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

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10

11 **Abstract**

12 Globally, particulate matter (PM) emissions are a growing cause of concern due to the potential
13 impact on human health and environment. The agricultural sector is responsible of the 17% of
14 the total anthropogenic emission of PM₁₀ and the agricultural operations (tilling, harvesting,
15 residue burning etc.) have been recognized as one of the main drivers of this contribution. This
16 topic has been addressed in many articles, focusing on the impacts coming from different steps
17 of the agricultural production system and using different assessment methods. The aim of this
18 review is to identify the main agricultural operations producing particulate emission, providing
19 a collection of the Emission Factors (EF) available in literature. The most used EFs
20 determination methods have also been described, by focusing on pros and cons of each
21 method. Issues and lacks of information to be addressed by future research have been
22 highlighted. It has been observed that very few PM emission assessment have been done by
23 taking into consideration whole cropping systems and the information available is fragmented

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

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

27

28 **1. Introduction**

29 Particulate matter (PM), is considered, both in urban and rural area, as one of the most
30 concerning air pollutants due to its effect on human health and environment (Douglas et al.,
31 2018; Giannadaki et al., 2018; Giannakis et al., 2019). The agricultural sector largely
32 contributes to the emissions of PM₁₀ and PM_{2.5}, being responsible of the 17% and 5% of the
33 total anthropogenic emissions respectively (EEA, 2016). The contribution of different sectors to
34 the total PM₁₀ emissions is summarized in Figure 1. Among the main agricultural activities
35 contributing to the emissions are livestock rearing and open field crop management. The
36 contribution of open field activities is particularly difficult to estimate, due to the wide variety of
37 field operations and crops and to the importance of climatic factors as drivers of PM emissions.
38 This literature review focuses on primary particulate matter (PM₁₀ and PM_{2.5} fractions)
39 emissions from open field agricultural operations. The main objective is to identify the
40 agricultural operations producing particulate emission and to highlight, for each of those
41 practices, the main health concerns, as induced by emission magnitude, particle size and
42 particle characteristics. To fulfill this goal, information for each agricultural operation was
43 gathered from literature, focusing primarily on available Emission Factors (EFs). A further aim
44 of this review work was to identify the most common EFs determination methods used in current
45 literature and to highlight their pros and cons. Moreover, the main PM mitigation measures were
46 reported along with their target operation and the expected mitigation effect.

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

49

50 2. **Main agricultural operations contributing to PM emissions**

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

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

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

71 China tillage and harvesting account for the three fourth of the total agricultural emissions, with
72 tillage being the main pollution source. Also in California, although the environmental conditions
73 are very different from the ones of the above-cited surveys, tillage and land preparation have
74 been considered to be the main agricultural PM₁₀ source, accounting for the 65% of total
75 agricultural emissions (Clausnitzer and Singer, 1997). Differently, Amann et al. (2012) have
76 estimated that the main agricultural source of PM emissions in Europe is the burning of
77 residues, which, according to their estimations, contributes to the total PM₁₀ and PM_{2.5}
78 emissions for the 7.6% and 9.6% respectively, while ploughing tilling and harvesting altogether
79 account only for the 4.7% (PM₁₀) and 1.5% (PM_{2.5}) of total emissions. In the African continent
80 agricultural biomass burning emissions are recognized as the second most important source of
81 PM, following natural mineral dust emissions by wind erosion, and being responsible for half of
82 the premature deaths in Central Africa (Bauer et al., 2019). Similarly, studies carried out in India
83 suggest that also in that continent the main agricultural contributor to PM emissions is biomass
84 burning (Pandey et al., 2014; Guo et al., 2017).

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

88

89 *2.1. Tillage and soil preparation*

90 Tillage and soil preparation techniques are responsible of producing a significant amount of
91 primary PM emissions. The exact amount of PM₁₀ emissions produced can vary a lot according
92 to environmental conditions, especially soil moisture (Chen et al., 2017; Öttl and Funk, 2007;
93 Flocchini et al., 2001) and to the specific tilling implement used (Moore et al., 2013). This implies
94 a strong variability in the emission factors obtained during different measurement campaigns,

95 even if done in the same area and applying the same cultivation practices (Table 1; Wang et
96 al., 2010). The European guidelines, in fact, set a wide reference range of emission factor
97 values for tilling operations, going from 25 to 225 mg m⁻² (for PM₁₀) and from 1.5 to 10 mg m⁻²
98 (for PM_{2.5}), where the two values are obtained by measuring the emissions during tillage of wet
99 and dry soil, respectively (Funk et al., 2008).

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

106 Concerning the emissions of particles in the smaller size fractions (PM_{2.5}), Moore et al. (2013)
107 found practically no PM_{2.5} emissions during soil tillage operations. On the contrary, (Chen et al.,
108 2017) observed a PM_{2.5}/PM₁₀ ratio during tillage equal to 28%. This contradiction can be
109 explained by the findings of Carvacho et al. (2004), who observed that the PM_{2.5} soil emission
110 potentials are higher in soils containing more silt, while they tend to be lower in sandy soils.

111 Table 1 summarizes EFs estimations for tillage operations, referring to different tilling
112 implements. The implements used for soil preparation can induce different PM emissions as
113 compared one to another (Table 1). Some authors observed that comparisons between
114 emission factors related to the use of different tools could be unreliable because of the
115 impossibility of standardizing the environmental conditions among trials (Holmén 2001, Cassel
116 et al., 2003; Wang et al., 2010). However, the emission factors reported in Table 1, which are
117 related to different operations, can be used for gathering general indications. The emission
118 factors reported are divided by tilling operation type, although some authors (Holmén et al.,

119 2001, Cassel et al., 2003) stated that, as crop calendars may affect the period in which certain
120 operations are performed, it should be better to further categorize EFs per crop type or per
121 month. A further consideration to be done is that the methods used to estimate the emission
122 factors vary considerably according to different authors, increasing the uncertainty of possible
123 comparisons.

