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Revisiting Sustainability of Fungicide Seed Treatments for Field Crops

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Chemical seed treatment began with cereals with the use of brine in 1637, arsenic in 1755, and copper sulfate in 1760 (Russell 2005). This practice has been widespread in agriculture especially following the introduction of new chemistry classes. Typically, chemical seed treatment consists of the application of pesticides (fungicides, insecticides, nematicides, and rodenticides) to seed to control diseases and pests affecting seeds and seedlings (White and Hoppin 2004). Some seed treatment products are sold as combinations of one or more of these pesticides, and bird repellents sometimes included (Kennedy and Connery 2008). These pesticides can be applied to the seed in several ways without modification of the shape and size of seeds, such as dust application and film coatings, although there are a few exceptions, such as pelleting (Pedrini et al. 2017; Fig. 1). Since seed treatment does not generally alter the shape and size of seeds, the seed color is often modified (Fig. 2) to make treated seed less attractive to birds, differentiate between brands, alert farmers and others that seeds are treated and cannot be used for animal feed, and to facilitate cleaning operations in the case of an accidental spillage (Fig. 3).

Fungicide seed treatment (FST) is used to control: i) fungal pathogens that are seed surface-borne, such as those that cause covered smuts of barley and oats, bunt of wheat, black point of cereal grains, seedborne safflower rust, and pathogens that are both soilborne and seedborne (McMullen and Lamey 2000; Paveley et al. 1996); ii) internally seedborne fungal pathogens such as the loose smut fungi of cereals (Khanzada et al. 2002; McMullen and Lamey 2000; Paveley et al. 1996); and iii) soilborne pathogens that attack germinating seeds and seedlings both pre- and postemergence (McMullen and Lamey 2000; Paveley et al. 1996). While the first two groups of pathogens associated with seed are true fungi, the third group of pathogens associated with soil include either true fungi or oomycetes. After sowing a given crop, all these pathogens may cause a disease known as damping-off that involves a range of symptoms (Lamichhane et al. 2017), including nongermination due to seed decay or rotting (Fig. 4), prevention of seedling emergence before or after germination (Figs. 5 and 6), or the rotting and collapse of seedlings at the soil level, also known as seedling blight (Fig. 7). While the use of certified seeds limits preplanting risks due to seedborne pathogens, the postplanting risks due to soilborne pathogens represent the most important challenge for farmers. For example, damping-off disease causes up to 93% emergence failure in forage legumes annually across Australia (Simpson et al. 2011). Similarly, pre- and postemergence losses of a number of field crops due to damping-off range from 5 to 80% (Lamichhane et al. 2017). The incidence of damping-off disease increases following sowing into cool and moist soil conditions that are favorable for many soilborne pathogens, mainly for oomycetes, and unfavorable for seed germination and seedling emergence.

For field crops, FST is a common practice, although the percentage of seed-treated hectares varies for different crops and geographical areas (White and Hoppin 2004). In the U.S., almost 100% of corn and peanuts are treated, followed by cotton, potato, wheat, and soybeans (White and Hoppin 2004). In Australia, seed treatments are widely used for all field crops (Almasudy et al. 2015; You et al. 2020). In France, FST frequently occurs and the most recent data, based on a national questionnaire survey, shows that 93% of field crops sown in France were treated (Agreste 2014, 2019; Fig. 8). Seed treatment may be done by the seed distributor, seed company, and

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the farmer, although the respective proportion of the seed lots that are treated by each party may vary from one crop to another.

Three types of fungicides are used for FST in terms of their mobility (Fig. 9; Table 1). The first group are fungicides that act by contact; these are surface protectants that target seed surface-borne and soilborne pathogens. The second group of fungicides are locally systemic and target both seed surface-borne and internally seedborne pathogens. Finally, the third group of fungicides includes those that are xylem mobile and thus are systemically translocated. However, there are fungicides that may have more than one type of mobility. Under field conditions, all these fungicides target pathogens that attack germinating seed or emerging seedlings for up to 4–5 weeks from sowing (Kazda et al. 2005).

In this paper, we revisit the sustainability of fungicide seed treatments for field crops with a focus on Franco-Australian-North American context. We first describe the rate and volume of most commonly used active ingredients (a.i.) for FST of field crops. We then discuss benefits and limits of FST, especially risks related to operators' health (those who apply, handle, and use treated seeds) and nontarget soil organisms. Finally, we provide recommendations to increase benefits and limit risks related to FST.

Rate and Volume of Fungicides Used for Seed Treatment

An exact estimation of the percentage of area sown to crops treated with FST is lacking and often complicated, either because it is difficult to obtain this information from retailers or because it fluctuates from one season to another. This is especially so because farmers decide to use (or not use) FST based on their potential costs (seed costs, seed treatment price) and benefits (expected grain sale price) to reduce economic risk and increase profitability (Gaspar et al. 2015). Seed and seed treatment costs may represent a considerable amount of the input costs for a farmer. For example, soybean seed and FST costs constitute 48% of the farmers' input cost in the U.S. which corresponds to over US$7.5 billion annually (American Soybean Association 2015). Overall, farmers with poorly drained or no-till fields, less diversified crop rotations, and those planting early into cool and wet soils, and fields with a history of postplanting problems (e.g., soil crusting, flooding, soil compaction, or poorly drained soils) are most likely to benefit from FST (Mündel et al. 1995; Serrano and Robertson 2016, 2018). To the best of our knowledge, there is no information on the average volume of fungicides that are applied to the environment via seed treatment and databases such as FAOSTAT and EUROSTAT do not report these data. Here, based on the average rate of most frequently used fungicides for seed treatment of major field crops (Table 2), we made a first attempt to estimate the total average volume of key fungicide a.i.s introduced to the environment in Australia, the E.U., and the U.S. during a cropping season. We made this estimation taking into account the total area harvested for each crop (FAOSTAT 2017) and the scenario of 100% FST. For example, more than 23,000, 59,000, and 54,000 m^3 metalaxyl-M; more than 9,000, 23,000, and 21,000 m^3 fludioxonil; and more than 18,000, 47,000, and 43,000 m^3 tebuconazole were used in Australia, the E.U., and the U.S., respectively, in cropping season 2017. Likewise, 33,000 and 78,000 m^3 a.i./cropping season of thiram are used in Australia and the U.S., respectively, while this fungicide has been recently banned in the E.U. (Table 3; Supplementary Material).

