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PM emissions from open field crop management: emission factors, assessment methods and mitigation measures – A review

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Abstract

Globally, particulate matter (PM) emissions are a growing cause of concern due to the potential impact on human health and environment. The agricultural sector is responsible of the 17% of the total anthropogenic emission of PM_{10} and the agricultural operations (tilling, harvesting, residue burning etc.) have been recognized as one of the main drivers of this contribution. This topic has been addressed in many articles, focusing on the impacts coming from different steps of the agricultural production system and using different assessment methods. The aim of this review is to identify the main agricultural operations producing particulate emission, providing a collection of the Emission Factors (EF) available in literature. The most used EFs determination methods have also been described, by focusing on pros and cons of each method. Issues and lacks of information to be addressed by future research have been highlighted. It has been observed that very few PM emission assessment have been done by taking into consideration whole cropping systems and the information available is fragmented

onto single cropping activities. In addition, very few mitigation measures have been developed so far.

Keywords: particulate matter; field operations; emission factors; mitigation measures

1. Introduction

Particulate matter (PM), is considered, both in urban and rural area, as one of the most concerning air pollutants due to its effect on human health and environment (Douglas et al., 2018; Giannadaki et al., 2018; Giannakis et al., 2019). The agricultural sector largely contributes to the emissions of PM_{10} and $PM_{2.5}$, being responsible of the 17% and 5% of the total anthropogenic emissions respectively (EEA, 2016). The contribution of different sectors to the total PM_{10} emissions is summarized in Figure 1. Among the main agricultural activities contributing to the emissions are livestock rearing and open field crop management. The contribution of open field activities is particularly difficult to estimate, due to the wide variety of field operations and crops and to the importance of climatic factors as drivers of PM emissions. This literature review focuses on primary particulate matter (PM_{10} and $PM_{2.5}$ fractions) emissions from open field agricultural operations. The main objective is to identify the agricultural operations producing particulate emission and to highlight, for each of those practices, the main health concerns, as induced by emission magnitude, particle size and particle characteristics. To fulfill this goal, information for each agricultural operation was gathered from literature, focusing primarily on available Emission Factors (EFs). A further aim of this review work was to identify the most common EFs determination methods used in current literature and to highlight their pros and cons. Moreover, the main PM mitigation measures were reported along with their target operation and the expected mitigation effect.

The gaps of information on the subject were highlighted on the base of the review made and some of the niches that could be filled by future research were outlined.

2. Main agricultural operations contributing to PM emissions

Farmers enter the field several times per year for many different purposes and, each time, they potentially produce dust emissions. Those emissions are mainly due to the raising of soil particles due to the passage of heavy machineries, but also to the pulverization of biomass (e.g. crop residues or animal wastes). In particular, the main agricultural operations during which fine particles are released in the atmosphere are soil tillage, harvesting, burning of crop residues, sowing, manure and fertilizer distribution (Sharrat and Auvermann, 2014). Also spraying operations can contribute to PM emissions, both through primary drift of droplets (Carlsen et al., 2006a; Grella et al., 2019) and secondary drift of evaporating compounds (Carlsen et al., 2006b). It was decided not to include spraying operations in the current review because this subject constitutes a research field of his own.

The amount of fine particles produced varies consistently among the different operations. Moreover, there are many parameters, such as environmental conditions (Avecilla et al., 2017), soil and crop type (Madden et al., 2010), soil moisture (Funk et al., 2008; Madden et al., 2010) and mechanical implements (Clausnitzer and Singer, 1996), that can strongly influence the entity and the physical and chemical characteristics of emitted PM.

Despite the variability of those parameters and of estimation methods applied to calculate PM emission factors, most of the authors tend to agree on which operations are mostly contributing to total particulate matter emissions. According to Pattey (2015), who has performed a survey on agricultural PM emissions in Canada, tillage is the operation that contributes the most to the total agricultural emissions. Similarly, Chen et al. (2017) have observed that in Northeastern

China tillage and harvesting account for the three fourth of the total agricultural emissions, with tillage being the main pollution source. Also in California, although the environmental conditions are very different from the ones of the above-cited surveys, tillage and land preparation have been considered to be the main agricultural PM10 source, accounting for the 65% of total agricultural emissions (Clausnitzer and Singer, 1997). Differently, Amann et al. (2012) have estimated that the main agricultural source of PM emissions in Europe is the burning of residues, which, according to their estimations, contributes to the total PM10 and PM2.5 emissions for the 7.6% and 9.6% respectively, while ploughing tilling and harvesting altogether account only for the 4.7% (PM10) and 1.5% (PM2.5) of total emissions. In the African continent agricultural biomass burning emissions are recognized as the second most important source of PM, following natural mineral dust emissions by wind erosion, and being responsible for half of the premature deaths in Central Africa (Bauer et al., 2019). Similarly, studies carried out in India suggest that also in that continent the main agricultural contributor to PM emissions is biomass burning (Pandey et al., 2014; Guo et al., 2017).

In the following paragraphs, the main agricultural operations involved in PM emissions will be addressed, collecting information about the origin and the characteristics of emitted particles, available emission factors and parameters affecting emissions.

2.1. Tillage and soil preparation

Tillage and soil preparation techniques are responsible of producing a significant amount of primary PM emissions. The exact amount of PM_{10} emissions produced can vary a lot according to environmental conditions, especially soil moisture (Chen et al., 2017; Öttl and Funk, 2007; Flocchini et al., 2001) and to the specific tilling implement used (Moore et al., 2013). This implies a strong variability in the emission factors obtained during different measurement campaigns, even if done in the same area and applying the same cultivation practices (Table 1; Wang et al., 2010). The European guidelines, in fact, set a wide reference range of emission factor values for tilling operations, going from 25 to 225 mg m^{-2} (for PM_{10}) and from 1.5 to 10 mg m^{-2} (for $PM_{2.5}$), where the two values are obtained by measuring the emissions during tillage of wet and dry soil, respectively (Funk et al., 2008).

The particulate matter blown away from the fields, during and after soil preparation activities, is mainly composed of mineral particles with a lower amount of organic particles (Goossens and Riksen, 2004), thus being coarser as compared to those emitted during harvesting and straw burning (Chen et al., 2017, 2015). Nonetheless, according to Bogmann et al. (2005), who did a total solid particles (TSP) emission assessment in a European environment, 50% of the particles emitted during tillage have a diameter of less than 20 µm.

Concerning the emissions of particles in the smaller size fractions ($PM_{2.5}$), Moore et al. (2013) found practically no $PM_{2.5}$ emissions during soil tillage operations. On the contrary, (Chen et al., 2017) observed a $PM_{2.5}/PM_{10}$ ratio during tillage equal to 28%. This contradiction can be explained by the findings of Carvacho et al. (2004), who observed that the $PM_{2.5}$ soil emission potentials are higher in soils containing more silt, while they tend to be lower in sandy soils.

Table 1 summarizes EFs estimations for tillage operations, referring to different tilling implements. The implements used for soil preparation can induce different PM emissions as compared one to another (Table 1). Some authors observed that comparisons between emission factors related to the use of different tools could be unreliable because of the impossibility of standardizing the environmental conditions among trials (Holmén 2001, Cassel et al., 2003; Wang et al., 2010). However, the emission factors reported in Table 1, which are related to different operations, can be used for gathering general indications. The emission factors reported are divided by tilling operation type, although some authors (Holmén et al., 2001, Cassel et al., 2003) stated that, as crop calendars may affect the period in which certain operations are performed, it should be better to further categorize EFs per crop type or per month. A further consideration to be done is that the methods used to estimate the emission factors vary considerably according to different authors, increasing the uncertainty of possible comparisons.

