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Evaluation of particulate matter (PM_{10}) emissions and its chemical characteristics during rotary harrowing operations at different forward speeds and levelling bar heights

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Abstract

Particulate matter (PM) is an air pollutant which poses a considerable risk to human health. The agricultural sector is responsible of the 15% of the total anthropogenic emissions of PM_{10} (PM fraction with aerodynamic diameter below 10 μm) and soil preparation activities have been recognized as one of the main drivers of this contribution. The emission factors (EF) proposed by European environmental agency (EEA) for tilling operations are based on very few studies, none of which has been made in Italy. Moreover, few studies have considered the influence of operative parameters on PM_{10} emissions during tilling. The aim of this work was to assess PM_{10} emission and dispersion during rotary harrowing and to understand how operative parameters, such as forward speed and implement choice may affect PM release. A further objective was to assess the near field dispersion of PM_{10} to address exposure risks. Emission factors (EFs) were determined during two different trials (T1 and T2). During T1, the effect of tractor speeds (0.6, 1.1 and 1.7 m s^{-1}) on PM_{10} emissions was investigated, while in T2 a comparative essay was made to study the influence of levelling bar height on emissions. The average ground level downwind concentrations of PM_{10} during harrowing operation was estimated through dispersion modelling. The observed PM_{10} EFs for rotary harrowing were 8.9 ± 2.0 mg m^{-2} and 9.5 ± 2.5 mg m^{-2} on T1 and T2, respectively. The heavy metal content of soil-generated PM_{10} was also assessed. In the generated PM, the elemental concentrations were higher than ones in soil. As, Cd and Ni concentration levels, determined in PM_{10} near to the tractor path, were also high,

being several times higher than the annual average regulatory threshold levels in ambient air, as defined by the European regulation.

KEYWORDS: PM_{10}; emission factors; metals; soil preparation; harrowing

CAPSULE: PM_{10} emission factors for rotary harrowing have been determined with different tractor speeds, and relevant metal contents were found in emitted PM_{10}.

1. Introduction

The increase in atmospheric concentrations of particulate matter (PM) is a major cause of concern, having been associated with acute and chronic health effects and even with the rise in mortality and morbidity rates (WHO, 2006; Tonne et al., 2016). Many emission sources contribute to PM_{10} (PM fraction with aerodynamic diameter below 10 µm), among which agriculture may play a significant role, being held responsible for the 15% of total anthropogenic PM_{10} emissions in Europe (EEA, 2019). Agricultural emissions of primary particulate mainly derive from wind erosion of agricultural soils, livestock farming activities and crop management (Maffia et al., 2020). Crop management activities have been recognized to be a substantial contributor to the overall emissions (Sharratt and Auvermann, 2014). Currently, the emission factors (EF) used by the European Environmental Agency (EEA) for crop management operations are based on a limited number of studies and did not take into account the different tilling implements used by farmers. Moreover, few studies have considered the influence of operative parameters on PM_{10} emissions during tilling (Maffia et al., 2020).

Issues related to PM emissions and atmospheric concentrations have recently been at the centre of public attention in Northern Italy due to the associated health risks. In fact, the latest report of the Italian institute for environment protection and research has highlighted exceedances of the recommended daily PM_{10} concentration threshold (50 µg m^{-3}) for more than 35 days per year in most monitoring stations of the Po Valley (Cattani et al., 2019).

The northwest part of this area, where the present trials took place, is characterized by a low average annual wind speeds, which fall often below 1 m s^{-1} (Fratianni et al. 2007), and by being intensively exploited, both by industrial and farming activities, and densely populated. To face the high PM pollution of the area (Cattani et al., 2019) it is important to acknowledge its specific climatic conditions and to start assessing local emission factors for the main emission sources, to provide the policy makers with up to date information to address the air quality issue.

Health risks linked to PM are not only due to the size of the particles or to the concentration, but also to its elemental composition (Kendall et al., 2004). Particularly, many studies have focused on the potentially toxic effects due to Trace Elements (TE) adsorbed on PM_{10} in urban and roadside environments (Padoan et al., 2016; Zhang et al., 2019; Wu et al., 2020).

Agricultural soils are well known for being both sources of PM_{10} and, at least in certain areas, enriched in TE due to both anthropogenic and natural sources (Li et al., 2019). In fact, the application of pest control products and organic fertilizers, such as pig manure, has been shown to increase the soil reserves of TE such as Cu, Zn and Mn (Brun et al., 2001; Guo et al., 2018). Nevertheless, few information is available on the concentrations of these elements in the airborne PM_{10} emitted during tilling or wind erosion events. A recent investigation (Wang et al., 2016) has shown that the TE concentrations in PM_{10} of 4 different agricultural regions in China were higher than the expected, with carcinogenic risk above the acceptable limits due mostly to Pb, Co, Ni and Cd concentrations. It is therefore important to consider particle composition when assessing PM emissions from agricultural sources.

The main aim of this study was to improve the knowledge on PM_{10} emissions during soil preparation operations and, in particular, on those due to rotary harrowing. Emissions from rotary harrowing (coupled with packer roller and with levelling bar) were assessed in low wind conditions, to provide a local EF for this operation, which has been poorly studied before. Further objectives were to assess the effect of operative parameters, such as tractor speed and levelling settings on the emission value. In addition, the characteristics of the emitted PM_{10} and their near field dispersion were assessed to obtain a broader picture of the impact that harrowing operations can have on human health.

The field experiments presented hereafter are the first assessments of PM emission from land preparation activities performed in Northern Italy. In this specific area, the environmental, topographic, and demographic conditions could heavily influence both the amount of emission related to soil cultivation and their potential contribution to the total PM exposure levels.

2. Materials and methods

2.1. Experimental layout and Field measurements

Two different trials, T1 and T2, were performed in July and October 2019, respectively, in two different locations of the Piemonte region, Italy (44°50'27.9" N, 7°21'32.2" for T1; 44°54'52.9" N, 7° 23' 45.9" E for T2) in two fields with a sandy-loam soil for T1 trials and a loamy soil for T2 trials. In both trials, measurements of PM_{10} were carried out at each tractor passage using an optical PM monitor (TSI, DustTrack™ II model 8530), with a sampling frequency of 1 Hz. The PM monitor was placed alongside the area tilled by the tractor at 4 m (Figure 1). The instrument was moved to the next passage line after each pass and placed either east or west of the line according to wind direction. The DustTrack monitor was placed in the field 1 hour before the start of the trial and continued sampling until 1 hour after the trial, to assess the background PM_{10} concentration.

