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## Soil PM10 emission potential under specific mechanical stress and particles characteristics

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(Article begins on next page)

1 SOIL PM<sub>10</sub> EMISSION POTENTIAL UNDER SPECIFIC MECHANICAL STRESS AND PARTICLES  
2 CHARACTERISTICS

3  
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16  
17 ABSTRACT

18 Soil can be resuspended in the atmosphere due to wind or mechanical disturbances, such as  
19 agricultural activities (sowing, tilling, etc.), producing fine particulate matter (PM). Agriculture is  
20 estimated to be the third PM<sub>10</sub>-emitting sector in Europe, emitting more than the transportation  
21 sector. However, very few emission figures are available for the different cropping operations.  
22 Moreover, soil Emission Potential (EP) is extremely variable, since is influenced by factors such as  
23 humidity, texture, chemical composition, and wind speed.

24 Due to their similarity to tilling emission mechanisms, Soil Resuspension Chambers (SRC) are the  
25 most suitable method to estimate the impacts of these factors on soil susceptibility to emit PM<sub>10</sub>  
26 during cropping operations (Emission Potential, EP).

27 The main objective of this work is to assess the EP of different agricultural soils used for maize  
28 cropping in North-Western Italy, studying the influence of soil moisture and physico-chemical  
29 characteristics. Therefore, a SRC was developed, based on previous studies, with the goal of  
30 being relatively small, easy to operate and low-cost. Using the gathered data, a log-linear multiple  
31 regression model was developed to allow soil EP estimation from few physico-chemical  
32 parameters (moisture, sand/silt ratio and organic carbon content). The model allows to tailor field  
33 Emission Factors (EF) of specific cropping operations to different soil and moisture conditions and  
34 was applied to an EF for rotary harrowing, defined in a previous study.

35 The concentration of Potentially Toxic Elements (PTE) in soil-emitted PM<sub>10</sub> was determined,  
36 founding an enrichment up to 16 times higher than in the original soil, evidencing a possible cause  
37 of concern for operator's safety during agricultural activities.

38

39 KEYWORDS

40 Emission Model; Particulate Matter; PM<sub>10</sub>; Potentially Toxic Elements; Soil Dust

41

42 1. INTRODUCTION

43 Soil is a natural source of fine Particulate Matter (PM), both in urban and in rural environments  
44 (Padoan and Amato, 2018; Soleimanian et al., 2019). Soil particles can be suspended in the  
45 atmosphere mainly due to wind erosion and to mechanical disturbances, such as agricultural  
46 activities (Maffia et al., 2020a; Sharratt and Auvermann, 2014).

47 Along with the long-term adverse health effects of atmospheric PM<sub>10</sub> pollution (Tonne et al., 2016),  
48 several studies highlighted the importance of crustal components of PM and of soil-derived PM<sub>10</sub>  
49 (Wu et al., 2020; Galindo et al., 2018; Padoan et al., 2016; Kendall et al., 2004). These  
50 components are of crucial importance in terms of total emissions and chemical composition and  
51 are possibly enriched of inorganic and organic pollutants (Padoan et al., 2017; Brunekreef and  
52 Holgate, 2002).

53 In Europe, agriculture is estimated to be the third PM<sub>10</sub>-emitting sector, emitting more than the  
54 transportation sector according to the European Environment Agency (EEA, 2020). Farm-level  
55 agricultural operations, such as land preparation activities (sowing, tillage, etc.) and outdoor animal  
56 rearing (herd movement and animal activity), are one of the most relevant contributors to anthropic  
57 PM emissions (EEA, 2020). However, very few emission figures are available for the different  
58 cropping operations (Maffia et al., 2020b; Öttl et al., 2007; Holmén et al., 2001).

59 PM emissions from cropping activities are extremely variable, since they are influenced by many  
60 factors, such as soil humidity, texture and chemical composition (e.g. the mineral and organic  
61 matter content), and wind speed (Avecilla et al., 2017; Funk et al., 2008). These factors, together  
62 with the mechanical implements used for cropping operations, determine the field emissions.  
63 Addressing these factors one by one, and determining their specific effect on the emissions is,  
64 therefore, of crucial importance to standardize field emission data and to compare them  
65 successfully.

66 Several laboratory methodologies have been proposed to investigate the impacts of these factors  
67 on soil Emission Potential (EP), the soil capacity to emit PM<sub>10</sub> per unit weight, over a certain  
68 period. Among these methodologies, the most common are soil resuspension chambers (SRC)  
69 and wind tunnels (WT) (Mendez et al., 2013; Pietrodangelo et al., 2013; Madden et al., 2010;  
70 Moreno et al., 2009; Gill et al., 2006). SRC rely on mechanical disturbance or abrasion to achieve  
71 soil resuspension, with the possibility to collect resuspended particles using a depression or

72 forced-air ducts. Conversely, WT rely only on wind speed effect. Due to the similar resuspension  
73 mechanism applied, SRC are more suitable than WT to estimate soil susceptibility to emit PM<sub>10</sub>  
74 during cropping operations, while WT are more appropriate to estimate wind erosion rates.  
75 The main objective of the work is to assess the EP of different agricultural soils used for maize  
76 cropping in North-Western Italy, studying the influence of soil moisture and physico-chemical  
77 characteristics on the EP of those soils. Therefore, a SRC was developed, based on previous  
78 studies (Maffia et al., 2020b; Madden et al., 2010), with the goal of being relatively small, easy to  
79 build and low-cost. Using the gathered data, we developed a model to allow soil EP estimation  
80 from some simple physico-chemical parameters, to tailor field emission factors (EF) of specific  
81 cropping operations to different soil and moisture conditions. Moreover, we analysed the  
82 Potentially Toxic Elements (PTE) concentration of soil-emitted PM<sub>10</sub> to assess the health and  
83 environmental risk of the resuspended particles, potentially eroded and transported to different  
84 environmental compartments or affecting farmers.

85

## 86 2. MATERIALS AND METHODS

### 87 2.1. *Soil Sampling and physico-chemical characterization*

88 Soils were sampled in different locations in Piemonte (North-West of Italy). The areas were chosen  
89 based on the regional soil map (Regione Piemonte, 2020), selecting seven soils with different  
90 physico-chemical properties in order to represent the range of soil texture in cultivated soils of  
91 Piemonte. The selected soils are typically invested with Maize, which is the most cultivated  
92 summer crop in northern Italy. Soil classification was defined according to WRB Soil Taxonomy  
93 (IUSS, 2015).

