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Pesticide-laden dust emission and drift from treated seeds during seed drilling: a review

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Abstract

Dressing seeds with pesticides to control pests is a widespread practice with important advantages. Recent incidents of bee losses, however, have directed attention to the emission of abraded pesticide-coated seed particles to the environment during sowing. This phenomenon of drift of pesticide dust can lead to pesticide contamination of air, water and other natural resources in crop-growing areas. This review article presents the state of the art of the phenomenon of dust emission and drift from pesticide seed dressing during sowing and its consequences. Firstly, pesticide seed treatment is defined and its pros and cons are set out, with the focus on dust, dust emission and dust drift from pesticide-coated seed. The factors affecting emission of pesticide dust (e.g. seed treatment quality, seed drilling technology and environmental conditions) are considered, along with its possible effects. The measuring techniques and protocols and models currently in use for calculating the behaviour of dust are reviewed, together with their features and limitations. Finally, possible mitigation measures are discussed, such as improving the seed quality and the use of modified seed drilling technology, and an overview of regulations and stewardship activities is given.

Keywords: crop protection; dust drift; seed coating; seed treatment; modelling; mitigation; neonicotinoids

1 INTRODUCTION

The advantages of using pesticides are well known, including their role in producing an abundant, diverse and low-cost food supply.[1] In past decades, however, there has been an increase in critical attention from the general public and the scientific community regarding the application of pesticides and reduction of risks from pesticides in agriculture.[2,3] The intrinsic properties of pesticides can make them harmful to non-target organisms[4,5] and cause adverse effects on human health[6,7] and the environment.[8] In the past few decades, farmers and horticulturists worldwide have shifted from using highly toxic pesticides to less toxic alternatives.[9] One of the main problems with the use of pesticides is their transport from cultivated areas to air,[10] water[11] and other natural resources[12] via the following main pathways: spray drift,[13–15] surface run-off,[16,17] leaching through the soil profile,[18,19] volatilisation,[20,21] point-source pollution,[22,23] wind erosion of soil particles with adsorbed pesticides[24,25] and dust drift.[26,27] This literature review focuses on drift of pesticide dust arising from the use of dressed seed during seed drilling.

Dressing seeds with pesticides is a widespread and effective way to control pests using smaller doses with potentially less harmful side effects.[28,29] The technology also makes it possible to combine different applications into only one sowing procedure, helping to reduce the use of fuel and the risks of soil erosion and compression and thus assisting low-intensity farming practices and an integrated pest management policy. The main disadvantages of this technique are that residues of systemic pesticides can be present in the guttated water, plant pollen and nectar of seed-dressed plants,[30,31] and that abraded seed particles can be emitted to the environment during sowing.[32,33] In the last few years, this emission has resulted in bee losses in several countries and contamination of surface water, among other things. The main factors affecting the risk from dust drift are the seed treatment quality, the seed drill technology and the environmental conditions.[27]

This review article presents a summary of the latest information on the phenomenon of emission of dust from pesticide seed dressing during sowing and its consequences. Firstly, pesticide seed treatment is defined and its pros and cons are set out, with the focus on the aspects of dust and dust emission from pesticide-coated seed. The factors affecting dust emission, such as seed treatment quality, seed drilling technology and environmental conditions, are considered, as well as the possible effects of emission of pesticide dust. The available measuring techniques and protocols and models currently in use for calculating the behaviour of dust are reviewed, and their features and limitations are highlighted. Finally, possible mitigation measures are discussed, such as improving the seed quality and the use of modified seed drilling technology, and an overview of regulations and stewardship activities is given.

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2 PESTICIDE SEED TREATMENT

2.1 Definition of seed treatment

Seed treatment is the process of applying fungicidal and/or insecticidal seed-dressing products onto various types of seed as a protective coating to create a 'protective zone' of active ingredient (AI) in the soil against soilborne pathogens and insects. Systemic seed treatments also provide additional protection against early-season foliar diseases and insects. More selective seed treatment products for fungal pathogens or insect pests were introduced in the 1970s and 1980s.[34] Depending on the market requirements, a combination of different seed treatment products (fungicides and insecticides) is normally applied at varying application rates. For maize seed, the quantities of AIs generally range from 0.1 to 1.5 mg seed $^{-1}$ or from 10 to 100 g ha^{-1}, depending on the type of product.[30,31,33,35–38] Neonicotinoids, which include the commercial products imidacloprid, thiamethoxam, clothianidin, acetamiprid and nitenpyram, are the most commonly used systemic insecticides for treatment of seeds.[39] They are important for agriculture because of their activity against a broad range of insects (many sucking insects and some Heteroptera, Coleoptera and Lepidoptera) in various crops such as maize (*Zea mays* L.), cotton (*Gossypium* spp.), sunflower (*Helianthus annuus* L.), oilseed rape (*Brassica napus* L.), winter rape (*Brassica napus* L.) and several cereals.[40–43]

2.2 Pros and cons of seed treatment

Seed treatment has many advantages when compared with other application methods of pesticides in the field. When seed-dressing preparations are used, the substance is applied directly to the seed, and smaller amounts of the active substance are required in seed dressing than in a field application.[44,45] The smaller rate reduces concentrations in the environment,[28,45] and the planting of the seed in soil reduces the potential exposure of non-target organisms.[46] Additionally, the applied products can provide protection from the time of seedling emergence well into the growing season,[43,47] which limits the need to apply pesticides by other techniques. For the above reasons, treating seeds is an important aspect of integrated pest management programmes.[34,44]

Although seed treatments have important benefits, they also pose certain risks, e.g. accidental exposure of the workers producing or applying the seed treatments, contamination of the food supply by accidental mixing of treated seed with food, translocation of systemic pesticides to guttation drops,[30,48,49] nectar and pollen[27,50] and contamination of the environment by the emission of abraded seed particles during sowing. Problematic incidents from drift (see Section 6) have mainly been associated with the application of neonicotinoid insecticides[39] as a seed dressing.

