Soil PM10 emission potential under specific mechanical stress and particles characteristics

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SOIL PM_{10} EMISSION POTENTIAL UNDER SPECIFIC MECHANICAL STRESS AND PARTICLES CHARACTERISTICS

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ABSTRACT

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

Due to their similarity to tilling emission mechanisms, Soil Resuspension Chambers (SRC) are the most suitable method to estimate the impacts of these factors on soil susceptibility to emit PM_{10} during cropping operations (Emission Potential, EP).

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

The concentration of Potentially Toxic Elements (PTE) in soil-emitted PM_{10} was determined, founding an enrichment up to 16 times higher than in the original soil, evidencing a possible cause of concern for operator's safety during agricultural activities.

KEYWORDS

Emission Model; Particulate Matter; PM10; Potentially Toxic Elements; Soil Dust

1. INTRODUCTION

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

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

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

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

Several laboratory methodologies have been proposed to investigate the impacts of these factors on soil Emission Potential (EP), the soil capacity to emit PM_{10} per unit weight, over a certain period. Among these methodologies, the most common are soil resuspension chambers (SRC) and wind tunnels (WT) (Mendez et al., 2013; Pietrodangelo et al., 2013; Madden et al., 2010; Moreno et al., 2009; Gill et al., 2006). SRC rely on mechanical disturbance or abrasion to achieve soil resuspension, with the possibility to collect resuspended particles using a depression or forced-air ducts. Conversely, WT rely only on wind speed effect. Due to the similar resuspension mechanism applied, SRC are more suitable than WT to estimate soil susceptibility to emit PM_{10} during cropping operations, while WT are more appropriate to estimate wind erosion rates.

The main objective of the work is to assess the EP of different agricultural soils used for maize cropping in North-Western Italy, studying the influence of soil moisture and physico-chemical characteristics on the EP of those soils. Therefore, a SRC was developed, based on previous studies (Maffia et al., 2020b; Madden et al., 2010), with the goal of being relatively small, easy to build and low-cost. Using the gathered data, we developed a model to allow soil EP estimation from some simple physico-chemical parameters, to tailor field emission factors (EF) of specific cropping operations to different soil and moisture conditions. Moreover, we analysed the Potentially Toxic Elements (PTE) concentration of soil-emitted PM_{10} to assess the health and environmental risk of the resuspended particles, potentially eroded and transported to different environmental compartments or affecting farmers.