Among the main primary tillage operations, the most polluting one, in terms of PM emissions, appears to be ripping, followed by conventional plowing and disking (Clausnitzer and Singer, 1997, 1996; Holmén et al., 2001). As for secondary operations, it was highlighted, from a study conducted by Moore et al. (2013), that during a second passage performed on a field with the same implement the generated emission rates of the finer ($PM_{2.5}$) tend to be higher. Similarly, other studies have shown that the final operations, such as land planning and floating, tend to produce higher emission rates than the primary ones (Cassel et al., 2003; Clausnitzer and Singer, 1997, 1996). This effect is probably due to the progressive disaggregation of soil aggregates that have been proven to affect PM_{10} emissions (Madden et al., 2010). The effect of tillage on windblown dust and PM emissions was also shown to be affected by the implement choice (Lopez et al., 1998; Pi et al., 2018; Singh et al., 2012), being for example higher with disking that with under cutter tillage (Pi et al., 2018).

Moreover, tillage does not only contribute directly to PM emissions, but it can also affect the dust dispersion events caused by wind events or other disturbances. This is due to the effect of tillage on soil physical properties (especially aggregate stability and overall soil structure) and to the removal of soil cover with the incorporation of crop residues into soil (Gao et al., 2014; Sharratt et al., 2010). Particularly, Sharratt et al. (2010) observed that intense tillage practices could affect wind erosion in the after copping period (especially in case of summer fallows), leading to higher sediment fluxes during strong wind events.

Another aspect to be considered is that tillage practices can possibly lead to the emission of pesticide particles, previously deposited onto the soil trough pesticide spraying (Grella et al., 2017) or sowing or coated seeds (Forero et al., 2017).

2.2. Harvest and post-harvest operations

Harvesting operations are recognized to be among the major sources of PM in agriculture (Chen et al., 2017; Clausnitzer and Singer, 1996; Pattey, 2015). As compared to dust particles emitted during soil tillage, those produced by harvesters tend to be finer and to have a higher content of organic particles (Telloli et al., 2014). Chen et al. (2017b) conducted a study in which they observed a dramatic increase of $PM_{2.5}$ concentrations in the air during harvesting periods both in urban and rural areas (in the Changchun region in Northeastern China), confirming the potential importance of harvesting practices in determining the raising of $PM_{2.5}$ environmental levels. Moreover, harvest generated dusts are also recognized for carrying bioactive components. For example, wheat dust can contain endotoxins and mycotoxins that induce negative health effects (de Rooij et al., 2017; Douglas et al., 2018; Halstensen et al., 2013; Traversi et al., 2011).

Table 2 shows some of the EF estimations that were made for harvesting operations, classified per crop type. As can be seen in Table 2, harvesting related EFs are characterized by a great variability, mainly due to the variety of harvesting implements adopted for different crops and, in some cases, even for the same crop. In addition, for several crops, such as forage crops, the harvesting procedure consists of many different steps, each having its own emission potential. The EF assessments available in literature focus on few main crops, while the actual contribution of several others remains practically unknown. In fact, even the environmental agency guidelines (USEPA, 1995) proposes emission factors only for few crops, such as wheat and cotton.

Another important aspect to consider is that the crop originated dusts, and grain dust especially, are not only those released during the harvester's passage. In fact, further emissions occur during post-harvest activities, such as yield transport, storage and drying. Those operations can be attributed to the agricultural sector because they are usually performed at farm level (even grain drying is often performed by farmers). In the USEPA gas emission inventory (USEPA, 2003) the EFs reported for truck loading and transport of grains, both for wheat and sorghum, are equal to 12 g m^{-2} (wheat loading), 22 g m^{-2} (sorghum loading), 110 g m^{-2} (wheat transport) and 200 g m^{-2} (sorghum transport). Comparing those EFs with the ones proposed by EPA for the actual harvest of those two crops, it appears that the first post-harvest steps account for 41.8% (transport) and 16.7% (loading) of the total (harvest + loading + transport) emissions, which is more than half of the total emissions. Considering that, if also grain drying and cleaning operations were considered, the post-harvest contribution would be even greater, it is important to include those steps in emission inventory databases to obtain a reliable representation of total harvest related emissions.

2.3. Crop residue burning

The burning of agricultural residues is recognized to generate high emission of GHG (Arai et al., 2015; Murali et al., 2010) and particulate matter (Dennis et al., 2002; Hays et al., 2005) and to strongly affect rainwater composition (Coelho et al., 2011). Furthermore, as pointed out by Kumar et al. (2019) straw burning affects the overall environment, causing a loss of ecosystem services. Nonetheless, agricultural residue crop burning is still a widespread management practice, partially due also to its effect on pest and weed control at very low costs.

In Europe, the burning of crop residue is not allowed according to the directive 2008/98/EC, due to its effects on human health. However, in many less developed regions and countries this management practice is still common in most of the main cropping systems, such as in rice, wheat and maize cropping (Gupta et al., 2004), while in sugarcane cropping system it is often a step of the harvesting process (Franca et al., 2014). This makes it a very complex subject to address, being the crop type itself one of the parameters affecting both the chemical characteristics and the amount of the emitted particles. Table 3 summarizes some of the main EFs estimation for crop residue burning of different crops, measured both through laboratory, field and aircraft measurements. As can be seen in Table 3, the reported EFs for different crops range between 21.5 and 1.8 g kg^{-1} for PM_{10}, and the $PM_{2.5}/PM_{10}$ also ranges between 0.52 and 0.98. The EFs vary a lot also for the same crop. This could be partially due to the fact that many different methods are used to estimate EFs. Therefore, although many EFs have been published, it is difficult to select a reference EF, due to the wide range of proposed values. Moreover, many measurements were performed under laboratory conditions (Santiago-De la Rosa et al., 2018; Mugica-Álvarez et al., 2018; Li et al., 2017) and the results can not directly be transferred to EFs under field conditions. Laboratory determinations of EFs, although they do not examine actual fire, have the advantage of allowing more strict comparisons among different crop biomasses as compared to field measurements, due to the standardization of environmental conditions.

The size and composition of particles generated from biomass burning are different from those from other agricultural operations. These particles are in fact finer and most of them are in the $PM_{2.5}$ of even in the PM_1 fraction range (Le Canut et al., 1996, Yokelson et al., 2009, Oanh et al, 2011). This is of particular importance since the concentration of finer particles ($PM_{2.5}$ range) has been associated with an increase in mortality risk (Pope III, 2002). Moreover, Oanh et al. (2011) observed the presence of organochlorine pesticides in particles generated from rice straw burning. The presence of these and other organic compounds could lead to an increase toxicity of the emitted particles. The main parameters affecting the emissions, other than the crop type are the moisture content (Hayashi et al., 2014), the meteorological conditions and fire control activities (Oanh et al, 2011).

2.4. Sowing

Seed drilling machines, operating on agricultural fields, also produce particulate matter emissions. The emitted particles generate mainly from soil, but a small portion comes from the seeds, which are abraded during sowing activity. There are few available experimental data on the entity of total PM_{10} emissions during sowing. Air aerosol concentrations measured during corn sowing were reported to be equal to 1.02 mg m^{-3} (Clausnitzer and Singer, 1996), being approximately equal to those induced by tooth harrowing and other soil preparation practices, as reported by the same authors. During seeding, which is usually performed after several land preparation activities, land particles may raise with more ease than during previous tillage passes, due to the progressive loss of soil structure, as described by Madden et al. (2010).
A further aspect regarding dust emissions during sowing is the potential drift of dressed seed particles, containing pesticides that could be spread in the surrounding environment. This particular issue is a cause of concern due to its potential effects on wildlife, and especially on pollinators, and led the European Food Safety Authority to produce a specific risk assessment guidance book (EFSA, 2013). The amount of seed abraded dust emitted during sowing vary among different crop seeds, being higher for maize and lower for rapeseed and oilseed

(Nuyttens et al., 2013). Seed coating particles do not only spread onto the soil or in the surrounding environment, but can also contaminate the seed drilling machine, leading to further health risks (Manzone et al., 2016).

Tapparo et al. (2012) conducted an essay with three different types of drilling machines while sowing seeds treated with Clothianidin (1.25 mg/seed), Thiamethoxam (0.6 mg/seed) and Fipronil (0.5 mg/seed) and calculated the emissions factors (on TSP) that were equal to 0.043 – 0.153 mg m^{-2}, 0.074 mg m^{-2} and 0.045 mg m^{-2} , respectively, of emitted insecticides. They also observed that only a small amount of those particles was associated with the PM_{10} fraction of the emitted dust. Though the PM_{10} associated compounds may travel further distances from the field as compared to the ones linked to coarser particles (Tapparo et al, 2012).