2.3 Seed treatment methods

In the early days of seed dressing, the seed was usually mixed with the preparation on the farm itself. In Belgium and most other EU countries, these practices are now forbidden, and seed dressings must be applied in specialised enclosed installations. In most cases, seed dressings in the form of dry powders, slurries or liquids are applied to seeds in certified seed-dressing stations.[38] Specific techniques are used to dress the seeds, e.g. auger mixers, rotating drums, curtain seed dressing and rotostat seed coaters.[51] Application of seed dressing generally takes place in a closed system in which the preparation is pumped directly from the container into the closed machine. After application, closed transport to an automatic packing machine takes place. Although the seed-dressing preparation should normally not be exposed to the environment before opening of the seed packing on-farm,[52] workers handling pesticide-dressed seeds were found to be exposed.[53]

Besides the AI, the seed treatment products consist of other components such as adhesive substances, dispersion substances and colourants. The most common seed treatment formulations are flowable concentrates, wettable powders and liquids. The complexity of seed treatment ranges from a basic dressing (where the seed is dressed with a dry formulation or wet treated with a slurry or liquid formulation) to coating and pelleting.

3 DUST FROM PESTICIDE-TREATED SEED

Differing amounts of abraded dressing particles can be produced as a result of the dressing process, storage conditions, handling and movement before the drilling and breaking of seeds inside the drill. These particles contain various quantities of AI. Additional abrasion powder is also produced during sowing.[33]

Following the bee poisoning case in the Upper Rhine Valley in 2008 (see Section 6), Pistorius *et al.*[50] measured the amount of dust in 82 different maize seed batches. Different varieties of maize and different insecticides were tested by sieving the seeds over a 6 mm sieve. The size of dust particles was separated into a fraction of finer dust (<0.5 mm) and coarse dust (>0.5 mm). Amounts of dust ranged from 2 to 60 g per 80 000 kernels (amount needed to seed 1 ha), with an average of 3.6 g of fine dust and 4.9 g of coarse dust. The coarse dust mainly contained larger plant particles (glumes) broken from the treated maize seeds. Fine dust mainly seemed to appear under conditions of suboptimal coating processes. Larger concentrations of clothianidin were found in the fine dust fraction (18.5–28.2%) compared with the coarse dust fraction (11.4–14.7%). Marzaro *et al.*[54] measured concentrations of chlothianidin pesticide of approximately 20% in large-fragment maize seed coating taken at the air outlet of the drilling machine. These concentrations are much larger than the concentrations of the same products applied as a spray liquid solution.[55] Concentrations of clothianidin in the fine dust were not significantly affected by the amount of fine dust per seed bag, while an increase in the amount of coarse dust tended to reduce the concentration of clothianidin.[50] Whereas seed batches of maize generally contained dust particles in varying but consistently large amounts, seed batches of other crops, such as sugar beet or winter oilseed rape, contained very small amounts of dust, respectively 0.035 and 0.27–0.81 g ha^{-1}.[38] Forster[56] reported that 90% of batches of oil seed rape contained less than 1 g ha^{-1} of dust, whereas 100% of the batches of maize contained more than 1 g ha^{-1} of dust. Nilsson[57] measured residues of seed-dressing substances on the packaging of empty seed bags (both plastic and paper) and found only very small concentrations.

In some countries, talc is typically added to seed boxes to reduce friction and stickiness and ensure the smooth flow of seed during planting.[31] Much of the talc (which has been in contact with the treated seeds) is emitted during planting, either into the ground or into the air via the exhaust fan. Krupke *et al.*[31] measured extremely large concentrations of pesticide (e.g. up to 15 000 mg kg^{-1} clothianidin) in waste talc exposed to treated seed. They also found residues of neonicotinoid insecticide (e.g. up to 9.6 µg kg^{-1} clothianidin), as well as residues of herbicide (e.g. up to 52.0 µg kg^{-1} atrazine) in soil samples taken in and around their test site.

Dust from this soil may land on flowers frequented by bees or onto the insects themselves.

A more detailed characterisation of dust from coated seed in terms of particle size distribution, texture and shape, density, surface and aerodynamical characteristics is needed. Techniques are available mainly from different studies on soil erosion and dust, such as laser diffraction instruments, sedimentation and (wet and dry) sieving techniques and optical methods.[58–60]

4 DUST EMISSION AND DRIFT FROM ESTICIDE-TREATED SEED

Several authors have investigated the emission and drift of pesticides during sowing of dressed seeds. Dust emission is the release of pesticide dust from the seeder. Dust drift is then defined as the off-target movement of this pesticide dust during or shortly after the application, mainly under the influence of air currents.[61]

Greatti *et al.*[32,62] studied the risk of emission of imidacloprid from different types of Gaucho®-dressed maize seed sown with a pneumatic seed drill. They measured an emission from the fan of the drill ranging from 120 to 240 μg imidacloprid g^{-1} paper filter collector during a period of 240 s. Small scales from the seeds were also found on the filters.[62] On the same day of sowing, they found levels of dust drift of imidacloprid of up to 123.7 ng g^{-1} vegetation on vegetation near the maize fields. Residues were found on the neighbouring vegetation (both grass and flower samples) up to 4 days after sowing.[32] The control plots also contained low levels of imidacloprid, in spite of careful cleaning of the seed drill after each sowing operation. This indicates that cleaning of seed drills seems to have a large potential for being a point-source emission.[22,23] It also shows that a dirty drill could temporarily pollute areas in which dressed seeds are not used.

Schnier *et al.*[26] measured an average emission rate of around 4% of the applied dose in the field with a standard dressing formulation.