94 The map with the sampling points (Figure SM1) and the table with coordinates, soil classification  
95 and meteorological parameters (Table SM1) are reported in the Supplementary Material (SM).

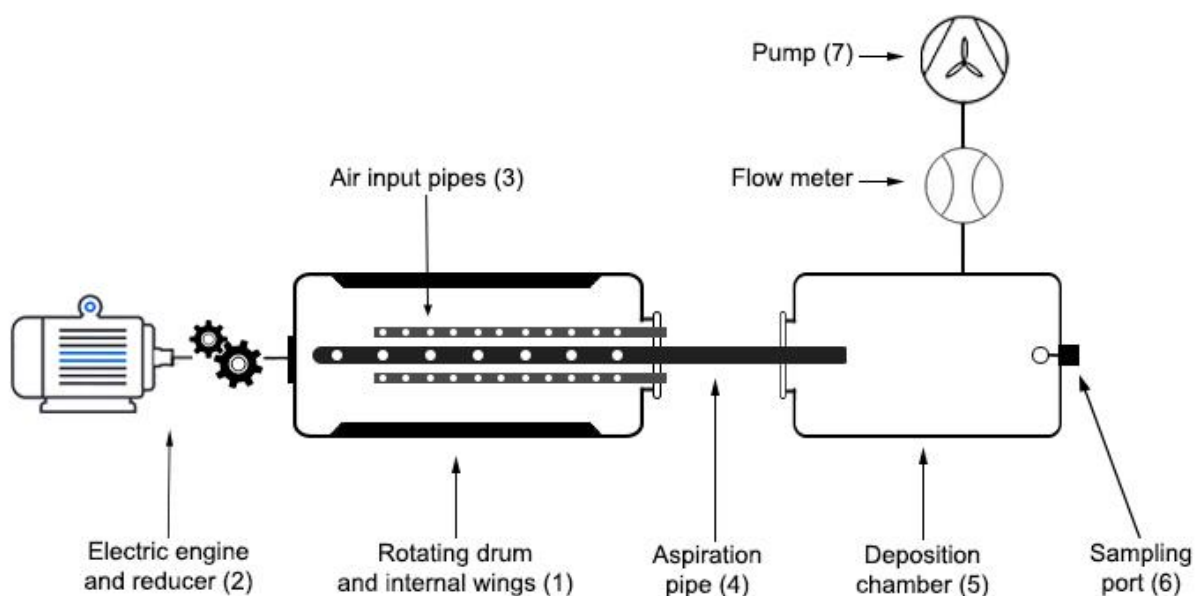
96 At each location, 15 subsamples were taken by applying a non-systematic X sampling scheme  
97 (Colombo and Miano, 2015). The topsoil subsamples were collected to a depth of 25 cm, which  
98 was considered the most used depth in tilling practices and quartered in the field to obtain 7 soil  
99 samples.

100 The samples were air-dried and sieved to 2 mm before physico-chemical analyses. We determined  
101 soil texture, pH, total carbon and nitrogen content and carbonates. All analyses were performed  
102 according to official Italian methods for soils (Colombo and Miano, 2015). The fraction of particles  
103 <10 µm was estimated by repeated sedimentation and decanting, as in Ajmone-Marsan et al.  
104 (2008). Field capacity (FC) was then determined for each soil according to the official method  
105 proposed by MiPAF (1997).

106

### 107 2.2. *Soil resuspension chamber*

108 A soil resuspension chamber (SRC) was developed starting from the rotating drum in Maffia et al.  
 109 (2020a), using the best experiences from Gill et al. (2006) and Madden et al. (2009). The SRC  
 110 system is represented in Figure 1. Soil samples were re-suspended in a rotating drum (1) with a  
 111 25 L capacity and a rotation frequency of 26 revolutions per minute, powered by an electric engine  
 112 (2) with 0,75 kW of power and an electric potential of 220 V. During the trials, the drum was closed  
 113 by a flange. Four flexible PVC tubes (0.4 m long with 8 mm diameter), provided with a series of  
 114 small holes (diameter 0.3 mm), were nested on the flange and allow clean air to enter the drum.  
 115 During soil re-suspension, the air was sucked from the drum (1) through an aspiration pipe (4),  
 116 which allowed the emitted dust to reach a deposition chamber (5). The air stream was forced by a  
 117 vane pump (5; VTE3, Rietschle), drawing the air from the deposition chamber and inducing an air  
 118 flow of 30 L min<sup>-1</sup>, calibrated through a flux meter, through the system. The re-suspended  
 119 particulate matter was sampled through a sampling port (6) using both an optical PM monitor  
 120 (Grimm 11-D, Grimm Aerosol Technik), to assess particle quantity, or a filter-based low-volume  
 121 impactor (MSSI Multistage Impactor, TCR Tecora®), to define particles elemental composition.  
 122



123  
 124

125 Figure 1. Scheme of the soil resuspension chamber. Soil is manually placed in the rotating drum  
 126 (1) before the experiment, while PM instrumentation is connected to the sampling port (6).  
 127

127

128

### 2.3. Experimental protocol and Emission Potential estimation

129 Resuspension trials of each sample were accomplished by placing a soil aliquot inside the SRC  
 130 rotating drum and re-suspending it for 15 min. Different tests were conducted to define the most  
 131 suitable soil quantity, to generate reproducible data without saturating the PM monitor. The final  
 132 experiments were conducted using 5g of each soil and were performed in triplicate to ensure the  
 133 consistency of the method.

134 The EP was defined at four different moisture contents (calculated as 0, 15, 30 and 40%, by  
135 weight, of the soils FC) for each soil, for a total of 84 trials. The equation used to define soil EP (mg  
136 kg<sup>-1</sup>) was the following:

$$137 \quad EP = \frac{C}{1000} * \frac{P * t}{S}$$

138 Where C represents the particle concentration (µg m<sup>-3</sup>) measured by the Grimm PM monitor, P the  
139 system airflow (m<sup>3</sup> min<sup>-1</sup>), calculated as the sum of the pump flow and the flow of the Grimm  
140 internal pump (1.2 L min<sup>-1</sup>), S the mass of the soil sample used (kg), and t the considered timespan  
141 (min).