The positioning of the instrument was arranged similarly to what done in previous studies (Faulkner, 2013; Kasumba et al., 2011), with the sampler inlet placed at 1 m aboveground and with a fixed distance between the sampler and the tractor path of 4 m. According to the results of Holmén et al. (2008) and Kasumba et al. (2011), obtained in New Mexico, sampling at higher distances from the source could lead to underestimate the concentration of finer PM fractions due to vertical dispersion of the plume and to the increased distance between the sampler inlet and the plume centre.

Meteorological data were collected using a weather station mounted in a corner area of the field, with every side free from obstacles. The weather station has two 3D anemometers (Campbell scientific, 3D Metek uSonic-Omni), mounted at 2 and 4 m above ground respectively, and a temperature probe (HOBO, U12). The anemometers data were sampled at a rate of 5 Hz.

Field trials were carried out with a 12 rotors, 3 m working width, rotary power harrow (Frandent Eternum R303-19, Frandent Group s.r.l., Italy). The harrow was equipped with a packer roller (0.55 m diameter) on T1, whereas a levelling bar was installed in T2 in order to evaluate EF in different implement configurations. In T2, the roller was replaced with a couple of wheels mounted on the same tillage depth adjustment system.

The rotary harrow was hooked up to the three point hitch of a four-wheel-drive row crop tractor (Fendt 718 Vario, AGCO GmbH, Germany) having a 132 kW maximum engine power and an unladen mass of 7155 kg (OECD, 2010). A ballast of 1200 kg was also linked to the front three point hitch in order to reduce wheels slip.

During harrowing PTO rotation speed was maintained at about 1000 rpm achieving a rotor angular speed of 285 rpm, while the tillage depth was set to 10 cm.

In T1, 36 passages were performed, although some of those had to be later excluded from the analyses due to sudden changes in wind direction that resulted in imprecise EF estimations (the final number of calculated passages was 32). The length of each harrower passage has been, in both cases, of 40 m. The experimental layout was designed in order to test the effect of three different tractor speeds (S1 = 0.6 m s^{-1}, S2 = 1.1 m s^{-1} and S3 = 1.7 m s^{-1}), where S2 is the one normally implied by farmers, on PM_{10} emissions. S1, S2 and S3 passages were randomized inside large plots (3 m wide and 120 m long), that were considered as blocks for the statistical analysis and served to the purpose of limiting the variability linked with soil heterogeneity and wind speed. The scheme of a large plot layout and of PM sensor positioning is represented in Figure 1.

In T2, 24 tractor passages were performed (two of those were lost due to sudden wind direction changes). The experimental layout was designed in order to test the effect of levelling bar height on PM_{10} emissions. The bar attachment height was alternatively adjusted to two different levels, a lower, L, and a higher one, H. The attachment height of the bar was tested both with the bar perpendicular to the ground (S) and inclined of a 45° angle (I). In addition, the distance of the bar from the harrower was varied during the trial among D1 (23 cm from the harrower) and D2 (28 cm from the harrower). The combinations of bar attachments heights and orientations resulted in different distances between the bar and the point of the harrower teeth, being of 14, 16.5, 17 and 20 cm for L-S, L-I, H-S and H-I respectively. The different configurations and the split plot experimental layout are graphically represented in Figure 2. The plot was organized so as to reduce the time-lapse among passages involved in direct comparison, limiting the variability linked with changing environmental conditions (such as wind speed). The levelling bar is commonly installed on rotary harrows to improve soil fragmentation during harrowing by keeping the soil closer to the harrow rotors for a longer period. The variation of the vertical position and of the distance of the bar from rotors will change soil interaction with rotors tines, modifying aggregates size and affecting PM emissions (Madden et al., 2010). Bar inclination, instead, was an experimental solution aimed to reduce draught and, therefore, fuel consumption.

Soil conditions in T1 and T2 were different. In T1 harrowing was performed on bare soil after tillage, while on T2 only a superficial incorporation of crop residues (maize stalks) had been performed, leaving a rougher surface with some residues still on the surface. In both cases soil samples were taken at 0-15 cm depth.

At each sampling site, sub-samples were collected in the center of each parcel (36 sub-samples in T1 and 24 in T2), mixed into one sample and quartered in field. Soils were dried at room temperature and sieved with a 2-mm sieve prior to laboratory analyses.

2.2. Elaboration of meteorological data

Start and end times of each tractor passage were recorded during field measurements. The passage time intervals were used to clip the output file of the anemometer, to obtain the average wind components (u, v, w) at the time of each peak. Wind components were then used to assess main wind speed (WS) and wind direction (WD) according to Stull (2012).

The Pasquill Guifford class (PG_{class}) was estimated for each passage by first calculating the Monin Obhukov Length (L_{lenght}) and then estimating the stability class according to the table in Smith et al. (1995). The L_{lenght} was estimated using the Bigleaf R package (Knauer et al., 2018), according to the method described in Foken (2008). The input parameters required by Bigleaf were air temperature (T_{air}), atmospheric pressure (p), friction velocity (u*) and sensible heat flux (H). T_{air} was retrieved by field measurements; p was assessed from elevation using Bigleaf package (Knauer et al., 2018); u* was calculated from wind data according to the method in Stull (2012); H was assessed on the base of the estimation procedure proposed by Hanna and Chang (1992).

2.3. Dispersion modelling to estimate EFs and downwind concentration increases

EFs were estimated using a backward lagrangian model (WindTrax). The input parameters to the model were WS (at 2 and 4 m of height), WD (at 2 and 4 m of height), PG_{class}, T_{air}, average PM_{10} concentration (at four meters from the source) and average background PM_{10} concentration. The model was set to simulate the dispersion of 10^6 particles and the surface roughness (Z_0) was set to the reference value (1 cm), parameterized for "bare soil" conditions. The emission source was modelled as an area source having the same dimension of the plot tilled at each harrower passage. Modelling tilling sources as areas rather than moving point sources is the most common solution for EFs estimation through backward modelling (Faulkner, 2013; Funk et al., 2008; Jahne et al., 2015).