2. MATERIALS AND METHODS

2.1. Soil Sampling and physico-chemical characterization

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

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

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

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

2.2. Soil resuspension chamber

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

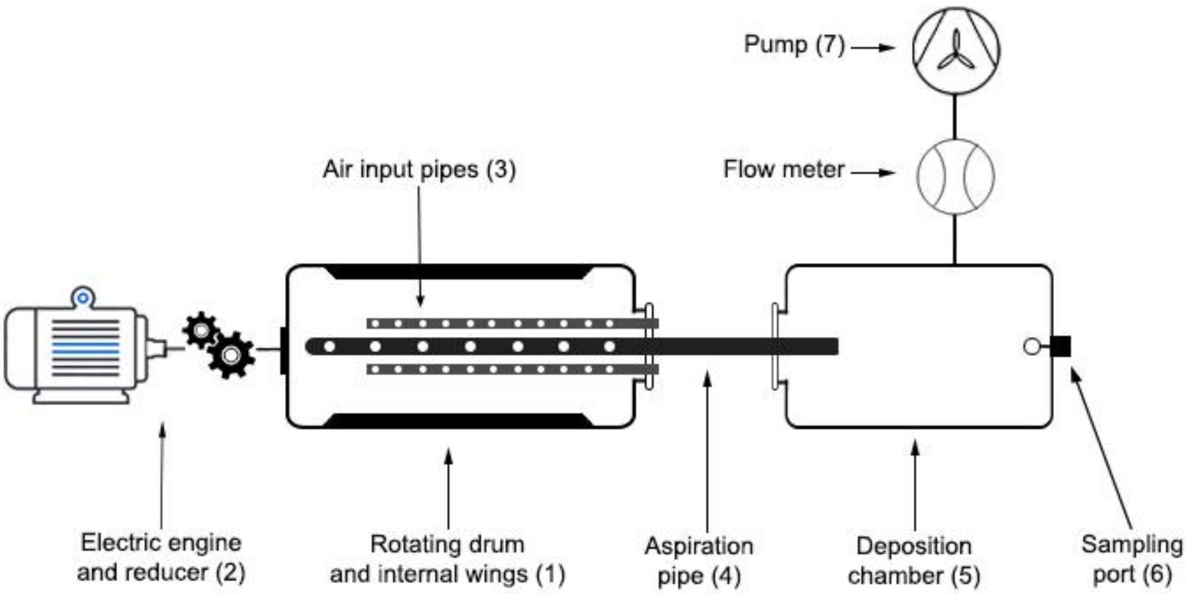

Figure 1. Scheme of the soil resuspension chamber. Soil is manually placed in the rotating drum (1) before the experiment, while PM instrumentation is connected to the sampling port (6).

2.3. Experimental protocol and Emission Potential estimation

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

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

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

Where C represents the particle concentration (μg m^{-3}) measured by the Grimm PM monitor, P the system airflow (m^3 min^{-1}), calculated as the sum of the pump flow and the flow of the Grimm internal pump (1.2 L min^{-1}), S the mass of the soil sample used (kg), and t the considered timespan (min).

2.4. Filter-based Particulate Matter sampling and elemental analysis

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

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

Major and trace element pseudo-total contents were determined in the original soils and in PM_{10}. One-gram soil samples were digested in *aqua regia* (HNO_3:HCl, 1:3) using microwave extraction (Ethos D, Milestone). Similarly, half of each PM_{10} filter was microwave digested and blank filters were analysed to ensure a correction for their possible elemental release. Solutions were then filtered on cellulose filters (Whatman n° 41) and diluted with ultrapure water before analysis. Elemental concentrations were assessed in all samples using ICP-MS (NexION 350D, PerkinElmer). All the analyses were performed in duplicate and using certified reference materials (CRM 141R and 142R, Community Bureau of Reference, Geel, Belgium) to ensure accuracy and correct recoveries.

The enrichment ratios (ER), i.e. the ratios between elemental concentrations in soil-originated PM_{10} compared to bulk soil, were calculated as follows:

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

Where C_{PM} is the concentration (mg kg^{-1}) in resuspended PM_{10} and C_{soil} is the concentration in the original soil (mg kg^{-1}).

2.5. Statistical analyses

The effect of the physico-chemical characteristics on the EP of the investigated soils was analysed using multiple log linear regression. Predictors were chosen on the base of their level of correlation with the EP logarithm. The correlation matrix also allowed to check for collinearity. To account for the soil particle size distribution, we tried to use all the three parameters (sand, silt and clay) together, only two of them and using the different ratios. Clay, probably because of its scarce variation in the soil set, did not have a high correlation coefficient with EP and, when added to the model, the prediction (fitting) did not improve. We decided to use the sand-silt ratio as a proxy for the complete particle size distribution because was the one preforming better in the prediction model. This choice was made since, as highlighted by Madden et al. (2010), the ratio between two textural components can be a good descriptor of soil characteristics. Moreover, it allowed to achieve a more parsimonious model. Sand and silt performed better than clay as predictors, probably since these two components are the ones that vary the most in selected soils. The linearity and homoscedasticity assumptions were tested graphically and by means of a Shapiro-Wilk test. The analyses were performed using R statistical software (R core team, 2019).

3. RESULTS

3.1. *Soil physico-chemical characteristics*

The physico-chemical characteristics of the analysed soils are reported in Table 1.
The studied soils presented a relatively wide textural variability with sand contents ranging from 14 to 82 %, silt contents ranging from 9 to 40 % and clay contents ranging from 9 to 33 %. Soil texture, and especially fine fractions content, is known to be a key factor in determining PM_{10} emissions (Madden et al., 2010; Funk et al., 2008), thus the content in <10 μm particles was analysed, ranging from 9.5 to 51 % in the observed soils.
Carbonate concentrations were variable but low in all the soils. Organic carbon (OC) contents were in line with typical Italian agricultural soils (Jones et al., 2020), varying in the range 0.8 – 2.2%.