Benefits of Fungicide Seed Treatment

FSTs usually offer broad spectrum protection, in that the a.i.(s) targets an entire genus or numerous species. Note that active ingredient mode of action needs to match the intended target pathogen group (i.e., oomycetes versus true fungi). Correct application of the FST is required to obtain the greatest net benefit. These benefits include improved seedling emergence, plant height, plant vigor, and plant and root biomass through protection from seedborne and soilborne pathogens (Anderson and Buzzell 1982; da Silva et al. 2017; Dorrance and McClure 2001; Guy et al. 1989). In addition, FST helps prevent seed transmission of seedborne pathogens (Khanzada et al. 2002), protects above-ground plant parts from infection by airborne pathogens early in the season hence reducing their sporulation levels (Sundin et al. 1999), and slows disease epidemic development (e.g., phoma stem canker of oilseed rape; Khangura and Barbetti [2004]). Other advantages of FST include i) cost effectiveness, compared with 'broadacre' (broadcast) pesticide applications (Greenhalgh and Clarke 1985; Greenhalgh et al. 1994); ii) user friendliness, as the use of seed treatment products reduces the need

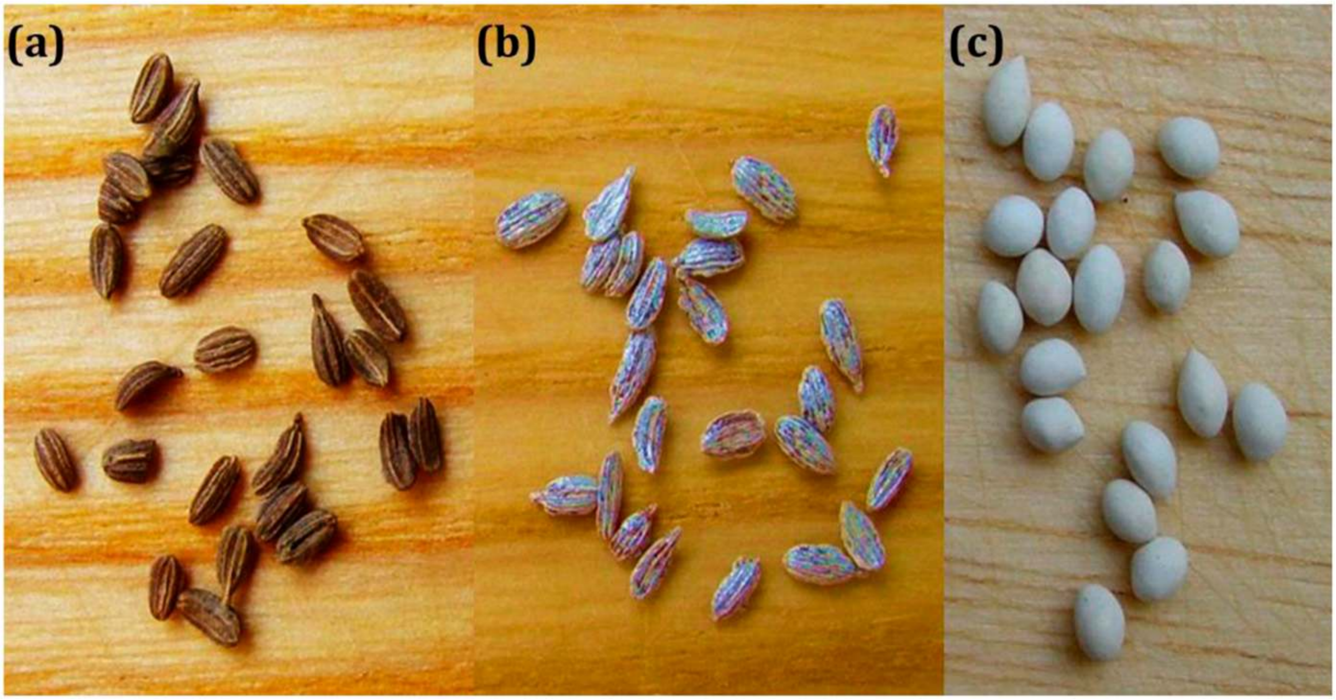

Fig. 1. Comparison of untreated (**a**), dust-applied (**b**), and pelleted (**c**) seeds. Seed pelleting coats the seed with protectants (fungicides, pesticides, insecticides, nematicides, predator deterrents, and herbicides) and other substances (micronutrients, growth stimulants, symbionts, and binding and protective polymers) in layers. Pelleted seeds therefore are subjected to consistent modifications of the original seed shape and size.

to handle chemicals on-farm, unless the farmer does seed treatments; and iii) less reliance on favorable weather conditions in terms of field access, compared with foliar spray applications (Munkvold et al. 2014). In addition, FST can be used to 'guarantee' successful germination and/or emergence of seedlings, by immediately protecting germinating seed, in contrast to in-furrow treatment mixed with fertilizers or foliar sprays that are not immediately available to germinating seeds or seedlings until a later stage of seedling development. In addition, the method by which chemicals are applied and introduced into the environment using FST offers advantages over fungicide application via in-furrow applications or those via foliar applications. For example, an FST only has an approximate 60 m^2 of contact per ha (Khangura and Barbetti 2004) in contrast to use of a fungicide applied via an in-furrow application mixed with fertilizers that has roughly 10 times more area of contact per ha, or a foliar spray, which has approximately 170 times more area of contact per ha (Greenhalgh and Clarke 1985; Greenhalgh et al. 1994). Further, the amount of a.i. required to achieve disease control as FST is often

Fig. 2. Treated seeds of field crops. Clockwise from top right: corn (blue), pea (dark purple), wheat (light red), rice (white), sunflower (black), peanut (light purple), oat (blood red), and soybean (yellow) in the center. Colors are applied to indicate that these seeds are treated and that they cannot be used for food or feed purpose (used with permission from BASF).

considerably less (5 to 10% of a.i. ha^{-1}) than the amount of a.i. applied as an in-furrow or foliar spray. Khangura and Barbetti (2004) compared fungicide treatments involving fluquinconazole as an oilseed rape seed treatment at 6.6 g a.i. kg^{-1} seed, flutriafol as an in-furrow treatment mixed with fertilizer at 100 g a.i. ha^{-1}, and foliar applications of flusilazole at 100 g a.i. ha^{-1}. They found all fungicide treatments substantially reduced blackleg severity and increased yields across four field locations. An additional benefit of FST over other application methodologies is control of seedborne infections of soilborne and other pathogens carried on seed (Paveley et al. 1996).