124 Among the main primary tillage operations, the most polluting one, in terms of PM emissions,
125 appears to be ripping, followed by conventional plowing and disking (Clausnitzer and Singer,
126 1997, 1996; Holmén et al., 2001). As for secondary operations, it was highlighted, from a study
127 conducted by Moore et al. (2013), that during a second passage performed on a field with the
128 same implement the generated emission rates of the finer (PM_{2.5}) tend to be higher. Similarly,
129 other studies have shown that the final operations, such as land planning and floating, tend to
130 produce higher emission rates than the primary ones (Cassel et al., 2003; Clausnitzer and
131 Singer, 1997, 1996). This effect is probably due to the progressive disaggregation of soil
132 aggregates that have been proven to affect PM₁₀ emissions (Madden et al., 2010). The effect
133 of tillage on windblown dust and PM emissions was also shown to be affected by the implement
134 choice (Lopez et al., 1998; Pi et al., 2018; Singh et al., 2012), being for example higher with
135 disking than with under cutter tillage (Pi et al., 2018).

136 Moreover, tillage does not only contribute directly to PM emissions, but it can also affect the
137 dust dispersion events caused by wind events or other disturbances. This is due to the effect
138 of tillage on soil physical properties (especially aggregate stability and overall soil structure)
139 and to the removal of soil cover with the incorporation of crop residues into soil (Gao et al.,
140 2014; Sharratt et al., 2010). Particularly, Sharratt et al. (2010) observed that intense tillage
141 practices could affect wind erosion in the after cropping period (especially in case of summer
142 fallows), leading to higher sediment fluxes during strong wind events.

143 Another aspect to be considered is that tillage practices can possibly lead to the emission of
144 pesticide particles, previously deposited onto the soil through pesticide spraying (Grella et al.,
145 2017) or sowing or coated seeds (Forero et al., 2017).

146

147 *2.2. Harvest and post-harvest operations*

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

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

166 agency guidelines (USEPA, 1995) proposes emission factors only for few crops, such as wheat
167 and cotton.

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

182

183

184 *2.3. Crop residue burning*

185 The burning of agricultural residues is recognized to generate high emission of GHG (Arai et
186 al., 2015; Murali et al., 2010) and particulate matter (Dennis et al., 2002; Hays et al., 2005) and
187 to strongly affect rainwater composition (Coelho et al., 2011). Furthermore, as pointed out by
188 Kumar et al. (2019) straw burning affects the overall environment, causing a loss of ecosystem

189 services. Nonetheless, agricultural residue crop burning is still a widespread management
190 practice, partially due also to its effect on pest and weed control at very low costs.

191 In Europe, the burning of crop residue is not allowed according to the directive 2008/98/EC,
192 due to its effects on human health. However, in many less developed regions and countries
193 this management practice is still common in most of the main cropping systems, such as in rice,
194 wheat and maize cropping (Gupta et al., 2004), while in sugarcane cropping system it is often
195 a step of the harvesting process (Franca et al., 2014). This makes it a very complex subject to
196 address, being the crop type itself one of the parameters affecting both the chemical
197 characteristics and the amount of the emitted particles. Table 3 summarizes some of the main
198 EFs estimation for crop residue burning of different crops, measured both through laboratory,
199 field and aircraft measurements. As can be seen in Table 3, the reported EFs for different crops
200 range between 21.5 and 1.8 g kg⁻¹ for PM₁₀, and the PM_{2.5}/PM₁₀ also ranges between 0.52 and
201 0.98. The EFs vary a lot also for the same crop. This could be partially due to the fact that many
202 different methods are used to estimate EFs. Therefore, although many EFs have been
203 published, it is difficult to select a reference EF, due to the wide range of proposed values.
204 Moreover, many measurements were performed under laboratory conditions (Santiago-De la
205 Rosa et al., 2018; Mugica-Álvarez et al., 2018; Li et al., 2017) and the results can not directly
206 be transferred to EFs under field conditions. Laboratory determinations of EFs, although they
207 do not examine actual fire, have the advantage of allowing more strict comparisons among
208 different crop biomasses as compared to field measurements, due to the standardization of
209 environmental conditions.

210 The size and composition of particles generated from biomass burning are different from those
211 from other agricultural operations. These particles are in fact finer and most of them are in the
212 PM_{2.5} or even in the PM₁ fraction range (Le Canut et al., 1996, Yokelson et al., 2009, Oanh et

213 al, 2011). This is of particular importance since the concentration of finer particles (PM_{2.5} range)
214 has been associated with an increase in mortality risk (Pope III, 2002). Moreover, Oanh et al.
215 (2011) observed the presence of organochlorine pesticides in particles generated from rice
216 straw burning. The presence of these and other organic compounds could lead to an increase
217 toxicity of the emitted particles. The main parameters affecting the emissions, other than the
218 crop type are the moisture content (Hayashi et al., 2014), the meteorological conditions and fire
219 control activities (Oanh et al, 2011).