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

Soil	Sand (%)	Silt (%)	Clay (%)	Textural class	Particles < 10 μm (%)	Field Capacity (% V/V)	pH	OC (g kg^{-1})	Inorganic C (g kg^{-1})	N (g kg^{-1})	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

3.2. *Emission Potential*

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

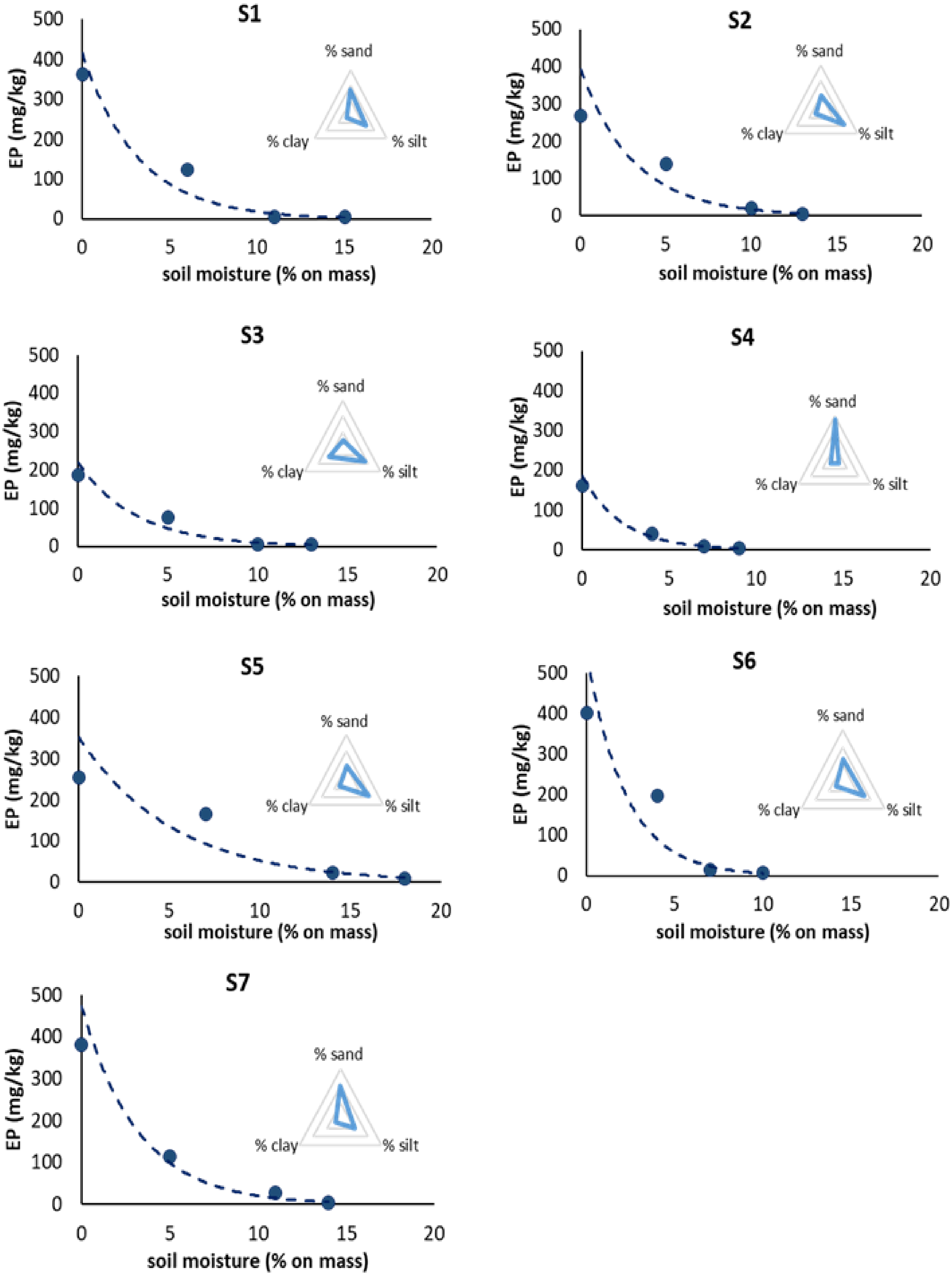

Figure 2. Emission Potential of selected soils as measured using the PM monitor.

