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*Running title: Effects of slurry management on soil aggregates*

**Summary**

Effects of applications of pig slurry on soil aggregate stability are not well understood in dryland agriculture. This research aims to (i) identify aggregate stability tests that give a reliable description of the soil's behaviour when pig slurry (PS) is applied to calcareous soil and (ii) interpret them in terms of chemical, biological, morphological and physical soil properties for soil quality assessments. Soil samples from eight fertilizer treatments (mineral fertilizers and PS), applied over seven growing seasons were analysed. We applied five methodologies to examine different mechanisms of aggregate breakdown. Porosity was characterized by image analyses. There was minimum resistance to the mechanical breakdown of aggregates when slurries were applied 12 months before analysis. Recent applications of slurry (3 months before the analysis) improved resistance to implosion caused by the penetration of water into dry aggregates (slaking), although the opposite result can occur if the method of evaluation is not chosen properly. Recent applications of PS also enhanced soil respiration and increased soil porosity in the 25–100 μm size range (packing pores between aggregates) and in the 100–400 μm size range (interaggregate or faunal pores). In dryland systems and in the winter cereal cropping season, the resistance of dry aggregates to slaking is improved temporarily if PS is applied at N rates equivalent to around 1.7 Mg OM $ha^{-1}$ $year^{-1}$.

*Keywords: Aggregate breakdown dynamics, arid soil, pore-size distribution, soil fertility, soil respiration.*

**Highlights**

- How does soil aggregate strength change in response to pig slurry (PS) applications?
- Improve understanding of PS as a fertilizer and its effect on soil quality assessments
- Changes in aggregate stability are controlled by time since pig slurry application
- The effects of PS on the increment of packing pores between aggregates are transient

## Introduction

The stability of soil aggregates and architecture of the pore space affect the movement and storage of water, aeration, erosion, biological activity and the growth of crops. The chief mechanisms of aggregate breakdown by water (Le Bissonnais, 1996) are: (i) compression of air entrapped inside aggregates during wetting, which occurs when dry aggregates are immersed in water or rapidly wetted, (ii) breakdown by microcracking of aggregates because of internal pressure from differential swelling of clays, (iii) mechanical breakdown of aggregates by external pressures caused by raindrop or other impacts and (iv) physicochemical dispersion caused by changes in the double-layer forces that act between electrically charged colloids. Slaking and differential swelling induce changes in soil structure because they result in the breakdown of larger macroaggregates to smaller microaggregates. Raindrop impact and physicochemical dispersion may cause the release of soil particles. Every cause of aggregate breakdown requires different methodologies to measure it. Some differences arise from the swelling potential of different soil minerals (Emerson, 1964) because the clay fraction in natural aggregates usually consists of a mixture of minerals of various particle sizes. In semiarid environments, the presence of carbonates interferes with the relation between clay minerals and soil aggregation, resulting in enhanced macroaggregate stabilization in carbonate-rich soil but with less porosity within the macroaggregates (Virto *et al.*, 2013). Furthermore, because calcium is adsorbed better to clay surfaces than is sodium, it reduces swelling and dispersion, which preserves structural integrity. The type of clay minerals also affects the proportion of air and water in an aggregate. The air-filled porosity of aggregates dominated by kaolinite and illite is larger than that of aggregates dominated by smectite (Oades, 1986), which also implies greater hydraulic conductivity

in the former. Kaolinite and illite have more rigid structures than smectite, and the stress induced by the rapid entrapment of air inside aggregates containing kaolinite and illite facilitates slaking (Tessier *et al.,* 1990). Slaking is also affected by the initial water content. Slaking decreases as the initial water content of aggregates increases until saturation is reached (Panabokke & Quirk, 1957).

Size distribution, quantity and stability of aggregates determine the amount and distribution of pore spaces associated with them. Soil pore characteristics are required for the complete assessment of habitat availability for micro-fauna and microorganisms, of the aptitude for root growth, of fluid transport through the soil profile and of soil aeration. Lynch & Bragg (1985) suggested that pores of 0.1–15 μm hold water available to plants, pores larger than 30–60 μm allow water to drain under gravity and those >60 μm are important in gas exchange. The pore spaces affect almost everything that occurs in the soil; they are affected by particle-size distribution, soil structure and forces that disrupt this. Micromorphology techniques with 2-D images from undisturbed soil thin sections enable us to study the porosity of the 3-D soil body because some stereological relations exist, such as the one that equates pore volume density to their areal extent in 2-D (Ringrose-Voase & Nortcliff, 1987).

There is clear evidence that microorganisms are involved in the aggregation process because microbial activity controls the production of exudates which act as binding agents in aggregates (De Gryze *et al.,* 2005). In any soil where clay is present, interactions between the polysaccharide exudates, organic colloids and other products of decomposition promote stability (Dontsova & Bigham, 2005). Soil structure is improved by the addition of organic materials to soil (Tisdall & Oades, 1982). Nevertheless, detailed information about the effects of pig (*Sus scrofa domesticus*) slurries on soil physical properties is lacking. This is an important issue in Spain

because it is the leading European country for pig production, and pig slurries are often applied directly to fields each year, mainly in dryland farming systems. Furthermore, slurries of different origin have different composition; the main differences are between slurries from fattening pigs and sows (Yagüe *et al*., 2012a).

Apart from its OM content, pig slurry (PS) can affect soil structure in various ways. Slurries supply Na, Mg and Ca in addition to the three major nutrients (N, P and K). The exchangeable cations ($K^+$, $Na^+$, $Mg^{2+}$ and $Ca^{2+}$) affect aggregation. Sodium ($Na^+$) causes mainly swelling or dispersion or both of clay particles and slaking of unstable aggregates (Crescimanno *et al.,* 1995). Aggregate dispersion generally leads to rapid crusting of the soil, slow infiltration and great mobility of particles in water. In calcareous soil (with exchangeable sites saturated with calcium), both $Ca^{+2}$ and $Mg^{+2}$ reduce clay dispersion (Amézketa & Aragües, 1995). Furthermore, the adsorbed $K^+$ limits clay dispersion because of its hydration energy, which is equivalent to 72% of that of adsorbed $Na^+$ (Levy & Torrento, 1995).

The main goal of this study was to assess methodologies that can reflect potential changes in aggregate stability with the application of PS to calcareous soil. We began with the hypothesis that success in quantifying potential changes in aggregate stability after a medium period (seven growing seasons) of PS use: (i) will be closely linked to the dominant breakdown mechanism taking place, (ii) the best evaluation method should be supported by other soil properties such as chemical (cation exchange capacity, CEC), biological (soil respiration) and physical (pore-size distribution from image analyses in spite of the scale differences between aggregates or the soil fraction, and porosity in the bulk soil) and (iii) the differences between the methods could be affected by the length of sampling time since the last slurry application.

The choice of methods took into account the different mechanisms of aggregate breakdown and the factors affecting them, such as the method of wetting. Although the aggregate stability tests were designed mainly to compare different types of soil or climatic conditions for a given soil (Le Bissonnais, 1996), we applied them to compare time-dependent changes associated with fertilizer management.

## Materials and methods

### *Site description*

The experiment was in the Ebro valley (NE Spain). The area has a Mediterranean semiarid climate with an average annual precipitation of 436 mm for the period 2000–2010. The altitude is 443 m a.s.l. and the coordinates are 41° 52' 29" N, 1° 09' 10" E. The soil is classified as a Typic Xerofluvent (Soil Survey Staff, 2014) and the surface horizon (0–0.30 m) had a pH of 8.2 (1:2.5 soil:distilled water), organic matter content of 20.1 g $kg^{-1}$, CEC was 11.1 $cmol_c$ $kg^{-1}$ and the texture is a silty loam (131 g $kg^{-1}$ sand, 609 g $kg^{-1}$ silt and 260 g $kg^{-1}$ clay). Illite and chlorite are the dominant clay minerals with traces of talc and 1:1 clays such as kaolinite (Figure 1). The soil is not saline and calcium carbonate ($CaCO_3$) content was 300 g $kg^{-1}$.

The experimental site was established in 2002 and winter cereals were grown until 2011, except for the 2007–08 cereal growing season when the field was left fallow. The rotation was: three years barley (*Hordeum vulgare* L.) and one year wheat (*Triticum aestivum* L.). Sowing was done between late October and early November, and after harvest (end of June to early July) straw was removed from the fields for animal bedding and feed.

The experimental area was divided into three blocks and seven fertilizer treatments were assigned at random to the plots in each block. These treatments yielded an average

biomass (at 0% humidity) that ranged from 2985 to 3543 kg grain $ha^{-1}$ $year^{-1}$. One control (no N, no OM applied) with an average grain yield (0% humidity) of 2624 kg $ha^{-1}$ $year^{-1}$ was also included to give eight treatments in total (Table 1). Apart from this control, one treatment received only mineral fertilizer and the rest (six treatments) included PS of different origins, either fattening pigs (FS) or sows (SS). Just before sowing, four treatments received 30 t $ha^{-1}$ $year^{-1}$ of slurry from fattening pigs (30FS), the remaining four did not receive slurry or mineral nitrogen (0). In February (at the cereal tiller growth stage), the soil of six of the treatments received fertilizer. Two of them received mineral nitrogen fertilizer (M): 60 or 120 kg N $ha^{-1}$ $year^{-1}$ (60M or 120M), two received slurry from fattening pigs: 20 or 60 t $ha^{-1}$ $year^{-1}$ (20FS or 60FS) and the last two received slurry from sows: 60 or 90 t $ha^{-1}$ $year^{-1}$ (60SS or 90SS). In the two treatments where slurry was applied only at tillering (0–60FS or 0–90SS, rates at sowing and tillering, respectively), the average range of OM applied (1764–2622 kg $ha^{-1}$ $year^{-1}$) was similar to the range applied (1681–2491 kg $ha^{-1}$ $year^{-1}$) to plots that received slurry only at sowing (30FS–0 or 30FS–60M, rates at sowing and tillering, respectively) or combined with slurry at tillering (30FS–20FS or 30FS–60SS, rates at sowing and tillering, respectively).