As for soil particles emitted during sowing and planting, other than having a direct environmental impact, they can also affect the drift of seed coating pesticides by exerting an abrasive effect on seeds. This effect was confirmed by the findings of Schaafsma et al. (2018) who observed that, while sowing with a vacuum seeder machine, 15 mg m^{-2} of soil dust passed through the planter, inducing the loss of 0.24 mg m^{-2} of Clothianidin active ingredient.

Moreover, the emission of seed coating compounds from agricultural fields does not occur only because of seed abrasion during seed drilling, but it can happen as a consequence of further disturbances such as soil tillage and high wind events which can induce the removal of soil bounded residues from fields. Forero et al. (2017) were able to detect neonicotinoids in fugitive dust during tillage (the concentration ranged from traces to 4.48 ng m^{-3}) and high wind events. This kind of effect highlights how different operations (like sowing and tilling) can influence each other. Because of these interactions, it could be better to consider the emissions crop-wise, by evaluating the emission factors and the environmental risks of the sequence of activities needed for growing a specific crop as a whole.

2.5. Manure and fertilizer spreading

Manure spreading is recognized to be one of the contributors to primary PM emissions in the agricultural sector (Sharrat and Auvermann, 2014). Nonetheless, there are practically no measured emission factors available in literature regarding this operation.

The importance of PM emission from land application of manure is strongly linked to the composition of the generated particles. Manure generated dust, in fact, includes bioaerosol emissions, which implies pathogen exposure risks both for agricultural operators and for inhabitants of near field residential areas. This effect has been described by Jahne et al. (2015b), who demonstrated that infection risks for certain pathogens are higher for people living near manure application sites. A further aspect to be considered is that bioaerosol from manure spreading could contaminate the nearby crops (especially in case of leafy vegetables), causing the contamination risk to rise above acceptable levels in the first 160 m from the application point (Jahne et al., 2016).

Manure is not the only biomass applied to agricultural soils nowadays, since many other organic materials are frequently used as soil fertilizer or amendments. Among those biomasses some of the most controversial ones, due to their potential load of pathogens and pollutants (Akbar-Khanzadeh et al., 2012), are sewage sludges. In their paper, Paez-Rubio et al. (2007) determined the quantity of dust particles emitted during the spreading of biosolids, being equal to 7.6 ± 6.3 mg of PM_{10} per kg of dry biomass applied (the spreading was performed from a stationary position and thus all the measured emissions derived from the biomass, since the soil was not disturbed).

Recent researches (Jahne et al., 2016; Jahne et al., 2015a; Jahne et al., 2015b; Kang et al., 2014) focused mainly on the aspect of bio-aerosol and bacteria emissions during manure spreading, while few of them report also the total PM10 emissions. Furthermore, very few information is available on the effects of spreading implements and tractor speed on the emissions, although those aspects could affect the emissions.

Similarly to manure spreading, also chemical fertilizer application can lead to PM emissions. In fact, abraded fertilizer particles can be released during land application. Pattey and Qiu (2012) reported an estimation of the PM emitted per ton of applied fertilizer, being equal to 1.09 kg t^{-1} for PM10 and 0.31 kg t^{-1}.

A further aspect to be considered is that, both manure and fertilizer spreading operations do not only contribute to primary PM emissions, but those are also considered as some of the main sources of ammonia (NH_3) emissions in the atmosphere (Plautz, 2018). Thus, due to the reactions between of NH_3 with sulfur and nitrogen oxides in the atmosphere, leading to secondary aerosol formation (particularly in the $PM_{2.5}$ fraction), those operations can account for both a direct and indirect contribution to dust pollution (Backes et al., 2016; Plautz, 2018).

3. Emission factors assessment methods

The PM Emission Factors for agricultural operations currently available in literature were obtained by using several different methods, some being more common than others. The six main methods used in recently published papers are the following:

- Vertical profiling method;
- Dispersion modeling;
- Atmospheric tracer technique;
- Carbon mass balance method;
- LiDAR technology;
- Laboratory measurement methods.

3.1. Vertical profiling method

The vertical profile method is a micrometeorological method which relies on field measurements of wind speed and PM_{10} concentration to infer the wind speed and PM concentration profiles. The method is well described by several authors (Holmén et al., 2008, 2001; Wang et al., 2010) and it is similar to the method used to estimate ammonia emission rates (IHF method, Ryden and McNeill, 1984). The wind speed profile can be obtained, using the logarithmic wind profile equation (Stull, 1988), by measuring the wind speed with a 3D sonic anemometer or by measuring the wind speed at two different heights.

The concentration profile is obtained by measuring the PM concentration at four different heights, with optical PM monitors (particle counters) placed on a vertical array. The chosen heights depend on the distance of the array from the emission area.

The EFs are then obtained by fitting the two profiles into the following equation (Holmén et al., 2001):

$$\mathrm{EF} = \int_{zo}^{zmax} \frac{u(z)c(z)tcos(\theta)}{w}\, dz$$

Where EF is the emission factor (mg/m^2), z is the height above ground (m), z_0 is the surface roughness length (Stull, 2001), $u(z)$ is the average wind speed at height z (meters per second) during the treatment (calculated from u_* and ζ based on the Similarity theory in Stull, 2001), $c(z)$ is the mean concentration at height z (meters), t is the length of time of the treatment, θ is the angle between the measured wind direction and the direction that is perpendicular to the tractor path, *w* is the upwind width of soil worked during the test period, and z_{max} is the height at which the concentration is esteemed equal to 0.00.

This method allows calculating EFs relying exclusively on field measurements, but it has some drawbacks:

- A high number of instruments is needed to perform concentration and wind speed measurements at different heights;
- The estimation of the vertical concentration profile, the plume height and the wind speed profile implies a certain level of uncertainty as it is based on punctual measurements;
- The distance of the PM monitors from the operation path strongly affects both the magnitude of estimated EFs and the particle size distribution detected downwind.

As for the distance in which to measure the PM concentration downwind, Holmén et al. (2008) noted a difference in the $PM_{2.5}/PM_{10}$ ratio between a near source emission measurement ($PM_{2.5}/PM_{10}$ of about 50%) and a far from source measurement ($PM_{2.5}/PM_{10}$ of about 10%). According to the authors, this difference could be due to the fact that the finer PM fraction ($PM_{2.5}$) tends to be dispersed more vertically, which makes detection in long range concentration measurements more difficult.

3.2. Definition of the EFs through dispersion modeling

Atmospheric dispersion models can be utilized to perform EF estimations for agricultural field operations. The most commonly used models are designed primarily to predict concentration of pollutants downwind of a source with a known emission rate, ER (µg s^{-1}). Nonetheless, models are often used inversely to predict Emission Factor (EF) of a source of pollution starting from downwind concentration measurements (Faulkner et al., 2009).

The ERs, and thus the EFs, calculated through this procedure correspond to those that would have generated the measured concentration in the exact measuring spot under simulated conditions. As a consequence, the reliability of the EF estimation does not only rely on the concentration measurement, but also on the characteristics of the chosen model and on its capability of taking into consideration as many influencing parameters as possible (e.g. meteorological variables).

Several dispersion models have been used to estimate EFs from agricultural fields up to now, and they can be distinguished in three main categories:

- Gaussian models (e.g. ISC3, AERMOD);
- Eulerian models;
- Lagrangian models.

The intrinsic differences between these models has been discussed in several works dealing with dispersion modeling in general (Holmes and Morawska, 2006; Leelőssy et al., 2014). Some authors performed direct comparison between models, as done by Faulkner et al. (2009), who compared the actual reference EPA model (AERMOD) and the former one (ISC3-ST) for assessing harvesting PM_{10} EFs and found no statistical difference between them. Other authors (Wang et al., 2010, 2009), preferred to compare modeled EFs with data obtained by different methods, with techniques such as the use of LiDAR technology (treated in paragraph 3.3).