The Landwirtschaftliches Technologiezentrum Augustenberg demonstrated that drift of free dust emitted by pneumatic seeding machines (vacuum systems) onto oil seed rape at 1 m distance amounted to about 100 μg dust kg^{-1} oilseed rape.[56]

5 FACTORS RELATED TO RISK FROM DUST DRIFT

The most important factors affecting the risk of dust drift from treated seed can be divided into three groups: seed treatment quality, seed drilling technology and environmental conditions.[27]

5.1 Seed treatment quality

The seed treatment quality or the abrasion resistance of treated seeds has been identified as one of the key drivers of contamination of the environment through abrasion of dust particles containing AIs during sowing.[27] The main factors influencing the quality of the seed coating in terms of dustiness and abrasion resistance are: (1) the quality and cleanness of the seed; (2) the formulation; (3) the seed treatment method (see Section 2.3); (4) the application recipe.[27,34]

Based on Nikolakis *et al.*[27] seeds should be properly cleaned before treatment to be free of any organic dust particles, as such particles greatly affect the amount of dust produced by the treated seeds at a later stage. An adequate aspiration system is important for removing all dust particles before the seed enters the seed treatment machine. The quality of the formulation of the seed treatment products is also important. The main parameters are the particle size of the solids (i.e. AIs, pigments, etc.) and the content of appropriate polymers (so called 'stickers') in the formulation. Dry powder formulations tend to sift off the seeds, while liquid treatments are fixed better and are more difficult to remove from the seeds.[38] Stickers further enhance the intrinsic adhesiveness. Finally, the recipe of the final seed treatment slurry is important because it influences the final quality of the seed coating. Supplementary and appropriate adhesives (film coatings) are added to ensure adhesion.

Furthermore, the coating process must prevent the production of new dust during handling, transport and sowing.[50] Greatti *et al.*[32] also found that seeds of maize hybrids coated with the same product had different emissions of dust. Quantitative measurement of the abrasion resistance of treated seeds after coating is done using the Heubach test. This method has been identified as the standard test (see Section 7.1) and has been included in many studies.[27,33,54]

5.2 Seed drilling technology

Three seeding methods can be distinguished by the horizontal pattern of seed placement.[63] Broadcast seeding, mainly used for cover crops, refers to random scattering of seeds on the soil surface. Bulk drilling is the random placement of seeds of closely spaced crops (such as cereals) in furrows that are then covered. This is mostly performed with a mechanical (Fig. 1a) or a pneumatic machine using overpressure to divide the seeds between the different drill coulters (Fig. 1b). In precision seeding or precision drilling, the seeds are planted in rows and the spacing of seeds within the rows is uniform,[64,65] e.g. in maize, sunflower, cotton, bean and sugar beet. Precision seed planters can be divided into three main categories based on the seed singulation mechanism: vacuum singling, mechanical singling and overpressure singling. The majority of precision seed planters use a vacuum for seed singling (Fig. 1c).

These vacuum-based pneumatic seed drills provide a precise deposition of seeds[66] by aspirating seeds from a deposit via suction pressure, generated by a central centrifugal fan, onto a perforated disc. The resulting exhaust air, which can contain varying quantities of abraded seed treatment particles, is emitted via the high-velocity outlet airstream of the machine through the fan opening. For standard equipment, the airstream outlet is generally placed directly on the fan, and the outlet is directed upwards approximately 1.5–2 m above the ground, which results in a potentially large dispersion of abraded seed coating particles in the environment.[26,33,36] Marzaro *et al.*[54] measured an exhaust air flow rate of 150 L min^{-1}. Moreover, the rotating sowing discs can lead to additional dust abrasion. Because of their use in spring during the planting season of maize, their popularity of use and their working principle, incidents of dust drift have mainly been reported for these vacuum-based pneumatic seed drills. To the present authors' knowledge, only Heimbach *et al.*[67] have performed a dust drift field trial comparing a mechanical and a pneumatic bulk drilling machine using the same batch of seeds. The mechanical bulk drill gave smaller, but still significant, dust drift values compared with the pneumatic bulk drill.

5.3 Environmental conditions

Although not yet studied in detail, environmental conditions can also clearly affect the risk of dust drift. The risk of damage from

A B C

Figure 1. Different types of seed drilling machinery: (A) a mechanical bulk drilling machine, Amazon D9 3000 Special; (B) a pneumatic bulk drilling machine, Kuhn Venta nc 3000; (C) a vacuum-based precision seed drill, Gaspardo ST Stella 300.

dust drift increases in landscapes where many small-sized maize fields are located in a diverse agricultural landscape with canola fields, orchards and other bee-attractive crops, etc.[27] This results in many field boundaries being exposed to drift, especially when the maize drilling and the flowering season of the neighbouring plants take place at the same time. Weather conditions also play a role. Dry and windy weather conditions enhance both the formation and drift of dust.[36] Greatti *et al.*[32] also showed that climate affected the persistence of imidacloprid on the vegetation, and that heavy rainfall washed much of the pesticide residues from the vegetation.

6 EFFECTS OF EMISSION OF PESTICIDE DUST

The effects of systemic insecticides – mainly those belonging to the neonicotinoid family – on insects,[68,69] particularly bees,[38,70–74] are well known. Bees (Apidae), along with other insects, are the primary pollinators of most agricultural crops and wild plants and therefore have great economic and ecological importance.[75,76] Some insecticides employed in maize and sunflower seed dressing, among others, have been claimed to play a role in the decline of honey bees (*Apis mellifera* L.), although the mechanisms are not yet fully understood.[31,54] Blacquière *et al.*[77] summarised 15 years of research on the hazards and effects of neonicotinoids on bees. Additionally, the EFSA[38] published a guidance document for the risk assessment of plant protection products on bees. They defined drift of dust from treated seeds as one of the potential pesticide exposure routes for bees, as several incidents of bee poisoning have recently occurred that were caused by dust from abraded particles of the seed dressing containing bee-toxic products. The products were released during the drilling process and subsequently deposited either directly onto the bees or onto flowering, bee-attractive crops and weeds in adjacent vegetation strips and fields. Hence, bees may come into contact with pesticide dust in several ways: by direct contact (when bees fly through the drift cloud), by indirect contact (when bees walk on contaminated leaves of the vegetation) or by ingestion (when bees collect nectar,[78] pollen[31,79] or dew from the vegetation contaminated with the dispersed dust).[38] The LD_{50} values estimated for contact with the cuticle are 18, 22 and 30 ng bee^{-1} for imidacloprid, clothianidin and thiamethoxam respectively.[72]