142

#### 143 2.4. Filter-based Particulate Matter sampling and elemental analysis

144 Soil-emitted PM<sub>10</sub> was sampled on quartz fibre filters (Ahlstrom Munksjo, Microquartz fibre paper  
145 MK360, Ø47 mm). Before use, filters were dried at 205 °C for 5 hours and conditioned for 48 hours  
146 at 20 °C and 50 % relative humidity; then weighed three times every 24 h and kept in Petri dishes.  
147 Used filters were conditioned for 48 h and weighed using the same procedure.

148 Between consecutive samples, the SRC was thoroughly washed with deionized water and run for  
149 15 min without soil to avoid cross-contamination.

150 Major and trace element pseudo-total contents were determined in the original soils and in PM<sub>10</sub>.  
151 One-gram soil samples were digested in *aqua regia* (HNO<sub>3</sub>:HCl, 1:3) using microwave extraction  
152 (Ethos D, Milestone). Similarly, half of each PM<sub>10</sub> filter was microwave digested and blank filters  
153 were analysed to ensure a correction for their possible elemental release. Solutions were then  
154 filtered on cellulose filters (Whatman n° 41) and diluted with ultrapure water before analysis.  
155 Elemental concentrations were assessed in all samples using ICP-MS (NexION 350D,  
156 PerkinElmer). All the analyses were performed in duplicate and using certified reference materials  
157 (CRM 141R and 142R, Community Bureau of Reference, Geel, Belgium) to ensure accuracy and  
158 correct recoveries.

159 The enrichment ratios (ER), i.e. the ratios between elemental concentrations in soil-originated PM<sub>10</sub>  
160 compared to bulk soil, were calculated as follows:

$$161 \quad ER = \frac{C_{PM} - C_{soil}}{C_{soil}}$$

162 Where C<sub>PM</sub> is the concentration (mg kg<sup>-1</sup>) in resuspended PM<sub>10</sub> and C<sub>soil</sub> is the concentration in the  
163 original soil (mg kg<sup>-1</sup>).

164

#### 165 2.5. Statistical analyses

166 The effect of the physico-chemical characteristics on the EP of the investigated soils was analysed  
167 using multiple log linear regression. Predictors were chosen on the base of their level of correlation  
168 with the EP logarithm. The correlation matrix also allowed to check for collinearity. To account for

169 the soil particle size distribution, we tried to use all the three parameters (sand, silt and clay)  
 170 together, only two of them and using the different ratios. Clay, probably because of its scarce  
 171 variation in the soil set, did not have a high correlation coefficient with EP and, when added to the  
 172 model, the prediction (fitting) did not improve. We decided to use the sand-silt ratio as a proxy for  
 173 the complete particle size distribution because was the one performing better in the prediction  
 174 model. This choice was made since, as highlighted by Madden et al. (2010), the ratio between two  
 175 textural components can be a good descriptor of soil characteristics. Moreover, it allowed to  
 176 achieve a more parsimonious model. Sand and silt performed better than clay as predictors,  
 177 probably since these two components are the ones that vary the most in selected soils. The  
 178 linearity and homoscedasticity assumptions were tested graphically and by means of a Shapiro-  
 179 Wilk test. The analyses were performed using R statistical software (R core team, 2019).

180

### 181 3. RESULTS

#### 182 3.1. Soil physico-chemical characteristics

183 The physico-chemical characteristics of the analysed soils are reported in Table 1.

184 The studied soils presented a relatively wide textural variability with sand contents ranging from 14  
 185 to 82 %, silt contents ranging from 9 to 40 % and clay contents ranging from 9 to 33 %. Soil  
 186 texture, and especially fine fractions content, is known to be a key factor in determining PM<sub>10</sub>  
 187 emissions (Madden et al., 2010; Funk et al., 2008), thus the content in <10 µm particles was  
 188 analysed, ranging from 9.5 to 51 % in the observed soils.

189 Carbonate concentrations were variable but low in all the soils. Organic carbon (OC) contents were  
 190 in line with typical Italian agricultural soils (Jones et al., 2020), varying in the range 0.8 – 2.2%.

191

192 Table 1. Soil physico-chemical characterization, texture was calculated according to Soil Science  
 193 Division Staff (2017).

Soil	Sand (%)	Silt (%)	Clay (%)	Textural class	Particles < 10 µm (%)	Field Capacity (% V/V)	pH	OC (g kg <sup>-1</sup> )	Inorganic C (g kg <sup>-1</sup> )	N (g kg <sup>-1</sup> )	C/N ratio
S1	51	40	9	Loam	18.2	37.9	8.2	8.8	2.7	1.4	9
S2	30	56	14	Silt Loam	25.3	32.3	7.5	8.3	1.2	1.3	8
S3	14	53	33	Silty Clay Loam	51.4	33.0	6.9	11.6	1.0	1.8	7
S4	82	9	9	Loamy Sand	9.5	23.6	6.9	9.5	8.5	1.1	16
S5	30	54	16	Silt Loam	37.9	45.7	6.2	22.0	1.9	3.2	8
S6	40	46	14	Loam	31.6	24.9	7.7	10.0	1.0	1.8	6
S7	59	31	10	Sandy Loam	19.8	35.6	6.0	11.8	1.7	1.8	8