A simulation was ran per each tractor passage performed on the two field days. The output given by the model was an Emission Rate (ER, mg m^{-2} s^{-1}) referred to the modelled area source. The ER was later converted in EF (mg m^{-2}) according to the following formula:

$$EF = ER\ t_{pass}$$

Where t_{pass} is the elapsed time (s) between the start and the end of each passage. The above equation follows the principle presented by Faulkner et al. (2009).

Near source concentration increases during harrowing have been estimated and plotted using the GRAL model (using its open source graphical user interface, GUI), which is a high resolution lagrangian model and has previously been used to assess PM dispersion from tilling (Funk et al., 2008). Moreover, the model has been proved to be particularly suited for modelling under low wind speed conditions (Öttl et al., 2005; Öttl et al., 2002). Two dispersion simulations (one for T1 and one for T2) were realised considering for both an equal area source, with a surface of 1 ha and a squared shape, so that the concentration increases can be related to a known area source of regular size and properly compared. The main inputs to the model were WS, WD, PG_{class} and the PM_{10} emission rate (kg h^{-1}). The average WS and the prevalent WD observed during D1 and D2 passages were used to run two different simulations. The stability classes used were B and D for T1 and T2, respectively. The ER was obtain converting the estimated EFs on both days into kg ha^{-1} and considering that harrowing a surface of 1 ha at an average speed of 3 km h^{-1} requires 1 h of time. Downwind concentration was estimated at a height of 1 m (over the ground level) and the horizontal grid resolution was of 1 m.

2.4. Soil analysis

All samples were analysed for pH (1:2.5 soil:water), total carbon and nitrogen (TC, TN) (UNICUBE, Elementar), carbonates (volumetric method), bulk density and field humidity according to the official Italian methods (Colombo & Miano, 2015). The particle-size distribution (PSD) was measured via the sieve-pipette method (Gee and Bauder, 1986).

To determine the pseudo-total metal content in soil, *aqua regia* (HCl:HNO3 3:1 v/v) microwave extraction was performed (Ethos D, Milestone). The elemental pseudo-total contents of 22 elements (listed in Table 3) were determined in all samples using ICP-MS (NexION 350D, Perkin Elmer). All analyses were performed in duplicate. Accuracy was verified using a Certified Reference Material for *aqua regia* soluble contents (CRM 141R, Community Bureau of Reference, Geel, Belgium). Recoveries were between 95 – 105 % for all elements. All reagents were of ultrapure or analytical grade.

2.5. Soil resuspension in laboratory and PM_{10} filter analyses

The soils collected in the field, after being dried as for chemical analyses, were re-suspended under laboratory condition to simulate PM_{10} emission during tilling. Soil was re-suspended using a soil resuspension chamber, which was assembled using a rotating plastic (PET) drum (Madden et al., 2010), having a cylindrical form, a total volume of 25 L and a circular opening of 15 cm of diameter. The drum was moved by an electric engine (0.75 kW) at an average speed of 26 rpm. A filter based high volume sampler (TCR Tecora®, Echo Hi-Vol), working with a 220 L min^{-1} flow rate, was placed in front of the drum opening to sample the out coming PM_{10} particles. The scheme of the resuspension system is illustrated in Figure 3.

A sample of 1 kg of soil was re-suspended for each trial (T1 and T2) and the re-suspension activity lasted 1 h for each one.

Before sampling, quartz fibre filters (Ahlstrom Munksjo, Micro-quartz fibre paper MK306, Ø102 mm) were dried at 205 °C for 5 h and conditioned for 48 h at 20 °C and 50% relative humidity. Blank filters were weighed three times every 24 h and kept in PETRI holders. After sampling, filters were brought back to the laboratory and weighted after 24 and 48 h of conditioning at the same temperature and humidity conditions. Filters were analysed for their pseudo-total elemental content as soils to ensure the comparability of the measures. Microwave acid digestion using 10 ml of *aqua regia* was performed using half filter in PTFE bombs (Ethos D, Milestone). Resulting solutions were filtered on cellulose filters (Whatman Grade 5) and diluted with ultrapure water to a final volume of 50 ml. Elemental contents were determined in all samples using ICP-MS (NexION 350D, Perkin Elmer).

It was assumed that heavy metals content in PM_{10} emitted under field conditions derives entirely from soil and that the eventual contribution of the tractor combustion engine is negligible (Telloli et al., 2014). Therefore, it was possible to relate the chemical analyses on the re-suspended PM to the field measured PM_{10} concentrations. The elemental concentration of TE in PM_{10} (C_{dust}, µg g^{-1}) was then converted to elemental concentration in the air at 4 m distance from the tractor (C_{air}, µg m^{-3}), by referring it to the overall PM_{10} concentration measured in the field (C_{PM10}, g m^{-3}) according to the following formula:

$$C_{air} = C_{dust}\, C_{PM10}$$

2.6. *Statistical analysis*

A statistical analysis was conducted using the R software (R Core Team, 2019) to highlight differences among EFs and ERs observed for rotary harrowing with different operational parameters. For T1, the effect of tractor speed on EFs and ERs was tested (significance level chosen was $\alpha < 0.05$) implementing a mixed model (lme procedure from nlme R package; Pinheiro et al., 2018) to account for the nested experimental design. The model was set having tractor speed (S) as a fixed factor and the plot as random factor. The distribution of within-groups errors and random effects were graphically assessed to verify the model assumptions (Pinheiro et al., 2006). The mean EF values were calculated (using *emmeans* R package; Lenth, 2019) for each tractor speed level and post-hoc test comparison were performed according to the Bonferroni post-hoc method (using the *multcomp* R package; Hothorn et al., 2008).

For T2, the data were analysed through a mixed model (*lme* procedure from *nlme* R package; Pinheiro et al., 2018) accounting for the nested effects included in the split plot layout of the experiment. The model included, as fixed effects, the three operation parameters (bar orientation, distance, and height) and their interaction. The random effects were distributed on the three levels of the split plot, which included the following nested effects: height in distance, distance in orientation and orientation in parcel.