220

221 *2.4. Sowing*

222 Seed drilling machines, operating on agricultural fields, also produce particulate matter
223 emissions. The emitted particles generate mainly from soil, but a small portion comes from the
224 seeds, which are abraded during sowing activity. There are few available experimental data on
225 the entity of total PM₁₀ emissions during sowing. Air aerosol concentrations measured during
226 corn sowing were reported to be equal to 1.02 mg m⁻³ (Clausnitzer and Singer, 1996), being
227 approximately equal to those induced by tooth harrowing and other soil preparation practices,
228 as reported by the same authors. During seeding, which is usually performed after several land
229 preparation activities, land particles may raise with more ease than during previous tillage
230 passes, due to the progressive loss of soil structure, as described by Madden et al. (2010).

231 A further aspect regarding dust emissions during sowing is the potential drift of dressed seed
232 particles, containing pesticides that could be spread in the surrounding environment. This
233 particular issue is a cause of concern due to its potential effects on wildlife, and especially on
234 pollinators, and led the European Food Safety Authority to produce a specific risk assessment
235 guidance book (EFSA, 2013). The amount of seed abraded dust emitted during sowing vary
236 among different crop seeds, being higher for maize and lower for rapeseed and oilseed

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

240 Tapparo et al. (2012) conducted an essay with three different types of drilling machines while
241 sowing seeds treated with Clothianidin (1.25 mg/seed), Thiamethoxam (0.6 mg/seed) and
242 Fipronil (0.5 mg/seed) and calculated the emissions factors (on TSP) that were equal to 0.043
243 – 0.153 mg m⁻², 0.074 mg m⁻² and 0.045 mg m⁻² , respectively, of emitted insecticides. They
244 also observed that only a small amount of those particles was associated with the PM₁₀ fraction
245 of the emitted dust. Though the PM₁₀ associated compounds may travel further distances from
246 the field as compared to the ones linked to coarser particles (Tapparo et al, 2012).

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

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

261

262 *2.5. Manure and fertilizer spreading*

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

266 The importance of PM emission from land application of manure is strongly linked to the
267 composition of the generated particles. Manure generated dust, in fact, includes bioaerosol
268 emissions, which implies pathogen exposure risks both for agricultural operators and for
269 inhabitants of near field residential areas. This effect has been described by Jahne et al.
270 (2015b), who demonstrated that infection risks for certain pathogens are higher for people living
271 near manure application sites. A further aspect to be considered is that bioaerosol from manure
272 spreading could contaminate the nearby crops (especially in case of leafy vegetables), causing
273 the contamination risk to rise above acceptable levels in the first 160 m from the application
274 point (Jahne et al., 2016).

275 Manure is not the only biomass applied to agricultural soils nowadays, since many other organic
276 materials are frequently used as soil fertilizer or amendments. Among those biomasses some
277 of the most controversial ones, due to their potential load of pathogens and pollutants (Akbar-
278 Khanzadeh et al., 2012), are sewage sludges. In their paper, Paez-Rubio et al. (2007)
279 determined the quantity of dust particles emitted during the spreading of biosolids, being equal
280 to 7.6 ± 6.3 mg of PM₁₀ per kg of dry biomass applied (the spreading was performed from a
281 stationary position and thus all the measured emissions derived from the biomass, since the
282 soil was not disturbed).

283 Recent researches (Jahne et al., 2016; Jahne et al., 2015a; Jahne et al., 2015b; Kang et al.,
284 2014) focused mainly on the aspect of bio-aerosol and bacteria emissions during manure

285 spreading, while few of them report also the total PM10 emissions. Furthermore, very few
286 information is available on the effects of spreading implements and tractor speed on the
287 emissions, although those aspects could affect the emissions.

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

292 A further aspect to be considered is that, both manure and fertilizer spreading operations do
293 not only contribute to primary PM emissions, but those are also considered as some of the main
294 sources of ammonia (NH₃) emissions in the atmosphere (Plautz, 2018). Thus, due to the
295 reactions between of NH₃ with sulfur and nitrogen oxides in the atmosphere, leading to
296 secondary aerosol formation (particularly in the PM_{2.5} fraction), those operations can account
297 for both a direct and indirect contribution to dust pollution (Backes et al., 2016; Plautz, 2018).

298

299 **3. Emission factors assessment methods**

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

- 303 - Vertical profiling method;
- 304 - Dispersion modeling;
- 305 - Atmospheric tracer technique;
- 306 - Carbon mass balance method;
- 307 - LiDAR technology;
- 308 - Laboratory measurement methods.

309

310 3.1. Vertical profiling method

311 The vertical profile method is a micrometeorological method which relies on field measurements
312 of wind speed and PM₁₀ concentration to infer the wind speed and PM concentration profiles.

313 The method is well described by several authors (Holmén et al., 2008, 2001; Wang et al., 2010)
314 and it is similar to the method used to estimate ammonia emission rates (IHF method, Ryden
315 and McNeill, 1984). The wind speed profile can be obtained, using the logarithmic wind profile
316 equation (Stull, 1988), by measuring the wind speed with a 3D sonic anemometer or by
317 measuring the wind speed at two different heights.

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

321 The EFs are then obtained by fitting the two profiles into the following equation (Holmén et al.,
322 2001):

323

$$324 \quad EF = \int_{z_0}^{z^{max}} \frac{u(z)c(z)tc\cos(\theta)}{w} dz$$

325

326 Where EF is the emission factor (mg/m²), z is the height above ground (m), z_0 is the surface
327 roughness length (Stull, 2001), $u(z)$ is the average wind speed at height z (meters per second)
328 during the treatment (calculated from u^* and ζ based on the Similarity theory in Stull, 2001),
329 $c(z)$ is the mean concentration at height z (meters), t is the length of time of the treatment, θ is
330 the angle between the measured wind direction and the direction that is perpendicular to the

331 tractor path, w is the upwind width of soil worked during the test period, and z_{\max} is the height
332 at which the concentration is esteemed equal to 0.00.