Lagrangian models have been also developed as “backward models” (models which are properly designed calculate EFs starting from measured concentration values and meteorological data). A model featuring this kind of analytical procedure, known as BLS (Backward Lagrangian Stochastic) model (Flesch et al., 1995, 2004), has been specifically developed for agricultural open field applications and, until now, it has been mainly used to estimate emissions of ammonia and other gases. The BLS model has been used to estimate

PM emission rates from cattle feedlots (Bonifacio et al., 2013; Mcginn et al., 2010) and has been reported to have several advantages, like the possibility to manage multi-plot sources (Gericke et al., 2011) and to calculate emission for short time periods (e.g. a few hours; Mcginn et al., 2010). Those characteristics could allow the BLS model to be a useful tool for EF estimation from open field operations, which are usually occurring over short time periods.

3.3. Atmospheric tracer technique

The atmospheric tracer technique has been included in this list although it has been sparely used for EF estimations in the agricultural environment. In fact, it has been proposed by (Qiu and Pattey 2008), who used it to estimate EFs for wheat harvesting. The method measures simultaneously the concentration of PM (using a tapered element oscillating microbalance, TEOM 1400a, Thermo Scientific,Waltham, MA, USA) and a tracer gas both upwind and downwind of the tractor path. By placing a tracer emitting device on the tractor, with a known ER, it is possible to infer the PM emission rate through a simple proportion, as follows:

$$ER_{(PM10)} = \frac{[PM_{10}]ER_{(tracer\ gas)}}{[tracer\ gas]}$$

Where $ER_{(PM10)}$ and $ER_{(tracer\ gas)}$ are the emission rates of the pollutant and of the tracer respectively, while [PM_{10}] and [tracer gas] are the two concentrations as measured downwind. The so obtained ER can then be transformed to an EF by multiplying it for the duration or the operation and dividing it for the treated surface. As for the choice of the tracer gas Qiu and Pattey (2008) chose the Dinitrogenoxide (N_2O, measured with a closed-path tunable diode laser, TGA-100, Campbell Scientific, Logan, Utah, USA) because of its low background level variability and because, although it can be emitted from soils, the emission levels are low. Other tracer gases may be tested in the future.

The main drawback of the atmospheric tracer technique is the assumption of equal transportation dynamic (through convective fluxes) of fine particulate and of the tracer gas. Nonetheless, considering that similar determination methods have been used to estimate gas emissions in agriculture and in other environments, especially in source apportionment studies (Jordan et al., 2006; Lamb et al., 1986; Viana et al., 2008), the tracer method can be considered as an established methodology.

Qiu and Pattey (2008) also performed a comparison between the EFs obtained with the tracer technique and those calculated by using the AERMOD model (on the same experiment) and found no significant difference. It appeared though, that the EFs obtained with the tracer method had a lower variability as compared with the modeled ones.

Thus, this technique seems to be a viable alternative to the other methods described, being potentially capable to give equally good results with a lower level of measurement efforts. Further evaluation of the method should be performed in the future to study its performances with different atmospheric stability and wind speed conditions.

3.4. Carbon mass balance method

The carbon mass balance method is one of the most diffuse methods for assessing emissions from crop residue burning events. The methods uses an approach wich is somehow similar to the atmospheric tracer technique. EFs for PM emissions are estimated by referring the overall emission of organic carbon to the total initial carbon content of the burnt biomass. This is made possible by the fact that crop biomass is a carbonaceous fuel and the pollutant are substantially organic compound. It is therefore possible to relate the emission of PM to that of a reference specie (R_{specie}), usually CO or CO_2 (Andreae, 2019). This is done by first relating the measured mixing ratios of PM and R_{specie}, to obtain the so called emission ratios, which are more correctly referred to as normalized excess mixing ratios (NEMRs; Akagi et al., 2011). NEMRs are obtained according to the following formula:

$$NEMR_{\frac{PM}{R_{specie}}} = \frac{\Delta PM}{\Delta R_{specie}}$$

Where ∆PM is the difference between the PM concentration in the plume and its background concentration and ΔR_{specie} is the difference between the plume concentration of R_{specie} and its background concentration.

A further step is then required to assess EFs starting from NEMRs, by implementing the following formula (Andreae, 2019):

$$EF_{PM} = NEMR_{\frac{PM}{R_{specie}}} \frac{MW_{PM}}{MW_{R_{specie}}} EF_{Rspecie}$$

where EF_{PM} is the PM emission factor, MW_{PM} and $MW_{Rspecie}$ are the molecular weights of the species the investigated PM fraction and the reference specie respectively, and $EF_{Rspecie}$ is the known or assumed emission factor of the reference species (often CO or CO_2).

Although the procedure to estimate the emission is quite simple and reliable, some complication can be encountered. Sometimes, for example, the estimation of Background concentrations can pose some issue, especially with reference gases such a CO_2, which is characterized by having many sources and sinks in the surrounding environment, that can easily lead to under or overestimations. Moreover, to adopt this technique, it must be assumed that PM and R_{specie} are equally dispersed from the source to the sampling point, which is not forcefully true. Phenomena such as PM dry deposition and aggregation could in fact lead to an underestimation of the emission.

Another important aspect in determining the reliability of the method is the actual sampling strategy used. In fact, the mass balance technique can be coupled both with ground based (Akagi et al., 2014) and aircraft sampling data (Andreae et al., 1998, Le Canut et al., 1996), while in certain occasions both sampling strategies can be used (Burling et al., 2011). The main advantages of aircraft measurements are the possibility of assessing emissions coming from large areas and the capability of measuring the concentration inside the plume, better estimating the concentration of the more volatile particles. In fact, as highlighted by Holmén et al. (2008), finer particles ($PM_{2.5}$) tend to disperse more vertically than coarser ones. This is crucial in case of crop burning emissions, since most of the produced particle are in finest PM fractions (Yokelson et al., 2009). The main disadvantage of aircraft measurements, on the other hand, is the higher cost implied by the use of aircrafts.

3.5. Use of LiDAR technology for EFs and plume parameter estimation

The LiDAR (Laser Imaging Detection and Ranging) technology has often been used, in recent years, to study particle emissions from agricultural operations and especially to derive plume dispersion parameters. The first applications, such as the one carried out by Holmén et al (2001, 1998), pointed out that LiDAR measurement could be used to estimate vertical and horizontal dispersion coefficients of field dust plumes and proposed an ER estimation method through LiDAR calibration with filter samplers. This applications also allow to evaluate the uncertainty of plume height estimations with the vertical profile method (Holmén et al., 2001). Similarly, LiDARs have also been used to evaluate the uncertainty of plume parameter estimation performed with models. Wang et al. (2010) compared EFs estimated with LiDAR and with the

AERMOD model and found that, although similar, the results obtained with LiDAR had smaller uncertainty intervals.

In a more recent study (Holmén et al., 2008), involving the use of a backscatter LiDAR, plume size and plume movement were studied through LiDAR images and this information allowed to observe that, under convective conditions, the plume tends to move more vertically than laterally. This kind of information could be useful to answer some methodological questions, like if the PM concentration measurements are better done near or far from the emitting source (Holmén et al., 2008). A further advantage of the more recent LiDAR application is that it is possible to differentiate aerosols of different origins (Gregorio et al., 2018; Holmén et al., 2008), such as the engine exhaust plume and the soil dust plume coming from a single area source. Willis et al. (2017), by coupling LiDAR measurements with PSD quantification through stationary sampler and micrometeorological measurements, were further able to calculate ER, at a whole facility scale, from LiDAR measurements.

In recent years, the LiDAR technology has become an important tool for EF estimation, especially during experimental trials, being often used as reference method to evaluate models (Moore et al., 2015; Wang et al., 2009). The main negative aspects of this evaluation technique are linked to its costs and to its complexity in terms of instrument use and calibration requirements. On the other hand, this technique is the most informative one in terms of plume shape and plume dynamics.