In 1998 in France[80] and in 1999 and 2000 in Italy,[81] beekeepers already reported suspected impacts of pesticide seed dressings on honey bees resulting in high mortality in a number of bee hives during the spring season. A presumed link was made between their bee losses and the use of imidacloprid seed dressing (Gaucho®) on maize seeds.[81] However, based on two field trials in 2001 and 2002, Schnier *et al.*[26] concluded that it was very unlikely that the bee colony losses in 2000 were linked to the drilling of Gaucho® seed, although no other possible causative factors were found. They performed a replicated cage test with honey bees to examine whether the deposits of emitted dust particles rates could adversely affect honey bee colonies foraging on flowering plants. During the spring planting season of 2000–2003, French beekeepers reported high mortality rates in their apiaries at the time of sowing maize and sunflowers.[82]

In the following years, important incidents took place in Italy,[81] Slovenia,[83] Germany (2008, region of Bad-Württemberg, clothianidin),[84] France (2008, Alsace, clothianidin)[85] and the United States (2010, Indiana, clothianidin and thiamethoxam).[31]

After the German incident in 2008,[84] residues of clothianidin of up to 100 μg kg^{-1} were found in plants of neighbouring fields,[27] as well as in dead honey bees.[36] About 12 500 bee colonies were heavily weakened.[86] The symptoms of poisoning included loss of foraging bees, acute and enhanced mortality, weakened colonies, reduced honey production, brood damage and breeding problems. A coincidence of several worst-case factors aggravated the impact of the emission of pesticide dust: poor seed treatment, use of unmodified pneumatic seed drills, delayed sowing because of bad weather, which resulted in maize sowing concurrent with oilseed rape flowering, and dry and windy weather during sowing.[36,84] The correlation between colony losses and the sowing of maize seeds dressed with neonicotinoids was demonstrated by Bortolotti *et al.*[81] with concentrations of AI in dead bee samples ranging from 1.01 to 240.6 ng g^{-1} for imidacloprid, from 3.67 to 39.2 ng g^{-1} for clothianidin and from 24.8 to 138 ng g^{-1} for thiamethoxam. In recent years, several studies have confirmed the lethal effect of dust drift from pesticide seed dressing on bees during sowing of seeds coated with neonicotinoid insecticides.[54,55,62,87,88] Girolami *et al.*[55] showed that a single pass with a standard pneumatic drilling machine is sufficient to kill all bees exposed to the exhaust air on the emission side. With a modified drill with deflectors, the bee survival rate was still below 50%.

In the above incidents, sources of neonicotinoids were found in the field as well as in the adjacent vegetation, but the mechanism by which the bees come into contact with the pesticides was not fully understood. Marzaro *et al.*[54] therefore studied this and concluded that acute poisoning of bees during sowing is presumably caused by aerial contamination and direct exposure rather than from contact with marginal vegetation. Moreover, high humidity seemed to have a synergistic influence on the toxicity of insecticides that came into contact with bees.[55] Krupke *et al.*[31] suggest that bee mortalities are probably caused by a combination of contact (dust drift) and oral exposure. Recent bee losses in Spain could not be attributed to the use of sunflower seeds treated with fipronil, but were caused by two pathogens, *Varroa destructor* and *Nosema ceranea*.

From the above it is clear that the effect of emission of pesticide dust has mainly gained public attention through the various cases of bee poisoning, and that bees and their products are known to be important indicators of environmental pollution.[89,90] On the other hand, the emission of pesticides during seeding will also affect other terrestrial and aquatic organisms, users, bystanders,[91] etc., although this has been much less studied. This is confirmed by Hardstone and Scott,[92] who found that bees are no more sensitive to any of the six classes of insecticides (carbamates, nicotinoids, organochlorines, organophosphates, pyrethroids and miscellaneous) than other insect species. Similarly, Kuhlau[52] monitored surface water quality in four stream areas in Sweden from 2002 to 2006, and two of the detected AIs, metalaxyl and bitertanol, could be linked to sowing treated seed of processing peas and winter wheat.

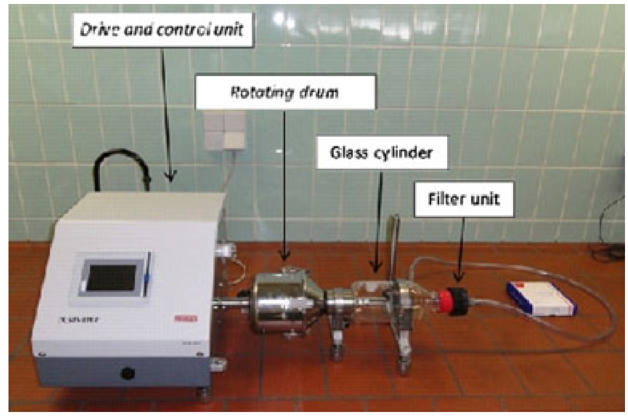

Figure 2. Heubach dustmeter for quantifying the abrasion potential of seed treatment coatings.

7 MEASURING TECHNIQUES AND PROTOCOLS

7.1 Abrasion potential of seed treatment coating – Heubach method

Among the various methods used to determine the abrasion potential of seed treatment coatings, the Heubach method is widely accepted as being the most practical (Fig. 2). The Heubach method, which is used as a reproducible measuring technique for seed treatment quality by measuring the abrasion potential of seed treatment coatings, has the following advantages[93]:

- It actively stresses treated seeds, which simulates mechanical stress after treatment (e.g. bagging, transport and sowing).
- It measures abrasion of coarse non-volatile and volatile dust particles, not the AI, and thus no analytical capacity is required.
- The ready-to-use equipment (Heubach dust meter) is commercially available and is a relatively fast and inexpensive method.
- A standardised procedure is available, which allows for comparison of results between different locations.