Limits of Fungicide Seed Treatment

The purported effectiveness of FST in providing broad-spectrum and systemic control of economically important seed- and soilborne diseases and the perception that seed treatments reduce overall pesticide use and have lower environmental impacts, compared with other application techniques, are the drivers behind increased use of seed treatments over the years. While the volume of pesticide a.i.s used for seed treatment is much lower than that used for foliar treatments, either to control soilborne or airborne pathogens, the regular introduction of a number of pesticides through FST raises several concerns related to operators' health and to nontarget soil organisms as discussed below. Where appropriate, comparisons of FST are made with other nonseed chemical application methods.

No Obvious Economic Return for Farmers

Field crops are generally low value crops, compared with industrial and vegetable crops, and consequently input costs often play a decisive role in farmers' cost of production. However, the limit of FST is that a farmer may choose to spend money on one without realizing a return on investment. In such a case, farmers may doubt the effectiveness of FST in controlling soilborne diseases. Indeed, even in the short term, the effectiveness of FST may significantly vary among cultivars, locations, sowing dates and rates, and years (Abati et al. 2014; Guy and Oplinger 1989; Rossman et al. 2018). Although FST may improve crop stand in high risk situations (conducive pedo-climatic conditions and presence of the pathogen in the soil), the profitability of this practice remains in question especially when FSTs are used when there is no risk of seedling disease and reduced stand establishment (Rossman et al. 2018). A recent study conducted across a wide spatio-temporal gradient in Iowa, U.S.A., demonstrated inconsistent crop establishment and yield responses due to soybean seed treatment (Serrano 2017). This means that FST may not be essential to achieve high plant stands, at least for crops that compensate stand losses during their further development, through ramification (e.g., oilseed rape), indeterminate or semideterminate growth (e.g., soybean), and tillering (e.g., wheat).

While the positive effects of FST on crop establishment can be easily observed and quantified under controlled conditions (Serrano and Robertson 2018; Urrea et al. 2013), this effect is not always noticed under field conditions. This is because most seed and seedling diseases of field crops are known as disease complexes, caused by synergistic interactions of multiple soilborne pathogens. In such a case, fungicides that are highly effective under controlled conditions against individual soilborne pathogens generally fail to produce significant benefits in field trials as recently reported from southern Australia (Barbetti and You 2017b; You et al. 2020). This is the reason for which many field attempts to control root rot of subterranean clover using fungicides have been, at best, discouraging in Australia (Maughan and Barbetti 1983; Wong et al. 1985).

Seed costs now constitute a greater percentage of operating costs due to associated seed technology fees (Lambert and Lowenberg-DeBoer 2003). Consequently, a farmer may be reluctant to use FST if there is nil or little profit related to this practice. In 2014, the United States Environmental Protection Agency stated there were limited-to-no benefits associated with the use of insecticide seed treatments in Midwestern soybean (https://www.epa.gov/pollinator-protection/benefits-neonicotinoid-seed-treatments-soybean-production). This statement may also be valid for FST. Despite these challenges, it is clear that there exists significant but rarely exploited opportunities for utilizing low-cost chemical seed treatments to ensure successful stand establishment and to ensure early seedling productivity when sowing crops or forages. However, more consistent and successful use of FST requires prior knowledge of the identity of the target pathogen or the pathogens in the soilborne complexes. Improved definition of the target pathogen(s) would undoubtedly lead to greatly improved application of FST, which is an important recommendation from this review.

Development of Resistance by Soilborne Pathogens

Overall, the risk of fungicide resistance development by damping-off pathogens, and oomycetes in particular, is greater when fungicides are applied on aerial plant parts (with repeated aerial applications), or when fungicides are applied as a soil drench (Lookabaugh and Shew 2016, 2017; Montes et al. 2016; Pérez et al. 2009; Porter et al. 2009; Qi et al. 2012). Fungicide resistance risk increases when fungicide modes of action are not rotated (i.e., when the same mode of action is applied multiple times). Almost all field crops are affected by the same soilborne pathogens causing damping-off (reviewed by Lamichhane et al. 2017), and consequently these crops are often treated with the same a.i. For example, metalaxyl/mefenoxam have been used to control oomycetes while fludioxonil is used to control *Fusarium* sp. causing damping-off (Ramusi et al. 2017). Nevertheless, the risk of resistance development