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

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

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

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

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

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

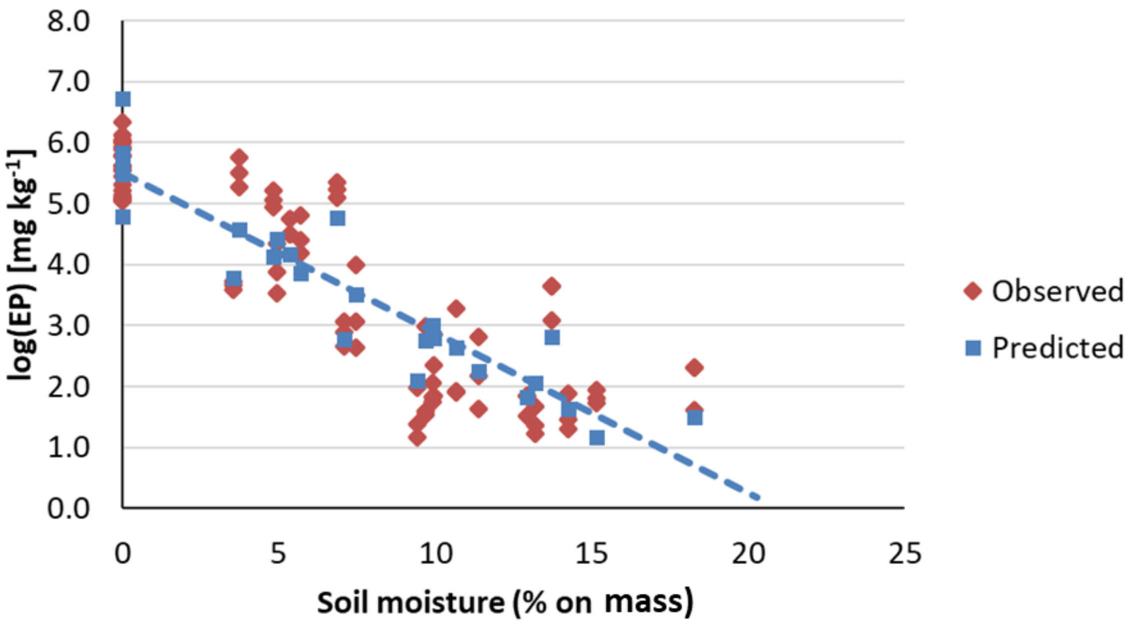

Figure 3. Observed and predicted data, as obtained using the log-linear prediction model

3.3. *Elemental contents in soil and soil-originated PM$_{10}$*

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

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

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

	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**
				g kg^{-1}			
Mg	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
Al	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
K	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
Mn	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
Fe	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^{-1}			
Li	38 ± 1	39 ± 0.1	52 ± 1.1	33 ± 1	55 ± 1	46 ± 2	37 ± 2
Co	18 ± 0.5	17 ± 0.2	22 ± 0.4	10 ± 0.4	19 ± 0.3	22 ± 2	17 ± 0.7
V	51 ± 4	64 ± 5	84 ± 2	31 ± 2	52 ± 3	65 ± 4	57 ± 4
Ni	108 ± 3.1	84 ± 2	108 ± 2	85 ± 3	63 ± 1	85 ± 10	94 ± 8
Cr	122 ± 6	104 ± 3	154 ± 3	88 ± 6	64 ± 2	85 ± 9	100 ± 4
Zn	78 ± 3	79 ± 5	107 ± 3	78 ± 5	195 ± 4	136 ± 28	85 ± 17
Cu	36 ± 2	28 ± 0.6	34 ± 0.6	22 ± 1	69 ± 1	61 ± 3	35 ± 4
As	9 ± 4.5	6 ± 3	9 ± 3	4 ± 1.4	19 ± 5	19 ± 3	10 ± 3
Sr	62 ± 22	41 ± 2	71 ± 2	98 ± 3	45 ± 5	32 ± 10	26 ± 3
Mo	11 ± 0.2	12 ± 0.2	12 ± 0.1	12 ± 0.3	12 ± 0.1	12 ± 0.1	13 ± 1
Cd	7 ± 0.8	7 ± 0.8	7 ± 0.8	7 ± 0.8	7 ± 0.8	7 ± 0.8	7 ± 0.8
Sn	11 ± 0.5	11 ± 0.4	11 ± 0.2	12 ± 0.3	11 ± 0.1	11 ± 0.4	11 ± 0.4
Sb	9 ± 1.0	9 ± 1.0	9 ± 0.9	9 ± 1.0	10 ± 1.0	10 ± 1.0	9 ± 0.9
Ba	70 ± 3	109 ± 2	120 ± 3	59 ± 5	139 ± 10	127 ± 12	101 ± 17
Pb	21 ± 0.2	20 ± 0.4	25 ± 0.6	25 ± 1	31 ± 0.7	31 ± 0.5	26 ± 3

