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**Effects of mechanical separation on GHG and ammonia emissions from cattle
slurry under winter conditions**

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51 **Abstract**

52 Effects of cattle slurry mechanical separation on CO₂, CH₄, N₂O and NH₃ emissions
53 during slurry management under winter conditions was investigated in a laboratory
54 study. Greenhouse gas (GHG) emissions during storage and soil application of raw
55 cattle slurry by broadcasting of its liquid and solid fractions was assessed. Carbon
56 dioxide was the predominant emission source during both storage and soil application
57 of manure on a CO₂-eq basis, but CH₄ was the predominant GHG emission from stored
58 slurries. During storage, NH₃ fluxes from liquid fractions were higher than from the
59 solid fraction, but the solid fraction was the main source of NH₃ emissions after land
60 application: on average, ~70% of total ammoniacal N applied to soil was lost.
61 Combining losses during storage and after soil application of both liquid and solid
62 fractions, total CO₂-eq emissions of the combined fractions were 11% higher than that
63 from raw cattle slurry. Results suggest that mechanical separation of cattle slurry
64 should not be used by farmers unless other GHG emission reduction measures are
65 adopted.

66 *Keywords:* greenhouse gases, ammonia, cattle, slurry separation.

67 *Abbreviations:* CO₂ eq, carbon dioxide equivalents; GHG, greenhouse gas; TAN, total
68 ammoniacal N; TC, total carbon; TKN, total Kjeldahl N; TN, total N; TS, total solids;
69 VS, volatile solids.

70

71 **1. Introduction**

72 Storage and handling of cattle manure contributes to emissions of CO₂, CH₄, N₂O
73 and NH₃ to the atmosphere (FAO, 2006). A report from IPCC (2007) revealed that
74 CH₄ and N₂O are the most important greenhouse gases (GHG) in terms of climate
75 change because of their strong absorption of infrared radiation. Goebes et al. (2003)
76 reported that NH₃ causes various environmental problems, such as odour,
77 eutrophication, acidification of soils, and atmospheric particulate matter formation.

78 In Italy, animal manure management is responsible for ~70% NH₃ (Valli et al.,
79 2000), ~8% CH₄ and ~9% N₂O anthropogenic emissions (APAT, 2006), and their
80 contribution to GHG air emissions is increasing due to the growing demand for animal
81 based foods (FAO, 2006). Italy has undertaken to reduce its GHG emissions by 6.5%
82 by 2012 relative to 1990 levels (UNFCCC, 1997). Thus, manure management practices
83 that minimize GHG impacts on air quality need to be investigated. Mechanical
84 separation of animal slurry into solid and liquid fractions is currently becoming a

85 common practice in Italy, due to the ability to improve the flexibility of slurry
86 application and reduce environmental risks (Burton, 2007). On farms where land area
87 is insufficient for disposal of N in slurry, separation of the solids can also reduce
88 manure transport costs (Balsari et al., 2008), thereby making it easier for producers to
89 conform to the manure N limits set by the Nitrates Directive (91/676/EC). However,
90 mechanical separation of slurry has the potential to increase GHG and NH₃ emissions
91 compared to traditional slurry management (Amon et al., 2006; Dinuccio et al., 2008;
92 Fangueiro et al., 2008a), mainly due to high emissions during storage of the solid
93 fraction. In contrast, the effect of mechanical separation of slurry on gaseous emissions
94 on overall slurry management (*i.e.*, storage + land application) is not yet clear due to
95 the lack of experimental data. With the aim to cover this knowledge gap, a laboratory
96 scale study was completed in order to assess CO₂, CH₄, N₂O and NH₃ emissions from
97 storage and soil application of raw cattle slurry by broadcasting separated liquid and
98 solid fractions.