Apart from yield records, the treatments were chosen because they enabled comparisons between the amounts of OM applied and between the different application times. Treatments 0–90SS and 30FS–0 had similar average amounts of OM applied over the seven growing seasons (Table 1). These rates of OM applications were also increased by 50% in two other treatments (0–60FS and 30FS–20FS). Finally, we added an intermediate rate of treatment of 30FS–60SS with an increment of 25% in the OM applied.

167 Slurries were applied by the splash plate method. The control and the plots with
168 only mineral N fertilizer (0–120M, rate at sowing and rate at tillering, respectively)
169 received mineral phosphorus (42 kg P $ha^{-1}$ $year^{-1}$) and potassium (89 kg K $ha^{-1}$ $year^{-1}$)
170 before sowing.

171 All fertilizers applied just before sowing were incorporated into the soil and mixed
172 with the stubble remaining in the field by tillage with an offset disc harrow (0–0.15 m).
173 This incorporation favours a uniform distribution of slurries at depth. The size of plots
174 that had pig slurry was 274 $m^2$ (11-m wide and 25-m long) and the size of the control
175 plots and plots with mineral fertilizer only (0–120M) was 174 $m^2$ (7-m wide and 25-m
176 long).

177 *Soil sampling, chemical and biological soil analysis*

178 Soil sampling was done two days before top-dressing on 23 February 2011 (after 7
179 years of fertilizer treatments and one of fallow). This means that four treatments were
180 sampled three months after the last slurry application (S3mo) and two treatments were
181 sampled twelve months after the last slurry application (S12mo). From each treatment
182 and block, soil samples were taken at 0–10-cm depth with a corer (7 cm in diameter
183 with steel bores) to assess aggregate stability and biological activity, and for chemical
184 analysis. For each plot (associated with a specific treatment), four points were sampled.
185 Part of each sample was air-dried and stored, and the rest was refrigerated before
186 processing. All samples were sieved gently to 2 mm before being analysed.

187 Furthermore, undisturbed soil samples from a similar depth to the above were taken
188 to study porosity from soil thin sections. From each treatment, three undisturbed soil
189 samples with a rectangular prism shape (6.2 cm × 9.1 cm × 19.3 cm) were taken from
190 the three replicate blocks to give 72 samples or rectangular prisms. The undisturbed

191 rectangular prisms were dried at room temperature and impregnated with polyester resin
192 with a fluorescent dye (Uvitex©, CibaGeigy Ltd, Manchester, England). One vertical
193 thin section (50-mm wide, 130-mm long) was made from each prism. Pore morphology
194 was evaluated qualitatively.

195 From each thin section, three fields (31.5-mm wide, 42.0-mm long) were selected to
196 obtain images with an Olympus® C-7070 wide zoom camera (Olympus Corporation,
197 Tokyo, Japan) under three light conditions: parallel polarizers (PPL), crossed polars
198 (XPL) and incident UV light. The latter was processed with ImageJ (Rasband, 2008) to
199 obtain digital binary images (with PPL and XPL as control) from which the total
200 porosity was analysed statistically. Each image set was used to analyse pore-size
201 distribution based on an 'opening' algorithm of mathematical morphology with the
202 Quantim4 library (Vogel, 2008). Pore sizes in the following four ranges (values in
203 micrometres): 25–65, 65–100, 100–200, 200–400 and > 400 μm were identified.

204 Cation exchange capacity and exchangeable cations were evaluated (for each
205 treatment and block) by extraction with ammonium acetate 1N (pH=7) in a composite
206 sample (obtained from the four sampled points) of each plot. The exchangeable cations
207 $K^+$, $Na^+$, $Mg^{2+}$ and $Ca^{2+}$ were determined following Hendershot *et al.* (2008).

208 Microbial activity and aggregate stability procedures required three and four
209 replicates, respectively, to be analysed for each plot and it should be evaluated as soon
210 as possible after sampling. Therefore, these procedures were applied to samples from
211 the different treatments from one block only in the central area of the experimental site.

212 Soil respiration (Alef, 1995) was determined by measuring the $CO_2$ produced
213 during a 21-day incubation experiment at 28±2ºC, measured at 1, 7, 14 and 21 days
214 during the incubation period. For each treatment and the three replicates, 100 g of soil
215 adjusted to 65% of its water-holding capacity was placed in a 2 l hermetic glass jar with

a vial containing 25 ml 0.1M NaOH; the NaOH was titrated with 0.1M HCl with phenolphthalein as the indicator.

*Physical soil analysis: methods for measuring aggregate stability*

Aggregate stability was measured first according to aggregate-size distribution (mean weight diameter, MWD), which included three different methods for three different initial disrupting forces: slow wetting ($MWD_{SW}$), fast wetting ($MWD_{FW}$) and stirring after pre-wetting, which causes mechanical breakdown ($MWD_{MB}$). Water-stable aggregates were also determined by the wet method ($WSA_{WET}$) and its modification ($WSA_{DRY}$), which avoided initial slow pre-wetting. Four laboratory replicates were used for each plot and every aggregate stability method.

The MWD relates to the aggregates that remain after the various treatments leading to disaggregation. Treatments included: slow wetting which measures the stability of aggregates affected by differential swelling (microcracking of aggregates), fast wetting which measures the resistance of soil aggregates to the implosion caused by the penetration of water into soil aggregates (slaking) and by the dissolution and dispersive actions of water, and stirring after pre-wetting which measures the stability of aggregates subjected to mechanical breakdown (stirring). Analyses were done following the method of Amézqueta *et al.* (1996) which uses 1–2-mm diameter aggregates, but includes the size fraction < 0.25 mm. These authors used ethanol in one of the tests and in the measurement of disaggregation because it enables different breakdown mechanisms to be studied independently. Ethanol prevents slaking and swelling because of its relatively low surface tension and its much smaller dielectric charge than that of water. In addition, particles do not reaggregate during drying (Merzouk & Blake, 1991).

239 The different disrupting mechanisms were applied to 4 g of soil aggregates: (i) slow
240 wetting, where aggregates were placed on a 0.25-mm mesh sieve and wetted until
241 saturation in a vapour chamber (deionized water), (ii) fast wetting, where aggregates
242 were placed on a 0.25-mm mesh sieve and immersed gently for 10 minutes in 100 ml of
243 deionized water and (iii) stirring after pre-wetting, where aggregates were immersed
244 gently in 50 ml of ethanol for 10 minutes. Following this, the ethanol was removed
245 carefully by decantation and the aggregates were transferred to an Erlenmeyer flask
246 filled with 50 ml deionized water, and the level was adjusted to 200 ml. The Erlenmeyer
247 was corked and agitated end over end 20 times, and left for 30 minutes to allow coarse
248 particles to settle. After removing the excess water by pipette, the remaining soil–water
249 mixture was transferred to a 0.25-mm mesh sieve.

250 In all procedures, the sieves were transferred to the modified Yoder apparatus and
251 disaggregation involved moving the sieves immersed in ethanol (95%) up and down
252 mechanically 10 times over a distance of 1.3 cm.

253 The fraction > 0.25 mm was oven-dried (105ºC, 24hours) and dry-sieved for 1
254 minute on a column of four 6.5-cm diameter sieves with mesh sizes of 2.0, 1.0, 0.5 and
255 0.25 mm with a standard mechanical sieve shaker.

256 The aggregate stability for each treatment was expressed as MWD (μm). It was
257 calculated by Equation (1):

258 $$\mathrm{MWD} = \sum_{i=1}^{n} W_i \times D_i \times 10^3, \qquad (1)$$

259 where $n$ is the number of aggregate size fractions considered in the analysis, $D_i$ is the
260 mean diameter of aggregates that can potentially stay in the $i$th and $i$+1 sieves in the
261 four size class: $D_1$=1.5 mm (≥ 1 mm to 2 mm), $D_2$=0.75 mm (≥ 0.5 mm to 1 mm),
262 $D_3$=0.375 mm (≥ 0.25 mm to 0.5 mm) and $D_4$=0.125 mm (< 0.25 mm), and $W_i$ is the

263 mass percentage of each fraction, which equals the dry weight of aggregates in the *i*th
264 size fraction (g) divided by the sum of total sieved dry soil weight fractions (g)
265 including the smallest (< 0.25 mm) after disaggregation.