The equipment exists of a drive and control unit, a rotating drum, a glass cylinder and a filter unit. The principle is that the treated seed is mechanically stressed inside the rotating drum while a vacuum pump creates an air flow through the rotating drum, the glass bottle and the attached filter unit. Abraded particles are transported from the rotating drum by the air flowing through the glass cylinder and collected on the filter medium inside the filter unit. While volatile dust particles settle on the filter, coarse non-volatile particles are separated and collected in the glass cylinder. The amount of volatile or fine dust collected on the filter medium is determined gravimetrically and represents the so-called Heubach value (HV), which is generally expressed as grams of dust per 100 000 seeds or per 100 kg of seed. Average Heubach values of batches of maize collected in Germany, France and Hungary ranged from 0.26–1.22 g per 100 000 seeds, with maximum values ranging from 0.40 to 4.15 g per 100 000 seeds.[94] Besides maize, cereals seem to be most sensitive to dust abrasion. Mean Heubach values (g ha^{-1}) of more than 300 batches sampled in 2008–2010 ranged from 1.9 to 3.0 for barley, from 2.3 to 7.7 for wheat, from 0.9 to 4.1 for triticale and from 0.7 to 7.3 for rye.[95]

Some authors also collected the coarser dust collected on the bottle of the glass of the Heubach instrument in order to assess the total dust. For example, Biocca *et al.*[33] measured Heubach values ranging from 0.723 to 1.833 g per 100 kg and total dust values ranging from 5.95 to 20.99 g per 100 kg for four types of maize seed dressing. The mass of maize seed might range from 0.35 to 0.445 g $seed^{-1}$,[96] and the seed rate is generally about 75 000–80 000 seeds ha^{-1}.[50,54,97,98] Nikolakis *et al.*[27] confirmed the major importance of seed treatment quality by comparing dust drift values in field conditions for two seed treatment qualities (HV 1.2 seeds and HV 0.1 seeds) with a standard unmodified vacuum-pneumatic maize drilling machine.

To the present authors' knowledge, the exact size of the particles collected with the Heubach method is unknown, but it is certainly very small compared with the size range of the total driftable dust fraction in field conditions because of the very low air velocities in the glass cylinder ($\pm$ 0.04 m s^{-1}) at the prescribed air flow rate.[93] Additionally, no direct relation between HV and (potential) drift values in field conditions has been established up to now.

7.2 Dust emission measurements

Dust drift field experiments with different techniques and seed treatment qualities are time consuming and expensive, and they cannot be made under directly comparable and repeatable conditions (soil, wind speed and direction, etc.). For these reasons, various authors have measured dust emission or the dust drift potential under controlled and repeatable conditions, as done in different spray drift studies.[99]

Balsari *et al.*[97] determined the dust drift potential of different pneumatic sowing techniques in static indoor conditions by introducing a dust tracer in the fan air inlet and measuring the dispersion of the dust tracer using 138 mm petri dishes.

Giffard and Dupont[87] also conducted static indoor tests with different coated seeds and filter papers to catch dust disseminated in the air.

Biocca *et al.*[33] presented an indoor sowing simulation test system in which artificial wind conditions were created by means of an axial fan orchard sprayer. In a 22.5 m long downwind sampling area, petri dishes filled with 50% acetonitrile–water captured the falling dust and provided the concentration of the AI at ground level. At the same time, three air samplers with 0.2 µm PTFE (Teflon®) disc filters were used to detect the AI in the air according to the standard CEN/TR 15547.[100] The results showed regularly decreasing concentrations as distance increased, both in the air and on the ground. They also proposed a data processing method that, from the values observed at a fixed point, provided the theoretical concentration of the AI that would occur in the field, under the same conditions of wind speed and direction and working speed.

Schnier *et al.*[26] used a commercial car filter in order to trap any abraded dust emitted during the drilling. Similarly, Herbst *et al.*[98] described a test used to evaluate the mechanical strain applied to dressed seeds where the machines are operated on a stationary test rig and an isokinetic sampler is used to sample the air from the fan outlet. Tapparo *et al.*[101] measured emission of dust at 5 and 10 m of a static machine sowing treated corn seeds (Heubach values of <3 g per 100 kg of seeds) using Zambelli pumps (model ZB1 timer; Zambelli, Milan, Italy). Emissions of dust ranging from 0.46 to 1.53 g dust ha^{-1} were observed, corresponding to 0.55–1.84% of the employed insecticide released in the air as dust.

7.3 Dust drift field measurements

Dust drift values, under realistic working conditions, can only be obtained by means of dust drift field experiments, which are time consuming and resource intensive. To date, exposure of off-crop habitats to seed treatment dust released during sowing has been assessed in a very limited number of field drift studies. The EFSA[38] reported that more experimental data are needed for risk assessment purposes.

In a preliminary field experiment, Greatti *et al.*[62] highlighted the loss of imidacloprid from pneumatic seed drills. Later, Greatti *et al.*[32] verified both the amount of contamination and the persistence of the AI on leaves and flowers of spontaneous plants growing near maize fields in north-eastern Italy that had been planted with Gaucho®-dressed seeds. The escape of the AI from the fan drain of the pneumatic seed drill was monitored using paper filters, and samples of grass and flowers were collected from the borders of sown fields.

Nikolakis *et al.*[27] conducted an extensive field dust drift study using Poncho Pro®-dressed maize seeds. Overall, more than 70 ha of agricultural land, typical for maize growing under European conditions, was employed for testing different types of sowing machinery and seed treatment qualities. Each technique was tested in the field by sowing dressed seeds on an area of approximately 1.0 ha at a drilling rate of 80 000 seeds ha^{-1}. Dust was collected at distances of 1–50 m from the drilled area during the drilling procedure, using two types of collector. Petri dishes were placed on the soil surface to collect the ground deposits, and passive dust collectors were installed at various heights to collect the airborne dust fraction. Additionally, another set of petri dishes was installed downwind in the off-crop sampling area after the drilling process to investigate whether the dust that deposited during sowing within the drilling area would be dislodged from the soil surface and transported downwind.