99

100 **2. Materials and methods**

101 The experiment was a randomised block design with three treatments being: (1)
102 raw cattle slurry, (2) separated liquid and (3) separated solid manure and four
103 replicates per treatment. Raw cattle slurry (~21 kg) was separated using a lab scale
104 mechanical separator as described by Dinuccio et al. (2008). Samples of 1000 cm³ of
105 each manure type were stored at 5 ± 0.5 °C for a period of 30 d in an open vessel with
106 1500 cm³ capacity and gas samples were collected and analyzed at 2 to 3 d intervals.
107 The bulk density of the solid fraction was estimated at 0.40 kg 1000 cm³.

108 After storage, replicate samples were collected and used in a soil application
109 experiment which was in a climate controlled room at 10 ± 0.5 °C. Open glass vessels
110 with 1500 cm³ capacity, 0.20 m height, 0.10 m base diameter and 0.095 m top
111 diameter) were filled with 1000 cm³ of soil. The soil was a loamy sand soil (USDA,
112 1977) with 837 g/kg sand, 143 g/kg silt, 19.4 g/kg clay; pH = 7.43, total C = 8.79 g/kg,
113 total N = 1.18 g/kg. After collection, the soil was sieved through a 4 mm screen and
114 stored in moist form, in the dark, at 4°C prior to the start of the experiments. The bulk
115 density of 1.16 g cm³ of the undisturbed soil was achieved by shaking the vessels until
116 the required soil volume was reached. The tested manures were homogeneously
117 applied on the soil surface at a rate of 70 kg/ha of total Kjeldahl N (TKN). Non-
118 fertilized soil was used as a Control. At the time of manure application the gravimetric

119 soil moisture content was 98 g/kg. Each application experiment lasted for 7.0 d, with
120 gaseous emission measurements immediately after manure application ($t= 0$) and 0.5,
121 1.0, 2.0, 3.0, 4.0, 5.0 and 7.0 d after manure application. Net CO₂, CH₄, N₂O and NH₃
122 emission fluxes were calculated as the difference between emission fluxes recorded
123 from the amended soils and those measured from the Control.

124 Flux measurements from both storage and soil application were collected by
125 dynamic chamber method using a gas trace analyzer (1312 Photoacoustic Multi-gas
126 Monitor and Multipoint Sampler, Innova Air Tech Instruments, Ballerup, Denmark)
127 following the protocol described by Dinuccio et al. (2008). Additionally, at the
128 beginning of each experiment, materials from each replicate were characterized for pH,
129 total solids (TS), volatile solids (VS), TKN, total ammoniacal N (TAN), total carbon
130 (TC) and total N (TN; Table 1) according to procedures described by Heiermann et al.
131 (2009) and Plöchl et al. (2009).

132 Gaseous losses were expressed in CO₂-eq using conversion factors of 1, 25, 298,
133 and 2.98 respectively, for CO₂, CH₄, N₂O and NH₃ (IPCC, 2007). To estimate effects
134 of cattle slurry mechanical separation on gaseous emissions, total CO₂, CH₄, N₂O and
135 NH₃ losses were corrected by considering mass distribution of solid (18%) and liquid
136 (82%) fractions to the whole separated raw cattle slurry. Afterwards, total losses
137 (Dinuccio et al., 2008) of the gases were expressed as kgCO₂-eq/Mg of treated raw
138 cattle slurry.

139 All data were processed with ANOVA procedures. Data distribution normality was
140 verified using the Kolmogorov–Smirnov test. Assumption of equal variance of
141 different groups was tested using Bartlett’s test. Means were separated by Tukey test
142 and differences were considered to be significant for $P < 0.05$. All statistical analyses
143 were performed with SPSS 12.0 for Windows (SPSS, 2006). Due to the variability of
144 CO₂, CH₄, N₂O and NH₃ flux intensity, variances were not homogeneous when
145 comparing different sampling days. Therefore, independent analysis were performed
146 for each date of sampling. Cumulative CO₂, CH₄, N₂O and NH₃ emissions were
147 analyzed by a two-way ANOVA using manure management phase (storage, soil
148 application) and manure type (raw cattle slurry, liquid fraction, solid fraction) as fixed
149 factors.