3. Results

3.1. Environmental conditions during the trials: soil characteristics and atmospheric conditions

In T1, wind speed and direction varied consistently during the tractor passages. The average wind speeds were 0.81±0.07 and 0.91±0.07 m s^{-1} at 2 and 4 m above ground, respectively. Atmospheric stability condition was estimated to fall within the B PG_{class}, meaning that the atmosphere was unstable during the essay. In T2, wind speed was slightly higher as compared to T1 (1.46±0.12 m s^{-1} at 2 m and 1.7±0.15 m s^{-1} at 4 m). Atmospheric stability condition fell in the PG_{class} C (slightly unstable atmosphere) for most passages, exception made for 6 of them, for which the PG_{class} was B. The atmospheric stability condition of each passage was used for modelling the EF. Windrose graphs illustrating the frequencies of main wind directions and speeds during T1 and T2 are shown in Figure 4 and 5 (the graphs were obtained applying the openair R package by Carslaw and Ropkins, 2012).

The low wind speed conditions observed are consistent with the annual average wind speed reported for the Piedmont region by the regional ambient protection agency (ARPA Piemonte; Fratianni et al., 2007).

Table 1 illustrates the main physico-chemical characteristics of the analysed soils. Both soils were sub-acid and their total carbon content was similar and in line with their agricultural use, as well as the other determined chemical characteristics. The moisture content of the soils during the trial was 8.64 ± 0.03 % and 9.02 ± 0.02 %, on mass, in T1 and T2, respectively. Although the finer texture of T2 soil as compared to T1 could lead to a higher emission potential, it is speculative to draw conclusion on the base of texture information only, since it is known that also soil aggregates stability can have a great impact on the final emissions (Madden et al., 2010).

The overall environmental conditions observed during both T1 and T2, with coarse soil texture, relatively high soil moisture content and low wind speed conditions, may lead, according to previous studies, to relatively low emissions (Avecilla et al., 2017; Cassel et al., 2003; Madden et al., 2010).

3.2. *EFs for rotary harrowing and effect of operational parameters on the emissions and plume concentrations*

The results of the statistical analyses for T1 and T2 tilling events are summarized in Table 2. In T1, the average EF for rotary harrowing with packer roller was 8.9 ± 2.0 mg m^{-2}, considering data gathered at all three speeds. The tractor speed was shown to alter significantly the EFs, with the lower speed (S1) causing higher emissions compared to S2 and S3 (Table 2). On the contrary, tractor speed had no significant effect on the ERs. In T2, the average EF for rotary harrowing with packer roller was of 9.5±2.5 mg m^{-2} (averaging all the trials). No significant effect on the emissions was highlighted for bar height, bar orientation and bar distance nor their interaction. From the obtained results, it appears that only bar distance could possibly affect the emission, since the average EFs are generally higher in D1 as compared to D2 (Table 2), although this effect is not statistically relevant. Some differences, although not significant ($P>0.05$), can be observed for different settings at distance D1, while practically no variation is shown among EFs at distance D2.

Peak concentrations measured during tractor passes, at 4 m distance, were 641±40 μg m^{-3} in T1 and 3461±329 μg m^{-3} in T2, averaging all the passages. The average downwind concentration increases near the source (at 1 m height) are plotted in Figure 4 and 5, as estimated for T1 and T2. Estimated PM_{10} concentration increments averaged between 12 (at the field edge) and 0.1 μg m^{-3} (at more than 300 m from the source). The plume in T2 appears to be less horizontally spread as compared to T1 (due to the different stability conditions). Downwind concentration in T2 also appears to be slightly higher. This was probably due both to the reduced plume dispersion and to the higher wind speed registered that day.

3.3. *Elemental characterization of soils and soil-emitted PM_{10}*

The particle size distribution of the elements in soils has been demonstrated to be a key parameter when exploring the possible risks associated to soil contamination (Ajmone Marsan et al., 2008; Kong et al., 2012; Padoan et al., 2017). *Aqua regia* extractable concentrations of elements in bulk soils are reported in Table 3. The TE contents in the resuspended PM_{10} fraction is expressed in Table 3 as enrichment ratio, being the ratio between the content of each element in the resuspended PM_{10} and in the bulk soil it originated from.

Both agricultural soils appeared as not contaminated (according to DLgs 152-2006), in accordance with their long-term agricultural use. In soils, most of the elements appeared enriched in the finer fraction. Only the major elements and, to some extent, the elements typical of the parent material (such as Li, Sc, Co) had a similar concentration in both size fractions.

The enrichment in the finer fraction was particularly evident for Cu, Zn, Mo, Cd, Sn and Ba, where the PM_{10} soil had concentrations one order of magnitude higher than the bulk soil.

From the soil-related PM_{10} fraction concentrations, we calculated the resulting concentration in air according to the total concentration of atmospheric PM at 4m of distance from the source (Table 4). From the results appear that the plume is enriched in TE, with point concentrations of As, Cd and Ni higher than the legislation limits for PM_{10} atmospheric pollution, respectively 6, 5 and 20 ng m^{-3} (MATTM, 2010). Although they refer to the annual average concentration, punctual concentrations in the plume during T2 were up to 50 times the limit.

4. Discussion

The PM_{10} emission factors calculated for rotary harrowing (8.9±2.0 in T1 and 9.5±2.5 mg m^{-2} in T2; averaged over all tractor passages) were found to be substantially lower as compared to the one reported by Öttl and Funk (2007) for fixed-tooth harrow in Germany on a sandy soil (83.3% of total sand), which was of 82 mg m^{-2}. The lower emissions observed are probably due to the overall soil and environmental conditions and to the different implement used. The soil, in both T1 and T2, had a high moisture content (8.64% in T1 and 9.02% in T2, on mass), being in the range of the threshold levels of soil moisture, of 2 and 10 % on mass, over which, according to Funk et al. (2008), very low PM emissions occur in sandy and silty soils respectively. The lower sand content in the two Italian soils could have favoured an improved soil structure and aggregation, which it is known to mitigate dust emissions (Madden et al., 2009). The shielding structure which is present in rotary harrows and absent in fixed-tooth ones could have important emission containment effect. Moreover, the wind speed registered during the trial was lower than the 1.9 m s^{-1} reported by Öttl and Funk (2007). Since the atmospheric conditions registered during the trials are quite common in the Northwest of Italy (Fratianni et al., 2007) and no previous assessments have been done for rotary harrows, the gathered EFs could be considered as a first reference for this type of soil tillage.