Giffard and Dupont[87] performed a field test with a pneumatic vacuum driller and two insecticide-coated sunflower seed varieties. They placed *Tibouchina*, an ornamental plant species known for its hairy leaves, as the receiving target for dust, within the sown fields. After the sowing events, bees were introduced into containers with *Tibouchina* leaves, and their mortality was assessed 4, 24, 48 and 72 h after exposure. Marzaro *et al.*[54] directly exposed bees to dust emitted by the drilling machines by putting bees in small cages around the sowing area and to avoid contact with the vegetation. Amounts of clothianidin of up to 100 ng bee^{-1} were detected on bees that had been directly dusted in flight during drilling.[55] Tapparo *et al.*[101] measured the atmospheric emission of dust containing the insecticide at a distance of 10 m along the wind direction from the drilling machine during the sowing of different types of treated corn, all with dust abrasion levels below 3 g per 100 kg of seeds. Using Zambelli pumps, they found concentrations of neonicotinoid of up to 13.1 μg m^{-3} air, values that are significantly larger than the bee LD_{50} values estimated for contact.[72]

Herbst *et al.*[98] described the field measuring protocol used nowadays for the official registration of drift-reducing sowing equipment in Germany (see Section 9.3). It uses a powdered fluorescent tracer dye (brilliant sulfoflavine) to represent the abraded chemical, which is injected directly into the fan of the machine (at a rate of 7 g min^{-1}) during the tests and blown out. This is much larger than the normal output of abraded chemical, but it allows for safe and cheap detection of the drift sediment. Field dust drift is measured downwind at distances of 1, 3 and 5 m from the field edge, using petri dishes with moistened filter papers. Harrington *et al.*[102] also included petri dishes, in addition to CD cases and flypaper, in their comparison of collection methods for pesticide drift from granular applications. To compare different drills, Friessleben *et al.*[36] also used petri dishes as collectors to monitor soil deposition of dust at 1, 3, 5, 10, 20, 30 and 50 m downwind of the sown field. Passive dust drift collectors to monitor the airborne drift were positioned at 5 and 30 m distance at 1, 2, 3, 4 and 5 m above the ground.

Neumann and Jene (2010, unpublished report No. IVADUST1) compared the collection efficiency of different sampling devices for the measurement of aerial and sedimenting dust drift in field conditions, and the relevant sampling height and duration were assessed. Petri dishes with a acetonitrile/water mixture were used for measurements of ground deposition. Different types of sampling system for 3D interception of dust were compared, i.e. a proxy hedge (cherry laurel branches attached to a construction fence and wetted with glycerol/water), gauze netting attached to a construction fence and wetted with glycerol/water, scourer pads on a pylon (up to 6 m in height), scourer pads and pipe cleaners attached to a construction fence, Big Spring Number Eight (BSNE)[103] passive dust samplers and high-volume active air samplers. All sampling devices provided quantifiable residue values with a reasonable variation between the replicates. The use of high-volume air samplers had technical problems (the filters became clogged), and dust drift decreased with height of sampling. Gauze netting and BSNE samplers produced area-normalised residue values that were closest to the values from the proxy hedge. They selected gauze netting as the most suitable sampling system because it represents a conservative estimate for natural vegetation, it is easy to handle and to standardise, the aerodynamic behaviour is similar to a hedge, it has a precisely defined projection area and it has the largest sampling area of all artificial samplers. In other studies on soil erosion, some other dust collection devices have been employed that can potentially be used for pesticide dust drift measurements, e.g. vaseline-coated slide cachers,[104] step-like passive split samplers,[105] the modified Wilson and Cooke sampler (MWAC),[106] isokinetic samplers[107], a cyclone-type trap (BEST)[108] and several others.

8 MODELLING OF UST, EMISSION OF DUST AND DUST DRIFT

Dust drift measurements are complex, and the process of dust drift is not sufficiently understood. A modelling approach is therefore valuable, as models contribute to a better understanding of the drift process and a better evaluation of different scenarios, and they can provide a platform for testing innovative mitigation measures. Many different types of atmospheric model for dispersion of particles exist, but few are sufficient for accurate modelling of drift of pesticide dust. In 2006, Holmes and Morawska[109] published an extensive review of these models. They include box models, Gaussian plume or puff models, Lagrangian models, Eulerian models, computational fluid dynamics (CFD) models and models that include aerosol dynamics. Atmospheric dispersion models range from simple to very complex, and they can differ in spatial and temporal scale, the type of sources they consider (point, line, area or volume sources), the type of pollutants they can handle and whether they account for factors such as atmospheric stability, turbulence, dry and wet deposition, chemistry or complex terrain.

Most efforts so far in modelling of dust dispersion have focused on air quality in urban environments such as street canyons.[110–119] Models have been developed for gaseous pollutants such as CO and NO_x and particulate emissions such as PM_{10} and $PM_{2.5}$ with an aerodynamic diameter below 10 and 2.5 µm respectively. The coarse fraction of the total suspended particles (TSPs) exhibits larger vertical concentration gradients than those usually observed in gases or fine particles. Larger-sized particles of complex shape and a wide range of density have not been elaborately treated. When modelling the dispersion of coarse-grained dust, gravitational settling becomes significant and the diffusion coefficient needs to be modified. Usually, this effect is neglected in dispersion models.[120] However, the coarse fraction in dust from seed treatments is large,[50] and it should be accounted for in a dust dispersion model.