150

151 **3. Results and Discussion**

152 *3.1 Storage experiments*

153 During the 30 d storage period, the CO₂, CH₄, N₂O and NH₃ emission fluxes
154 measured from the raw cattle slurry and its liquid fraction showed similar trends
155 (Figure 1). Carbon dioxide was the main GHG (Table 2) emitted during storage of the
156 solid fraction, in agreement with findings of Hao et al., (2004) and Pattey et al., (2005).
157 In term of CO₂-eq, CH₄ emission was the predominating GHG from stored liquid
158 manures, a finding supported by Berg et al. (2006). After 30 d of storage, the amount
159 of C lost by CH₄ emissions (Table 2) from the liquid fraction was higher ($P<0.05$) than
160 that lost from the raw cattle slurry, suggesting that mechanical separation of the solids
161 reduced the amount of carbon that was available for methanogenesis (Amon et al.,
162 2006; Møller et al., 2007). Nitrous oxide fluxes (Figure 1) from the solid fraction
163 ranged from 0.001 to 0.007 mg m²/h and were lower ($P<0.05$) than those from the raw
164 cattle slurry of 0.01 to 0.28 mg m²/h) and from the liquid fraction of 0.02 to 0.28 mg
165 m²/h) for most of the storage period. No N₂O was detected from all manures after 20 d
166 of storage. The lowest NH₃ emission rates (Figure 1) were from the solid fraction, but
167 were higher from the liquid fraction ($P<0.05$) compared to the raw cattle slurry for
168 most of the storage period. This was mainly due its lower TS content (Table 1), which
169 reduced development of a natural surface crust (Misselbrook et al., 2005).

170 3.2 Application experiments

171 Net CO₂ and CH₄ emission rates (Figure 2) from all amended soils peaked
172 immediately following manure application, probably due to release of CO₂ and CH₄
173 dissolved in slurry (Flessa and Beese, 2000). From 2 to 4 d after manure application,
174 net CO₂ emission fluxes from all amended soils were negative, probably due to CO₂
175 consumption by soil heterotrophic microorganisms (Fangueiro et al., 2007). Soil has
176 also been shown (Figure 2) to be a sink for CH₄ during the first few h after manure
177 application, probably due to the increased amount of easily degradable organic
178 compounds (*e.g.*, carbohydrates and volatile fatty acids) and available N that stimulate
179 activity of methanotrophs (Chadwick et al., 1997).

180 Net N₂O emissions from all amended soils peaked 24 h after manure application,
181 but then decreased to Control levels until the end of the investigation period. Peak rates
182 (Figure 2) ranged from 22.8 µgN₂O m²/h (*i.e.*, soil amended with the solid fraction)
183 and 217 µgN₂O m²/h (*i.e.*, soil with the raw cattle slurry). Such values are lower with
184 respect to those obtained in a recent laboratory scale experiment by Fangueiro et al.
185 (2008b) under conditions favourable to N₂O formation. Factors such as manure type, N
186 application rate, temperature, soil type, moisture and water holding capacity of the soil

187 have been suggested by Sahrawat and Keeney (1986) to affect N₂O production after
188 manure application to soil. The low air temperature (10°C) and soil moisture content
189 (98 g/kg), which are typical environmental conditions in many Italian areas in winter,
190 could be the reason for low N₂O emissions from soil applied manures. However, due to
191 the short 7 d time period of flux data collection, our results should not be used for
192 national inventory of N₂O emissions from soils. Net NH₃ emission rates (Figure 2)
193 from all amended soils peaked immediately following manure application and rapidly
194 declined to Control levels after 5 d. After soil application of the liquid fraction (Table
195 2), NH₃ emissions increased by about 60% compared to raw cattle slurry, probably due
196 to its higher pH and TAN/TKN ratio ($P < 0.05$, Table 1). Mechanical separation
197 decreased NH₃ emissions after manure application (Amon et al., 2006; Balsari et al.,
198 2008), as the low TS content of the liquid fraction may enable more rapid infiltration
199 of NH₄⁺ into soil. In this study, removal of solids from the raw cattle slurry was likely
200 not extensive enough to improve soil infiltration of the liquid fraction. After soil
201 application, the main GHG emitted from all manures was CO₂ (Table 2). Methane also
202 contributed ($P < 0.05$) to overall GHG emissions, whereas the contribution of N₂O and
203 NH₃ was very low.