266 The standard test for water-stable aggregates ($WSA_{WET}$) is the single-sieve (0.25
267 mm) method (Kemper & Rosenau, 1986). We placed 4 g of a 1–2 mm air-dried sample
268 (Mt) on the sieve which was wetted with deionized water vapour (slow wetting) to
269 saturation. The sieve was placed in a modified Yoder apparatus and was raised and
270 lowered through a 1.3-cm vertical distance for 3 minutes at a frequency of 0.6 Hz in
271 deionized water. Soil remaining on the sieve was oven-dried (105ºC, 24 hours) and
272 weighed to give the mass of the resistant or stable aggregates (Mr). After weighing,
273 aggregates were dispersed with an ultrasonic probe for 30 minutes. The fraction of each
274 sample remaining on the 0.25 mm sieve was oven-dried (105ºC, 24 hours) and weighed
275 to obtain the mass of >0.25 mm sand (Ms). The mass percentage of water-stable
276 (macro)aggregates (WSA) was calculated by Equation (2):

277 $$\mathrm{WSA}\,(\%) = \frac{\mathrm{Mr} - \mathrm{Ms}}{\mathrm{Mt} - \mathrm{Ms}} \times 100 \qquad (2)$$

278 In the modified test ($WSA_{DRY}$), air-dried samples (Wt) were processed directly
279 without being vapour wetted first in order to cause maximum disruption of aggregates.

280 *Statistical analysis*

281 The statistical analyses were done with SAS v9.4 (SAS Institute Inc., 2002–2012). Data
282 were analysed by an analysis of variance (ANOVA) and the residuals were checked for
283 normality and homogeneity of the variances. If these assumptions did not hold,
284 appropriate transformations were applied. The standard error of the difference between
285 means (SED) was computed and means were compared with Fisher's least significant
286 difference (LSD). Differences were considered significant at $P<0.05$.

The samples (four for each treatment) used to measure respiration and aggregate stability were taken from one block only, therefore, there is no true replication (pseudo-replication) and any significant differences identified must be treated with caution. The distances between samples within a plot can be larger than those between samples from different treatments (plots are 7 to 11-m wide and 25-m long), and the results of these properties are consistent with the differences obtained between treatments for the rest of measurements which did have true replication (three blocks).

## Results

### *Aggregate stability*

The coefficient of variation (CV) of aggregate stability data, irrespective of the applied test, was <19% except for $WSA_{WET}$ for the 0–90SS treatment (CV=24%). The $MWD_{MB}$, $MWD_{FW}$ and $WSA_{DRY}$ tests enabled us to detect differences between fertilizer treatments on aggregate stability (Table 2; Figure 2a,b). The $WSA_{DRY}$ test established a grading in the increase in stability following the treatment order (from the smallest to the largest value): control → mineral → S12mo → S3mo. In slurry treatments, the smallest values of $MWD_{MB}$ were also recorded in treatments where it was applied 12 months before, however, the opposite occurred for $MWD_{FW}$ (smallest values in S3mo treatments). The gentle slow-wetting methods ($WSA_{WET}$, $MWD_{SW}$) reduced disaggregation (Figure 2a,b), mainly in the larger (1–2 mm) aggregate class ($MWD_{SW}$, Figure 3).

### *Exchangeable cations*

There were no significant differences between the three blocks in exchangeable cations. Soil exchangeable $Mg^{2+}$ (Figure 4) increased to 1.34 $cmol_c\ kg^{-1}$ soil if slurries were

310 included in the fertilizer treatment compared to mineral fertilizer (0.66 $cmol_c$ $kg^{-1}$ soil).
311 Otherwise, $Na^+$ exchangeable cations tended to increase with time in treatments that
312 received slurries, although the differences between fertilizer treatments were not
313 significant (Table 3; Figure 4). Differences in $K^+$ contents were variable and significant
314 differences depended upon which treatments were compared.

315 *Soil respiration*

316 Average soil respiration after 21 days of incubation (Tables 4, 5) in recent (three
317 months previously) PS-amended soil (0.72–0.88 mg $CO_2$-C $kg^{-1}$ dry soil $hour^{-1}$) was
318 larger than from the control and mineral treatments (0.41–0.48 mg $CO_2$-C $kg^{-1}$ dry soil
319 $hour^{-1}$) and also from treatments (S12mo, 0–60FS and 0–90SS), which had received
320 slurries at the smallest rate twelve months previously (0.64 and 0.47 mg $CO_2$-C $kg^{-1}$ dry
321 soil $hour^{-1}$). The main differences were more evident during the first 14 days of the
322 incubation period (Table 6; Figure 5).

323 Water stable aggregates ($WSA_{DRY}$) and mean weight diameter with fast wetting
324 ($MWD_{FW}$) were plotted against accumulated respiration in a 21-day period. As
325 accumulated respiration increased, the $WSA_{DRY}$ increased but $MWD_{FW}$ decreased
326 (Figure 6).

327 *Soil porosity*

328 The qualitative assessment of porosity by micromorphology showed that the soil treated
329 with mineral fertilizer and the control had mainly fissures and vughs, whereas samples
330 fertilized with slurry tended to have compound packing pores between aggregates; these
331 were more evident for treatment with slurry from fattening pigs (Figure 7). The image
332 analyses showed an overall increase of total porosity in the plots fertilized with slurry
333 (Figure 7), which is supported by the results of the analysis of variance (Tables 7, 8) of

334 total porosity (> 25 μm). The pore-size distribution showed that recent slurry
335 application at sowing (3 months before sampling) increased porosity in the ranges from
336 25 to 100 μm and 100 to 400 μm when compared with mineral fertilizer or with the
337 control (no nitrogen) plots (Table 8). These differences tend to disappear when slurry
338 had been applied twelve months before sampling (Tables 7, 8).

339 **Discussion**

340 The consistency of our results of aggregate stability is shown by the coefficients of
341 variation, which fall within the accepted ranges in the literature (Saygin *et al*. 2012).

342 The slow-wetting treatment ($MWD_{SW}$ and $WSA_{WET}$) resulted in fewer differences
343 between fertilizer treatments (Table 2; Figure 2a,b). Slow-wetting before wet-sieving of
344 aggregates is an accepted practice because maximum aggregate stability is obtained in
345 saturated samples (Sun *et al.,* 1995). If later sieving is done in ethanol, the intensity of
346 disaggregation is even more limited (Le Bissonnais, 1996). We observed this in the
347 larger MWD of aggregates subjected to the slow-wetting procedure (Figure 3a,b,c).

348 An increase in $Mg^{2+}$, which occurred with our slurry treatments (Figure 4), might
349 cause considerable swelling if expanding clays are present. In our case they were absent
350 because illite and chlorite are the dominant clays (Figure 1). Because no significant
351 variation was detected in exchangeable $Na^{+}$ (Table 3; Figure 4), the observed changes in
352 aggregate stability for the different methods cannot be attributed to changes in the type
353 of adsorbed cations or to increments in the sodium adsorption ratio (SAR).

354 Our slurries had a small C:N ratio (~6–8, Table 1) with mineral $NH_4^{+}$-N up to 70%
355 of total N (Table 1). The large initial availability of N when slurries had been applied
356 just after stubble incorporation might reduce the proportion of macroaggregates
357 (Bossuyt *et al.,* 2001). The small $MWD_{FW}$ in S3mo samples (Figure 2a) because of the

lack of macroaggregates (Figure 3a) supports this hypothesis. In contrast, the $WSA_{DRY}$ test indicates a better resistance to slaking disaggregation in S3mo samples than in the 0–120M treatment (where no mineral N had been applied until tillering of the cereal) with the larger number of macroaggregates (> 250 μm). In fresh PS, organic carbon content is mainly in a water-soluble form (Bernal *et al.,* 1991) and hemicellulose is the major polysaccharide (Müller, 1980) with a content that might be up to 89% greater than that of cellulose, although lignin and cellulose are almost undigested by pigs. Polysaccharides can act as transitory binding agents (Tisdall & Oades, 1982). The predominance of easily degradable compounds is corroborated by soil respiration after 21 days of incubation in recent (S3mo) PS-amended soil (Tables 4, 5). The relation between $WSA_{DRY}$ and accumulated respiration (Figure 6) indicates more microbial activity occurs when the soil OM light fraction is greater (Yagüe *et al.,* 2012b). By opposite, when $MWD_{FW}$ is introduced as the stability test (Figure 6), the relation means that some transient binding agents (glues) associated with recent slurry incorporation (30FS treatments at sowing) could be affected first by dissolution with 10 minutes of immersion in deionized water, and second by ethanol because polysaccharides are soluble in both liquids (Lawther *et al.,* 1995). These transient binding agents are easily degraded by microorganisms, which contribute to the relatively large rates of respiration and lead to a negative relation with $MWD_{FW}$. Solubilization was reduced as the soil OM became more protected with time.

The largest values of $MWD_{FW}$ in S12mo samples can be explained by the nature of the soil. In carbonate-rich soil, aggregate formation associated with microbial activity co-exists with physicochemical pathways of aggregate formation. Fernández-Ugalde *et al*. (2011) hypothesized that macroaggregate stabilization mainly results from the formation of physical coatings and pore infillings of fine-sized secondary carbonates

383 that impregnate the light fraction of OM and decrease the porosity inside the aggregates,
384 which slows down the turnover of OM. This interaction between carbonates and added
385 organic matter possibly explains the larger $MWD_{FW}$ values where slurry had been
386 applied at cereal tillering only, twelve months before sampling (Figure 2a).