Another main field in dust dispersion research is fugitive dust from agricultural fields,[121–126] unpaved roads,[127,128] wind erosion on plains[129] and mines and quarries.[130–132] Drawbacks to using Gaussian models for modelling near-field dispersion of dust from agriculture operations are the model requirements of steady-state environmental conditions and releases from a continuous fixed-location line or point source. Agricultural sources of PM_{10} are usually moving sources because the operation equipment is continually travelling in the field.

Models such as ENVI-met[112] assume that the particles move according to a parameterised advection–diffusion equation, in which the parameters of diffusion and deposition depend on the particle diameter and external conditions. These models are usually employed to calculate the dispersion of a single component with certain spherical dimensions. To calculate deposition, these models take turbulence, Brownian diffusion, sublayer resistance and the settling velocity into account. For larger particles (>10 µm) this model means that deposition velocity in vegetation is only dependent on the settling velocity and the leaf area index (LAI). As deposition of abraded seed treatment particles in vegetation is crucial for the impact on sensitive fauna, and because vegetation can work as a buffer for dust drift, it is expected that these models will not be sufficiently detailed to make accurate predictions of dust drift. Endalew *et al.*[133] developed a model that explicitly takes into account the plant architecture for the calculation of air flow, particle movement and particle deposition. The calculation of the air flow and droplets in orchard spraying through a row of trees was validated successfully. The existing model of Endalew *et al.*[133] is insufficient for calculating dust deposition, however, because the model was developed for spherical droplets, whereas dust particles can have a wide range of different irregular shapes and densities. Non-spherical particles behave differently compared with spherical particles because the drag and lift forces are different.[134–136] Hölzer and Sommerfeld[134] established a new simple correlation formula for the drag coefficient of non-spherical particles in 2008. This new formula, which includes sphericity,

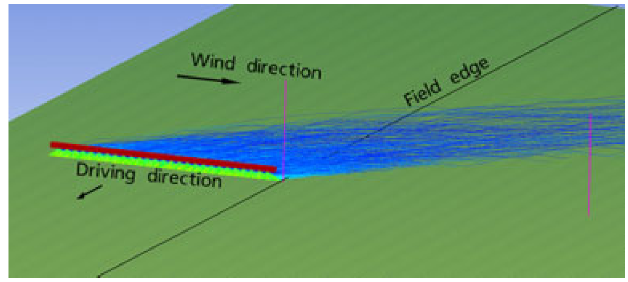

Figure 3. Spray drift prediction from a field sprayer on a field under cross-wind (CFD model[137]). The droplet tracks are coloured (blue: small droplets drifting across the field edge; green-yellow: heavy droplets depositing on target).

crosswise sphericity and lengthwise sphericity, accounts for the particle orientation over the entire range of Reynolds numbers up to the critical Reynolds number. Such a correlation may be easily used in the frame of Lagrangian computations where also the particle orientation along the trajectory is computed.

Computational fluid dynamics is a branch of fluid mechanics that uses numerical methods and algorithms to solve and analyse problems that involve fluid flows. As computers become ever faster and more powerful, CFD is being applied to many different types of problem of fluid flow. In 2007, Baetens *et al.*[137] developed a 3D CFD model for the prediction of spray drift in field spraying (Fig. 3). The model explained the variation in drift through varying boom height, wind velocity, wind direction and injection velocity of the droplets. The effect of meteorological conditions on the drift of solid seed treatment particles has not yet been quantified, but a similar relationship to that of spray drift[13,14] can be expected. In 2008, the German government decided to disallow seeding operations at wind velocities above 5 m s^{-1}.[56] This threshold value is arbitrary, however, and was not based on scientific research. A specific seed treatment dust dispersion model would help in quantitatively estimating the effects of meteorological conditions and seeder design and settings on dust drift. Considering the demonstrated potential of Baetens's model for spray drift, CFD seems to be a promising tool for this purpose.

9 MITIGATION MEASURES

The term 'mitigation' is used here in a broad sense, synonymous with 'risk reduction', which comprises all measures that lead to a lower risk of dust drift.[11] These mitigation measures include the use of an improved seed quality, modified machinery, regulations and stewardship activities. In contrast to spray drift, the use of hedges and border structures[138,139] as drift mitigation measures has not yet been studied for dust drift.

9.1 Improved seed quality

The right adhesive and the optimum application rate must be chosen as a function of the seed type and seed treatment products. This increases the chance of generating treated seeds with the maximum possible resistance to abrasion.[27] The surface properties and the geometry of different seed types (maize, canola, cereals, cotton, sunflower, vegetables, etc.) differ significantly, and thus specific adhesives are designed and generally applied for each seed type. Such adhesives are generally natural or synthetic polymers such as Arabic gum, carboxy methyl cellulose, gelatin, casein, polyvinyl acetate and many others.[140] Companies for seed treatment should be instructed on how to optimise the settings of the seed treatment machinery and be told which adhesives to use for maximum adhesion of the pesticide products. The method of seed treatment and the process of seed cleaning before and after coating also deserve attention. The standardised Heubach dust measurements (see Section 7.1) can be used to evaluate the seed treatment quality. Schnier *et al.*[26] compared the abrasion potential of three Gaucho® FS 350 formulations and found that the use of specific adjuvants optimised seed loading and reduced abrasion by 50%. Heimbach[95] found an average Heubach value of 1.4 g per 100 kg of wheat seeds when no adhesive was used, compared with 0.3 g per 100 kg when using an adhesive.

9.2 Modified seed drilling technology

Improving the quality of seed treatment is essential, but dust emission also needs to be reduced through technical solutions for sowing machines.