204 *3.3 Effect of mechanical separation on gaseous emissions*

205 In terms of CO₂-eq, the cumulative CO₂ and NH₃ emissions from storage and soil
206 application of liquid and solid fractions of mechanical separation raw cattle slurry
207 increased by 104% and 37% from storage and by 14% and 48% with soil application,
208 respectively. In contrast, N₂O emissions from storage and soil application were
209 reduced by 41% and 60%, respectively. Methane emissions were 14% lower from the
210 soil application phase only. Combined CH₄ and N₂O emissions from storage and soil
211 application of liquid and solid fractions (Table 2) were 9% and 59% lower than those
212 from raw cattle slurry. Nevertheless, considered as a whole, storage and soil
213 application of separated liquid and solid fractions resulted in a net increase of 11% in
214 GHG emissions compared with the storage and soil application of raw cattle slurry.

215

216 **5. Conclusions**

217 Under the conditions of this laboratory scale study, storage and soil application of
218 both liquid and solid fractions resulted an 11% increase in GHG emissions compared
219 to mixed raw cattle slurry. This was due to the 20% higher CO₂ and 44% higher NH₃
220 emissions during storage and application of both liquid and solid fractions than the

221 storage and soil application of the raw cattle slurry. Mechanical separation of cattle
222 slurry is not recommended unless other GHG emission reduction measures are
223 adopted. Since natural environments differ from the laboratory, results obtained from
224 our study should be validated at under field conditions.

225

226 **References**

227 Amon, B., Kryvoruchko, V., Amon, T., Zechmeister-Boltenstern, S., 2006. Methane,
228 nitrous oxide and ammonia emissions during storage and after application of dairy
229 cattle slurry and influence of slurry treatment. *Agric. Ecosyst. Environ.* 112, 153-
230 162.

231 APAT, 2006. Italian Greenhouse Gas Inventory 1990-2004. National Inventory Report
232 2006. Agency for Environmental Protection and Technical Services. Rome, Italy.

233 Balsari, P., Dinuccio, E., Santoro, E., Gioelli, F., 2008. Ammonia emissions from
234 rough cattle slurry and from derived solid and liquid fractions applied to alfalfa
235 pasture. *Aust. J. Exp. Agric.* 48, 198-201.

236 Berg, W., Brunsch, R., Pазsiczki, I., 2006. Greenhouse gas emissions from covered
237 slurry compared with uncovered during storage. *Agric. Ecosyst. Environ.* 112, 129-
238 134.

239 Burton, C.H., 2007. The potential contribution of separation technologies to the
240 management of livestock manure. *Livest. Sci.* 112, 208-216.

241 Chadwick, D.R., Pain, B.F., 1997. Methane fluxes following slurry applications to
242 grassland soils: Laboratory experiments. *Agric. Ecosyst. Environ.* 63, 51-60.

243 Dinuccio, E., Berg, W., Balsari, P., 2008. Gaseous emissions from the storage of
244 untreated slurries and the fractions obtained after mechanical separation. *Atmos.*
245 *Environ.* 42, 2448-2459.

246 Fangueiro, D., Chadwick, D., Dixonb, L., Bol, R., 2007. Quantification of priming and
247 CO₂ emission sources following the application of different slurry particle size
248 fractions to a grassland soil. *Soil Biol. Biochem.* 39, 2608-2620.