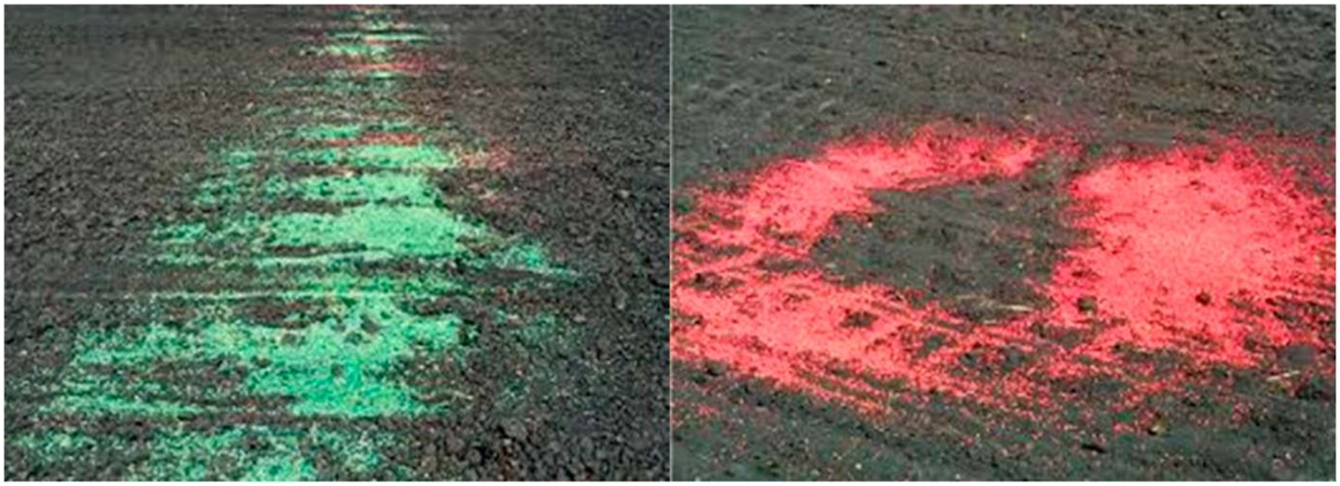

Fig. 3. Accidental spillage of treated seeds in a field plot during sowing operations. In such a case, the seeds should be immediately cleaned up or covered with soil to prevent exposure to birds and other wildlife (Source: Minnesota Department of Natural Resources).

seems to be lower via seed treatment, although resistance development by soilborne oomycetes to fungicides used for seed treatments have been reported (Dorrance et al. 2004; White et al. 2019).

Fig. 4. Seed decay and rotting of soybean that led to seed germination failure (left) and a healthy seedling emerged (right) under field conditions.

Fig. 5. Characteristic feature of damping-off of mustard caused by soilborne pathogens. Disease symptoms consist of stunted plants, reddening of dying plants, and poor plant density leading to crop establishment failure.

Fig. 6. Pre-emergence damping-off of forage legume (subterranean clover; *Trifolium subterraneum*) caused by *Phytophthora clandestina*. The pathogen affects germinating seeds and emerging seedlings that finally results in dead patches and poor crop stand development.

Exposure Risks to Operators

Inhalation of dust contaminated with fungicide is a potential risk while applying chemicals to seeds (primary exposure). Field crop seeds may be treated by the seed distributor, the seed company, or the farmer, with the majority of seed treatment performed by the distributor (White and Hoppin 2004). Although there are few data, it is likely that most farmers in developed countries use already-treated seeds rather than doing on-farm seed treatment. Employees of seed production stations and seed companies, who treat seeds on a regular basis, are at the greatest risk of primary exposure.

Another potential exposure risk occurs through inhaling dust when pouring treated seeds into planters or handling leftover seeds (secondary exposure). Secondary exposure occurs for every field crop with treated seed, but with the percentage of farmers exposed and their level of exposure differing from one crop to another (White and Hoppin 2004). However, the relative frequency of secondary fungicide exposure associated with sowing treated seeds may be generally lower than actively applying fungicide or with treated seed transfer operations. Because sowing and handling of treated seeds is often not considered when assessing farmer exposure to fungicides (White and Hoppin 2004), the number of farmers potentially exposed is likely underestimated. A large-scale survey including 50,000 farmers in Iowa and North Carolina reported over 90% sown crops with potentially treated seeds (Alavanja et al. 1996), suggesting that most farmers are subjected to secondary exposure. In a survey conducted in France, farmers reported that they did not always wear personal protective equipment when handling treated seeds, nor were they always aware about health risks associated with fungicide exposure (Agreste 2014).

Negative Impacts on Nontarget Soil Organisms

In the last decade, there has been a surge of published studies reporting the negative effects of neonicotinoid seed treatments on bees (Douglas and Tooker 2016). By contrast, there are relatively few studies that demonstrated negative effects of FST on nontarget soil organisms (Table 4). Some of the a.i.s are broad spectrum and thus affect both pathogenic and nonpathogenic fungi/oomycetes, thereby reducing ecosystem services provided by these organisms (Nettles et al. 2016; Van Hoesel et al. 2017; Zaller et al. 2016). We propose that a move toward higher application rates of FST and/or combinations of fungicides with different modes of action may increase negative effects on soil microbial diversity. Consequently, relative risks of higher application rates of FST and/or combinations of chemicals should be determined prior to implementing any such changes.

Negative Impacts of FST Costs

Some of the chemicals used to treat seeds are not cost effective and too narrow in scope (Gianessi and Reigner 2006). Research and outreach are thus needed to encourage best practices for selection of fungicides by farmers treating their own seed. Although metalaxyl is the only registered fungicide to control damping-off caused by oomycetes in many crops, this chemical is expensive and targets only one of several pathogens associated with damping-off (Gianessi and Reigner 2006). There are many alternative and cheaper fungicide treatments, especially the old broad-spectrum chemistries like thiram, mancozeb, maneb, zineb, and ziram, that not only could be more effective as they target a much wider range of soilborne pathogens associated with damping-off. Nevertheless, the limit of these broad-spectrum fungicides could be that they need to be applied at higher rates a.i. with consequent higher volume of a.i. in the environment, and thus more risks to those treating/using treated seed.

Recommendations to Increase Benefits and Limit Risks Related to FST

The need for FST depends on the type of crop, the season, and environmental conditions, especially when conducive for soilborne pathogens. For example, in the Pacific Northwest region of the United States, large seeded legumes like peas and chickpeas could not be grown without a seed treatment as *Pythium* spp. would significantly reduce the stand (Chen and Van Vleet 2016). Similarly, organic pea farmers in the Columbia basin of central Washington have a significant problem with damping-off that reduces crop establishment and yield (Alcala et al. 2016). In contrast, the impact of damping-off caused by *Pythium* spp. is lower on cereals in the same region (Paulitz 2006). Although there are hurdles associated with developing management recommendations for products that are applied prior to planting, for example determining which pathogens are present in a given field, it is possible to overcome these hurdles based on a farmer's experience that includes historical observations of seedling disease and disease or pathogen scouting and survey programs. Farmers may not fully appreciate the value of an FST since only treated seeds are planted and nontreated seeds are not used as a check or control to observe the disease incidence and severity to validate the value of the FST.

Fig. 7. Seedling blight of soybean caused by soilborne pathogens. The disease causes severe crop stand losses across many parts of the U.S. (Rossman et al. 2018). Despite an important recent increase in the use of treated seeds (Munkvold et al. 2014), damage due to soilborne pathogens have become a real challenge across these areas (Photo courtesy of Martin I. Chilvers, Michigan State University).