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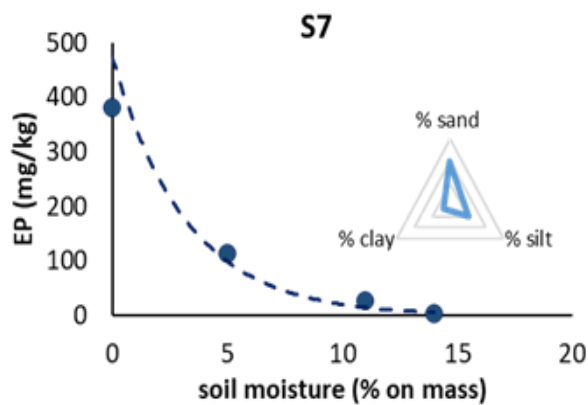
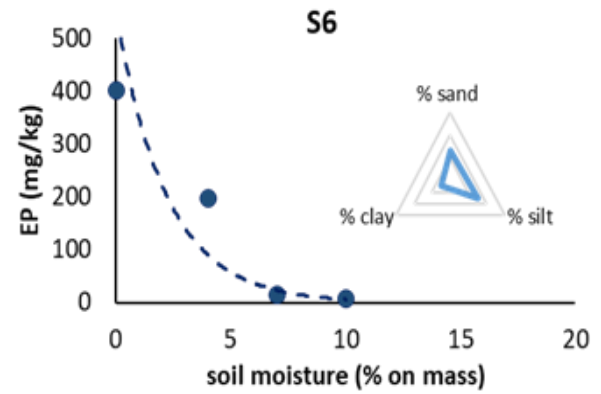
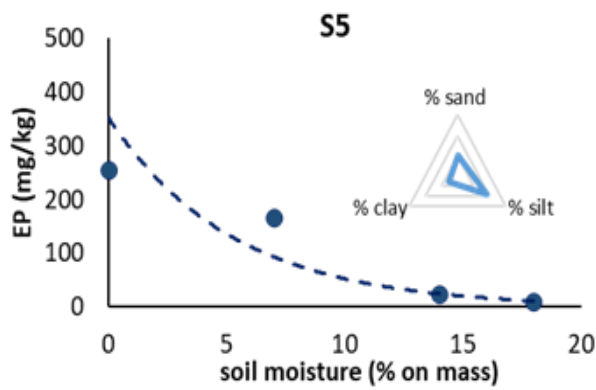
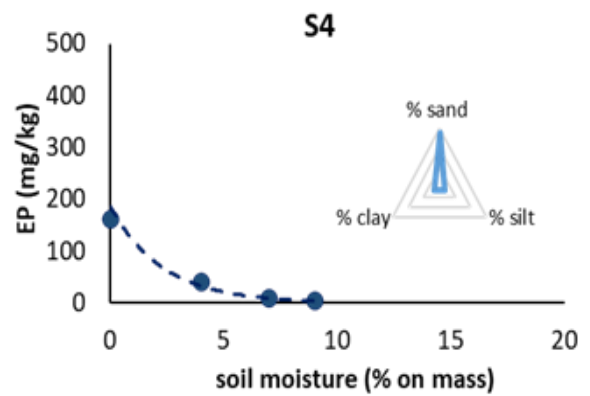
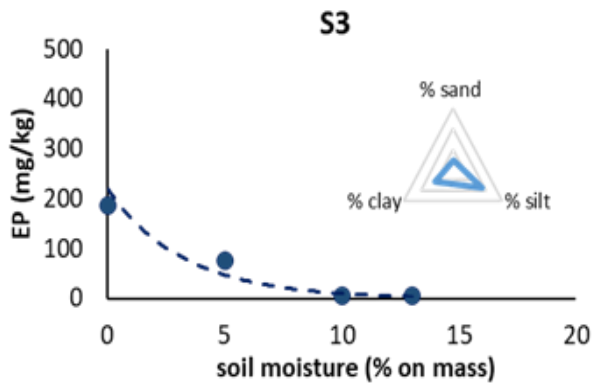
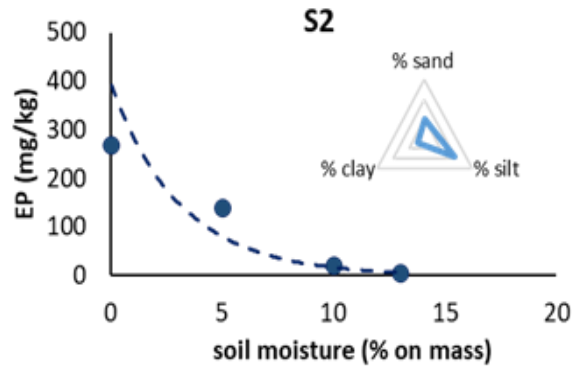
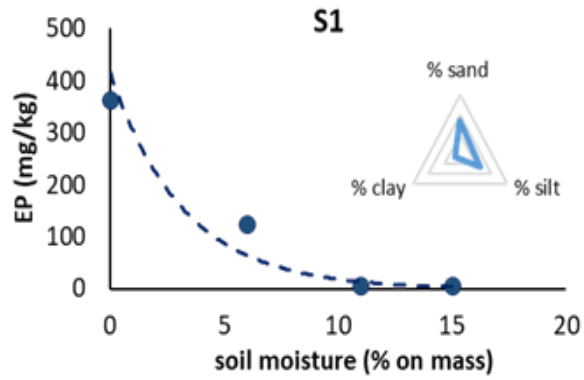
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196       3.2.   *Emission Potential*

197   Air-dried soils were considered as with zero percent moisture. Water was then added to each soil  
198   to achieve the desired percentage levels of FC (0, 15, 30 and 40%). Figure 2 shows the EP of the  
199   soils at the different soil moisture content. In Fig. 2 the mass percentage was used to normalize  
200   moisture values in the different soils. An exponential decrease of the soil EP with the increase of  
201   moisture found for all soils.

202





203

204

205

Figure 2. Emission Potential of selected soils as measured using the PM monitor.

206 Between the analysed chemical parameters, carbonate and total nitrogen contents were not  
207 linearly correlated to the EP of the soils. The effect of soil moisture content, texture, and OC  
208 content on the EP of the investigated soils was analysed by means of regression models.

209 Regarding texture, giving that the three components are interrelated, we calculated the model  
210 results using all the three parameters together and/or with each single fraction, finding no  
211 correlations with EP. Then, we used different ratios between two of them, finding this as best  
212 option, as in Madden et al. (2010). Among the possible ratios, the sand to silt quotient was the one  
213 better performing in the model, giving consistent results for all soils.