A difference between EFs for low (S1), standard (S2) and high tractor speed (S3) was observed during first trial. The emissions observed with S1 were in fact higher as compared to the other treatments, which did not differ significantly among each other. This could be due to the longer period in which the harrower insists on the same volume of soil when operating at the lower speed. This explanation is further confirmed by the fact that no significant difference was observed among the ERs generated at different speeds, meaning that the harrower emits the same amount of PM_{10} per second of work in each thesis. This indirect effect of tractor forward speeds probably could apply only to the rotary harrower, which actively disturbs the soil, but not for traditional soil tilling techniques, which have a passive action on the soil. Usaborisut and Praserkan (2019), and Kushwaha and Linke (1996) have shown that an increase in the tractor speed did not affect PM_{10} releases during harrowing, although a reduction of soil fragmentation should be obtained by raising the working speed. An increase in forward speed, in fact, determines a stretching of the cycloid described by the harrow rotors tines with a consequent increment of clods diameter (Raparelli et al., 2019).

In T2, altering bar height and orientation had no significant effects on PM_{10} emissions. The obtained results also showed a slight emission reduction while increasing the horizontal distance between the levelling bar and the harrower. However, this effect was not statistically relevant, and the bar distance could possibly affect the efficiency of the levelling bar itself. From field observations it appeared that, when the bar was positioned at distance D2, the soil failed to accumulate in correspondence of the harrower teeth. Therefore, to properly test this mitigation opportunity, further trials should be carried out to better investigate its effect on emissions but also on soil aggregates. It is important, when considering possible PM mitigation options, to maintain the efficacy of the agricultural operation unaltered.

Peak concentration measured during trials near the tractor passes were 641±40 µg m^{-3} in T1 and 3461±329 µg m^{-3} in T2. The higher concentration during T2 as compared to T1 was probably attributable to the higher wind speed, causing a more stable and focused plume, and to wind direction, diagonal to the tractor movement, which permitted the operator to put the sensor more in line with the plume centreline. The observed concentration levels were consistent with those reported in previous studies (Moore et al., 2015; Clausnitzer and Singer, 1997) during land preparation activities. The main concerns related to those concentrations are related to farmers' professional health risks. In fact, exposure to high levels of PM_{10} in farming environment can lead to severe health effects and possibly to fatal consequences (Molocznik, 2002; Kirkhorn and Garry, 2000; Schenker, 2000). Although modern tractor cabins are provided with technologies, such as air filters, to protect the operators from these risks, still a lot of assessments are to be done to ensure a sufficient personal protection and to provide a safe work environment for farmers.

Soil-related PM appeared to contain high concentrations of TE, especially those elements deriving predominantly from anthropic sources. Elements such as Cu, Zn, Ni, Cr, Cd, Sn and Ba had, in this fraction, concentrations higher than the legislation limits for soils, as observed in previous studies on different soils (Padoan et al., 2017). This, in turn, affected atmospheric concentrations of metals in the plume. These were calculated, for some of the regulated elements in Italy (Ni, As and Cd), up to 50 times the limit for the annual average threshold levels established by the legislation (MATTM, 2010). Although these were transient conditions, long term exposition to such high concentrations could affect worker's health.

Modelled plume concentrations showed that PM_{10} levels near the emission source can be substantially affected from harrowing operations (Figure 4). In fact, PM_{10} concentration increases due to one hour of field harrowing, calculated at 100 m downwind of the source, were estimated to be among 2 and 7 $\mu g\ m^{-3}$ in both T1 and T2. Even if those concentration increases may seem not too high at a first glance, it is important to take into account that land preparation activities (as well as other cropping activities) are performed over extended cropped regions (areas) and normally for several days or weeks. This concentration of agricultural emissions in space and time is one of the main aspects that lead to sudden air pollution increases in rural areas and nearby cities over specific year periods (Chen et al., 2017; Pavilonis et al., 2013). Moreover, PM coming for agricultural operations can affect air concentrations and cause relevant health effects even at medium and long-range distances (Hill et al., 2019).

5. Conclusions

The PM_{10} EFs for rotary harrowing with levelling bar and for rotary harrowing combined with packer roller were determined in low wind speed conditions. Since the atmospheric conditions in which the trials have been made are quite common in Northwest of Italy (Fratianni et al., 2007) and no previous assessment have been done for rotary harrowing in North Italy, the gathered EFs could be used as a first reference EFs for this type of soil tillage under moist soil conditions. A further assessment should be performed to investigate the PM flux caused by the same implement with drier soil conditions.

It was observed that lowering the tractor forward speed at 0.6 m s^{-1} has a negative effect on PM emissions, causing them to increase significantly.

Major and trace elements in soil-generated PM_{10} were analysed, founding a higher content of TE in the PM_{10} fraction than in the original soil sample, meaning that agricultural activities can play a role in the transient increase of metals content in the atmospheric PM_{10}, even in regions with low soil pollution.

Concentrations of PM_{10} at a distance of 4 m from the tractor passage where found to be up to 69 times higher than the daily limit fixed by WHO (2006), raising some concern for farmers health. Estimated concentration raises near-source were also substantial (plus 2 to 7 μg m^{-3} at 100 m of distance from the emission source). Moreover, elemental (Ni, As and Cd) concentration levels near the tractor path were also high, being several times higher than regulatory threshold levels.

This first study highlighted the need of studies on the assessment of the emissions from agricultural activities and to further investigate the effects of mechanic implements and operative parameters on emission fluxes. Moreover, the dispersion of agricultural PM should be assessed also including long-range transport, and focusing on the investigation of the potential health impact of the contaminants present in soil particulates.

Acknowledgements

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Table 1.

Soil characteristics	T1	T2
Coarse sand (%)	23	9
Fine sand (%)	33	31
Coarse silt (%)	12	14
Fine silt (%)	26	28
Clay (%)	6	18
pH (H_2O)	6.1	6.2
TC (%)	1.34	1.10
TN (%)	0.18	0.18
Soil density (g cm^{-3})	1.5	1.4

Table 2.