Seed treatments are often considered "insurance," particularly on higher value crops. Seed is expensive, and protecting that investment is made easier with high-quality seed treatments that are relatively inexpensive and that protect germinating seeds and emerging seedlings from soilborne pathogens. In addition, the ability to reduce seedborne inoculum over time makes FST popular among farmers. A good example is if farmers consistently use seed treatment to control bunts and smuts on cereals, these diseases can become minor problems over time. However, if seed treatments are then no longer applied, the inoculum slowly builds up again as disease becomes more prevalent each growing season. This increase in inoculum and consequently disease is particularly true when a conventional farm that used treated seed to manage a seedborne disease converts to organic production and no seed treatment is used.

Lack of use of FST over time may enhance the beneficial microbial communities, which in turn may help build suppressive soils to soilborne diseases. Even if farmers do not use FST, they could benefit from "the herd effect", similar to what is seen with human vaccines (i.e., if the vaccination rate is high enough, nonvaccinated people benefit). The potential long-term benefits obtainable from the lack of FST against the short-term benefits from FST deserves an in-depth economic and environmental evaluation. Recent studies on profitability and efficacy of soybean seed treatment showed that seed treatment effects on plant stand and yield were environment-specific (Gaspar et al. 2017; Rossman et al. 2018). This variability in the effectiveness of FST explains that the choice of an FST should be evaluated before planting a given crop, taking into account economic and environmental sustainability of this practice. Overall, the following points need to be addressed to limit risks due to FST.

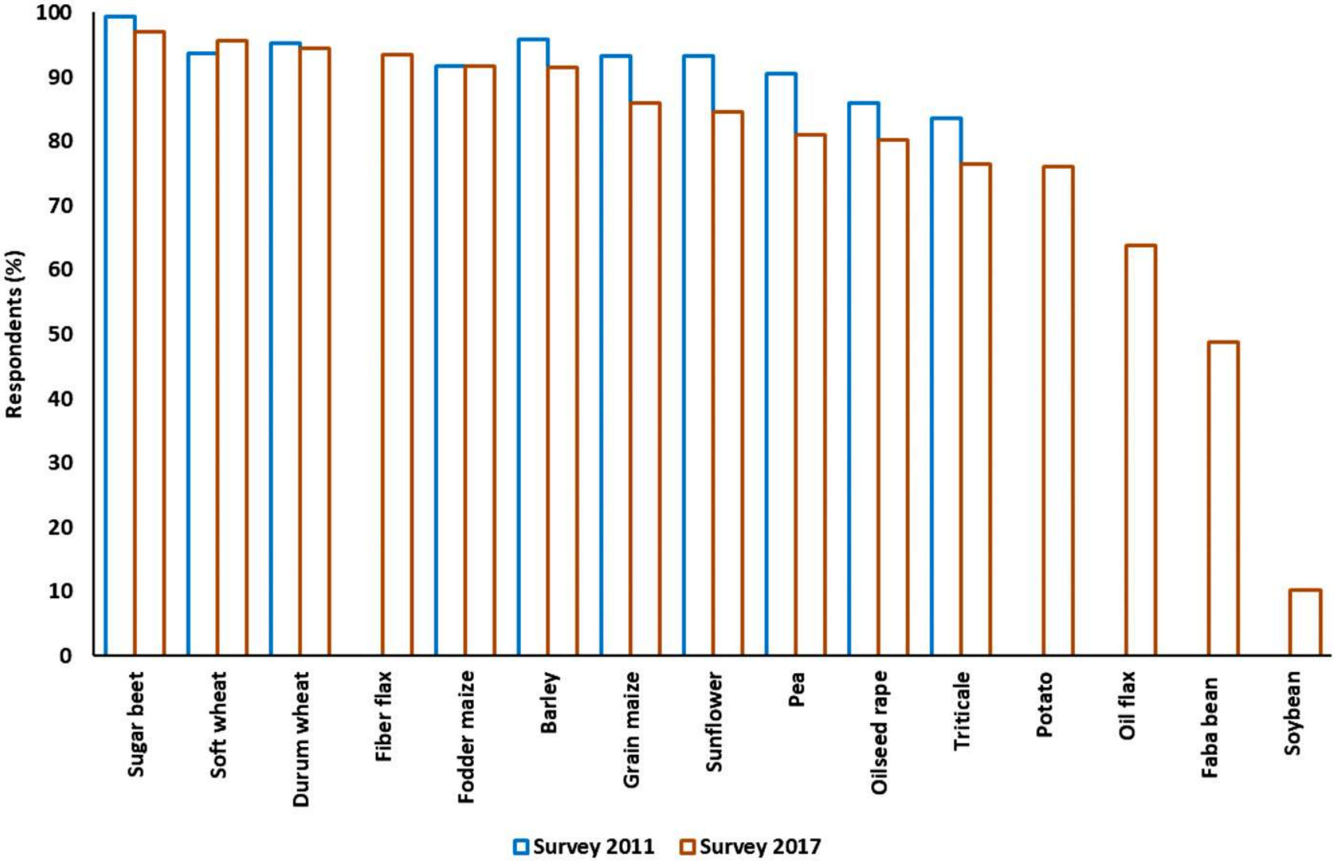

Fig. 8. Percentage of major field crops sown with treated seeds in France based on the results of a questionnaire survey in 2011 and 2017. The results were based on the survey of 25,000 and 28,000 farmers in 2011 and 2017, respectively. Seed treatments in 2017 were widespread and were highest for sugarbeet followed by barley, soft wheat, fiber flax, fodder maize, barley, grain maize, sunflower, pea, oilseed rape, triticale, potato, oil flax, faba bean, and soybean. The 2011 survey was not conducted for fiber flax, potato, oil flax, faba bean, and soybean (Agreste 2014, 2019).

Strictly Follow Regulations while Handling Pesticides

Most developed countries have extensive regulations in place to prevent or limit inappropriate, illegal, or otherwise unsafe use of conventional pesticides, including those used for seed treatment. The regulations and associated monitoring programs to minimize potential exposure of operators and determine how leftover seed is disposed have become increasingly stringent in many developed countries (Damalas et al. 2019; Handford et al. 2015). In addition, there have been associated advances in FST technologies to limit risks to applicators and users of fungicide-treated seed, as well as advances to limit potential adverse environmental impacts of FST. Nevertheless, these regulations, which include fungicide product label requirements for personal protective equipment, rates of application, methods of application, etc., are not always strictly followed by operators, in both developing and developed countries (Damalas et al. 2019; Kearney et al. 2015). Adhering strictly to all these regulations will certainly help reduce negative impacts of these chemicals on human health and on the nontarget soil organisms.