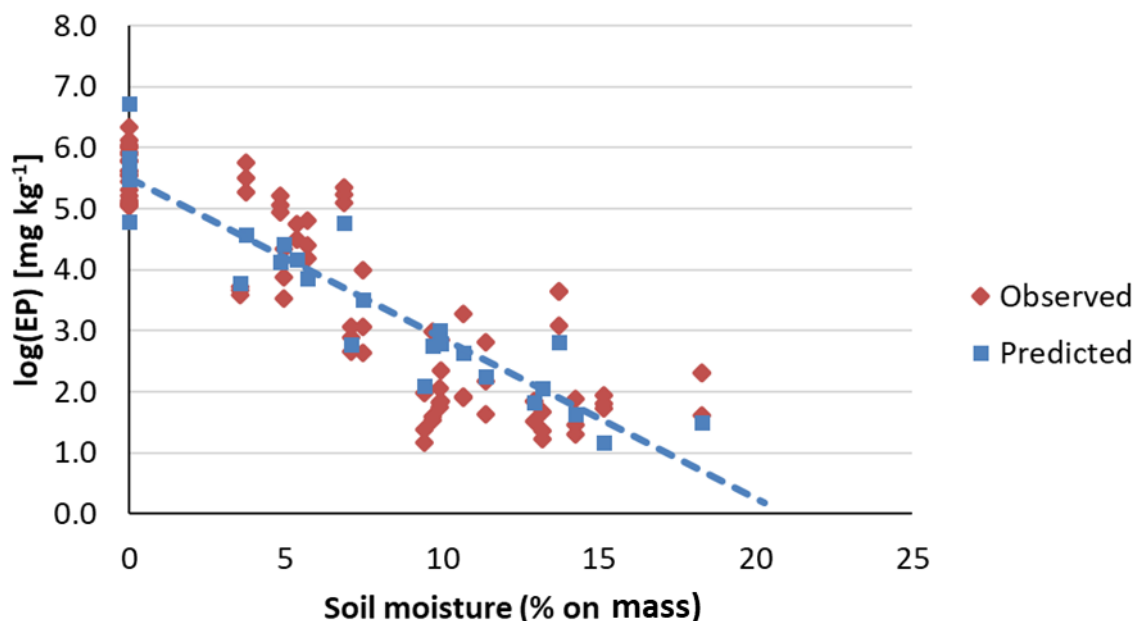
214 A multiple log linear regression best fitted the exponential response seen for the effect of moisture.  
215 All three tested variables had a highly significant ( $P < 0.001$ ) effect on the EP and the effect of each  
216 of those variables is summarized in the following formula:

$$\log(EP) = 4.83105 - 0.28583 H - 0.09625 Ss + 0.08871 OC$$

219 Where H is the soil moisture content (% on mass), Ss is the Sand/silt ratio in the soil and OC is the  
220 organic carbon content ( $\text{g kg}^{-1}$ ).

222 The model fitted the observed EP data well at both high and low moisture contents, with an  
223 adjusted- $R^2$  of 0.838. Figure 3 shows a comparison between observed and predicted log  
224 transformed EP data, according to the multiple regression model.

225



226  
227 Figure 3. Observed and predicted data, as obtained using the log-linear prediction model  
228

229

230

### 3.3. Elemental contents in soil and soil-originated $PM_{10}$

231 The concentrations of major and trace elements in the analyzed bulk soils and in their  
232 resuspended fraction are summarized in Tables 2 and 3.

233 Selected soils appeared as natural, uncontaminated areas, with elemental and PTE concentrations  
 234 in line with the regional baseline values (ARPA Piemonte, 2014) and lower than regional legislative  
 235 limits for agricultural soils (Regione Piemonte, 2000) and national limits for green areas (MATTM,  
 236 2006).

237

238 Table 2. Elemental concentrations of major and trace elements in soils S1 to S7.

	<b>S1</b>	<b>S2</b>	<b>S3</b>	<b>S4</b>	<b>S5</b>	<b>S6</b>	<b>S7</b>
	g kg <sup>-1</sup>						
<b>Mg</b>	14.2 ± 1.0	7.8 ± 0.1	10.1 ± 0.4	9.8 ± 0.7	9.4 ± 0.4	6.2 ± 0.3	7.5 ± 1.0
<b>Al</b>	22.8 ± 2.2	28.1 ± 1.2	36.6 ± 0.4	14.0 ± 1.7	25.9 ± 3.2	34.7 ± 3.5	23.7 ± 4.1
<b>K</b>	4.7 ± 0.3	7.5 ± 0.7	13.7 ± 0.7	5.1 ± 1.1	14.3 ± 3.6	7.2 ± 2.6	4.3 ± 2.0
<b>Mn</b>	0.9 ± 0.1	0.9 ± 0.01	1.1 ± 0.1	0.8 ± 0.03	1.4 ± 0.01	1.3 ± 0.01	1.3 ± 0.2
<b>Fe</b>	16.2 ± 5.4	14.1 ± 4.8	18.6 ± 2.3	12.1 ± 1.1	14.8 ± 2.2	18.2 ± 1.7	16.5 ± 2.5
	mg kg <sup>-1</sup>						
<b>Li</b>	38 ± 1	39 ± 0.1	52 ± 1.1	33 ± 1	55 ± 1	46 ± 2	37 ± 2
<b>Co</b>	18 ± 0.5	17 ± 0.2	22 ± 0.4	10 ± 0.4	19 ± 0.3	22 ± 2	17 ± 0.7
<b>V</b>	51 ± 4	64 ± 5	84 ± 2	31 ± 2	52 ± 3	65 ± 4	57 ± 4
<b>Ni</b>	108 ± 3.1	84 ± 2	108 ± 2	85 ± 3	63 ± 1	85 ± 10	94 ± 8
<b>Cr</b>	122 ± 6	104 ± 3	154 ± 3	88 ± 6	64 ± 2	85 ± 9	100 ± 4
<b>Zn</b>	78 ± 3	79 ± 5	107 ± 3	78 ± 5	195 ± 4	136 ± 28	85 ± 17
<b>Cu</b>	36 ± 2	28 ± 0.6	34 ± 0.6	22 ± 1	69 ± 1	61 ± 3	35 ± 4
<b>As</b>	9 ± 4.5	6 ± 3	9 ± 3	4 ± 1.4	19 ± 5	19 ± 3	10 ± 3
<b>Sr</b>	62 ± 22	41 ± 2	71 ± 2	98 ± 3	45 ± 5	32 ± 10	26 ± 3
<b>Mo</b>	11 ± 0.2	12 ± 0.2	12 ± 0.1	12 ± 0.3	12 ± 0.1	12 ± 0.1	13 ± 1
<b>Cd</b>	7 ± 0.8	7 ± 0.8	7 ± 0.8	7 ± 0.8	7 ± 0.8	7 ± 0.8	7 ± 0.8
<b>Sn</b>	11 ± 0.5	11 ± 0.4	11 ± 0.2	12 ± 0.3	11 ± 0.1	11 ± 0.4	11 ± 0.4
<b>Sb</b>	9 ± 1.0	9 ± 1.0	9 ± 0.9	9 ± 1.0	10 ± 1.0	10 ± 1.0	9 ± 0.9
<b>Ba</b>	70 ± 3	109 ± 2	120 ± 3	59 ± 5	139 ± 10	127 ± 12	101 ± 17
<b>Pb</b>	21 ± 0.2	20 ± 0.4	25 ± 0.6	25 ± 1	31 ± 0.7	31 ± 0.5	26 ± 3