387 Differences between S12mo and S3mo also resulted in the $MWD_{MB}$ test (Figure 2a),
388 but they show the reverse trend to that in $MWD_{FW}$, probably because carbonate coatings
389 do not protect the aggregates effectively from stirring. In our case, the mechanical
390 energy applied in the $MWD_{MB}$ test broke up the aggregates in the upper size range (1–2
391 mm), but it was insufficient to break up aggregates of the next size down; the main
392 proportion of aggregates was in the 0.5–1 mm range (Figure 3c).

393 The effect of PS application on aggregate stability to mitigate against slaking
394 ($MWD_{FW}$ or $WSA_{DRY}$ values) is important because slaking occurs when aggregates are
395 wetted rapidly. Rapid wetting occurs in our Mediterranean climate because the soil
396 surface is usually dry when the erratic rainfall occurs, and there is also little soil cover
397 from sowing until tillering. Furthermore, non-expanding clays such as illite, chlorite and
398 to a lesser extent kaolinite predominate in our soil and are more likely to be associated
399 with slaking than swelling clays (Emerson, 1964). In addition, the clay content of our
400 soil is small, which also means that slaking is more likely (Le Bissonnais, 1996).

401 Although aggregate stability does not necessarily decrease with decreasing
402 macroporosity (Bresson & Moran, 2004), the decreasing stability in $WSA_{DRY}$ (Figure
403 2b) is followed by a decrease of macroporosity in the 25–200 μm range.

404 Furthermore, total porosity (>25 μm) under mineral fertilizer did not differ
405 significantly (Table 8) from that under slurry fertilizer. This could arise from the
406 development of fissures (planar voids) that masked useful porosity (e.g. 0–120M,
407 Figure 7). The differences that appear at the 25–100 μm pore size (at which the S3mo

408 treatments surpassed mineral treatment) are important because these pores are packing
409 pores between the granular aggregates, and as such are involved in capillary movement
410 of water and soil aeration (Oades, 1984). These differences also appear, although less
411 clearly, between the 100 and 400 μm pore sizes, which correspond to interaggregate or
412 faunal pores involved in the fast drainage of water and root growth. As differences
413 disappear with time (mineral and S12mo), they could favour water infiltration in the
414 early stages of crop growth, which coincides with winter rains here. This idea requires
415 further research.

416 Overall differences between more recent to older slurry treatments, or between
417 more recent slurry and mineral fertilizer treatments are in accord with Du *et al.* (2016)
418 who found an increase in aggregates between 0.25–0.5 mm after the application of
419 biogas pig slurry. They suggested that the controlling factor for the formation of these
420 aggregates and microaggregates resulted from the combination of high specific surface
421 area of the organic molecules in the slurry together with the action of the functional
422 groups of the slurry hydrophilic colloids (Liang *et al*., 2005). Similarly, Grunwald *et al*.
423 (2016) explained this effect by the more fluid nature of slurry than biochar or manure as
424 aggregants, allowing it to spread more readily over the surfaces of soil components and
425 enhanced their ability to form aggregates.

426 **Conclusions**

427 In this dryland system, slaking is the main agent for aggregate breakdown in calcareous
428 soil. Nevertheless, if PS is the fertilizer, the stability tests ($MWD_{FW}$ and $WSA_{DRY}$) can
429 result in contradictory assessments on resistance to slaking. When $WSA_{DRY}$ reached the
430 largest values, $MWD_{FW}$ values were the smallest probably because of the water's
431 interaction with transient binding agents (water-soluble glues) from PS. Nevertheless,

further research is needed on the nature and evolution over time of these binding agents. Carbonates probably prevent OM decomposition, which can be deduced from evolution of the rate of respiration during a growing season and from differences in aggregate stability when mineral and organic fertilizers were compared. The introduction of pig slurry into fertilization strategies benefits porosity, mainly in the 25–200 μm range area, but again this is a transient effect. These pores are associated with the capillary movement of water, soil aeration, fast drainage of water and root growth, therefore this could be important in the water dynamics of the early crop cycle.

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557

## FIGURE CAPTIONS

**Figure 1** Diffraction spectra (X-rays) of raw, glycolated (for 48 hours) and heated soil samples. The clay phases identified are included.

**Figure 2** Average values of stability of aggregate tests: (a) mean weight diameter (MWD), slow wetting (SW), fast wetting (FW) and stirring after pre-wetting (mechanical breakdown, MB) and (b) water stable aggregates (WSA) standard method by Kemper & Rosenau (1986) with pre-wetting (WET) and the modified method without pre-wetting (DRY) for each fertilizer treatment: mineral (Mineral), slurry applied twelve months before sampling (S12mo) or slurry applied three months before sampling (S3mo). Treatment acronyms are described in Table 1.

**Figure 3** Size distribution of aggregates after fractionation into four classes (> 1 to 2 mm, > 0.50 to 1 mm, > 0.25 to 0.50 mm and < 0.25 mm) following three methods: (a) fast wetting, (b) slow wetting and (c) stirring after pre-wetting (mechanical breakdown), and for different fertilizer treatments: mineral (Mineral), slurry applied twelve months before sampling (S12mo) or slurry applied three months before sampling (S3mo). Treatment acronyms are described in Table 1.

**Figure 4** Average values of exchangeable cations ($K^+$, $Mg^{2+}$, $Na^+$ and $Ca^{2+}$) for each fertilizer treatment: mineral (Mineral), slurry applied twelve months before sampling (S12mo) or slurry applied three months before sampling (S3mo). Treatment acronyms are described in Table 1.

**Figure 5** Soil respiration average (mg $CO_2$-C $kg^{-1}$ soil $hour^{-1}$) after 1, 7, 14 and 21 days of incubation for each treatment: mineral fertilizer (Mineral), slurry applied twelve months before sampling (S12mo) or slurry applied three months before sampling (S3mo). Treatment acronyms are described in Table 1.

582 **Figure 6** Water aggregate stability modified without pre-wetting ($WSA_{DRY,}$ ●) and mean

583 weight diameter after fast wetting ($MWD_{FW,}$ ■) plotted against total cumulative

584 respiration (mg $CO_2$-C $kg^{-1}$ dry soil) for 21 days of incubation. The coefficient of

585 determination ($R^2$) shows the strength of association between the variables.

586 **Figure 7** Images of soil porosity (in black) from different fertilizer treatments: 0–0, 0–

587 120M, 30FS–0; 30FS–60M, 30FS–20PS and 30FS–60SS. Size of each image is

588 31.5-mm wide and 42.0-mm long. Acronyms of treatments are described in Table

589 1.

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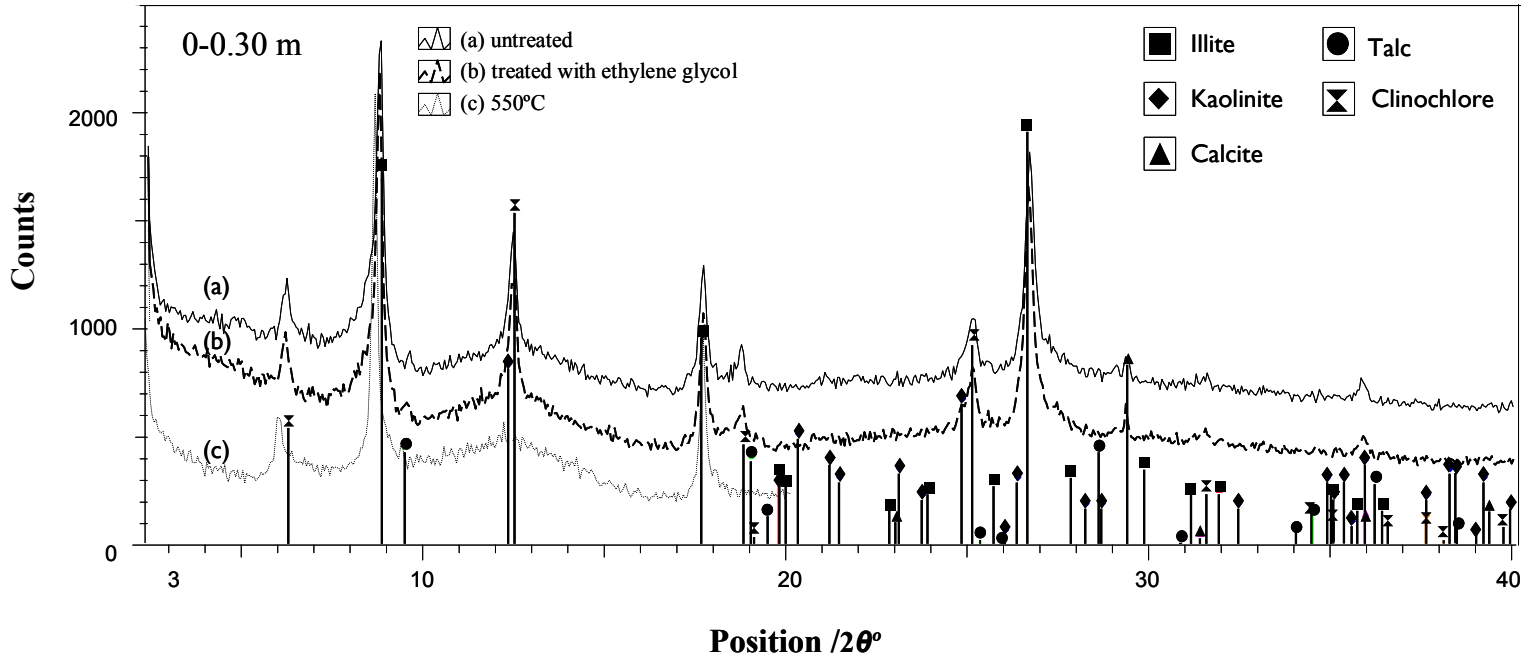