Limit or Avoid Use of Treated Seeds When Disease Risk is Low

FSTs are often used in what is considered a prophylactic or “cheap insurance” manner, even when disease incidence is low or not present at all (Rossman et al. 2018; Serrano 2017). If a field does not have a history of seedling disease/damping off because of low soilborne pathogen numbers, an FST is probably an additional and unnecessary input cost that cannot be recovered from prevented stand loss, replant situations, and final yield loss. In such situations, use of FST is likely unwarranted and should be avoided. However, this knowledge requires an ability and/or process to quantify the disease risk on individual farms.

Have Prior Knowledge About Key Potential Soilborne Pathogens in Your Field

Field crop seeds are often treated with a number of different fungicide a.i.s that target key soilborne pathogens. However, not all soils harboring these pathogens pose the same risk of damping-off as a given soil may contain other mutualistic or antagonistic microorganisms that reduce or even neutralize the pathogenic potential of soilborne pathogens (Hayden et al. 2018; Löbmann et al. 2016). Based on their previous experience and historical problems observed over the years, farmers may already know the prevalent pathogens in their soils via soil testing. If they do, this enables specific pathogens to be targeted, reducing the cost by identifying the particular fungicide needed and at the same time eliminating additional cost associated with the purchase of other unnecessary fungicides and/or seed treatments. Nevertheless, in many developed countries such as Australia and the U.S., characterized by big farm sizes, farmers tend to use already treated seeds and in such a case they have little choice as the

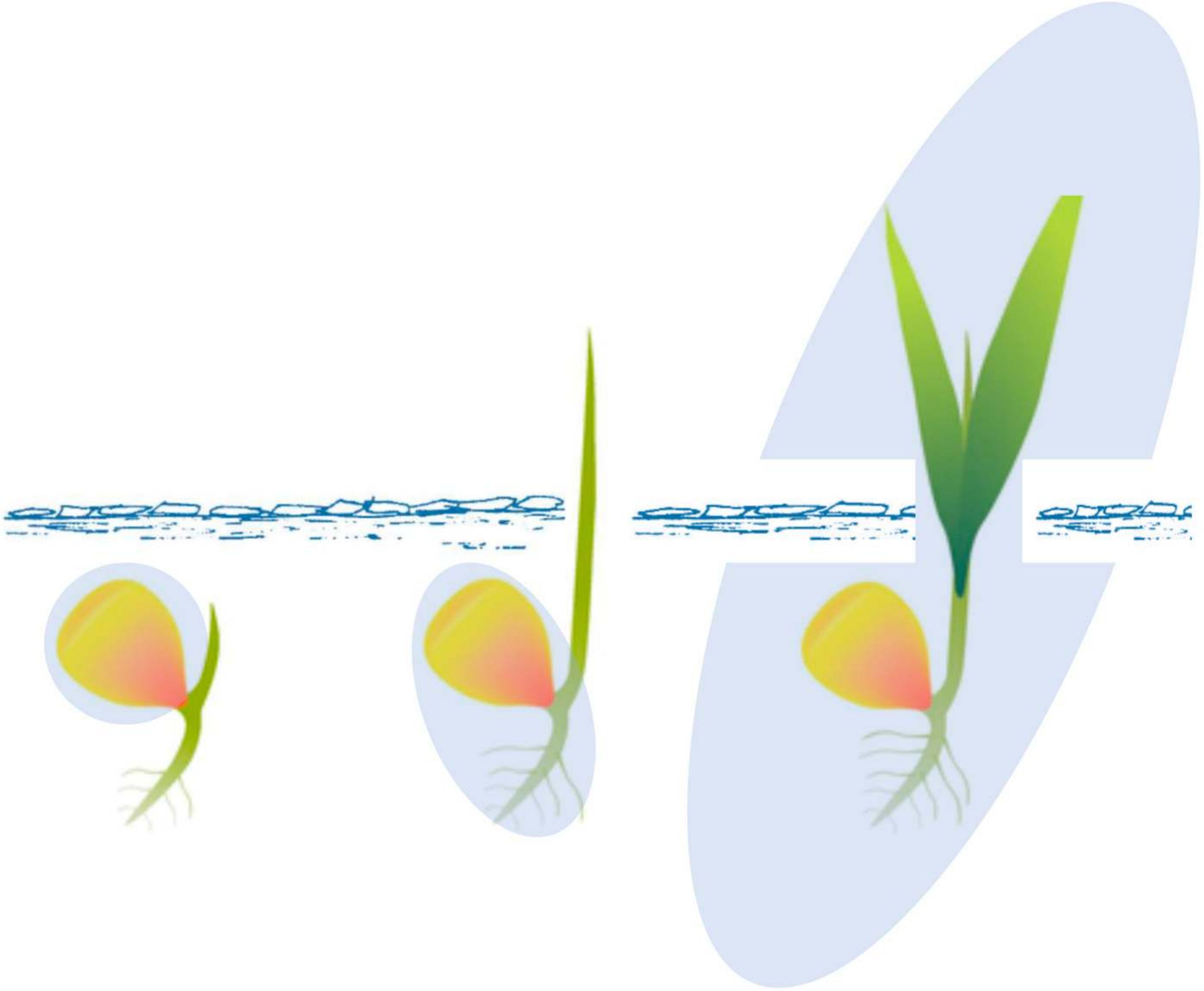

Fig. 9. Mobility of fungicides used for seed treatment. The light blue area shows the zone of protection covered by contact (left), locally systemic (middle), and fully systemic fungicides (right), respectively. Fungicides that are locally systemic or fully systemic in the xylem become mobile within the germinating seeds and emerging seedling after the seed has imbibed moisture and the germination process has been activated physiologically.

type of FST is often decided by the seed company. Quantification of inoculum level and determining the risks related to soilborne pathogens, especially where pathogen complexes are involved, is challenging in practice. Indeed, many real time PCR techniques have been developed in past decades, mainly in the U.S., for detection of *Pythium* spp. and *Rhizoctonia* spp. from the soil, but their application is very limited (Paulitz 2006). This is due to the lack of long-term agronomic data preventing investigations into potential relationships between inoculum density and seedling emergence rates or crop yields. An exception occurs in Australia where DNA of soilborne pathogens is routinely extracted from soil samples by commercial "PredictaB" DNA extraction service operated by South Australian Research and Development Institute, Adelaide (Ophel-Keller et al. 2008). This particular assay assists grain and forage producers in identifying which soilborne pathogens pose a significant risk to their crops prior to seeding and enables steps to be taken to minimize risk of yield loss. This assay has been found to be appropriate and accurate for the specified purpose for both grain crops (Herdina et al. 2004; Ophel-Keller et al. 2008) and forage legumes (Simpson et al. 2011).