3.6. Laboratory measurement methods

Although the environmental conditions are of crucial importance in determining PM emissions from cropping operations and cannot be simulated under laboratory conditions, several laboratory assessment methods have been applied to this specific field. Particularly, laboratory methods are used to assess the PM Emission Potential (EP, mg kg^{-1}), which is the potential capacity of a substrate to emit fine particles in a certain fraction range, of agricultural soils and crop biomass. Moreover, laboratory techniques have often been used to assess crop specific EFs for residue burning activities. The main methods are:

- Wind tunnels;
- Soil resuspension chambers;
- Open combustion chambers.

Wind tunnels are tunnel shaped dynamic enclosure systems, in which an air flow is forced over or through a certain volume of soil, causing it to re-suspend. Wind tunnels are generally more suited to assess wind blown PM emissions from fields (in wind erosion studies) than tillage induced ones, since they do not allow to simulate the active soil disturbance as generated by tilling implements (Funk et al., 2008). Nonetheless, in studies such as those by Funk et al. (2008), a wind tunnel has been used to assess emissions from soil under different moisture conditions, retrieving information very relevant to estimate tilling EFs variation with different soil moisture contents.

Soil resuspension chambers are built with the aim of actively re-suspending fine particles in a soil sample by mechanically agitating it. The most common soil resuspension mechanisms consist either of rotating drums, in which the soil sample is mechanically re-suspended (such as in Madden et al., 2009), or of abrader systems, in which the soil particles are propelled through a path allowing the abrasion action to cause the emission (such as in Chandler et al., 2002). After particle resuspension has been achieved, the polluted air stream is usually pulled or blown at a known rate (using pumps) toward a further sedimentation/sampling chamber, where PM_{10} is selected through an impactor and deposited on a filter (Chandler et al., 2002; Madden et al., 2009). The soil EP is then calculated dividing the mass of PM_{10} (mg) deposited on the filter after a certain sampling time, by the total volume of soil sample used (kg). A more comprehensive review of soil resuspension chamber designs and experimental methodologies has been provided by Gill et al. (2006).

Soil resuspension chambers have been used to study the effects of moisture, soil texture and soil structure on PM emissions from tillage (Madden et al., 2010; Madden et al., 2009; Carvacho et al., 2004; Chandler et al., 2002).

Open combustion chambers are the most common laboratory equipment used to simulate crop residue burning under laboratory conditions. Combustion chambers are normally constituted by a burning plate, on which the crop material is burned, and of a chimney, inside which the air is sampled to analyse PM concentration. To calculate crop specific EFs ($g\ kg^{-1}$), the air concentration of PM ($g\ m^{-3}$) inside the chimney is multiplied by total volume (m^3) of combustion gases passed through it and divided by the mass (kg) of the crop material. Although most open combustion chambers have similar designs (schemes can be found in Mugica-Álvarez, 2018; França et al., 2012), some alternative designs have been proposed, such as that described by Jenkins et al. (1990), who adopted a chamber shaped similarly to a wind tunnel, which was developed to simulate agricultural biomass burning emissions from wide surfaces. Another design option is the one adopted by Li et al. (2017), who used a chamber of small dimension ($0.23\ m^3$), which was characterized by having a HEPA filter placed at the air inlet and by being equipped with a second chamber in which polluted air is mixed before sampling. As in the case of soil resuspension devices, also combustion chambers have been used to assess the effect of substrate moisture on PM emission (Hayashi et al., 2014), other than assessing fuels of different types and origins (Christian et al., 2003).

In conclusion, laboratory trials are of crucial importance to acquire information on the effects that specific factors (such as substrate characteristics and moisture) have on the out coming emissions and allow to better comprehend the dynamics that are at the base of open field emission events.

4. Mitigation measures

The development and evaluation of PM mitigation measures for open field agricultural operations is not an easy task. This difficulty is partially due to the fact that EFs obtained from open field assessments are related to specific and not repeatable environmental conditions, which makes it difficult to assess the efficiency of mitigation measures through comparative trials. Nonetheless, several studies have tested PM or dust emission mitigation strategies.

Table 4 shows some of the main mitigation measures proposed for reducing PM emissions during agricultural operations.

Conservation tillage techniques are widely proposed as valid alternatives to traditional tilling for reducing PM emissions. Those techniques are able to exert a substantial mitigation of dust (Coates, 1996; Backer, 2005) and PM10 (Backer, 2005) emissions during land preparation. The emission reductions achieved with minimum and no tillage are mainly attributed to the reduction of tilling events, while practically no difference has been highlighted for the choice of the tilling implement (Coates, 1996, Backer et al., 2005).

Although conservation tillage is indubitably a good solution when it comes to reducing PM_{10} emissions, it can affect crop yields (Irmak et al., 2019) and cannot always be applied. Therefore, it would be valuable to explore the possibility of lowering the emission potential of implements used in conventional tillage for PM emission mitigation.

Several mitigation measures are proposed for harvesting operations, especially for certain crops, which are known for producing high PM_{10} emissions during harvest. Almond and hazelnut are two of the crops which have been addressed the most and for which harvester and abatement technology prototypes have been developed (Faulkner, 2013; Pagano et al., 2011). Moreover, the harvester operating parameters, such as airflow and harvester speed, were tested (Faulkner et al., 2009; Ponpesh et al., 2010). The prototypes and abatement technologies were successful in reducing PM_{10} emissions, reaching up to 79% and 18% of emission reduction respectively for almond and hazelnut harvesting (Table 4). The regulation of the harvester airflow gave good results as well, while no effect was obtained by lowering the harvester speed (Table 4).

As previously reported, post harvesting operations can strongly affect the overall harvest related PM_{10} emissions. Nonetheless, few published articles proposed mitigation measure for post harvesting emissions, such as the one published by Billate et al. (2004), who highlighted that in corn receiving operations reducing the drop height from the hopper bin and grain unloading rate (kg s^{-1}) can result in lower PM_{10} emissions.

From the literature review made, it appears that few crops have currently been addressed in terms of mitigation measure proposals for harvesting operations. Thus, more research is required, aiming to find solutions to reduce harvesting PM_{10} emissions from the main crops (e.g. maize, wheat etc.). Further mitigation measures should also be developed for immediate post harvesting operations.

For crop burning emissions, the mitigation approach is slightly different as compared to other activities. The main solutions are in fact aiming not to mitigate the emissions but to rather substitute residue burning as a residue management practice, favoring other more sustainable techniques. Ravindra et al. (2018) summarized these sustainable alternatives, going from soil incorporation of residues to their use for energy production through biomass or biogas plants. Other alternatives are the implementation of cattle feed with crop residues or the production of compost and biochar.

For sowing operations, different mitigation measures and driller prototypes have been proposed (Biocca et al., 2015; Pochi et al. 2015 Pagano et al., 2011). Those solutions focused on reducing the emission of seed coating particles (abating them up to 100%; Table 4) and the deposition of coating particles to the ground, but did not take into consideration the total PM_{10} emissions from sowing. Thus, there could be room for further studies adopting a broader approach and considering the soil particles emitted during seed drilling passages.

For manure and fertilizer spreading practically no technical solution has been evaluated for its capacity to reduce PM emissions. Future research should address this subject, possibly starting by testing the technology that has been developed to reduce the emission of ammonia emissions from field manure spreading.

5. Results of the review

In this section, collected data and information were summarized in order to:

a) Identify operations/crops with most crucial environmental impacts /EFs;

b) identify the main emission factor estimation methods and highlight their pros and cons;

c) review mitigation measures proposed for PM_{10} emission reductions in field emissions;

d) identify gaps in of knowledge on this specific topic and highlight future research opportunities.

5.1 Main agricultural operations contributing to PM emission

The EF determination is the first step to take in order to find feasible solutions to an environmental issue, such as PM emissions, and it also allows decision makers to produce regulations based on sound scientific data.

By reviewing the literature on PM emissions from agricultural activities it was evident that some activities such as tillage, residue burning and harvesting have been addressed more often than others, such as manure and fertilizer spreading or sowing. Moreover, these last two operations have been mainly studied from a very specific perspective, focusing only on a fraction of the total PM produced (namely the bio-aerosol component for manure spreading and the seed coating for sowing). Moreover, it was observed that for many countries in the world, such as Africa, India and South America, few or any specific EFs are available in scientific literature.