239 Resuspended PM10 fraction of soils present concentrations higher than bulk soils for most of the  
 240 elements, both crustal and PTE, in accordance with previous studies demonstrating a higher PTE  
 241 concentration in fine soil fractions (Maffia et al., 2020b; Padoan et al., 2018). Conversely to  
 242 previous studies, also major elements, such as Mg, Si, Fe and K, present higher values in soil-  
 243 derived PM10 of some soils.

244 Soil and soil-derived PM concentrations appear correlated both most of the soils, using Pearson  
 245 values, apart for soils S3 and S5, soils with the highest concentrations of Cr, Zn and Mg, in  
 246 particular. At the same time, these soils were the ones with the higher concentration of particles <  
 247 10  $\mu\text{m}$ .

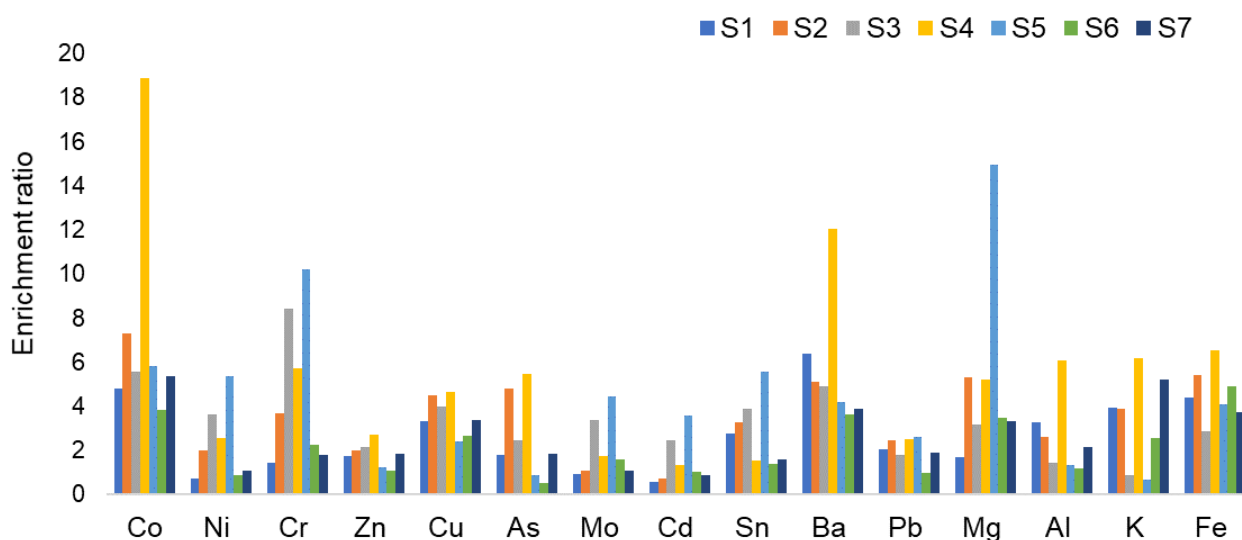
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249 Table 3. Elemental concentrations of major and trace elements in soil-derived PM10.

	S1	S2	S3	S4	S5	S6	S7
$\text{g kg}^{-1} \text{PM}_{10}$							
<b>Mg</b>	24 $\pm$ 12	42 $\pm$ 29	32 $\pm$ 19	51 $\pm$ 34	141 $\pm$ 27	22 $\pm$ 11	25 $\pm$ 13
<b>Al</b>	75 $\pm$ 31	73 $\pm$ 30	53 $\pm$ 24	85 $\pm$ 35	35 $\pm$ 21	41 $\pm$ 24	51 $\pm$ 12
<b>K</b>	19 $\pm$ 4	29 $\pm$ 8	12.4 $\pm$ 1.4	32 $\pm$ 6	9.8 $\pm$ 1.5	18 $\pm$ 6	22 $\pm$ 3
<b>Mn</b>	1.9 $\pm$ 0.7	2.1 $\pm$ 0.6	1.1 $\pm$ 0.4	2.2 $\pm$ 0.5	1.6 $\pm$ 0.4	0.7 $\pm$ 0.4	2.0 $\pm$ 0.1
<b>Fe</b>	71 $\pm$ 20	77 $\pm$ 19	54 $\pm$ 0.4	80 $\pm$ 11	60 $\pm$ 24	89 $\pm$ 55	62 $\pm$ 3
$\text{mg kg}^{-1}$							
<b>Li</b>	84 $\pm$ 15	74 $\pm$ 22	59 $\pm$ 30	89 $\pm$ 14	47 $\pm$ 12	54 $\pm$ 9	50 $\pm$ 18
<b>Co</b>	89 $\pm$ 22	124 $\pm$ 34	123 $\pm$ 49	199 $\pm$ 46	111 $\pm$ 41	85 $\pm$ 16	93 $\pm$ 26
<b>V</b>	123 $\pm$ 15	129 $\pm$ 20	152 $\pm$ 42	172 $\pm$ 9	121 $\pm$ 50	84 $\pm$ 8	94 $\pm$ 7
<b>Ni</b>	81 $\pm$ 29	169 $\pm$ 37	395 $\pm$ 24	219 $\pm$ 46	341 $\pm$ 16	74 $\pm$ 16	102 $\pm$ 21
<b>Cr</b>	174 $\pm$ 17	383 $\pm$ 154	1298 $\pm$ 148	504 $\pm$ 79	652 $\pm$ 216	192 $\pm$ 7	182 $\pm$ 21
<b>Zn</b>	135 $\pm$ 53	160 $\pm$ 70	229 $\pm$ 140	213 $\pm$ 98	243 $\pm$ 156	151 $\pm$ 99	160 $\pm$ 89
<b>Cu</b>	120 $\pm$ 22	126 $\pm$ 10	136 $\pm$ 33	104 $\pm$ 5	166 $\pm$ 10	163 $\pm$ 48	121 $\pm$ 4
<b>As</b>	17 $\pm$ 4	31 $\pm$ 9	22 $\pm$ 8	24 $\pm$ 2	16 $\pm$ 11	10 $\pm$ 0.2	18 $\pm$ 3
<b>Sr</b>	57 $\pm$ 7	78 $\pm$ 15	70 $\pm$ 11	84 $\pm$ 16	70 $\pm$ 28	77 $\pm$ 17	57 $\pm$ 4
<b>Mo</b>	11 $\pm$ 3	12 $\pm$ 3	39 $\pm$ 16	21 $\pm$ 7	54 $\pm$ 19	20 $\pm$ 3	14 $\pm$ 3
<b>Cd</b>	4.1 $\pm$ 2.1	5.2 $\pm$ 2.5	18 $\pm$ 8	9.6 $\pm$ 3.9	26 $\pm$ 11	7.4 $\pm$ 3.1	6.2 $\pm$ 2.5
<b>Sn</b>	31 $\pm$ 27	36 $\pm$ 42	45 $\pm$ 46	19 $\pm$ 17	61 $\pm$ 30	16 $\pm$ 11	18 $\pm$ 3
<b>Sb</b>	6.2 $\pm$ 2.5	7.6 $\pm$ 2.9	22 $\pm$ 11	13 $\pm$ 6	31 $\pm$ 16	10 $\pm$ 4	8.5 $\pm$ 3.5
<b>Ba</b>	443 $\pm$ 134	557 $\pm$ 70	591 $\pm$ 135	710 $\pm$ 36	586 $\pm$ 112	463 $\pm$ 34	395 $\pm$ 11
<b>Pb</b>	44 $\pm$ 17	49 $\pm$ 14	46 $\pm$ 0.4	62 $\pm$ 8	81 $\pm$ 2	32 $\pm$ 8	50 $\pm$ 2