249 Fangueiro, D., Coutinho, J., Chadwick, D., Moreira, N., Trindade, H., 2008a. Effect of
250 Cattle Slurry Separation on Greenhouse Gas and Ammonia Emissions during
251 Storage. *J. Environ. Qual.* 37, 2322-2331.

252 Fangueiro, D., Pereira, J., Chadwick, D., Coutinho, J., Moreira, N., Trindade, H.,
253 2008b. Laboratory assessment of the effect of cattle slurry pre-treatment on organic

254 N degradation after soil application and N₂O and N₂ emissions. *Nutr. Cycl.*
255 *Agroecosyst.* 80, 107-120.

256 FAO, 2006. *Livestock's Long Shadow: Environmental Issues and Options*. Rome,
257 Italy.

258 Flessa, H., Beese, F., 2000. Laboratory estimates of trace gas emissions following
259 surface application and injection of cattle slurry. *J. Environ. Qual.* 29, 262-268.

260 Goebes, M.D., Strader, R., Davidson, C., 2003. An ammonia emission inventory for
261 fertilizer application in the United States. *Atmos. Environ.* 37, 2539–2550.

262 Hao, X., Chang, C., Larney J.F., 2004. Carbon, Nitrogen Balances and Greenhouse
263 Gas Emission during Cattle Feedlot Manure Composting. *J. Environ. Qual.* 33, 37-
264 44.

265 Heiermann, M., Plöchl, M., Linke, B., Schelle, H., Herrmann, C., 2009. “Biogas Crops
266 – Part I: Specifications and Suitability of Field Crops for Anaerobic Digestion”.
267 *Agricultural Engineering International: the CIGR Ejournal*. Manuscript 1087. Vol.
268 XI.

269 IPCC, 2007. *Climate change 2007: The physical science basis*. Contribution of
270 Working Group I to the Fourth Assessment Report of the Intergovernmental Panel
271 on Climate Change. Cambridge University Press, Cambridge, UK and New York,
272 NY, USA.

273 Misselbrook, T.H., Brookman, S.K.E., Smith, K.A., Cumby, T., Williams, A.G.,
274 McCrory, D.F., 2005. Crusting of Stored Dairy Slurry to Abate Ammonia
275 Emissions: Pilot-Scale Studies. *J. Environ. Qual.* 34, 411-419.

276 Møller, H.B., Hansen, J.D., Sorensen, C.A.G., 2007. Nutrient recovery by solid-liquid
277 separation and methane productivity of solids. *Transactions of the ASABE* 50, 193-
278 200.

279 Pattey, E., Trzcinski, M.K., Desjardins, R.L., 2005. Quantifying the reduction of
280 green-house gas emissions as a result of composting dairy and beef cattle manure.
281 *Nutr. Cycl. Agroecosyst.* 72 (2), 173-187.