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

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

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

347

348 *3.2. Definition of the EFs through dispersion modeling*

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

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

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

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

365 The intrinsic differences between these models has been discussed in several works dealing
366 with dispersion modeling in general (Holmes and Morawska, 2006; Leelössy et al., 2014). Some
367 authors performed direct comparison between models, as done by Faulkner et al. (2009), who
368 compared the actual reference EPA model (AERMOD) and the former one (ISC3-ST) for
369 assessing harvesting PM₁₀ EFs and found no statistical difference between them. Other authors
370 (Wang et al., 2010, 2009), preferred to compare modeled EFs with data obtained by different
371 methods, with techniques such as the use of LiDAR technology (treated in paragraph 3.3).

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

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

383

384 *3.3. Atmospheric tracer technique*

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

392

$$393 \quad ER_{(PM_{10})} = \frac{[PM_{10}]ER_{(tracer\ gas)}}{[tracer\ gas]}$$

394

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

401 variability and because, although it can be emitted from soils, the emission levels are low. Other
402 tracer gases may be tested in the future.

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

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

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

417

418 *3.4. Carbon mass balance method*

419 The carbon mass balance method is one of the most diffuse methods for assessing emissions
420 from crop residue burning events. The method uses an approach which is somehow similar to
421 the atmospheric tracer technique. EFs for PM emissions are estimated by referring the overall
422 emission of organic carbon to the total initial carbon content of the burnt biomass. This is made
423 possible by the fact that crop biomass is a carbonaceous fuel and the pollutant are substantially
424 organic compound. It is therefore possible to relate the emission of PM to that of a reference

425 specie (R_{specie}), usually CO or CO₂ (Andreae, 2019). This is done by first relating the measured
426 mixing ratios of PM and R_{specie} , to obtain the so called emission ratios, which are more correctly
427 referred to as normalized excess mixing ratios (NEMRs; Akagi et al., 2011). NEMRs are
428 obtained according to the following formula:

$$429 \quad NEMR_{\frac{PM}{R_{\text{specie}}}} = \frac{\Delta PM}{\Delta R_{\text{specie}}}$$

430 Where ΔPM is the difference between the PM concentration in the plume and its background
431 concentration and ΔR_{specie} is the difference between the plume concentration of R_{specie} and its
432 background concentration.

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

$$435 \quad EF_{PM} = NEMR_{\frac{PM}{R_{\text{specie}}}} \frac{MW_{PM}}{MW_{R_{\text{specie}}}} EF_{R_{\text{specie}}}$$

436 where EF_{PM} is the PM emission factor, MW_{PM} and $MW_{R_{\text{specie}}}$ are the molecular weights of the
437 species the investigated PM fraction and the reference specie respectively, and $EF_{R_{\text{specie}}}$ is the
438 known or assumed emission factor of the reference species (often CO or CO₂).

439 Although the procedure to estimate the emission is quite simple and reliable, some complication
440 can be encountered. Sometimes, for example, the estimation of Background concentrations
441 can pose some issue, especially with reference gases such a CO₂, which is characterized by
442 having many sources and sinks in the surrounding environment, that can easily lead to under
443 or overestimations. Moreover, to adopt this technique, it must be assumed that PM and R_{specie}
444 are equally dispersed from the source to the sampling point, which is not forcefully true.
445 Phenomena such as PM dry deposition and aggregation could in fact lead to an
446 underestimation of the emission.

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

458

459 *3.5. Use of LiDAR technology for EFs and plume parameter estimation*

460

461 The LiDAR (Laser Imaging Detection and Ranging) technology has often been used, in recent
462 years, to study particle emissions from agricultural operations and especially to derive plume
463 dispersion parameters. The first applications, such as the one carried out by Holmén et al (2001,
464 1998), pointed out that LiDAR measurement could be used to estimate vertical and horizontal
465 dispersion coefficients of field dust plumes and proposed an ER estimation method through
466 LiDAR calibration with filter samplers. This application also allows to evaluate the uncertainty
467 of plume height estimations with the vertical profile method (Holmén et al., 2001). Similarly,
468 LiDARs have also been used to evaluate the uncertainty of plume parameter estimation
469 performed with models. Wang et al. (2010) compared EFs estimated with LiDAR and with the

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

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

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

489

490 *3.6. Laboratory measurement methods*

491 Although the environmental conditions are of crucial importance in determining PM emissions
492 from cropping operations and cannot be simulated under laboratory conditions, several
493 laboratory assessment methods have been applied to this specific field. Particularly, laboratory

494 methods are used to assess the PM Emission Potential (EP, mg kg^{-1}), which is the potential
495 capacity of a substrate to emit fine particles in a certain fraction range, of agricultural soils and
496 crop biomass. Moreover, laboratory techniques have often been used to assess crop specific
497 EFs for residue burning activities. The main methods are:

- 498 - Wind tunnels;
- 499 - Soil resuspension chambers;
- 500 - Open combustion chambers.

501 Wind tunnels are tunnel shaped dynamic enclosure systems, in which an air flow is forced over
502 or through a certain volume of soil, causing it to re-suspend. Wind tunnels are generally more
503 suited to assess wind blown PM emissions from fields (in wind erosion studies) than tillage
504 induced ones, since they do not allow to simulate the active soil disturbance as generated by
505 tilling implements (Funk et al., 2008). Nonetheless, in studies such as those by Funk et al.
506 (2008), a wind tunnel has been used to assess emissions from soil under different moisture
507 conditions, retrieving information very relevant to estimate tilling EFs variation with different soil
508 moisture contents.