The EFs gathered in Tables 1 and 2 are summarized in Figures 2, 3 and 4, in order to have an overall impression of the PM_{10} both crop-wise (for wheat, cotton, and maize) and operation-wise (tillage, harvest, sowing and fertilizer spreading). The graphs were made by averaging the EFs summarized in Tables 1 and 2 for tillage (the tillage comprehends three passages: plowing/disking, harrowing and land planning/floating) and harvest. The contribution of sowing operations was set equal for the three crops, in the absence of specific investigations, and was assumed to be equal to a tooth harrowing passage (82 mg m^{-2}), in agreement with the findings of Clausnitzer and Singer (1996). The contribution of fertilizer application was considered to be equal to 1.09 kg t^{-1} of applied fertilizer (as in Pattey and Qiu, 2012), with an application rate of 0.3 t ha^{-1} (the same application rate was used for the three crops, although a better approximation should be made for more precise applications).

Figures 2, 3 and 4 suggest that tillage practices are the most polluting operations in terms of PM_{10} emissions for all three crops represented here (among 75 and 83% of the overall emissions), as they consist of three or more passages, each one with his own emission potential. Harvesting follows as the second most emitting practice, being the one that varies the most among crops (from 10 to 19% of total emissions). Sowing and mineral fertilizer application have a lower impact (among 2 and 5 % of total emissions).

Also the total emission potential varies between crops, being higher for wheat (1,904 mg m^{-2}) and lower for cotton (1,718 mg m^{-2}) and maize (1,538 mg m^{-2}). This brief summary of the total emission for each is not a precise estimation, since it is based on data acquired under varying conditions and it does not consider all the steps of the cropping system. Still, it can be useful to provide a rough estimation of the emission magnitude and of the contributions of various crops and operations on total PM emissions.

5.2. Evolution of EF estimation methods

The EFs available in the literature were obtained through a large variety of estimation methods. This variety of methods makes it difficult to carry out comparisons between EFs, especially considering that it is not clear which method can be considered as the reference one.

One of the main objectives of this review was to list the main methods for open-field EF estimation and to understand the current research trends, since some methods are becoming obsolete and less used while some others are getting used more often and could eventually be considered as reference methods in the future. In fact, the vertical profile method, which has long been considered as a reference technique for EF estimation, has been abandoned by most researchers, mainly due to its high instrumentation costs, but also because it entails a certain uncertainty of results. Thus, some other methods tend to be preferred.

Particularly, the most common estimation methods appear to be those implementing dispersion models inversely to estimate emissions. Among dispersion models, Lagrangian models are considered more precise as compared to Gaussian models. Nonetheless, Gaussian models are still suggested as reference models by some regulatory agencies (such as the US-EPA with the AERMOD model) due to their simplicity of use. The use of models, in general, seems to be the preferred way to obtain EFs and emission inventories for regulatory purposes and the most common models have been used as reference to validate other EF estimation methods.

The main advantage in the use of LiDAR technology for EF estimation reside in the fact that it allows to study the plume dynamics and dispersion, being so more informative as compared to other methods. This method has the advantage of not relying on modeled environmental conditions, leading to estimates that can be more legitimately used to evaluate the efficacy of dispersion models, which are based on wind modelling.

The atmospheric tracer method, which was used by Qiu and Pattey (2008), and is worth to be mentioned, because it shares with the LiDAR technique the advantage of being independent from wind modeling.

In general, the current trend in EF estimation for agricultural field operation is moving toward the use of models as main estimation tools. Besides, for the evaluation of models reliability, it could be better to use field based methods, such as the LiDAR or the atmospheric tracer technique, that don’t rely on modeled environmental conditions, but on actual measurements.

5.3. Mitigation measures and development trends

The development of feasible mitigation measure for PM emissions is to be seen as the final aim of the process that starts with the evaluation of the emission factors. Although there are several articles dealing with PM mitigation measures, most of them focus on few operations. In fact, there are some operations, such as manure spreading, that were unaddressed in terms of solutions to reduce emissions. Also for tillage practices there were few articles focusing on mitigating the emission of PM, proposing mainly a reduction of tilling passages as main solution. Also for harvesting, the research focused on few crops. Differently, sowing operations have been widely discussed although the main focus has been on seed coating particle reduction more than on total PM_{10}. In conclusion, there are many gaps of knowledge in the field of agricultural PM emissions, where proposals for mitigation measures are still required, leaving open opportunities for future research and technology development.

Generally, a more intensive effort should be put into the development and testing of mitigation measures, especially for those operations that are majorly contributing to field derived PM_{10} emissions.

6. Future perspectives and research needed

The literature review highlighted that there is more information available on PM_{10} emission factors (EFs) from certain agricultural operations, such as tillage, harvesting and residue burning than from others, such as sowing and manure and fertilizer spreading. Moreover, emission assessment studies were usually conducted with an operation-wise approach, while it appears from literature that a crop-wise approach would lead to more precise estimations (being less influenced by seasonal variation). The lack of an overall view of the emissions, as they take place in each step of a productive system, could potentially lead to substantial underestimation of the overall emissions. To avoid this, all the operations that have not be taken into consideration for their overall PM_{10} emissions (such as sowing and manure spreading), but mainly for a particular kind of particle (namely seed coating or bio-aerosol) should be assessed.

As for the emission factor estimation methods, the most utilized ones in current research are those applying inverse dispersion models to estimate emissions rates from field, also thanks to their cost-effectiveness and adaptability. Other techniques that provide good results are LIDAR measurements and the atmospheric tracer techniques. Those two techniques are particularly interesting, because they do not rely on modeled atmospheric conditions, and could thus be used as basis for comparison for dispersion models.

The mitigation measures developed for in field PM_{10} emissions from agricultural operations are quite few. For tilling practices the main proposed solutions to abate emissions are the implementation of minimum or no tillage systems, while few efforts have been put into the estimation of the emission potential of tilling implements. For harvesting, adequate measures have been developed for a few crops, while many other are still to be addressed. The emission abatement measures proposed for sowing operations are focused on seed coating particles, while few information is even available on the total PM_{10} particles emitted. As for manure and fertilizer spreading no PM_{10} mitigation measure has been proposed or assessed.

Future research in the field of PM emissions from agricultural operations should aim to fill the current gaps of knowledge. Aspects for future work include:

- the emissions deriving from whole cropping systems, through step by step measurement and evaluation;
- the influence of implement choice and operation parameters on tillage induced PM_{10} emission with possible development of implements with low emission potential;
- the assessment of harvesting induced PM_{10} emissions for crops not yet assessed and the development of mitigation measures (e.g. harvester prototypes development and operation parameters management);
- the assessment of total PM_{10} emissions for solid and liquid manure application and the evaluation of mitigation measures.

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Table 4. Brief description and emission abatement rates of the main dust emission mitigation measures for agricultural operations as reported by various authors.

1172 Table 1.

Operation	PM_{10} EFs (mg m^{-2})	$PM_{2.5}$ EFs (mg m^{-2})	Region / country	Reference	EF estimation method
Tilling (plowing+disking+land planning)	31 - 119	3 - 33	Northeasthern China	Chen et al., 2017	Vertical profile method
Rolling	12.1±2.4	-	USA, New mexico	Wang et al., 2010	Vertical profile method
Listing	210±29.8	-			
Disking	44.8±6.4 – 202.8±13.5	-			
Plowing	120 - 1045	5	Europe	Oettl et al., 2007	Lagrangian dispersion modeling
Harrowing	82	29			
Disking	137	12			
Cultivating	186	6			
Root cutting	33.6	-		WRAP, 2006	Various methods
Disking, tilling, chiseling	134.5	-			
Ripping, subsoiling	515.6	-			
Land planing, floating	1401.1	-			
Weeding	89.7	-			

Disking (1st passage)	99.7±12.5	20.4±2.6	USA, California	Moore et al., 2013	LIDAR
Disking (2nd passage)	80.7±20.5	39.5±5.9			
Chiseling	79.5±13.1	35.8±5.9			
Land planning	281.9±28	13.8±3.9			
Disking (1st passage)	125.6 ± 57.9	-	USA, California	Moore et al., 2013	Gaussian dispersion modeling
Disking (2st passage)	149.2 ± 91.8	23.3 ± 7.4			
Chiseling	167.5	34.5 ± 115.1			
Land planning	41.3 ± 10.6	18.4			
Disking	78±6 – 1375±91	-	USA, California	Cassel et al., 2003	Vertical profile method
Floating	119±8 – 2322±145	-			
Land planning	1229±98 – 1704±128	-			
Ripping	507±292	-	USA, California	Holmén et al., 2001	Vertical profile method
Disking	91.2±104	-			

Table 2.

