC <sub>4</sub>			
		R <sup>2</sup>	level	R <sup>2</sup>	level	R <sup>2</sup>	level	R <sup>2</sup>	level	R <sup>2</sup>	level
Surface		<b>FW</b>	17	0.51	**	0.54	**	0.37	*	0.25	.
		<b>SW</b>	17	0.44	*	0.50	**	0.39	*	0.47	**
Subsurface		<b>FW</b>	17	0	ns	0	ns	0	ns	0.01	ns
		<b>SW</b>	17	0.23	.	0.29	.	0.07	ns	0	ns

539

540

Df= degrees of freedom; R<sup>2</sup>= adjusted coefficient of determination

541

FW: Fast wetting test. SW: Slow wetting test.

542

\*\* Model significant at the 1 % level

543

\* Model significant at the 5% level

544

. Model significant at the 10 % level

545

ns Model not significant at the 10 % level

546

WC<sub>0</sub>: soil water content at the time of sampling

547

WC<sub>1/2</sub>: average soil water content half a day prior to sampling

548

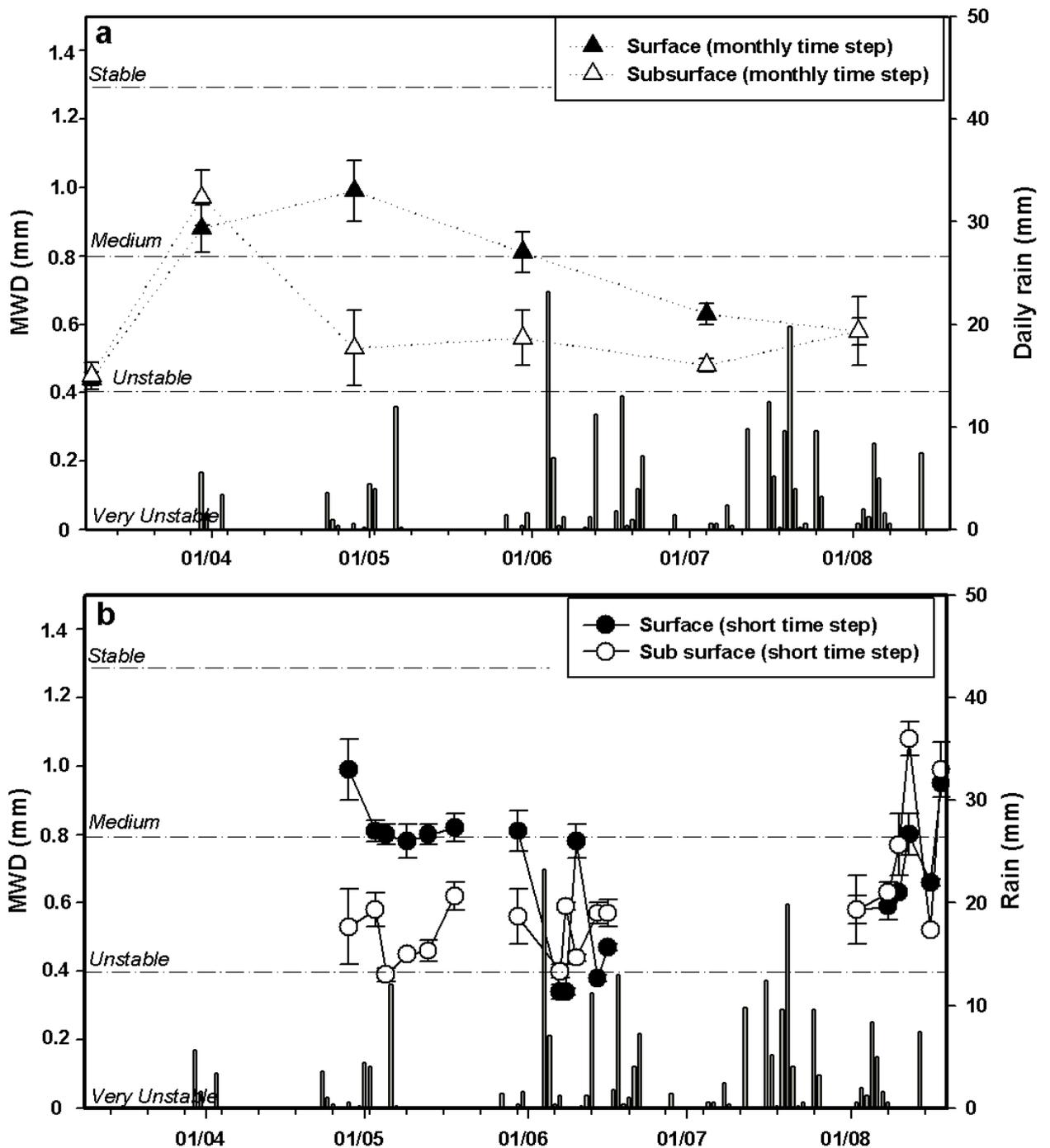
ΔWC<sub>4</sub> : difference between soil water content at the time of sampling and soil water