509 Soil resuspension chambers are built with the aim of actively re-suspending fine particles in a
510 soil sample by mechanically agitating it. The most common soil resuspension mechanisms
511 consist either of rotating drums, in which the soil sample is mechanically re-suspended (such
512 as in Madden et al., 2009), or of abrader systems, in which the soil particles are propelled
513 through a path allowing the abrasion action to cause the emission (such as in Chandler et al.,
514 2002). After particle resuspension has been achieved, the polluted air stream is usually pulled
515 or blown at a known rate (using pumps) toward a further sedimentation/sampling chamber,
516 where PM_{10} is selected through an impactor and deposited on a filter (Chandler et al., 2002;
517 Madden et al., 2009). The soil EP is then calculated dividing the mass of PM_{10} (mg) deposited

518 on the filter after a certain sampling time, by the total volume of soil sample used (kg). A more
519 comprehensive review of soil resuspension chamber designs and experimental methodologies
520 has been provided by Gill et al. (2006).

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

524 Open combustion chambers are the most common laboratory equipment used to simulate crop
525 residue burning under laboratory conditions. Combustion chambers are normally constituted by
526 a burning plate, on which the crop material is burned, and of a chimney, inside which the air is
527 sampled to analyse PM concentration. To calculate crop specific EFs (g kg^{-1}), the air
528 concentration of PM (g m^{-3}) inside the chimney is multiplied by total volume (m^3) of combustion
529 gases passed through it and divided by the mass (kg) of the crop material. Although most open
530 combustion chambers have similar designs (schemes can be found in Mugica-Álvarez, 2018;
531 França et al., 2012), some alternative designs have been proposed, such as that described by
532 Jenkins et al. (1990), who adopted a chamber shaped similarly to a wind tunnel, which was
533 developed to simulate agricultural biomass burning emissions from wide surfaces. Another
534 design option is the one adopted by Li et al. (2017), who used a chamber of small dimension
535 (0.23 m^3), which was characterized by having a HEPA filter placed at the air inlet and by being
536 equipped with a second chamber in which polluted air is mixed before sampling. As in the case
537 of soil resuspension devices, also combustion chambers have been used to assess the effect
538 of substrate moisture on PM emission (Hayashi et al., 2014), other than assessing fuels of
539 different types and origins (Christian et al., 2003).

540 In conclusion, laboratory trials are of crucial importance to acquire information on the effects
541 that specific factors (such as substrate characteristics and moisture) have on the out coming

542 emissions and allow to better comprehend the dynamics that are at the base of open field
543 emission events.

544

545 **4. Mitigation measures**

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

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

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

559 Although conservation tillage is indubitably a good solution when it comes to reducing PM₁₀
560 emissions, it can affect crop yields (Irmak et al., 2019) and cannot always be applied. Therefore,
561 it would be valuable to explore the possibility of lowering the emission potential of implements
562 used in conventional tillage for PM emission mitigation.

563 Several mitigation measures are proposed for harvesting operations, especially for certain
564 crops, which are known for producing high PM₁₀ emissions during harvest. Almond and
565 hazelnut are two of the crops which have been addressed the most and for which harvester

566 and abatement technology prototypes have been developed (Faulkner, 2013; Pagano et al.,
567 2011). Moreover, the harvester operating parameters, such as airflow and harvester speed,
568 were tested (Faulkner et al., 2009; Ponpesh et al., 2010). The prototypes and abatement
569 technologies were successful in reducing PM₁₀ emissions, reaching up to 79% and 18% of
570 emission reduction respectively for almond and hazelnut harvesting (Table 4). The regulation
571 of the harvester airflow gave good results as well, while no effect was obtained by lowering the
572 harvester speed (Table 4).

573 As previously reported, post harvesting operations can strongly affect the overall harvest
574 related PM₁₀ emissions. Nonetheless, few published articles proposed mitigation measure for
575 post harvesting emissions, such as the one published by Billate et al. (2004), who highlighted
576 that in corn receiving operations reducing the drop height from the hopper bin and grain
577 unloading rate (kg s⁻¹) can result in lower PM₁₀ emissions.

578 From the literature review made, it appears that few crops have currently been addressed in
579 terms of mitigation measure proposals for harvesting operations. Thus, more research is
580 required, aiming to find solutions to reduce harvesting PM₁₀ emissions from the main crops
581 (e.g. maize, wheat etc.). Further mitigation measures should also be developed for immediate
582 post harvesting operations.

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

590 For sowing operations, different mitigation measures and driller prototypes have been proposed
591 (Biocca et al., 2015; Pochi et al. 2015 Pagano et al., 2011). Those solutions focused on
592 reducing the emission of seed coating particles (abating them up to 100%; Table 4) and the
593 deposition of coating particles to the ground, but did not take into consideration the total PM₁₀
594 emissions from sowing. Thus, there could be room for further studies adopting a broader
595 approach and considering the soil particles emitted during seed drilling passages.

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

600

601 **5. Results of the review**

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

- 603 a) Identify operations/crops with most crucial environmental impacts /EFs;
- 604 b) identify the main emission factor estimation methods and highlight their pros and cons;
- 605 c) review mitigation measures proposed for PM₁₀ emission reductions in field emissions;
- 606 d) identify gaps in of knowledge on this specific topic and highlight future research
607 opportunities.