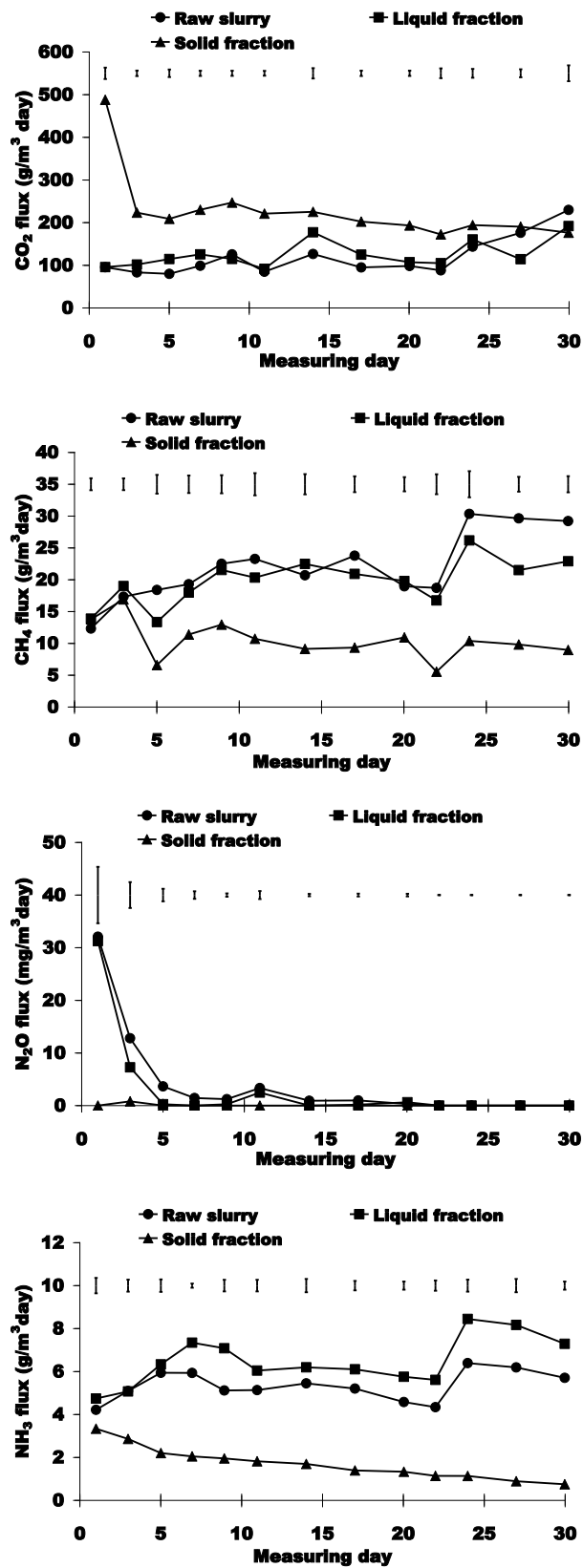
282 Plöchl, M., Hilse, A., Heiermann, M., Suarez, T., Budde, J., Prochnow, A., 2009.
283 “Hydrolytic enzymes improve fluidity of biogas feedstock”. *Agricultural*
284 *Engineering International: the CIGR Ejournal*. Manuscript 1529. Vol. IX.