Trial	Operative parameters			Mean EF (mg m^{-2})	SE	P_{value}
		Forward speed				
T1		**S1**		13.4[a]	2.1	0.002
		S2		3.6[b]	1.6	
		S3		4.8[b]	2.0	
	Distance	**Height**	**Orientation**			
T2	D1	H	S	33.7	9.0	0.060
		L	S	12.4	9.0	
		H	I	5.0	7.3	
		L	I	14.9	7.3	
	D2	H	S	5.0	3.3	
		L	S	6.1	3.3	
		H	I	5.5	4.4	
		L	I	3.8	4.4	

673 Table 3.

		T1		T2	
		Bulk soil 1	**Enrichment ratio in PM_{10} fraction**	**Bulk soil 2**	**Enrichment ratio in PM_{10} fraction**
Mg	%	0.95 ± 0.02	1.5	1.08 ± 0.04	1.7
Al		3.73 ± 0.02	1.0	3.05 ± 0.21	1.5
K		0.99 ± 0.04	1.0	0.67 ± 0.09	1.5
Ca		0.80 ± 0.07	3.1	0.47 ± 0.03	2.7
Fe		1.24 ± 0.01	2.0	4.36 ± 0.11	0.5
Li	($\mu g\ g^{-1}$)	50 ± 4	0.8	42 ± 2	1.3
Sc		13 ± 1	1.5	8.8 ± 1.3	1.6
V		86 ± 18	1.8	66 ± 5	1.6
Cr		189 ± 25	6.3	91 ± 24	5.0
Mn		1758± 110	1.5	1225 ± 19	1.5
Co		22 ± 1	2.2	20 ± 2	1.6
Ni		135 ± 11	4.4	84 ± 20	3.1
Cu		62 ± 5	7.3	66 ± 5	4.1
Zn		104 ± 8	7.8	58 ± 5	9.3
As		14 ± 1	0.9	13 ± 1	1.7
Sr		75 ± 3	2.8	34 ± 10	2.4
Mo		4.9 ± 3.7	21	< 0.05	
Cd		0.36 ± 0.05	39	0.13 ± 0.03	94.3
Sn		2.8 ± 0.2	13	2.6 ± 0.2	4.6
Sb		0.58 ± 0.25	20	0.58 ± 0.02	5.2
Ba		246 ± 6	5.5	86 ± 10	7.3
Pb		37 ± 0.4	2.5	27 ± 1	1.7

Table 4.

		T1	T2
Mg	µg m^{-3}	12	62
Al		29	157
K		6.4	34
Ca		8.1	44
Fe		14	76
Mn		1.2	6.2
Li	ng m^{-3}	34	183
Sc		9	50
V		67	363
Cr		294	1585
Co		21	111
Ni		168	906
Cu		176	949
Zn		345	1865
As		14	75
Sr		52	283
Mo		64	347
Cd		8	43
Sn		8	41
Sb		2	10
Ba		401	2168
Pb		29	154

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Figure 1. Scheme of T1 experimental units (S1, S2 and S3 passages randomised in a large plot) and positioning of the concentration (DustTrack) sensor.

Figure 2. Experimental settings of the harrower and split plot design adopted in T2.

Figure 3. Scheme of the soil resuspension and PM_{10} sampling system.

Figure 4. a) Windrose illustrating the frequencies of main wind directions and speeds during T1; b) Estimated downwind concentration increases near source (area of 1 ha) during T1..

Figure 5. a) Windrose illustrating the frequencies of main wind directions and speeds during T2; b) Estimated downwind concentration increases near source (area of 1 ha) during T2.

Figure 1.

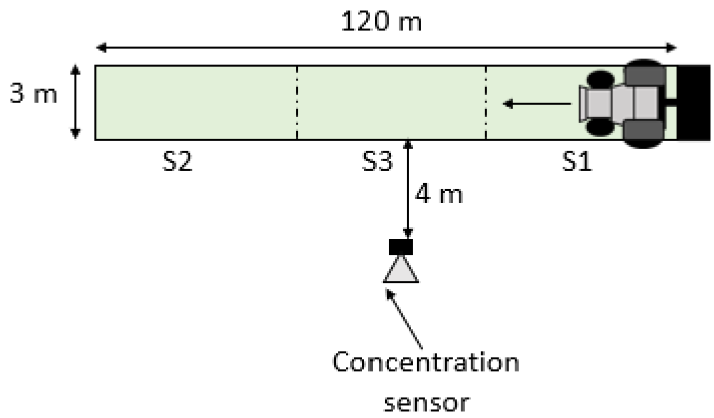


Figure 2.