Crop type	**PM_{10} emission factor (mg m^{-2})**	**$PM_{2.5}$ emission factor (mg m^{-2})**	**Region/country**	**Reference**	**EF estimation method**
Spring wheat	74±12	-	Canada	Qiu and Pattey, 2008	Atmospheric tracer technique
Cotton (picking)	107±13	-	USA, California	Cassel et al., 2003	Vertical profile method
Cotton (stalk cutting)	42±7	-			
Wheat	665±40	-			
Tomato	785±48	-			
Wheat	270	-	Europe	van der Hoek and Hinz, 2007	Adaptation of EFs from literature
rye	200	-			
barley	203	-			
oat	340	-			

halmond	275 - 381	18 - 26	USA, California	Faulkner et al., 2009	Gaussian dispersion model
wheat	170	-	USA	US-EPA AP 42	Various methods
sorghum	1110	-			
Corn	190.5			Wrap, 2006	Various methods
cotton	381.1				
fruit trees	9.5				
onions	190.5				
potatoes	190.5				
sugar beets	190.5				
Tomatoes	19.5				
vine crops	190.5				
wheat	650.1				

Table 3.

Crop type	PM10 emission factor (g kg-1)	PM2.5 emission factor (g kg-1)	Reference	EF estimation method
Alfalfa	11.11 ± 0.91	9.98±0.71	Santiago-De la Rosa et al. (2018)	Open combustion chamber
Barley	1.77 ± 0.19	1.19±0.10	Santiago-De la Rosa et al. (2018)	Open combustion chamber
Bean	2.75 ± 0.18	2.24±0.19	Santiago-De la Rosa et al. (2018)	Open combustion chamber
Bluegrass	7.48	-	Boubel et al. (1969)	Open combustion chamber
Corn	-	5.9 ± 0.7	Li et al. (2017)	Combustion stove
Cotton	13.37 ± 1.90	8.22±0.54	Santiago-De la Rosa et al. (2018)	Open combustion chamber
Cotton	-	15.2 ± 2.1	Li et al. (2017)	Combustion stove
Fescue	5.90	-	Boubel et al. (1969)	Open combustion chamber
Maize	3.3 ± 0.42	2.7±0.28	Santiago-De la Rosa et al. (2018)	Open combustion chamber
Rapeseed	-	16.9 ± 2.6	Zhang (2015)	Carbon mass balance method
Rapeseed	-	5.8 ± 1.3	Zhang (2015)	Carbon mass balance method
Rice	4.95 ± 0.52	3.04±0.24	Santiago-De la Rosa et al. (2018)	Open combustion chamber
Rice	-	14.7 ± 2.4	Li et al. (2017)	Combustion stove
Rice	-	20.3 ± 1.5	Zhang (2015)	Carbon mass balance method
Rice	-	9.6 ± 4.3	Zhang (2015)	Carbon mass balance method
Rice	9.4 ± 3.5	8.3±2.7	Oanh et al. (2011)	Carbon mass balance method
Rice	-	12±0.3	Hays et al. (2005)	Enclosure system
Rye (annual)	4.76	-	Boubel et al. (1969)	Open combustion chamber
Rye (perennial)	5.44	-	Boubel et al. (1969)	Open combustion chamber
Sorghum	21.56 ± 2.26	11.30±1.05	Santiago-De la Rosa et al. (2018)	Open combustion chamber
Soybean	-	3.2 ± 0.3	Li et al. (2017)	Combustion stove
Sugarcane	1.81 ± 0.14	1.19 ± 0.08	Mugica-Alvarez (2018)	Open combustion chamber
Sugarcane[a]	-	3.9	Andreae et al. (1998)	Carbon mass balance method coupled with aircraft measurements

Sugarcane	-	2.6 ± 1.6	França et al. (2012)	Open combustion chamber
Wheat	-	4.7±0.04	Hays et al. (2005)	Enclosure system
Wheat	4.07 ± 0.51	2.54±0.39	Santiago-De la Rosa et al. (2018)	Open combustion chamber
Wheat	-	5.8 ± 0.4	Li et al. (2017)	Combustion stove
Wheat	-	10.0 ± 1.2	Zhang (2015)	Carbon mass balance method
Wheat	-	6.1 ± 1.3	Zhang (2015)	Carbon mass balance method

[a] The EF reported by Andreae et al. (1998) was referred to the PM_3 size range, while here it is reported in the $PM_{2.5}$ column.

Table 4.

Reference	Operation	Mitigation measure	Emission abatement
Coates et al. (1996)	Conventional land preparation	Minimum tillage	45% (of TSP)
Backer et al. (2005)	Conventional land preparation	Conservation tillage system	up to 100% (of PM10)
Billate et al., (2004)	Corn receiving facilitilty (hopper bin - pit conveyor)	increasing grain flow rate + lowering drop height	92% (of total PM10)
Biocca et al., 2015	Maize sowing	filtering-recycling system	95-71% (of insecticide particles at ground level)
Pagano, 2011	Hazelnut harvesting	Harvester prototype	18% (of total PM10)
Pochi et al., 2015	Maize sowing	Modified driller	up to 100% (of active ingredient concentration in the air)
Chapple et al., 2014	Maize sowing	SweepAir® system	>99% (of seed coating particles)
Faulkner, 2013	Almond harvesting	3 different harvester prototypes	76 - 41 - 9% (of total PM10)
Faulkner, 2013	Almond harvesting	cyclone abatement technology	79% (of total PM10)

Ponpesh et al., 2010	Almond harvesting	Decreasing airflow	77% (of total PM10)
Faulkner et al., 2009b	Almond harvesting	reduction of harvester speed	no significant abatement

List of figures

Figure 1.