608

609 *5.1 Main agricultural operations contributing to PM emission*

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

613 By reviewing the literature on PM emissions from agricultural activities it was evident that some
614 activities such as tillage, residue burning and harvesting have been addressed more often than
615 others, such as manure and fertilizer spreading or sowing. Moreover, these last two operations
616 have been mainly studied from a very specific perspective, focusing only on a fraction of the
617 total PM produced (namely the bio-aerosol component for manure spreading and the seed
618 coating for sowing). Moreover, it was observed that for many countries in the world, such as
619 Africa, India and South America, few or any specific EFs are available in scientific literature.
620 The EFs gathered in Tables 1 and 2 are summarized in Figures 2, 3 and 4, in order to have an
621 overall impression of the PM₁₀ both crop-wise (for wheat, cotton, and maize) and operation-
622 wise (tillage, harvest, sowing and fertilizer spreading). The graphs were made by averaging the
623 EFs summarized in Tables 1 and 2 for tillage (the tillage comprehends three passages:
624 plowing/disking, harrowing and land planning/floating) and harvest. The contribution of sowing
625 operations was set equal for the three crops, in the absence of specific investigations, and was
626 assumed to be equal to a tooth harrowing passage (82 mg m⁻²), in agreement with the findings
627 of Clausnitzer and Singer (1996). The contribution of fertilizer application was considered to be
628 equal to 1.09 kg t⁻¹ of applied fertilizer (as in Pattey and Qiu, 2012), with an application rate of
629 0.3 t ha⁻¹ (the same application rate was used for the three crops, although a better
630 approximation should be made for more precise applications).
631 Figures 2, 3 and 4 suggest that tillage practices are the most polluting operations in terms of
632 PM₁₀ emissions for all three crops represented here (among 75 and 83% of the overall
633 emissions), as they consist of three or more passages, each one with his own emission
634 potential. Harvesting follows as the second most emitting practice, being the one that varies the
635 most among crops (from 10 to 19% of total emissions). Sowing and mineral fertilizer application
636 have a lower impact (among 2 and 5 % of total emissions).

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

643

644 *5.2. Evolution of EF estimation methods*

645

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

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

656 Particularly, the most common estimation methods appear to be those implementing dispersion
657 models inversely to estimate emissions. Among dispersion models, Lagrangian models are
658 considered more precise as compared to Gaussian models. Nonetheless, Gaussian models
659 are still suggested as reference models by some regulatory agencies (such as the US-EPA with
660 the AERMOD model) due to their simplicity of use. The use of models, in general, seems to be

661 the preferred way to obtain EFs and emission inventories for regulatory purposes and the most
662 common models have been used as reference to validate other EF estimation methods.

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

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

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

675

676 *5.3. Mitigation measures and development trends*

677 The development of feasible mitigation measure for PM emissions is to be seen as the final aim
678 of the process that starts with the evaluation of the emission factors. Although there are several
679 articles dealing with PM mitigation measures, most of them focus on few operations. In fact,
680 there are some operations, such as manure spreading, that were unaddressed in terms of
681 solutions to reduce emissions. Also for tillage practices there were few articles focusing on
682 mitigating the emission of PM, proposing mainly a reduction of tilling passages as main solution.
683 Also for harvesting, the research focused on few crops. Differently, sowing operations have
684 been widely discussed although the main focus has been on seed coating particle reduction

685 more than on total PM₁₀. In conclusion, there are many gaps of knowledge in the field of
686 agricultural PM emissions, where proposals for mitigation measures are still required, leaving
687 open opportunities for future research and technology development.

688 Generally, a more intensive effort should be put into the development and testing of mitigation
689 measures, especially for those operations that are majorly contributing to field derived PM₁₀
690 emissions.

691

692 **6. Future perspectives and research needed**

693

694 The literature review highlighted that there is more information available on PM₁₀ emission
695 factors (EFs) from certain agricultural operations, such as tillage, harvesting and residue
696 burning than from others, such as sowing and manure and fertilizer spreading. Moreover,
697 emission assessment studies were usually conducted with an operation-wise approach, while
698 it appears from literature that a crop-wise approach would lead to more precise estimations
699 (being less influenced by seasonal variation). The lack of an overall view of the emissions, as
700 they take place in each step of a productive system, could potentially lead to substantial
701 underestimation of the overall emissions. To avoid this, all the operations that have not be taken
702 into consideration for their overall PM₁₀ emissions (such as sowing and manure spreading), but
703 mainly for a particular kind of particle (namely seed coating or bio-aerosol) should be assessed.
704 As for the emission factor estimation methods, the most utilized ones in current research are
705 those applying inverse dispersion models to estimate emissions rates from field, also thanks to
706 their cost-effectiveness and adaptability. Other techniques that provide good results are LIDAR
707 measurements and the atmospheric tracer techniques. Those two techniques are particularly

708 interesting, because they do not rely on modeled atmospheric conditions, and could thus be
709 used as basis for comparison for dispersion models.

710 The mitigation measures developed for in field PM₁₀ emissions from agricultural operations are
711 quite few. For tilling practices the main proposed solutions to abate emissions are the
712 implementation of minimum or no tillage systems, while few efforts have been put into the
713 estimation of the emission potential of tilling implements. For harvesting, adequate measures
714 have been developed for a few crops, while many other are still to be addressed. The emission
715 abatement measures proposed for sowing operations are focused on seed coating particles,
716 while few information is even available on the total PM₁₀ particles emitted. As for manure and
717 fertilizer spreading no PM₁₀ mitigation measure has been proposed or assessed.

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

- 720 - the emissions deriving from whole cropping systems, through step by step
721 measurement and evaluation;
- 722 - the influence of implement choice and operation parameters on tillage induced PM₁₀
723 emission with possible development of implements with low emission potential;
- 724 - the assessment of harvesting induced PM₁₀ emissions for crops not yet assessed
725 and the development of mitigation measures (e.g. harvester prototypes development
726 and operation parameters management);
- 727 - the assessment of total PM₁₀ emissions for solid and liquid manure application and
728 the evaluation of mitigation measures.