285 Sahrawat, K.L., Keeney, D.R., 1986. Nitrous oxide emission from soils. *Adv. Soil Sci.*
286 4, 103-148.

287 SPSS, 2006. *SPSS for windows: Advanced statistics*, Release 12.0. SPSS, Chicago, IL.

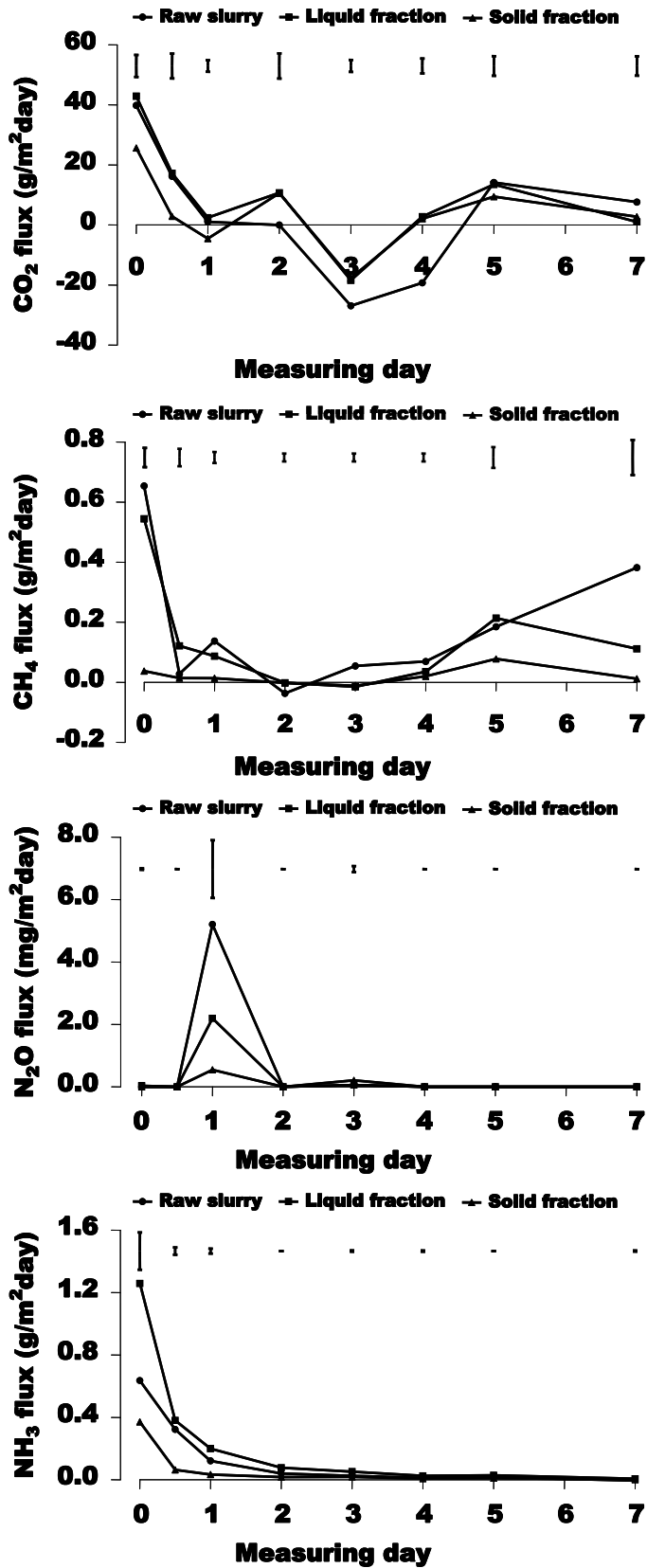
288 UNFCCC, 1997. The Kyoto Protocol. United Nations Framework Convention on
289 Climate Change. [http://unfccc.int/essential background/convention/items/2627.php](http://unfccc.int/essential%20background/convention/items/2627.php)
290 USDA, 1977. Keys to Soil Taxonomy. Soil Survey Staff, Soil Conservation Service
291 U.S. Dept. Of Agriculture, 7th edition. Pocahontas Press, Inc., Blacksburg, VA,
292 USA.
293 Valli, L., Fabbri, C., Bonazzi, G., 2000. A national inventory of ammonia and
294 greenhouse gas emissions from agriculture in Italy. In: Sangiorgi, F. (Ed.),
295 Technology Transfer: Proceedings of the Ninth International RAMIRAN 2000
296 Workshop, Gargnano, Italy, 6-9 September 2000, Cemagref, France, pp. 153-159.
297

298 Fig. 1.
 299 Average emission fluxes of CO₂, CH₄, N₂O and NH₃ during storage of the tested materials (raw cattle
 300 slurry, liquid fraction, solid fraction). The bars in the upper part of each graph represent Pooled standard
 301 error of mean (SEM).
 302



303
 304

305 Fig. 2.
 306 Net emission fluxes of CO₂, CH₄, N₂O and NH₃ after soil application of the tested materials (raw cattle
 307 slurry, liquid fraction, solid fraction). The bars in the upper part of each graph represent Pooled standard
 308 error of mean (SEM).
 309