Table 1. Key fungicides commonly used for seed treatment and their characteristics (sources: FRAC 2006; Krämer and Schirmer 2007; Mueller and Bradley 2008; https://www.apsnet.org/edcenter/disimpactmngmnt/topc/Documents/CommonAndTradeFungicides.pdf)

Chemical family	Fungicide common name	Mobility	Mode of action	Risk of resistance[a]	Manufacturer	Target disease	Target pathogen and effectiveness[b]			
							Pythium spp.	*Rhizoctonia* spp.	*Fusarium* spp.	*Phytophthora* spp.
Dicarboximide	Captan	Contact	Broad-spectrum	Low	Bayer CropScience	Damping-off	++	++	+	–
Dicarboximide	Iprodione	Localized penetrant/ translaminar	MAP/Histidine-kinase in osmotic signal transduction	Medium to high	Bayer CropScience	Damping-off	–	+++	+++	–
Thiadiazole	Etridiazole	Contact	Inhibits respiration	Low to medium	AgriGuard	Damping-off	+++	–	–	+++
Phenylpyrrole	Fludioxonil	Contact	Disrupts membrane integrity, broad-spectrum	Low to medium	Syngenta Crop Protection	Damping-off	–	+++	+++	–
Phenylamide	Metalaxyl	Xylem mobile	Inhibits RNA synthesis, active on oomycetes	High	Bayer CropScience	Damping-off	+++	–	–	+++
Phenylamide	Mefenoxam	Xylem mobile	Inhibits RNA synthesis, active on oomycetes	High	Syngenta Crop Protection	Damping-off	+++	–	–	+++
Carbamate benzimidazole	Benomyl	Xylem mobile	Inhibits tubulin formation in mitosis, broad-spectrum	High	Syngenta Crop Protection	Damping-off	–	–	+++	–
Carbamate benzimidazole	Thiophanate methyl	Xylem mobile	Inhibits tubulin formation in mitosis, broad-spectrum	High	Bayer CropScience	Damping-off	–	+++	+++	–
Carbamate	Thiram	Contact	Reacts with protein SH groups; broad-spectrum	Low	Bayer CropScience	Damping-off	+	++	+	–
Carbamate	Mancozeb	Contact	Reacts with protein SH groups; broad-spectrum	Low	Dow AgroSciences	Other[c]	V	V	V	V
Anilide	Carboxin	Locally systemic	Inhibits respiration (MET2, succinate dehydrogenase), activity includes basidiomycetes	Medium to high	Bayer CropScience	Other	V	V	V	V
Triazole	Difenoconazole	Xylem mobile	Sterol biosynthesis inhibition, broad-spectrum	Medium	Syngenta Crop Protection	Other	V	V	V	V
Triazole	Tebuconazole	Xylem mobile	Sterol biosynthesis inhibition, broad-spectrum	Medium	Bayer CropScience	Other	V	V	V	V
Triazole	Triadimenol	Xylem mobile	Sterol biosynthesis inhibition, broad-spectrum	Medium	Bayer CropScience	Other	V	V	V	V
Triazole	Prothioconazole	Xylem mobile	Sterol biosynthesis inhibition, broad-spectrum	Medium	Bayer CropScience	Other	V	V	V	V
Triazole	Triticonazole	Xylem mobile	Inhibits respiration (MET-III, cytochrome bc1), broad-spectrum	High	BASF	Other	V	V	V	V
Phenylurea	Pencycuron	Contact	Inhibitor of spindle microtubules assembly	Low	Bayer CropScience	Other	V	+++	V	V
Strobilurine	Azoxystrobin	Locally systemic	Inhibits respiration (MET-III, cytochrome bc1), broad-spectrum		Syngenta Crop Protection	Damping-off	–	+++	–	–
Strobilurin	Pyraclostrobin	Locally systemic	Inhibits respiration (MET-III, cytochrome bc1), broad-spectrum	High	BASF	Other	V	V	V	V
Strobilurin	Trifloxystrobin	Locally systemic	Inhibits respiration (MET-III, cytochrome bc1), broad-spectrum	High	Bayer CropScience	Other	V	V	V	V

[a] Risk of resistance is considered high when mode of resistance is known (or suspected) to be qualitative or some pathogens have already developed resistance within a few years under commercial use, medium when mode of resistance is quantitative, and low when the fungicide has multisite activity. Entries in this column were assigned by FRAC (https://www.frac.info).

[b] Excellent (+++); good (++); fair (+); poor or no activity (–); V: variable, depending on the target pathogen.

[c] Other diseases include root rots, smuts, bunts, seed and seedling blights, tan spots, powdery mildew, and spot blotch.