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

Soil and soil-derived PM concentrations appear correlated both most of the soils, using Pearson values, apart for soils S3 and S5, soils with the highest concentrations of Cr, Zn and Mg, in particular. At the same time, these soils were the ones with the higher concentration of particles < 10 µm.

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

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

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

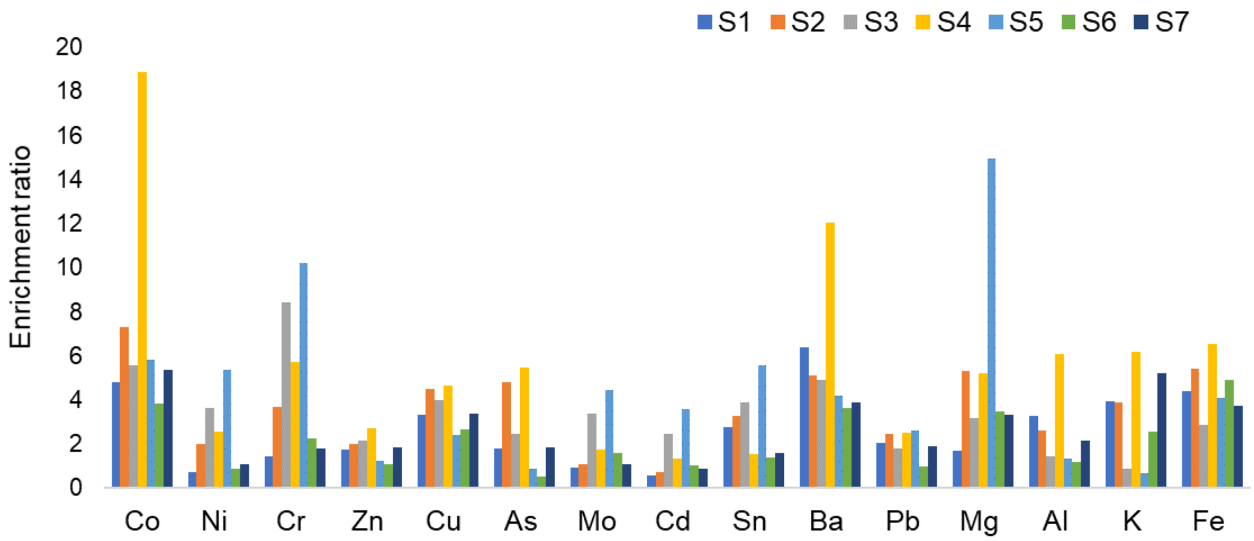

Figure 4. Enrichment ratios in resuspended PM_{10}

4. Discussion

The soils presented a wide range of sand and silt quantities, well representing the variety of the agricultural soils used for cereal cultivation in the Po plain. The observation of the EP curves (Figure 2) revealed an exponential relation among the EP and soil moisture content. It was also observed that the slope of the curve, the maximum emission value (at dry soil conditions), and the threshold moisture content at which no further emission is produced, varied according to soil type. The implemented log-linear regression model allowed to better understand and describe the influence of moisture, texture, and soil organic carbon content on the emissions. Soil moisture was shown to be the main emission driver, being negatively correlated with the EP. The granulometry also significantly affected the EP, with the sand to silt ratio being the most useful for model calculations, probably because in our set of soils these two parameters had a higher variability than the clay fraction, thus better representing the soil set. Indeed, single parameters, such as the total PM10 content in the soil were not good predictors of soil EPs, having low correlation coefficients.