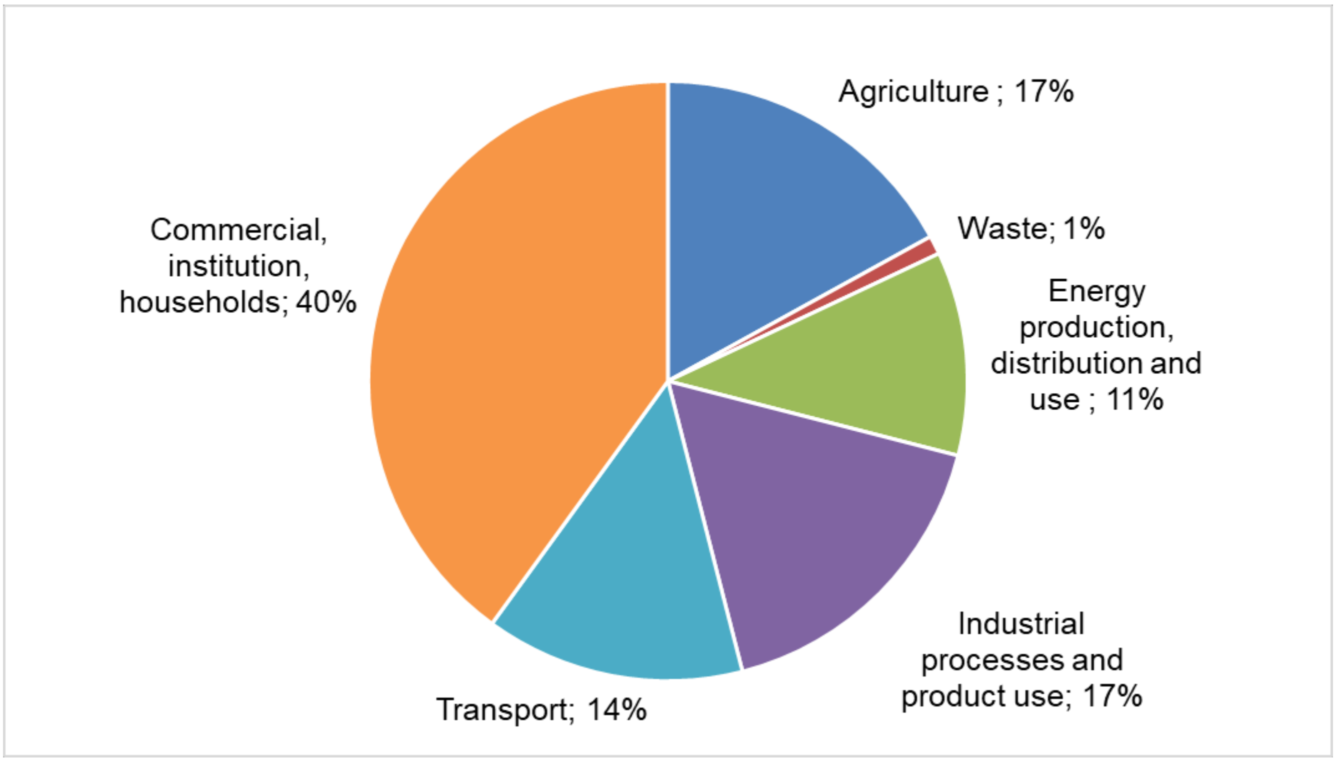

Agriculture ; 17%
Waste; 1%
Energy production, distribution and use ; 11%
Industrial processes and product use; 17%
Transport; 14%
Commercial, institution, households; 40%

Figure 2.

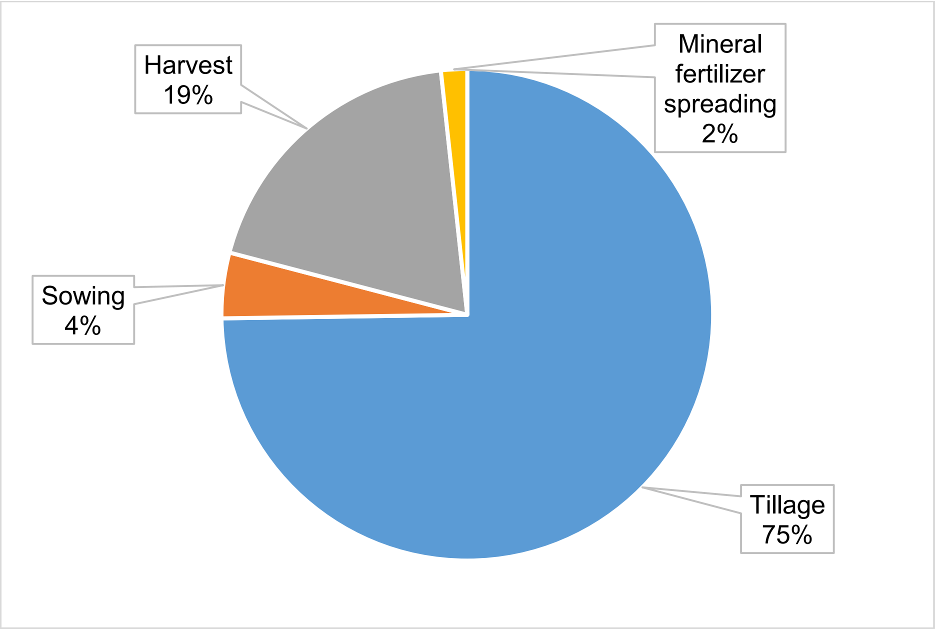

Mineral fertilizer spreading 2%
Harvest 19%
Sowing 4%
Tillage 75%

Figure 3.

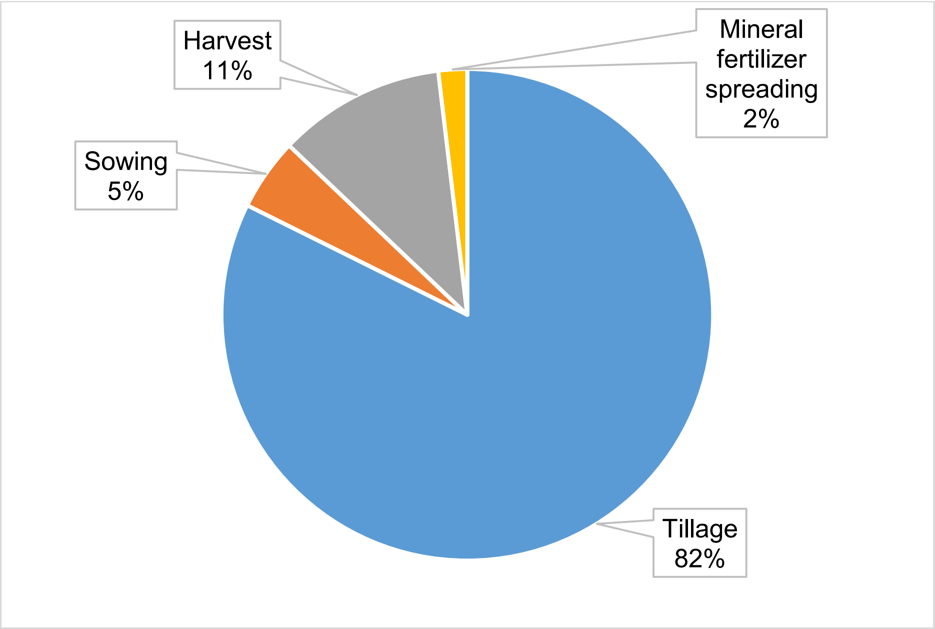
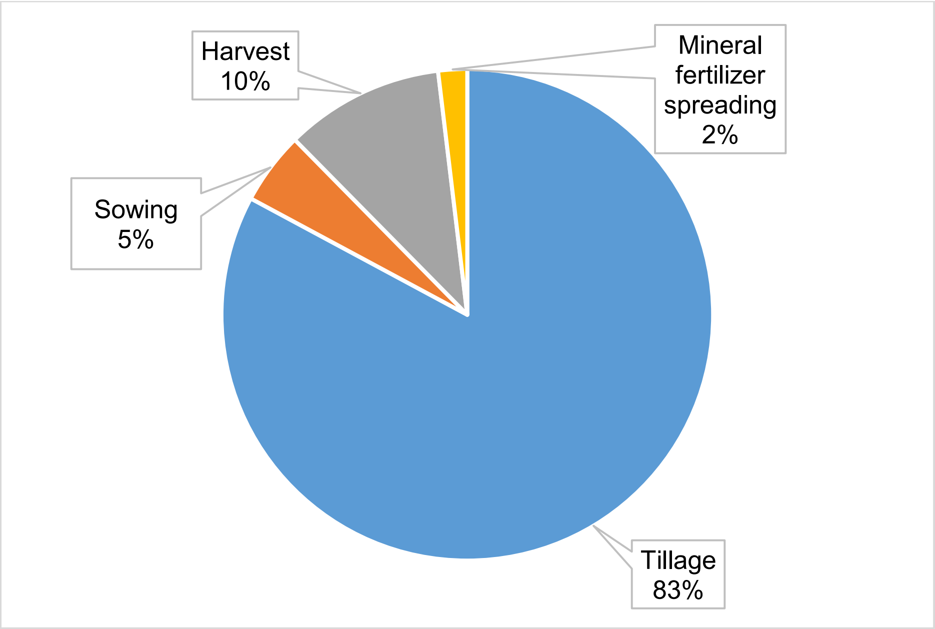

Harvest
11%
Mineral
fertilizer
spreading
2%
Sowing
5%
Tillage
82%

Figure 4.


Harvest
10%
Mineral
fertilizer
spreading
2%
Sowing
5%
Tillage
83%