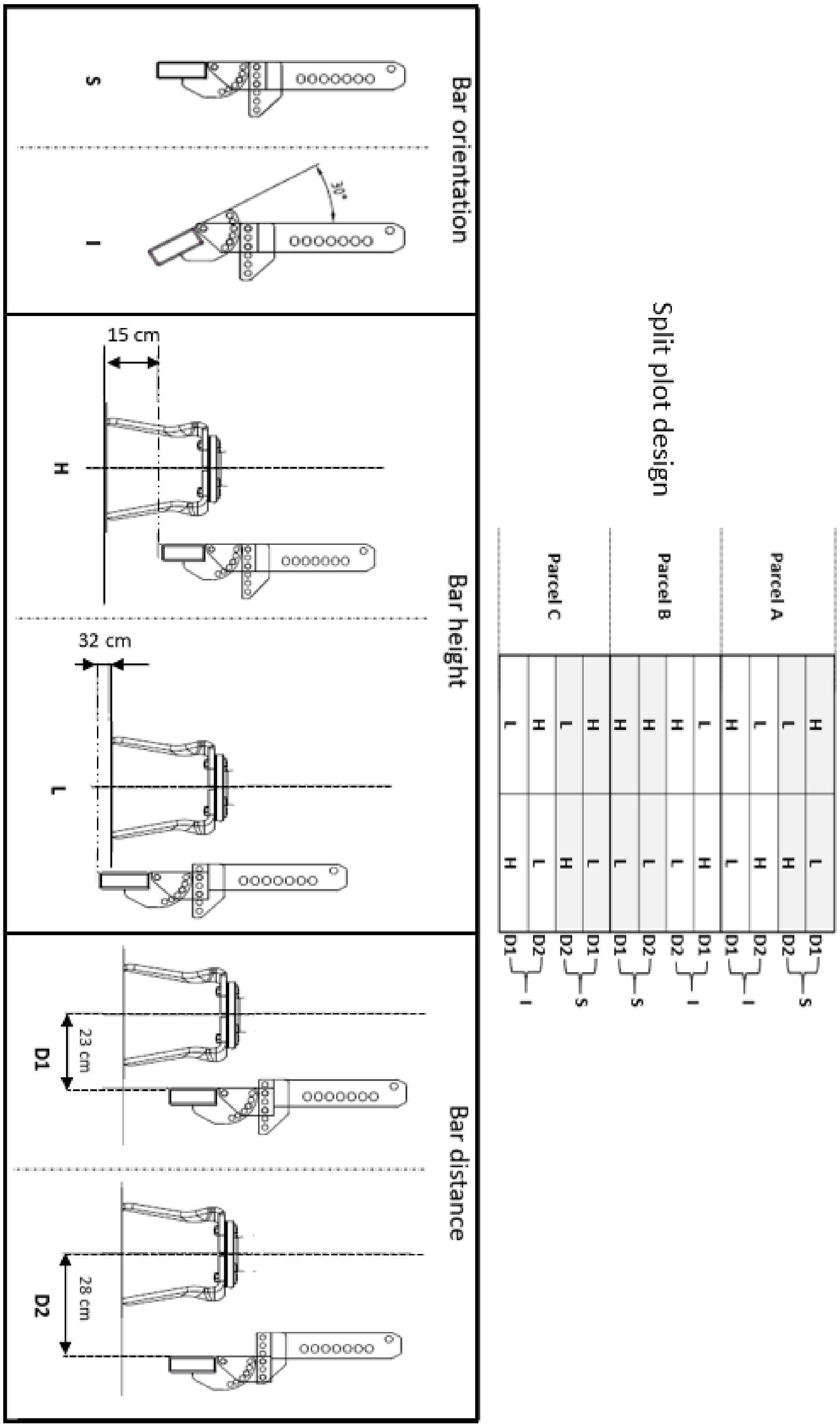

Bar orientation
S
I
30°
Bar height
15 cm
H
32 cm
L
Bar distance
23 cm
D1
28 cm
D2
Split plot design
Parcel C
Parcel B
Parcel A

Figure 3.

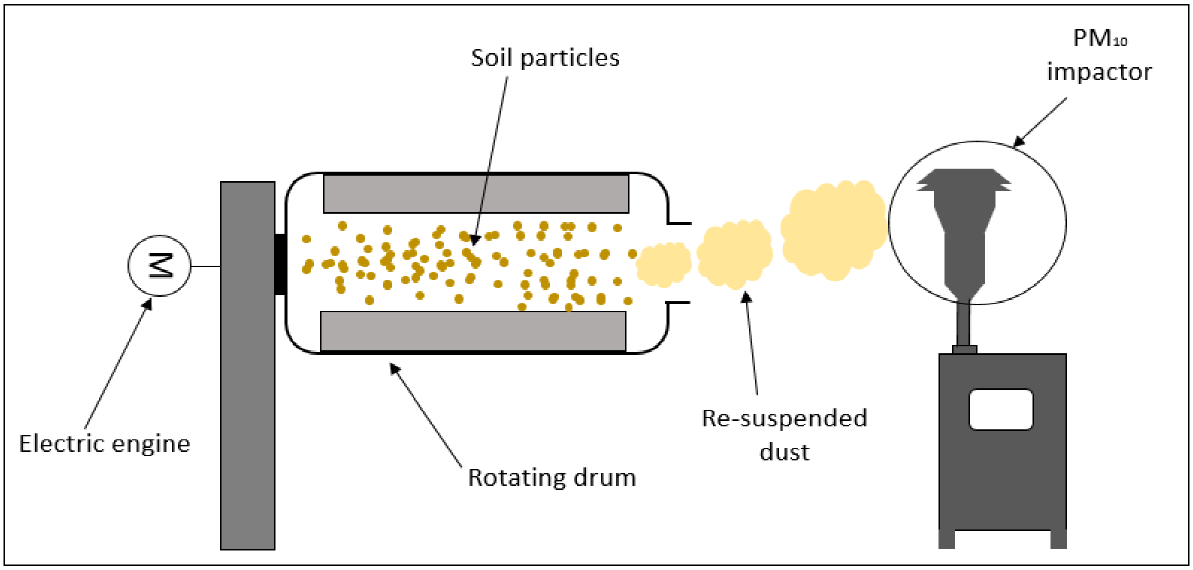

Soil particles
PM_{10}
impactor
M
Electric engine
Rotating drum
Re-suspended
dust

Figure 4.