729

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735

736 **7. References**

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1149 **List of tables**

1150 Table 1. PM₁₀ and PM_{2.5} EFs for different land preparation techniques as determined by
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1155 Table 3. PM₁₀ and PM_{2.5} EFs for residue burning of different crops as determined by various
1156 authors.

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1158 Table 4. Brief description and emission abatement rates of the main dust emission mitigation
1159 measures for agricultural operations as reported by various authors.

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1172 Table 1.

Operation	PM₁₀ EFs (mg m⁻²)	PM_{2.5} EFs (mg m⁻²)	Region / country	Reference	EF estimation method
Tilling (plowing+disking+land and planning)	31 - 119	3 - 33	Northeast hern 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	Oetl 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	-			

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1177 Table 2.

Crop type	PM₁₀ emission factor (mg m⁻²)	PM_{2.5} emission factor (mg m⁻²)	Region/countr y	Referenc e	EF estimation method
Spring wheat	74±12	-	Canada	Qiu and Pattey, 2008	Atmospheri c 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				

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1186 Table 3.

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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

1188 ^a The EF reported by Andreae et al. (1998) was referred to the PM₃ size range, while here it is
1189 reported in the PM_{2.5} column.

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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 facility (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

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1230 **List of figures**

1231 Figure 1. Contribution of the main sectors to total anthropogenic PM₁₀ emissions (adapted
1232 from EEA, 2016).

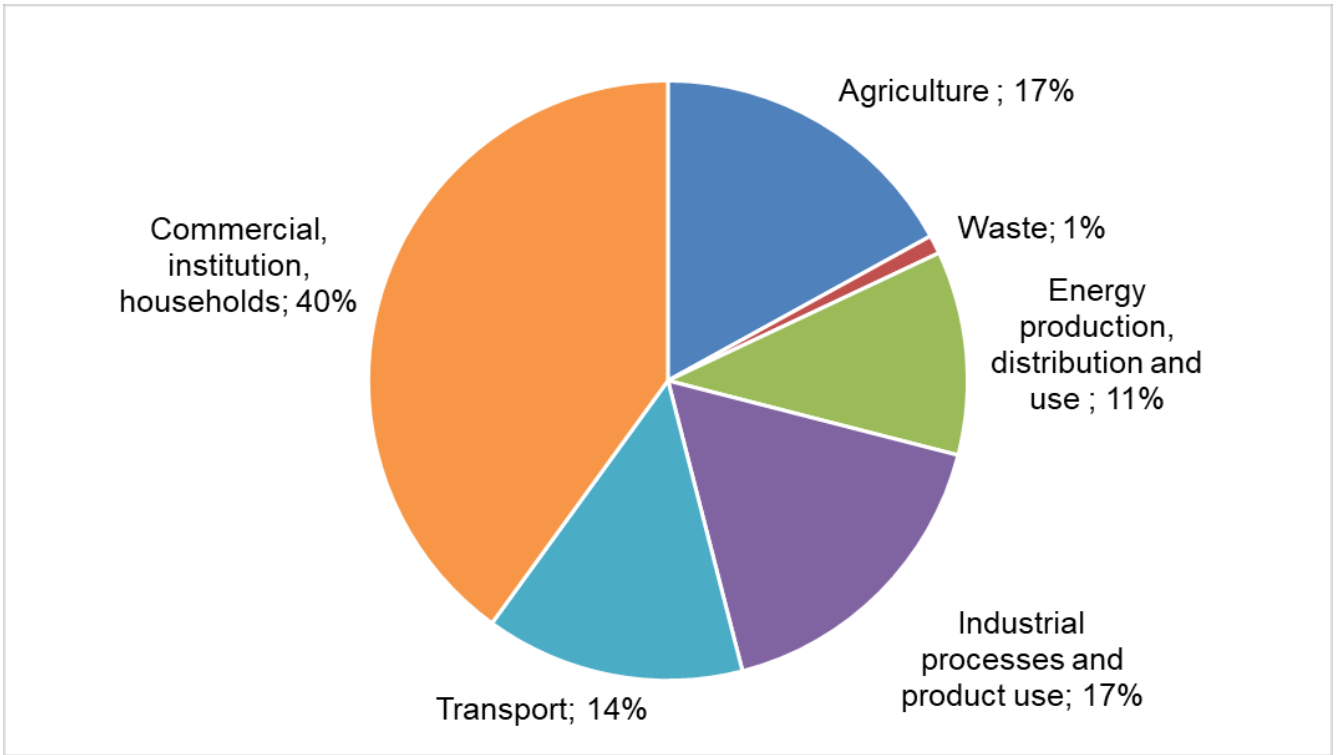
1233
1234 Figure 2. Summary of the contribution of tillage practices, harvesting, sowing and fertilizer
1235 spreading to the total PM₁₀ emitted from wheat cropping operations.

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1237 Figure 3. Summary of the contribution of tillage practices, harvesting, sowing and fertilizer
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1240 Figure 4. Summary of the contribution of tillage practices, harvesting, sowing and fertilizer
1241 spreading to the total PM₁₀ emitted from cotton cropping operations.

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1243 Figure 1.