250

251 The ERs, thus the enrichment in soil-emitted PM<sub>10</sub> compared to the bulk soils, varied largely  
 252 between the samples. Values for selected elements are reported in Figure 4. Increases of  
 253 elemental content, as compared to the original soil, up to 19, 10, 5, 5, 4, 4, and 3 times were  
 254 observed for PTE such as Co, Cr, Ni, Cu, Mo, Cd and Pb, respectively. The enrichment in  
 255 elements was more pronounced for some soils, as S4, the sandier one, and S5, the soil containing  
 256 more OC.  
 257



258  
 259 Figure 4. Enrichment ratios in resuspended PM<sub>10</sub>  
 260

261 4. DISCUSSION

262 The soils presented a wide range of sand and silt quantities, well representing the variety of the  
 263 agricultural soils used for cereal cultivation in the Po plain. The observation of the EP curves  
 264 (Figure 2) revealed an exponential relation among the EP and soil moisture content. It was also  
 265 observed that the slope of the curve, the maximum emission value (at dry soil conditions), and the  
 266 threshold moisture content at which no further emission is produced, varied according to soil type.  
 267 The implemented log-linear regression model allowed to better understand and describe the  
 268 influence of moisture, texture, and soil organic carbon content on the emissions. Soil moisture was  
 269 shown to be the main emission driver, being negatively correlated with the EP. The granulometry  
 270 also significantly affected the EP, with the sand to silt ratio being the most useful for model  
 271 calculations, probably because in our set of soils these two parameters had a higher variability  
 272 than the clay fraction, thus better representing the soil set. Indeed, single parameters, such as the  
 273 total PM<sub>10</sub> content in the soil were not good predictors of soil EPs, having low correlation  
 274 coefficients.

275 Comparing these results with previous studies we can hypothesize that the choice among Clay/Silt  
276 ratio and Sand/Silt ratio for representing soil texture in regression models has to be made  
277 according to the textural characteristics of the analysed soil samples.

278 Higher Sand/Silt ratios implied lower emissions, as most of the PM<sub>10</sub> particles belong to the silt  
279 fraction of the soils. This finding is in slight contrast with that of Madden et al. (2010), who  
280 observed a better agreement of the emissions with the Silt/Clay ratio although also in that case, a  
281 higher silt fraction implied higher emission.

282 The importance of ratios is evident also in the result of the soil S3, which had the highest fraction of  
283 <10µm particles (51.4%) and high clay but a relatively balanced silt/clay ratio, being the second  
284 lowest between our soils. This low ratio resulted in low emissions.

285 The findings of this study confirmed that utilizing two soil fractions to predict the emission is  
286 generally more effective and reliable than just using silt as a single predictor, as suggested by  
287 Carvacho et al. (2001) and also as suggested for PM<sub>10</sub> emissions due to traffic in the case of  
288 unpaved roads (EPA, 1998). The soil organic carbon content also has a significant effect on the  
289 EP, with high OC corresponding to high emissions. The combined effects observed for soil  
290 moisture, texture and OC are in accordance with previous findings by Funk et al. (2008), although  
291 the results they presented were obtained from a range of soils with more extreme characteristics.

292 As for the effect detected for soil OC, the observed emission enhancement is probably due to  
293 different factors; the first one is possibly linked to the density of organic particles, lower than  
294 mineral particles especially in the case of dry soils, a second factor could have been connected to  
295 the fact that organic particles in soils are often in the <PM<sub>10</sub> range and, therefore, when there is a  
296 higher OC content, more fine particles can be potentially emitted. This finding agrees with those of  
297 Funk et al. (2008), who found a similar relationship with soil humus content. Nonetheless, a higher  
298 OC content could also favor soil structure, which can reduce the emissions (Madden et al., 2009;  
299 Tatarko et al., 2020).