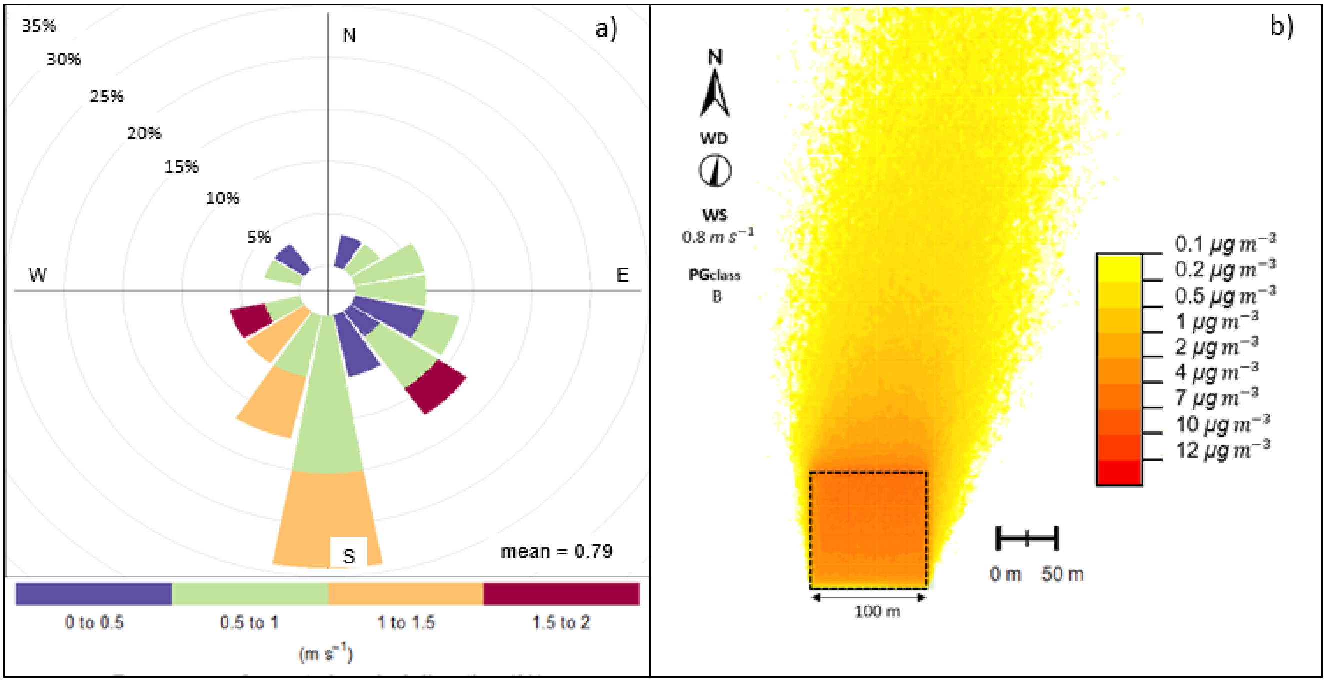
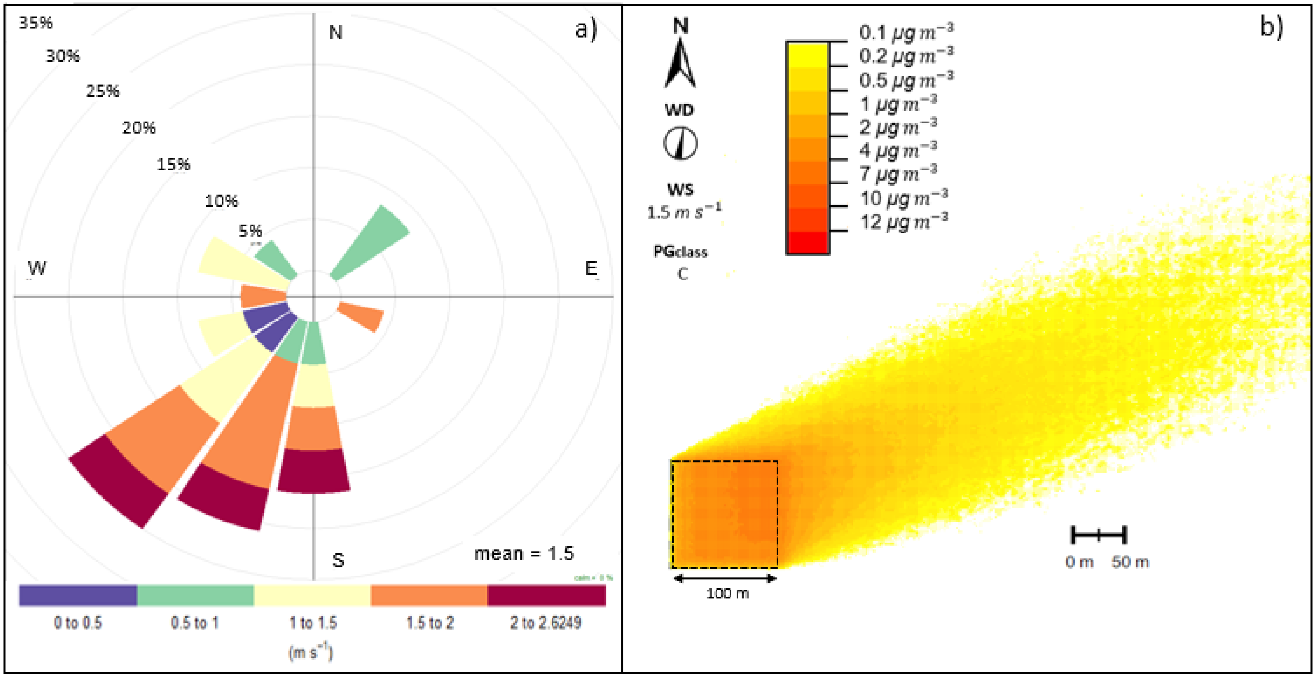

a)
N
W
E
S
35%
30%
25%
20%
15%
10%
5%
mean = 0.79
0 to 0.5
0.5 to 1
1 to 1.5
1.5 to 2
(m s^{-1})
b)
N
WD
WS
0.8 $m\,s^{-1}$
PGclass
B
0.1 $\mu g\,m^{-3}$
0.2 $\mu g\,m^{-3}$
0.5 $\mu g\,m^{-3}$
1 $\mu g\,m^{-3}$
2 $\mu g\,m^{-3}$
4 $\mu g\,m^{-3}$
7 $\mu g\,m^{-3}$
10 $\mu g\,m^{-3}$
12 $\mu g\,m^{-3}$
0 m 50 m
100 m

Figure 5.


a)
N
E
S
W
35%
30%
25%
20%
15%
10%
5%
mean = 1.5
0 to 0.5
0.5 to 1
1 to 1.5
1.5 to 2
2 to 2.6249
(m s^{-1})
b)
N
WD
WS
1.5 $m\,s^{-1}$
PGclass
C
0.1 $\mu g\,m^{-3}$
0.2 $\mu g\,m^{-3}$
0.5 $\mu g\,m^{-3}$
1 $\mu g\,m^{-3}$
2 $\mu g\,m^{-3}$
4 $\mu g\,m^{-3}$
7 $\mu g\,m^{-3}$
10 $\mu g\,m^{-3}$
12 $\mu g\,m^{-3}$
100 m
0 m
50 m