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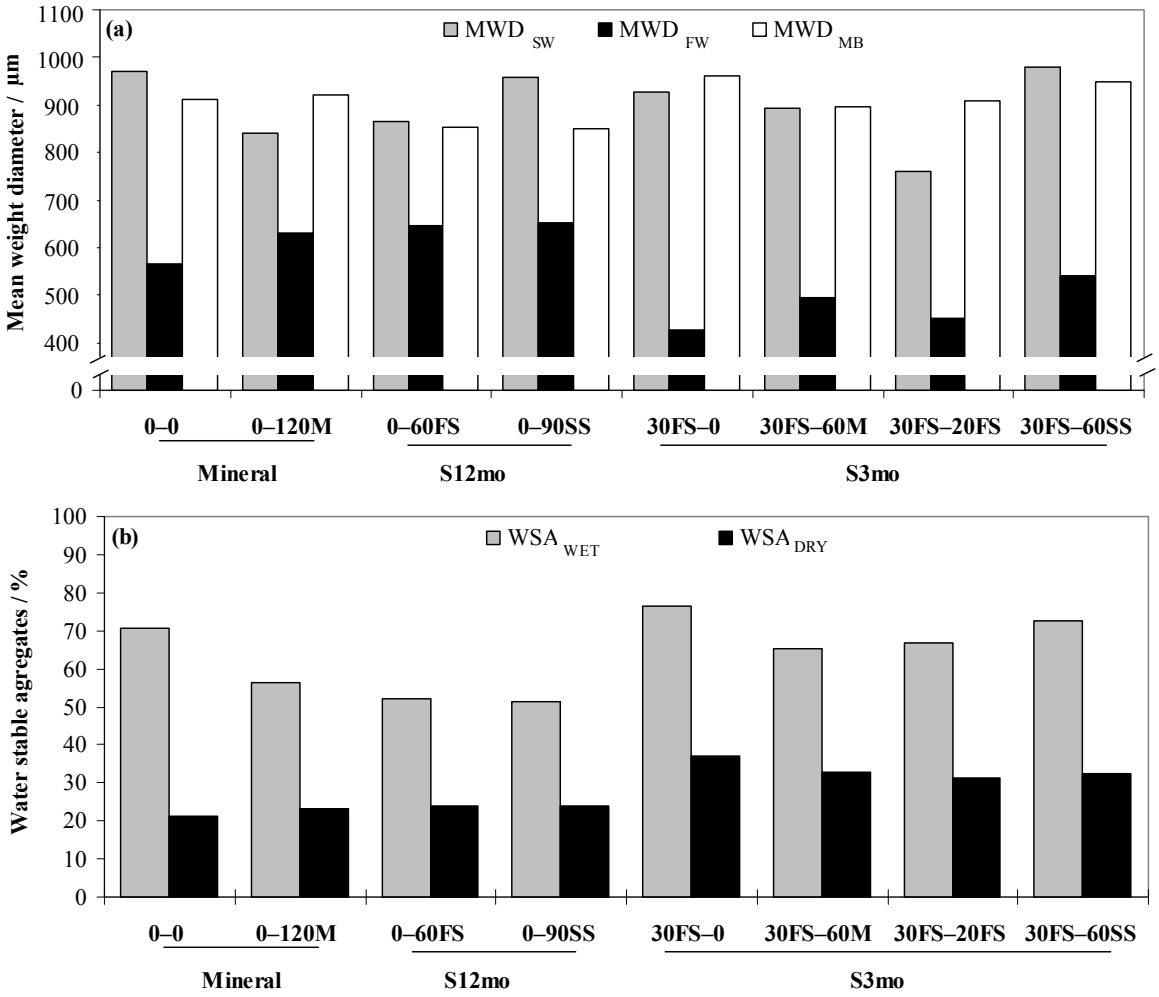


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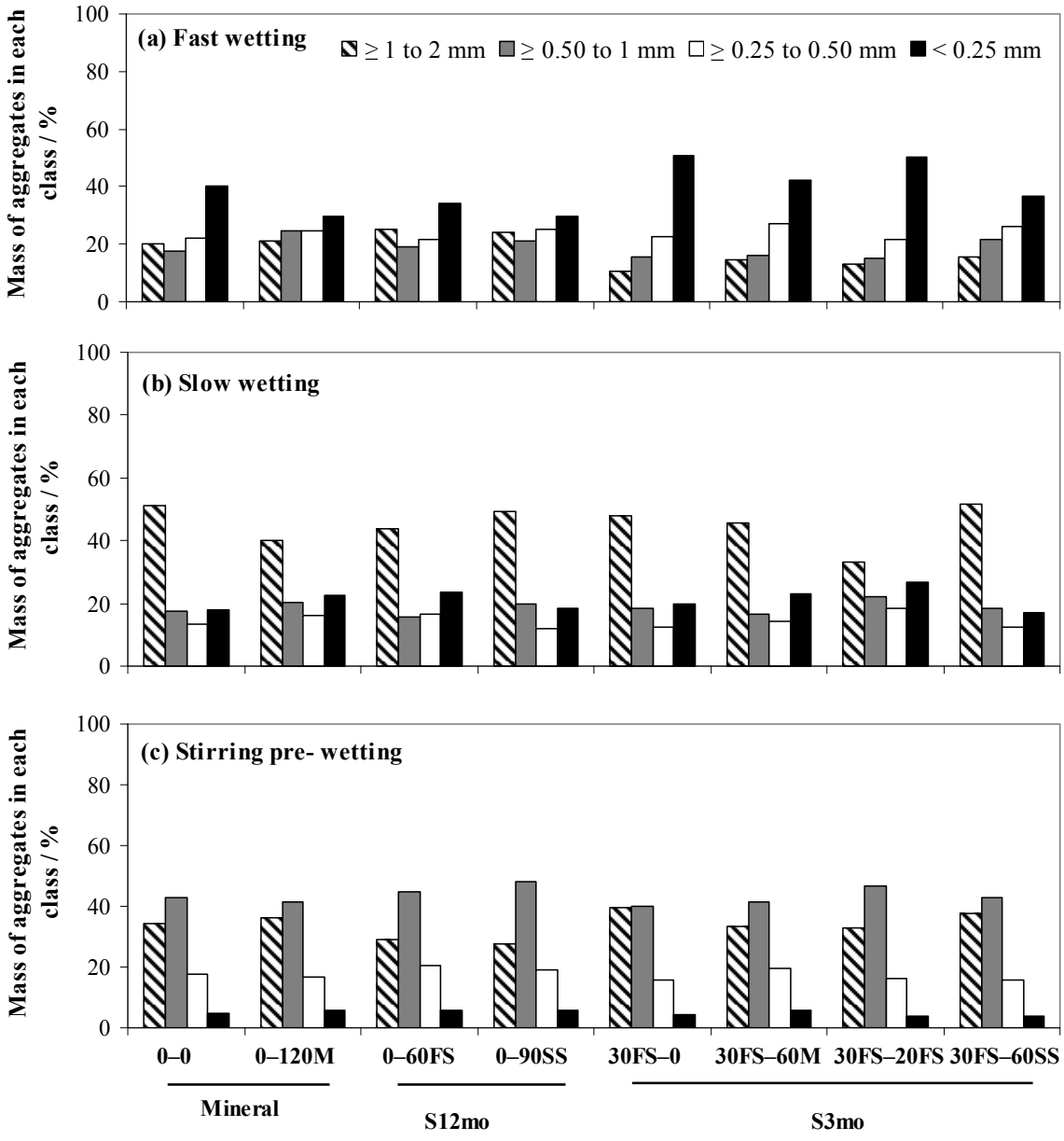


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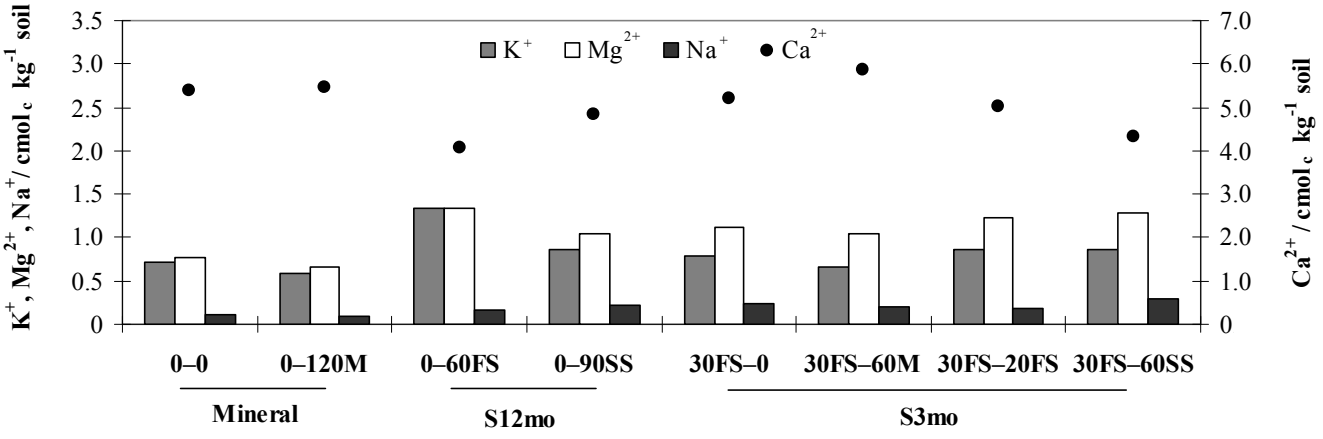