Various types of air deflector or device to reduce dust drift already exist. These generally aim to direct the air into the furrows created for seed distribution.[33,36] Moreover, the speed of the exhaust air of the vacuum system is reduced by ejecting the air via several tubes instead of one single outlet. At ground level, the exhaust air can be released via diffusers, cushions or within fertiliser discs.[27,36]

These deflectors or modification kits can generally be removed easily to restore 'conventional drill' conditions. Using air deflectors, Pochi *et al.*[141] found a reduction in the concentrations of AI in the air ranging from 72 to 95% compared with the reference. Herbst *et al.*[98] found that off-target ground deposition can be reduced by more than 90% using such a modified machine, while Biocca *et al.*[33] found that the use of deflectors resulted in a reduction in the emission of AI of approximately 50%. They also mention that avoidance of an excessive vacuum level can contribute to reducing dust drift. Nikolakis *et al.*[27] measured values of dust drift in field conditions of five modified vacuum-pneumatic drilling machines, a standard unmodified vacuum-pneumatic maize drilling machine, a drilling machine operating with compressed air and a mechanical sowing machine. They found that the modified vacuum-pneumatic maize drilling machines, together with the mechanical drilling machine and the drilling machine with compressed air, all performed similarly and all led to a significant reduction in dust drift compared with an unmodified vacuum-pneumatic maize drilling machine. On the other hand, different authors concluded that modified seed drilling machinery still emits significant amounts of micrometric dust particles, the effects of which on bees have been discussed above.[55,101,141] Additionally, many farmers still prefer to work without deflectors because of their high generation of soil dust, mainly during dry drilling conditions, resulting in a low visibility of the drilling process and contamination of the equipment.

Besides the use of air deflectors, Pessina and Facchinetti[142] suggest using a water filter to filter the exhaust air and then using the loaded water as a pesticide in the soil.

Thompson[143] estimated that dust drift during drilling can potentially be reduced by 99% by using modified seed drilling technology in combination with improved seed quality.

9.3 Regulations and stewardship activities

In most countries, a legal framework is in place to protect honey bees and other pollinator insects from the negative effects of pesticides and other agrochemicals according to the European Council Directive 91/414.

The seed quality standards for maize seeds differ from country to country, with Heubach values ranging from 0.75 to 1.3 g per 100 000 seeds.[56] In Germany and Austria, the maximum permissible Heubach value for methiocarb on maize is established at 0.75 g per 100 000 seeds.[56] Maize seeds dressed with methiocarb may only be sown with machines that reduce dust drift by at least 90% compared with conventional vacuum-pneumatic machines. For this purpose, a standard test procedure was set up in which modified drift-reducing sowing machines were compared with standard machines. The procedure consists of a field test (see Section 7.3) and an abrasion test in the lab (see Section 7.2).[98] Currently, over 150 dust-drift-reducing sowing techniques are approved and listed in the JKI list of drift-reducing maize sowing machines.[27,144]

The French authorities have set up a 'dust schedule' for seed coating factories that limits the discharge of dust to 4 g per 100 kg of coated seed.[87] In the Netherlands, a maximum level of 0.75 g dust per 100 000 seeds is enforced for all insecticides used as maize seed treatment.

In 2008 (following the Italian bee poisoning cases), the Italian government enacted the precautionary measure of suspending use of all four AIs registered for maize seed dressing (imidacloprid, thiamethoxam, clothianidin and fipronil). No incidents of bee poisoning were recorded in the springs of 2009 and 2010.[145]

In some countries like the Netherlands, France, Belgium and Germany, the use of deflectors is mandatory on sowing machines for certain products, although they are not always used in practice. This explains the stark variation in the share of modified sowing technology from country to country. In general, the risk assessment process differs from country to country, and drift mitigation strategies are not harmonised internationally.

In addition to regulations, the crop protection industry has initiated stewardship activities to increase the awareness of farmers, seed treatment companies and manufacturers of sowing equipment. The goal of these initiatives is to raise awareness of dust drift among those involved with seed treatment and to encourage them to minimise seed abrasion and emissions of pesticide seed dressing.

10 CONCLUSIONS

Seed treatment is the process of applying pesticide seed treatment products onto seeds as a protective coating to create a 'protective zone' of active ingredient in the soil against soilborne pathogens and insects. Systemic seed treatments also provide additional protection against early-season foliar diseases and insects. The use of seeds dressed with pesticides to control pests is widespread and has many advantages, but residues of systemic insecticides can be present in the guttated water, plant pollen and nectar of seed-dressed plants, and there is the possibility of emitting abraded seed particles into the environment during sowing. Bee losses due to dust drift of pesticides have mainly been associated with the use of neonicotinoid insecticides. The dust drift of pesticides may involve additional risks, however. The amount of abraded dressing particles and their characteristics mainly depend on the dressing process (quality and cleanness of the seed, the formulation, seed treatment method, etc.), the storage conditions and the handling and transportation before and during drilling. The Heubach test method has been identified as the standard test to determine the abrasion potential of coatings, although it only measures the very fine dust fraction. A detailed dust characterisation in terms of particle size distribution, texture and shape, density, surface and aerodynamic characteristics has not yet been performed for dust from coated seed, in spite of the availability of techniques to gather such information.

The dust drift risk is mainly affected by the seed treatment quality, the seed drill technology and environmental conditions. Similarly to spray drift studies, several authors have measured the emission of dust and the dust drift potential for different conditions and techniques under controlled and repeatable indoor conditions using a static machine. Others have measured real drift values in the field under realistic working conditions. Neither applied standardised measuring protocols, which are necessary to compare and exchange data and to use these data for risk assessment purposes. Dust drift mitigation measures mainly include the use of improved seed quality and modified machinery using air deflectors on vacuum-based pneumatic seed drills, which direct the air into the furrows opened for the seed distribution, or using a filter to filter the exhaust air.

Measurements of dust drift are complex, and the process of dust drift is not sufficiently understood. A modelling approach can therefore contribute to a better understanding of the drift process and a better evaluation of different scenarios, and can provide a platform for testing innovative mitigation measures. The use of computational fluid dynamics seems to be a promising tool for studying the combined effect of seed drilling technology, seed quality, soil and environmental conditions and landscape features on dust drift risk.

Some EU countries have enacted laws to protect honey bees and other pollinator insects from the negative effects of dust drift of pesticides. At least, all EU member states must have a similar level of quality for seed treatments and the mandatory use and classification of drift-reducing sowing equipment.

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