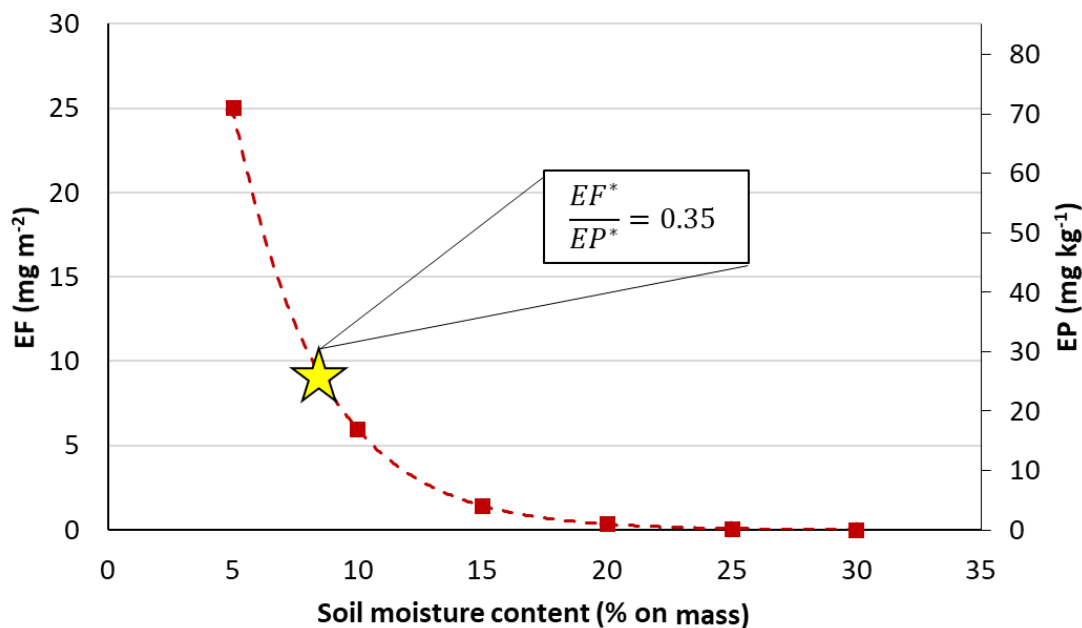
300 In conclusion, our calculations based on soils used in cereal cultivation because it is the most  
301 common practice in floodplain fields in Europe, but the emission potential estimation is applicable  
302 to every soil with similar characteristics. The EPs are intended as maximum emission values for  
303 agronomical practices such as ploughing or harrowing, and they are applicable to every crop type  
304 and soil to study the emission factors dependence with soil moisture.

305 To do so, an equation is proposed, to adapt the obtained EP curves to emissions from agricultural  
306 operations, allowing to estimate emission factors (EF; mg m<sup>-2</sup>) for different soils at different  
307 moisture levels:

$$308 \quad EF = \frac{EF^*}{EP^*} EP_M$$

309 Where EF\* and EP\* are, respectively, the EF measured in field conditions on a specific soil and  
310 with a specific moisture content and the EP related for that soil and moisture, and EP<sub>M</sub> is the EP for  
311 all other moisture levels needed to define an EF curve.

312 This procedure has been applied on the EF ( $8.9 \text{ mg m}^{-2}$ ) experimentally found for rotary harrowing  
 313 operations from Maffia et al. (2020b) and the graphical output is shown in Figure 5. Soil  
 314 characteristics are reported in the original paper. The  $EF^*/EP^*$  ratio could be proposed as a factor  
 315 identifying the effect of the mechanical tilling implements used for agricultural operations. Further  
 316 studies should be performed to calculate and compare  $EF^*/EP^*$  ratios for different agricultural  
 317 operations.



318  
 319 Figure 5. EF curve estimated for rotary harrowing operations (calculated from Maffia et al., 2020b)  
 320

321 The concentrations of trace elements in soils and soil-originated PM (Table 2 and 3) resulted very  
 322 different. Generally, an increase of the elemental contents in  $PM_{10}$  as compared to the original soils  
 323 was observed. The elements exhibiting the highest enrichment are the ones regarded as crustal-  
 324 related, according to previous studies in the same area (Padoan et al., 2017; Biasioli et al., 2012).  
 325 Chromium, Ba, Co, Mg, Ni and Fe were the elements mostly accumulated in the emitted  
 326 particulate. Although not all of them are considered toxic, all of them were found at very high  
 327 concentrations in all samples and, for PTE such as Cr, these values could be a cause of concern  
 328 for operator's safety during agricultural activities, as highlighted during a previous trial (Maffia et al.,  
 329 2020).

330 It has been observed that the soils in which the ER (Figure 4) raised to the highest levels (S4 and  
 331 S5) had particular characteristics. Soil 4 was the sandiest one and S5 had a very high fraction of  
 332 particles  $<10 \mu\text{m}$ . This behavior is in accordance with previous studies and could be due to the fact  
 333 that these elements are mostly bound to the clay fraction of soils, which has a higher prevalence of  
 334 adsorbing phase, such as iron oxides and organic material with high specific surface (Padoan et  
 335 al., 2020; 2017; Ajmone-Marsan et al., 2008). Moreover, S5 was the one with the highest OC  
 336 content, which had an emission enhancement effect.

337

## 338 5. CONCLUSIONS

339 An easy to build and low-cost soil resuspension chamber has been tested to assess PM<sub>10</sub> EP from  
340 soil and study the chemical characteristics of the emitted PM<sub>10</sub>. The Emission Potential (EP) of 7  
341 different soils, representing the variety of soil types for the cereal cropping area in the North-West  
342 of Italy, has been estimated at different moisture contents, obtaining soil-specific EP curves. A log-  
343 linear regression model, based on soil moisture, Sand/silt ratio and organic carbon content, was  
344 developed to describe the effect that those variables had on the emissions. The model showed a  
345 good fit to the experimental data and it will be possible to implement it, in order to obtain specific  
346 EF curves for typical cropping operations (e.g. tillage, harrowing, sowing etc.) on North-West Italian  
347 soils but also on different soils with similar characteristics, allowing to estimate emission factors  
348 (EF; mg m<sup>-2</sup>) for different soils at different moisture levels with limited effort. This will allow to  
349 overcome the difficulty of perming field trials in several moisture conditions to retrieve reliable EFs.  
350 The elemental content of both major and trace elements in soil-originated PM<sub>10</sub> resulted higher  
351 than in the original soil itself. It has been observed that the soils in which the ERs were the highest  
352 were the ones with the higher clay and PM<sub>10</sub>. The increase ratios reached one order of magnitude  
353 for some elements such as Cr, Co and Ba, reaching values of concern with regard to the operator's  
354 safety during agricultural activities.

355

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