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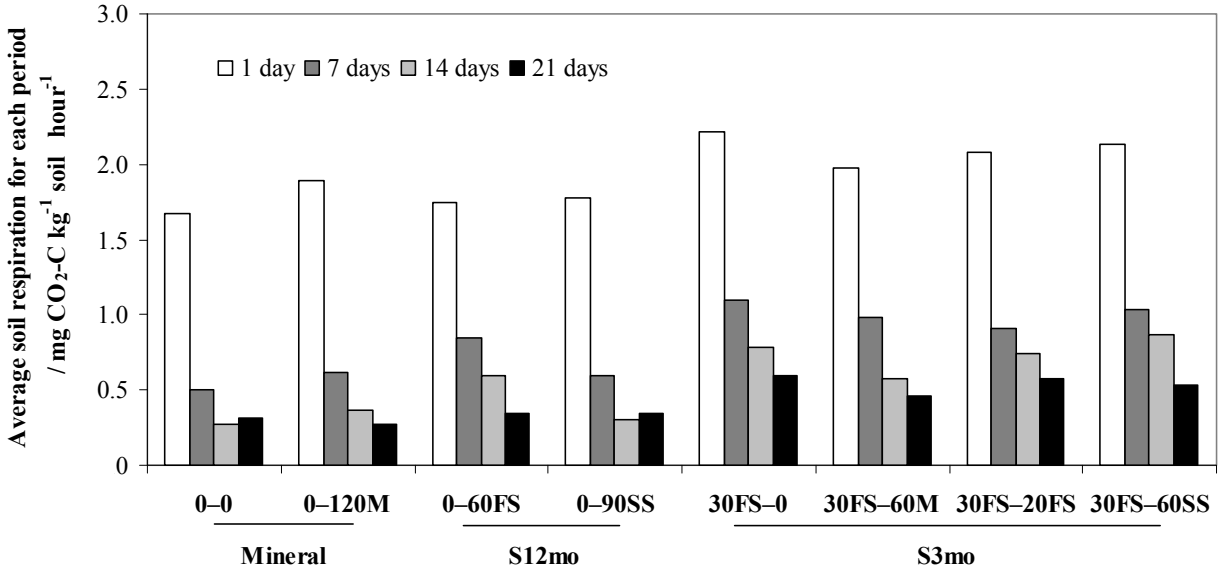


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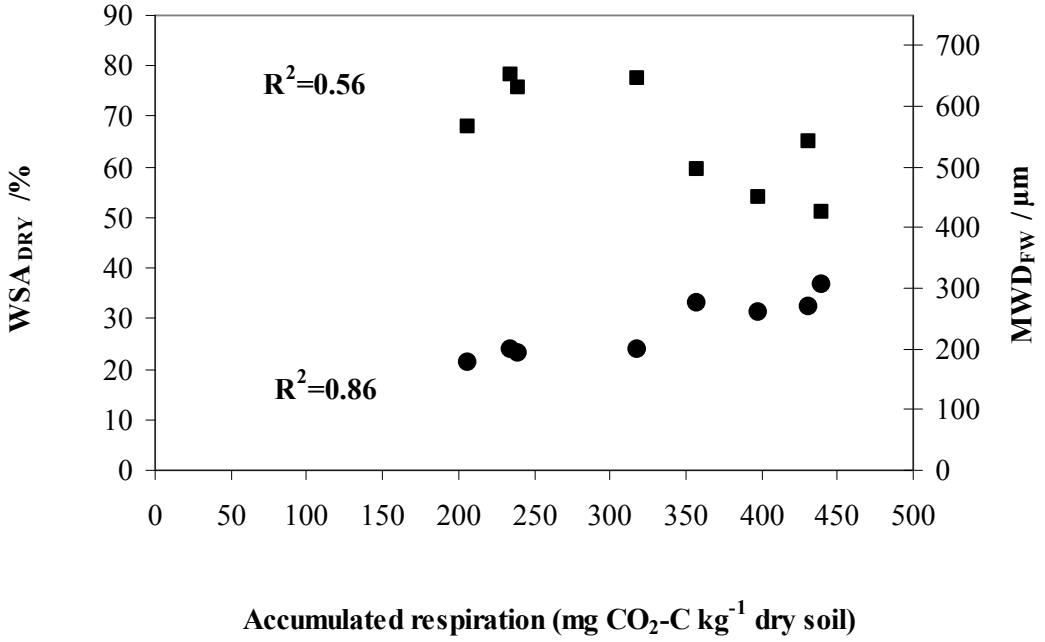


**Figure 6** Water aggregate stability modified without pre-wetting ($WSA_{DRY,}$ ●) and mean weight diameter after fast wetting ($MWD_{FW,}$ ■) plotted against total cumulative respiration (mg $CO_2$-C $kg^{-1}$ dry soil) for 21 days of incubation. The coefficient of determination ($R^2$) shows the strength of association between the variables.

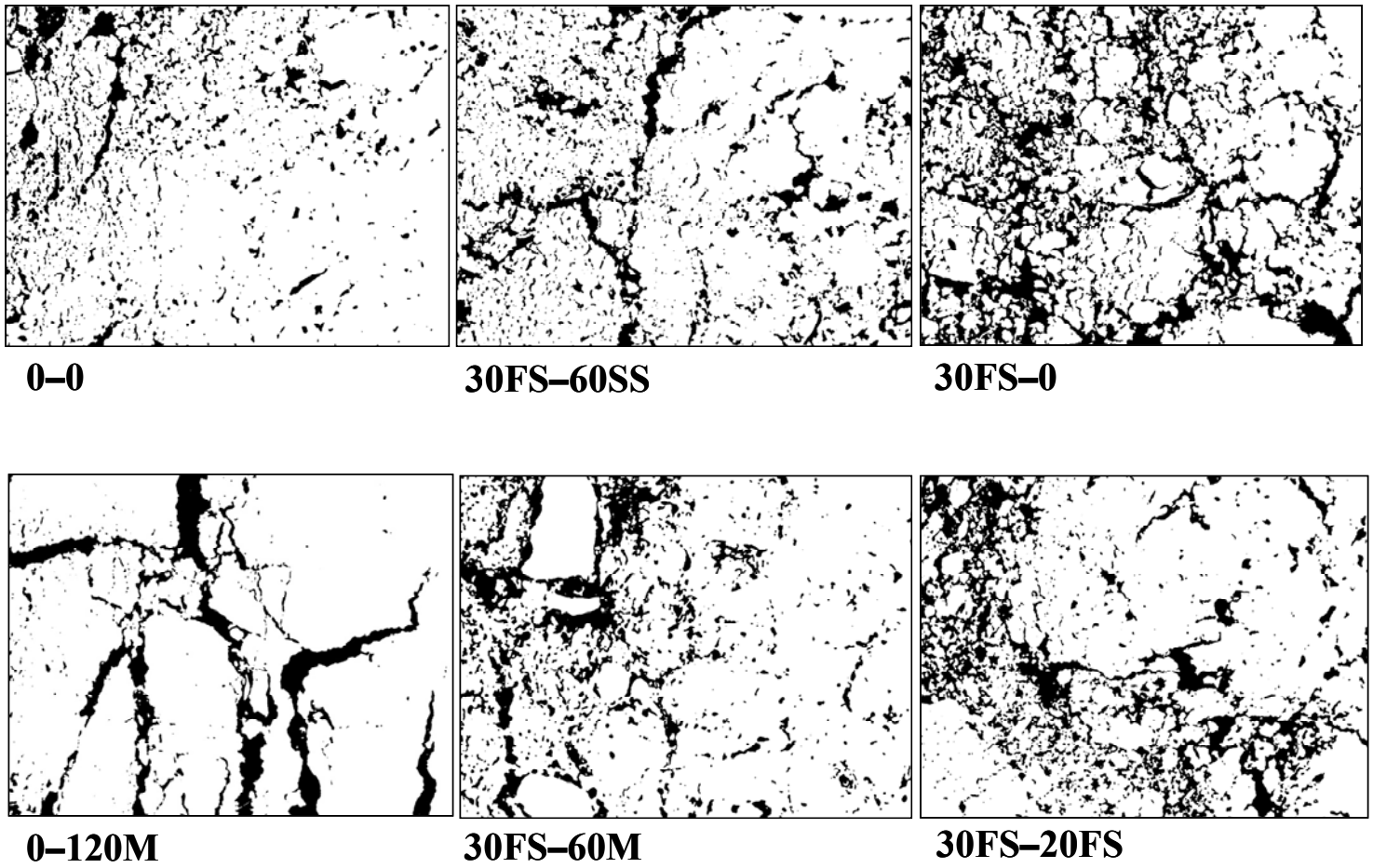


**Figure 7** Images of soil porosity (in black) from different fertilizer treatments: 0–0, 0–120M, 30FS–0; 30FS–60M, 30FS–20PS and 30FS–60SS. Size of each image is 31.5-mm wide and 42.0-mm long. Acronyms of treatments are described in Table 1.