311 Table 1.

312 Composition¹ of the tested manures at the beginning of the storage and soil application experiments.

	<i>pH</i>	<i>TS</i> g/kg	<i>VS</i> g/kg	<i>TKN</i> g/kg	<i>TAN</i> g/kg	<i>TAN/TKN</i>	<i>TC</i> g/kg	<i>TC/TN</i>
STORAGE²								
Raw cattle slurry	7.10	74.6	60.2	3.58	1.47	0.41	31.1	13.6
Liquid fraction	7.10	51.2	38.1	3.29	1.49	0.45	19.8	11.0
Solid fraction	8.30	192	173	5.59	1.16	0.21	83.1	27.4
SOIL APPLICATION³								
Raw cattle slurry	6.80 c	76.7 b	61.7 b	3.32 b	1.38 a	0.42 b	32.6 b	16.0 b
Liquid fraction	7.00 b	49.9 c	36.4 c	3.23 b	1.43 a	0.44 a	18.5 c	14.2 b
Solid fraction	8.50 a	186 a	163 a	3.57 a	0.20 b	0.06 c	71.6 a	19.3 a
SEM ⁴	0.016	0.857	0.845	0.141	0.000	0.003	1.821	0.022
P-value ⁵	<0.001	<0.001	<0.001	0.001	<0.001	<0.001	<0.001	0.002

313 TS, Total solids; VS, volatile solids; TKN, total Kjeldahl N; TAN, total ammoniacal N; TC, total
314 carbon; TN, total N.

315 ^{a-c} Data in a column followed by different letter differ at P<0.05.

316 ¹ Data in table are based on fresh manure weight.

317 ² Chemical analysis done on one sample.

318 ³ Chemical analysis done on four samples.

319 ⁴ SEM, Pooled standard error of mean.

320 ⁵ Significance level: P>0.05, not significant.

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325

326 Table 2.

327 Cumulative emissions of CO₂, CH₄, N₂O and NH₃ recorded over the storage (St) and soil application
328 (SA) experiments.

	Raw slurry		Liquid Fraction		Solid Fraction		SEM ¹	P-value ²		
	St	SA	St	SA	St	SA		Mm	T	Mn×T
C-CO₂										
g/kg TC	91.5 c	51.2 d	155 b	246 a	204 a	41.9 d	10.92	0.032	0.011	0.009
kg CO ₂ eq/Mg treated raw slurry (^A)	9.87 d	127 a	9.81 d	115 b	10.9 d	30.3 c	2.031	< 0.001	< 0.001	< 0.001
C-CH₄										
g/kg TC	6.40 c	13.1 a	9.01 b	12.5 a	3.48 d	0.98 e	1.094	0.013	< 0.001	0.003
kg CO ₂ eq/Mg treated raw slurry (^B)	17.3 c	45.3 a	13.3 c	32.7 b	4.65 d	6.47 d	0.911	< 0.001	< 0.001	< 0.001
N-N₂O										
g/kg TKN	0.03 c	0.48 a	0.02 c	0.21 b	< 0.01 c	0.07 c	0.029	< 0.001	0.006	0.014
kg CO ₂ eq/Mg treated raw slurry (^C)	0.05 c	0.78 a	0.03 c	0.29 b	< 0.01 c	0.03 c	0.049	< 0.001	0.001	0.003
N-NH₃										
g/kg TAN	102 e	140 c	128 c	225 b	123 dc	681 a	7.748	< 0.001	< 0.001	< 0.001
kg CO ₂ eq/Mg treated raw slurry (^D)	0.46 c	0.70 b	0.47 c	0.94 a	0.17 d	0.09 d	0.027	< 0.001	< 0.001	< 0.001
Total GHG (^A + ^B + ^C + ^D) (kg CO₂ eq/Mg treated raw slurry)	27.6 c	174 a	23.0 dc	149 b	15.8 d	36.9 c	2.258	< 0.001	< 0.001	< 0.001

329 ^{a-d} Data in a row followed by different letter differ at P<0.05.

330 ¹ SEM, Pooled standard error of mean.

331 ² Significance level: effect of manure management phase (Mm), manure type (T), interaction (Mn × T).

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333