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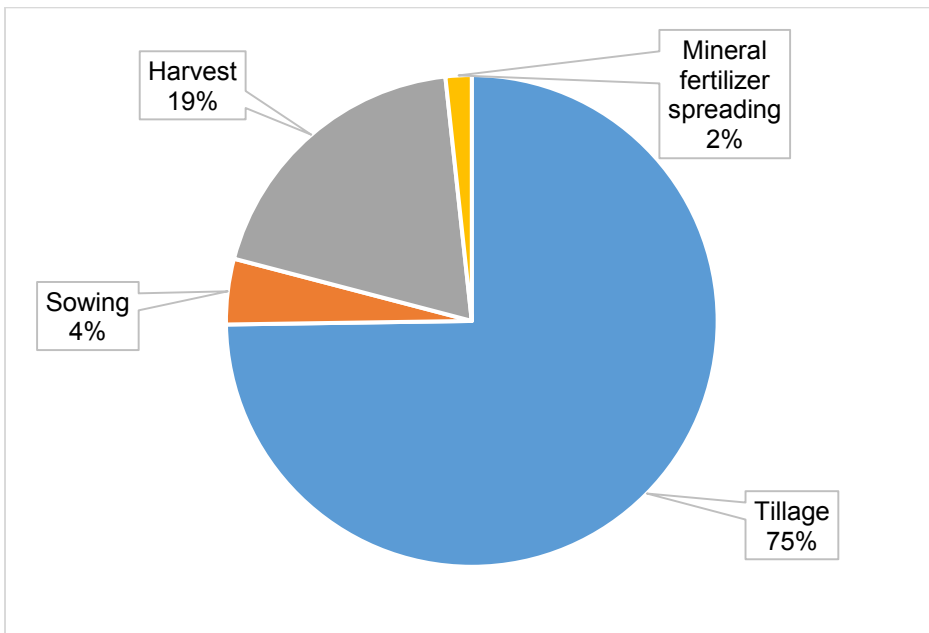
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1257 Figure 2.



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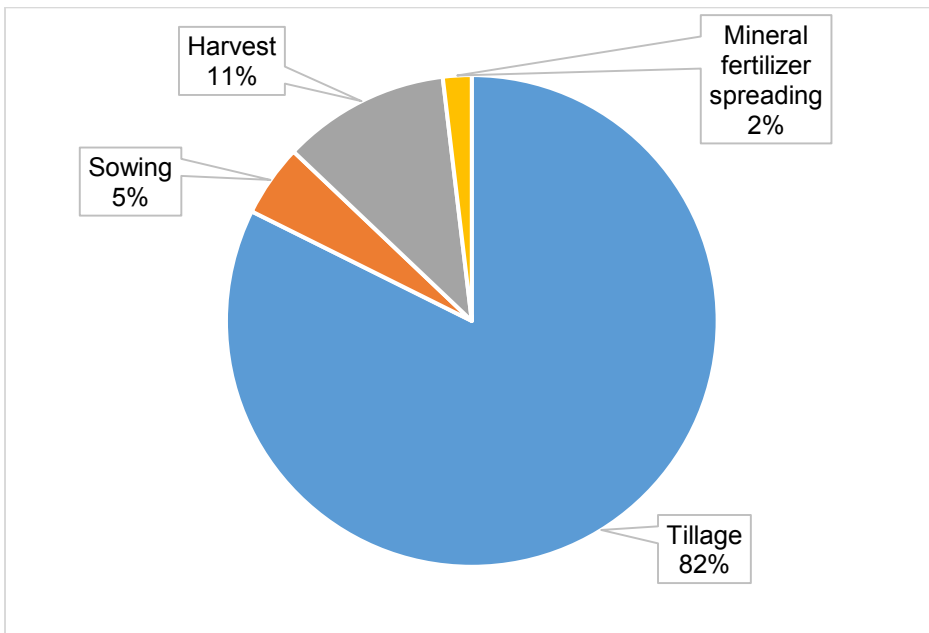
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1275 Figure 3.



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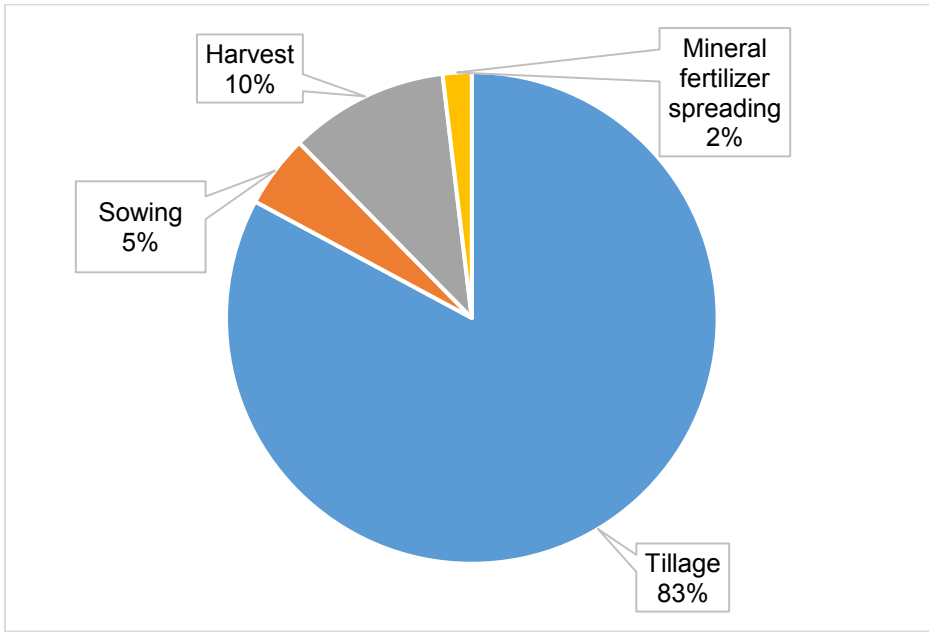
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1291 Figure 4.



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