**Table 1.** Annual fertilizer treatments including averages of the total nitrogen (TN), organic N (Norg) and organic matter (OM) applied and accumulated (seven cereal growing seasons) grain yields (0% humidity). Fertilizers (mineral or from different slurry sources) were applied annually at presowing (PreS) or tillering as a top-dressing (TopD) or both

| Sampling time and last fertilizer application[a] | Treatment | Annual fertilizer split | | 2002 to 2010 (7 campaigns) | | | Presowing fertilization in 2010–2011 campaign | | | Accumulated grain yield |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | TN | Norg | OM | TN | Norg | OM | |
| | | PreS | TopD | /kg ha$^{-1}$ year$^{-1}$ (SD[e]) | | | /kg ha$^{-1}$ year$^{-1}$ (SD[e]) | | | /kg ha$^{-1}$ |
| 12-mo, mineral | 0–0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 18 373 |
| | 0–120M[b] | 0 | 120M | 120 | 0 | 0 | 30 | 0 | 0 | 21 550 |
| 12-mo, slurry (S12mo) | 0–60FS[c] | 0 | 60FS | 405 (76) | 130 (70) | 2 622 (784) | 0 | 0 | 0 | 20 897 |
| | 0–90SS[d] | 0 | 90SS | 175 (102) | 61 (48) | 1 764 (1 228) | 0 | 0 | 0 | 24 800 |
| 3-mo, slurry (S3mo) | 30FS–0 | 30FS | 0 | 194 (48) | 59 (15) | 1 681 (240) | 170 (1) | 64 (2) | 1 854 (10) | 21 153 |
| | 30FS–60M | 30FS | 60M | 254 (48) | 59 (15) | 1 681 (240) | 170 (1) | 64 (2) | 1 854 (10) | 23 640 |
| | 30FS–20FS | 30FS | 20FS | 320 (33) | 102 (25) | 2 491 (254) | 170 (1) | 64 (2) | 1 854 (10) | 22 363 |
| | 30FS–60SS | 30FS | 60SS | 279 (44) | 82 (17) | 2 107 (273) | 170 (1) | 64 (2) | 1 854 (10) | 22 329 |

[a]12-mo and 3-mo, the last fertilizer was applied twelve or three months before sampling, respectively.
[b]M, mineral fertilizer applied as ammonium nitrate (AN). Numbers indicate the rate applied: 60 kg N ha$^{-1}$ year$^{-1}$ or 120 kg N ha$^{-1}$ year$^{-1}$.
[c]FS, slurry from fattening pigs. Numbers indicate the average theoretical applied rate: 20 t ha$^{-1}$ year$^{-1}$, 30 t ha$^{-1}$ year$^{-1}$ or 60 t ha$^{-1}$ year$^{-1}$.
[d]SS, slurry from sows. Numbers indicate the average theoretical applied rate: 60 t ha$^{-1}$ year$^{-1}$ or 90 t ha$^{-1}$ year$^{-1}$.
[e]SD, standard deviation.

**Table 2.** Analysis of variance (four replicates) of aggregate stability (Ag-Stab) with different tests: (a) mean weight diameter (MWD /μm), slow wetting (SW), fast wetting (FW) and stirring after pre-wetting (mechanical breakdown, MB) and (b) water stable aggregates (WSA /%) standard method by Kemper & Rosenau (1986) with pre-wetting (WET) and modified method without pre-wetting (DRY) for the different fertilizer treatments

| Ag-Stab test | Source | Degrees of freedom | Sum of squares | Mean square | *F* ratio | *P* |
|---|---|---|---|---|---|---|
| $MWD_{SW}$ | Between treatments | 7 | 155 967.9 | 22 281.1 | 0.72 | 0.65 |
| | Within treatments (residual) | 24 | 741 671.4 | 30 903.0 | | |
| | Total | 31 | 897 639.3 | | | |
| | SE[a] | 101.49 | | | | |
| $MWD_{FW}$ | Between treatments | 7 | 215 818.0 | 30 831.1 | 11.21 | <0.0001 |
| | Within treatments (residual) | 24 | 65 980.8 | 2 749.2 | | |
| | Total | 31 | 281 798.8 | | | |
| | SE, SED, LSD[a] | 30.27, 37.08, 76.52 | | | | |
| $MWD_{MB}$ | Between treatments | 7 | 43 712.7 | 6 244.7 | 9.71 | <0.0001 |
| | Within treatments (residual) | 24 | 15 436.0 | 643.2 | | |
| | Total | 31 | 59 148.7 | | | |
| | SE, SED, LSD[a] | 14.64, 17.93, 37.01 | | | | |
| $WSA_{WET}$ | Between treatments | 7 | 2 716.2 | 388.0 | 1.17 | 0.36 |
| | Within treatments (residual) | 24 | 7 987.2 | 332.8 | | |
| | Total | 31 | 10 703.4 | | | |
| | SE[a] | 10.53 | | | | |
| $WSA_{DRY}$ | Between treatments | 7 | 861.6 | 123.1 | 3.90 | 0.006 |
| | Within treatments (residual) | 24 | 757.4 | 31.6 | | |
| | Total | 31 | 1 619.0 | | | |
| | SE, SED, LSD[a] | 3.24, 3.97, 8.20 | | | | |

[a]SE, standard error of the mean /%; SED, standard error of a difference /%; LSD, least significant difference test /%; all for *P*= 0.05 with 24 degrees of freadom.

**Table 3.** Analysis of variance of exchangeable cations ($K^+$, $Mg^{2+}$, $Na^+$ and $Ca^{2+}$) expressed in $cmol_c\ kg^{-1}$ soil (three replicates) for the different fertilizer treatments

| Exchangeable cations | Source | Degrees of freedom | Sum of squares | Mean square | *F* ratio | *P* |
|---|---|---|---|---|---|---|
| $K^+$ | Between treatments | 7 | 1.054 | 0.150 | 23.19 | <0.0001 |
| | Between blocks | 2 | 0.004 | 0.002 | 0.28 | 0.76 |
| | Within treatments (residual) | 14 | 0.091 | 0.006 | | |
| | Total | 23 | 1.149 | | | |
| | SE, SED, LSD[a] | 0.046, 0.066, 1.141 | | | | |
| $Mg^{2+}$ | Between treatments | 7 | 1.231 | 0.176 | 5.35 | 0.0038 |
| | Between blocks | 2 | 0.009 | 0.005 | 0.14 | 0.87 |
| | Within treatments (residual) | 14 | 0.460 | 0.033 | | |
| | Total | 23 | 1.700 | | | |
| | SE, SED, LSD[a] | 0.105, 0.148, 0.317 | | | | |
| $Na^+$ | Between treatments | 7 | 0.098 | 0.014 | 1.89 | 0.15 |
| | Between blocks | 2 | 0.017 | 0.008 | 1.13 | 0.35 |
| | Within treatments (residual) | 14 | 0.104 | 0.007 | | |
| | Total | 23 | 0.218 | | | |
| | SE[a] | 0.050 | | | | |
| $Ca^{2+}$ | Between treatments | 7 | 7.511 | 1.073 | 0.94 | 0.50 |
| | Between blocks | 2 | 1.184 | 0.592 | 0.52 | 0.60 |
| | Within treatments (residual) | 14 | 15.905 | 1.136 | | |
| | Total | 23 | 24.600 | | | |
| | SE[a] | 0.615 | | | | |

[a]SE, standard error of the mean /%; SED, standard error of a difference /%; LSD, least significant difference test /%; all for *P*= 0.05 with 14 degrees of freadom.

**Table 4.** Analysis of variance of average hourly soil respiration (mg $CO_2$-C $kg^{-1}$ dry soil $hour^{-1}$) and accumulated respiration (mg $CO_2$-C $kg^{-1}$ dry soil) after 21 days of incubation (three replicates) for the different fertilizer treatments

| Variable | Source | Degrees of freedom | Sum of squares | Mean square | *F* ratio | *P* |
|---|---|---|---|---|---|---|
| Average respiration | Between treatments | 7 | 0.724 | 0.104 | 23.36 | <0.0001 |
| | Within treatments (residual) | 16 | 0.071 | 0.004 | | |
| | Total | 23 | 0.797 | | | |
| Accumulated respiration | Between treatments | 7 | 181 093 | 25 870 | 23.36 | <0.0001 |
| | Within treatments (residual) | 16 | 17 475 | 1 092 | | |
| | Total | 23 | 198 568 | | | |

**Table 5.** Average hourly soil respiration and accumulated respiration after 21 days of incubation (three replicates) obtained for each methodology and fertilizer treatment

| Sampling time and last fertilizer application[a] | Treatment | Average /mg $CO_2$-C $kg^{-1}$ dry soil $hour^{-1}$ | Accumulated /mg $CO_2$-C $kg^{-1}$ dry soil |
|---|---|---|---|
| 12-mo, mineral | 0–0 | 0.41 | 207 |
| | 0–120M[b] | 0.48 | 240 |
| 12-mo, slurry (S12mo) | 0–60FS[c] | 0.64 | 318 |
| | 0–90SS[d] | 0.47 | 234 |
| 3-mo, slurry (S3mo) | 30FS–0 | 0.88 | 440 |
| | 30FS–60M | 0.72 | 358 |
| | 30FS–20FS | 0.82 | 398 |
| | 30FS–60SS | 0.87 | 431 |
| | SE, SED, LSD[e] | 0.0365, 0.0545, 0.1154 | 19.08, 26.98, 57.20 |

[a]12-mo, 3-mo, the last fertilizer was applied twelve or three months before sampling, respectively.