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

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

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

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

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

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

To do so, an equation is proposed, to adapt the obtained EP curves to emissions from agricultural operations, allowing to estimate emission factors (EF; mg m^{-2}) for different soils at different moisture levels:

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

Where EF^* and EP^* are, respectively, the EF measured in field conditions on a specific soil and with a specific moisture content and the EP related for that soil and moisture, and EP_M is the EP for all other moisture levels needed to define an EF curve.

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

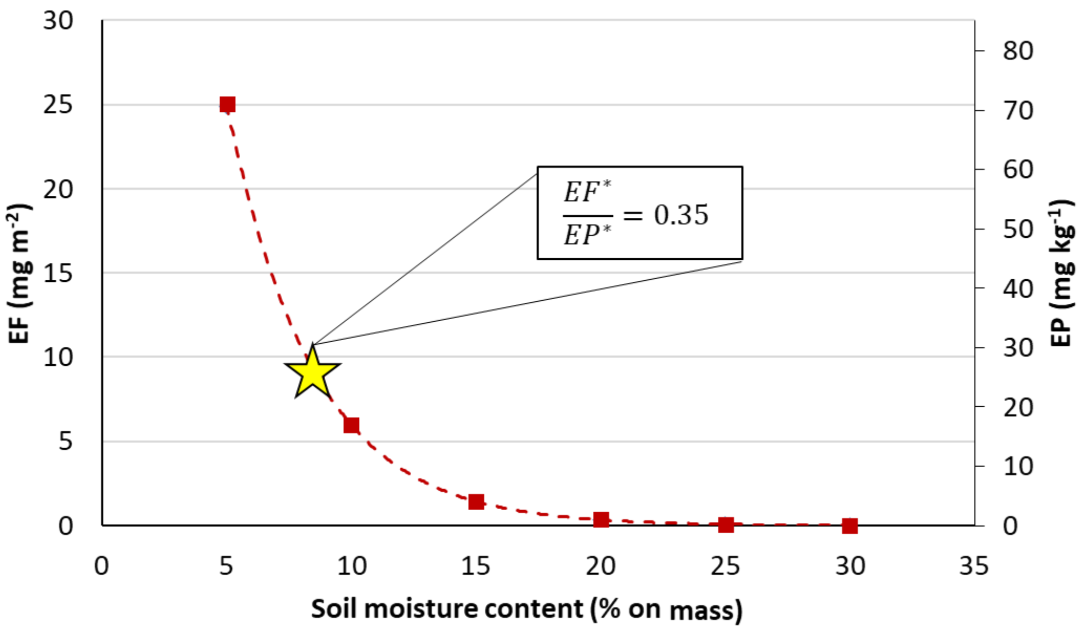

Figure 5. EF curve estimated for rotary harrowing operations (calculated from Maffia et al., 2020b)

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

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

5. Conclusions

An easy to build and low-cost soil resuspension chamber has been tested to assess PM_{10} EP from soil and study the chemical characteristics of the emitted PM_{10}. The Emission Potential (EP) of 7 different soils, representing the variety of soil types for the cereal cropping area in the North-West of Italy, has been estimated at different moisture contents, obtaining soil-specific EP curves. A log-linear regression model, based on soil moisture, Sand/silt ratio and organic carbon content, was developed to describe the effect that those variables had on the emissions. The model showed a good fit to the experimental data and it will be possible to implement it, in order to obtain specific EF curves for typical cropping operations (e.g. tillage, harrowing, sowing etc.) on North-West Italian soils but also on different soils with similar characteristics, allowing to estimate emission factors (EF; mg m^{-2}) for different soils at different moisture levels with limited effort. This will allow to overcome the difficulty of perming field trials in several moisture conditions to retrieve reliable EFs.

The elemental content of both major and trace elements in soil-originated PM_{10} resulted higher than in the original soil itself. It has been observed that the soils in which the ERs were the highest were the ones with the higher clay and PM_{10}. The increase ratios reached one order of magnitude for some elements such as Cr, Co and Ba, reaching values of concern with regard to the operator's safety during agricultural activities.

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