549

content four days before

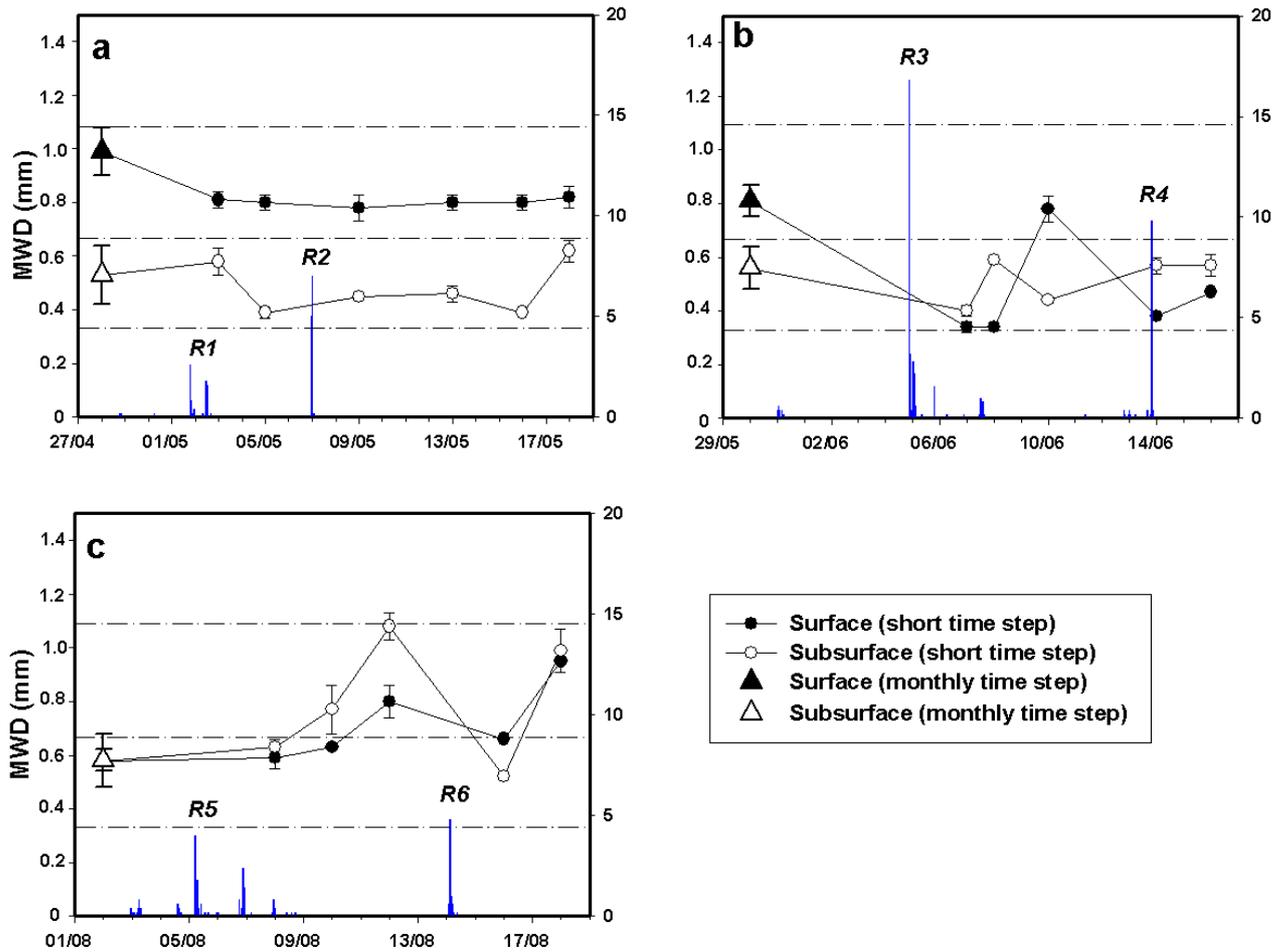
550

API: antecedent precipitation index



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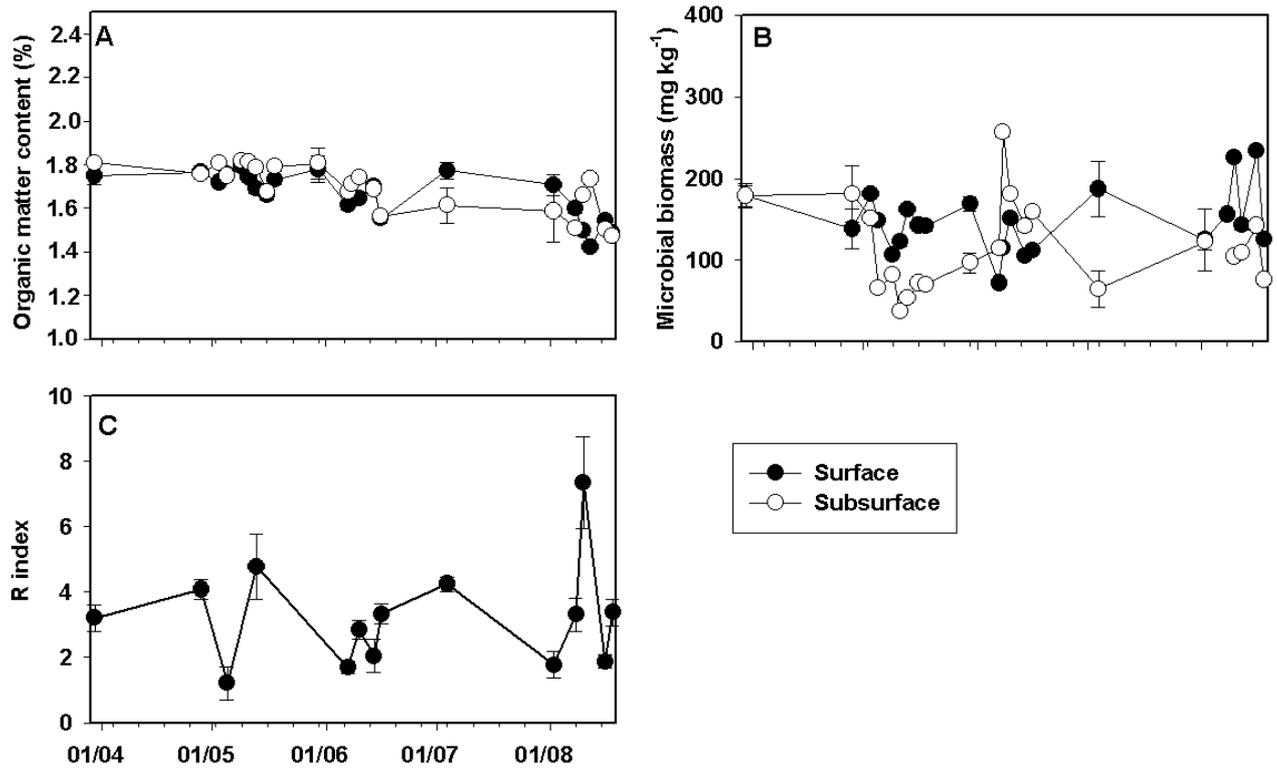
562 **Figure 2:** Temporal variation of aggregate stability for the slow wetting test at short time  
 563 step for (a) May , (b) June and (c) August.

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570



572 **Figure 3:** Temporal variation in (a) organic matter content, (b) microbial biomass and (c)  
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576

577

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