[b]M, mineral fertilizer applied as ammonium nitrate (AN). Numbers indicate the rate applied: 60 kg N $ha^{-1}$ $year^{-1}$ or 120 kg N $ha^{-1}$ $year^{-1}$.

[c]FS, slurry from fattening pigs. Numbers indicate the average theoretical applied rate: 20 t $ha^{-1}$ $year^{-1}$, 30 t $ha^{-1}$ $year^{-1}$ or 60 t $ha^{-1}$ $year^{-1}$.

[d]SS, slurry from sows. Numbers indicate the average theoretical applied rate: 60 t $ha^{-1}$ $year^{-1}$ or 90 t $ha^{-1}$ $year^{-1}$.

[e]SE, standard error of the mean /%; SED, standard error of a difference /%; LSD, least significant difference test /%; all for $P$= 0.05 with 16 degrees of freadom.

**Table 6.** Analysis of variance of soil respiration average (mg $CO_2$-C $kg^{-1}$ soil $hour^{-1}$) after 1, 7, 14, and 21 days of incubation (three replicates) for different fertilizer treatments

| Incubation period | Source | Degrees of freedom | Sum of squares | Mean square | F ratio | P |
|---|---|---|---|---|---|---|
| 1 day | Between treatments | 7 | 0.845 | 0.121 | 1.17 | 0.37 |
| | Within treatments (residual) | 16 | 1.650 | 0.103 | | |
| | Total | 23 | 2.495 | | | |
| | SE[a] | 0.185 | | | | |
| 7 days | Between treatments | 7 | 1.066 | 0.152 | 19.59 | <0.0001 |
| | Within treatments (residual) | 16 | 0.124 | 0.008 | | |
| | Total | 23 | 1.191 | | | |
| | SE, SED, LSD[a] | 0.051, 0.072, 0.153 | | | | |
| 14 days | Between treatments | 7 | 1.115 | 0.159 | 16.34 | <0.0001 |
| | Within treatments (residual) | 16 | 0.156 | 0.010 | | |
| | Total | 23 | 1.271 | | | |
| | SE, SED, LSD[a] | 0.057, 0.081, 0.171 | | | | |
| 21 days | Between treatments | 7 | 0.346 | 0.049 | 4.60 | 0.0055 |
| | Within treatments (residual) | 16 | 0.172 | 0.011 | | |
| | Total | 23 | 0.518 | | | |
| | SE, SED, LSD[a] | 0.061, 0.085, 0.180 | | | | |

[a]SE, standard error of the mean /%; SED, standard error of a difference /%; LSD, least significant difference test /%; all for *P*= 0.05 with 16 degrees of freadom.

**Table 7.** Analysis of variance of pore apparent diameter ranges according to different fertilizer treatments

| Range | Source | Degrees of freedom | Sum of squares | Mean square | F ratio | P |
|---|---|---|---|---|---|---|
| > 25 µm | Between treatments | 7 | 11.620 | 1.660 | 3.16 | 0.0082 |
| | Between blocks | 2 | 8.973 | 4.486 | 8.55 | 0.0007 |
| | Between samples within treatments | 16 | 11.464 | 0.717 | 1.37 | 0.2015 |
| | Within samples (residual) | 46 | 24.142 | 0.525 | | |
| | Total | 71 | 56.199 | | | |
| 25–65µm | Between treatments | 7 | 0.680 | 0.097 | 3.74 | 0.0028 |
| | Between blocks | 2 | 0.504 | 0.252 | 9.70 | 0.0003 |
| | Between samples within treatments | 16 | 0.436 | 0.027 | 1.05 | 0.4269 |
| | Within samples (residual) | 46 | 1.195 | 0.026 | | |
| | Total | 71 | 2.815 | | | |
| 65–100µm | Between treatments | 7 | 0.150 | 0.214 | 3.78 | 0.0026 |
| | Between blocks | 2 | 0.415 | 0.208 | 3.66 | 0.0336 |
| | Between samples within treatments | 16 | 0.543 | 0.034 | 0.60 | 0.8691 |
| | Within samples (residual) | 46 | 2.610 | 0.057 | | |
| | Total | 71 | 5.068 | | | |
| 100–200µm | Between treatments | 7 | 5.445 | 0.778 | 5.42 | 0.0001 |
| | Between blocks | 2 | 0.979 | 0.489 | 3.41 | 0.0416 |
| | Between samples within treatments | 16 | 1.172 | 0.073 | 0.51 | 0.9284 |
| | Within samples (residual) | 46 | 6.600 | 0.143 | | |
| | Total | 71 | 14.195 | | | |
| 200–400µm | Between treatments | 7 | 7.973 | 1.139 | 5.46 | 0.0001 |
| | Between blocks | 2 | 3.891 | 1.946 | 9.33 | 0.0004 |
| | Between samples within treatments | 16 | 2.903 | 0.181 | 0.87 | 0.6053 |
| | Within samples (residual) | 46 | 9.597 | 0.209 | | |
| | Total | 71 | 24.364 | | | |
| >400µm | Between treatments | 7 | 5.558 | 0.794 | 1.08 | 0.3930 |
| | Between blocks | 2 | 9.270 | 4.635 | 6.29 | 0.0038 |
| | Between samples within treatments | 16 | 15.445 | 0.965 | 1.31 | 0.2321 |
| | Within samples (residual) | 46 | 33.900 | 0.737 | | |
| | Total | 71 | 64.170 | | | |

The porosity data /% for each interval were transformed ($X^{0.5}$) to fulfil the requirements of normality and homogeneity of variances in ANOVA analysis.

**Table 8.** Porosity[a] areas for each fertilizer treatment and with different apparent pore diameter ranges

| Sampling time and last fertilizer application[b] | Treatment | Total porosity /% >25 µm | Pore ranges /% 25–65µm | 65–100µm | 100–200µm | 200–400µm | >400µm |
|---|---|---|---|---|---|---|---|
| 12-mo, mineral | 0–0 | 12.0 (3.37) | 0.5 (0.66) | 1.3 (1.12) | 2.7 (1.63) | 2.6 (1.58) | 4.8 (1.98) |
| | 0–120M[c] | 17.3 (4.01) | 0.3 (0.57) | 1.3 (1.12) | 3.6 (1.84) | 4.6 (2.05) | 7.4 (2.49) |
| 12-mo, Slurry (S12mo) | 0–60FS[d] | 19.8 (4.35) | 0.5 (0.67) | 1.7 (1.26) | 4.1 (1.97) | 5.0 (2.18) | 8.5 (2.70) |
| | 0–90SS[e] | 15.2 (3.88) | 0.7 (0.80) | 1.8 (1.31) | 3.7 (1.89) | 3.8 (1.92) | 5.3 (2.10) |
| 3-mo, Slurry (S3mo) | 30FS–0 | 23.2 (4.75) | 0.8 (0.86) | 2.5 (1.56) | 6.5 (2.54) | 8.0 (2.76) | 5.3 (2.17) |
| | 30FS–60M | 17.6 (4.16) | 0.6 (0.78) | 1.9 (1.38) | 4.5 (2.10) | 5.1 (2.22) | 5.5 (2.26) |
| | 30FS–20FS | 20.6 (4.46) | 0.8 (0.86) | 2.2 (1.47) | 5.8 (2.38) | 6.5 (2.50) | 5.2 (2.13) |
| | 30FS–60SS | 15.1 (3.82) | 0.6 (0.79) | 1.8 (1.34) | 4.2 (2.03) | 4.6 (2.10) | 3.8 (1.73) |
| | SE, SED, LSD[f] | 0.42, 0.34, 0.69 | 0.10, 0.08, 0.15 | 0.13, 0.11, 0.23 | 0.22, 0.18, 0.36 | 0.26, 0.22, 0.43 | 0.50. -, - |

[a]Numbers in brackets are the transformed values $x^{0.5}$.

[b]12-mo and 3-mo, the last fertilizer was applied twelve months or three months before sampling, respectively.

[c]M, mineral fertilizer applied as ammonium nitrate (AN). Numbers indicate the rate applied: 60 kg N $ha^{-1}$ $year^{-1}$ or 120 kg N $ha^{-1}$ $year^{-1}$.

[d]FS, slurry from fattening pigs. Numbers indicate the average theoretical applied rate: 20 t $ha^{-1}$ $year^{-1}$, 30 t $ha^{-1}$ $year^{-1}$ or 60 t $ha^{-1}$ $year^{-1}$.

[e]SS, slurry from sows. Numbers indicate the average theoretical applied rate: 60 t $ha^{-1}$ $year^{-1}$ or 90 t $ha^{-1}$ $year^{-1}$.

[f]SE, standard error of the mean /%; SED, standard error of a difference /%; LSD, least significant difference test /%; all for $P$= 0.05 with 46 degrees of freedom.