Table 2. A nonexhaustive list of the most utilized fungicides for seed treatment worldwide to control damping-off either alone or in association with other pesticides, their composition, recommended rate, and crops for which they are labeled (Source: https://www.syngenta.com)

Fungicide trade name[a]	Product rate (ml kg^{-1} seed)[b]	Pesticide composition (g a.i. liter^{-1})	Labeled crop[c]
Apron XL LS	0.20–0.40	Metalaxyl-M (339.2)	Oilseed rape, carrot, cereals, sorghum, garden beets, field peas, beans, soybeans, cucurbit vegetables, leafy greens
	0.40	Metalaxyl-M (339.2)	Forage legumes, turf grasses, sunflowers
Apron XL 350 ES	1.0	Metalaxyl-M (350)	Beetroot, lucerne, subterranean clover
	0.75	Metalaxyl-M (350)	Peas
	1.50	Metalaxyl-M (350)	Soybean
Ausatral Plus (Net)	5.0	Fludioxonil (10), tefluthrine (40).	Cereals
Beret Gold	2.0	Fludioxonil (25)	Cereals
Celeste Extra	2.0	Fludioxonil (25) and difenoconazole (25)	Cereals
Influx Quattro	0.50	Fludioxonil (37.5) + metalaxyl-M (29) + azoxystrobine (15) + thiabendazole (300)	Corn
Iprodione 250	1.0–4.0	Iprodione (250), liquid hydrocarbons (316)	Lupins
Maxim 480FS	1.0	Fludioxonil (480)	Cabbage, carrot, onion, spinach
Sativa IM RTU	3.93	Tebuconazole (4.8), metalaxyl (6.4), imidacloprid (16)	Barley, oats, triticale, wheat
Sativa 309 FS	0.05–0.48	Tebuconazole (309)	Barley, corn (field corn, field corn grown for seed, popcorn, sweet corn), oats, triticale, wheat
Signet 480 FS	3.0	Thiram (480)[d]	Barley, beans and peas, beets, broccoli, brussel sprouts, cabbage, canola, cantaloupe, carrot, cauliflower, collards, corn (field, sweet), cotton, cucumber, eggplant, flax, grasses, kale, lettuce, millet, mustard, oats, onion, ornamental flower seed, peanuts, pepper, pumpkin, radish, rice, rye, safflower, small seed legume, sorghum, spinach, squash, sunflower, tomato, triticale, wheat, and all other vegetable seeds
Spirato 480 FS	0.05–0.10	Fludioxonil (480)	Barley, bulb vegetables, corn, cotton, cucurbits, fruiting vegetables, herbs and spices, leafy vegetables, legumes, oats, peanuts, rice, sorghum, sunflower, wheat

[a] There are many other products that have different trade names but the same active ingredients, particularly a.i.s that are no longer protected by patents (patents have expired).

[b] This is the average broadcast product rate, which may differ from one country to another and may also differ depending on crop species or their thousand seed weight.

[c] Registered for use in one or more regions/countries worldwide.

[d] Recently banned in the E.U. but widely used elsewhere.

Table 3. Average estimated volume of some key fungicide active ingredients (m^3 of a.i./cropping season) applied to seeds and introduced to the soil to control damping-off disease in Australia, the E.U., and the U.S. (see Table 2 and Supplementary Data S1 for details). The exact quantity of a.i. applied via seed treatment depends on the crop species, environment into which seed lots are planted, and regional or local regulations.

	Metalaxyl-M (m^3/cropping season)			Fludioxonil (m^3/cropping season)			Tebuconazole (m^3/cropping season)			Thiram (m^3/cropping season)[a]		
Crop	Australia	E.U.	U.S.	Australia	E.U.	U.S.	Australia	E.U.	U.S.	Australia	E.U.	U.S.
Barley	5,801	14,169	949	2,320	5,668	380	4,641	11,336	759	83,533	B	13,664
Maize	22	2,785	11,045	9	1,114	4,418	18	2,228	8,836	322	B	159,045
Oat	1,484	3,826	468	594	1,530	187	1,187	3,060	374	21,373	B	6,740
Oilseed rape	61	2	18	24	1	7	49	2	15	875	B	262
Pea	298	1,478	604	119	591	242	238	1,183	483	4,293	B	8,695
Sorghum	14	5	80	6	2	32	12	4	64	208	B	1,152
Soybeans	18	535	21,737	7	214	8,695	14	428	17,390	260	B	313,016
Sugarbeet	NA[b]	21	6	NA	2	1	NA	5	1	NA	B	23
Sunflower	1	143	18	0	41	5	1	82	10	9	B	188
Triticale	69	3,129	NA	28	1,251	NA	56	2,503	NA	1,000	B	NA
Wheat	15,727	33,659	19,622	6,291	13,464	7,849	12,581	26,928	15,697	226,463	B	282,554
Total	**23,496**	**59,752**	**54,547**	**9,398**	**23,879**	**21,815**	**18,796**	**47,757**	**43,630**	**338,336**	**0**	**785,340**

[a] B: Recently banned in the E.U. but widely used elsewhere.

[b] NA: Data on harvested area not available.

Impact of Tillage on FST

The type of tillage system may affect the efficacy of an FST (Guy and Oplinger 1989; Wheeler et al. 1997). Although there is no consensus in the literature regarding the effect of tillage practices on soilborne pathogen prevalence (reviewed by Lamichhane et al. 2018), direct seeding in the presence of surface crop residue affects soil conditions such that they may be conducive for soilborne pathogens. In the absence of soil surface residue or mulch, no-till soil conditions are also likely to keep soil temperatures low, especially in temperate regions, that in turn may lead to a slow rate of germination and seedling growth and thus make seedlings more prone to pathogen infection. This is especially true across regions characterized by frequent rainfall events since the seedbed moisture plays a key role in damping-off diseases. For instance, soybean seed treatment was beneficial under no-till and with certain cultivars, but not in the higher yielding reduced tillage and conventional tillage systems (Guy and Oplinger 1989). Retaining surface crop residues, however, does encourage development of suppressive soils against pathogens like *Rhizoctonia* spp. that do not like the increased microbial competition that arises as a consequence of surface crop residue (Roget 1995). Moreover, tillage can reduce the pathogen disease pressure due to breaking up of hyphal networks and increased activity of competitive soil microbes from soil aeration (e.g., this disadvantages *Rhizoctonia* spp.), by dispersing and diluting pathogen inoculum throughout the soil rather than it frequently being concentrated in the surface soil layers, and by allowing faster root growth through the soil profile with corresponding reduced damping-off and root disease (e.g., these latter two disadvantage soilborne fungal and oomycete pathogens) (Barbetti and MacNish 1984; You et al. 2017; You and Barbetti 2019).

Plant Genotype and Sowing Date

FSTs should be considered if seed will be sown into cool and moist soil conditions, which could mean early in the growing season in the U.S. and France, and later in the growing season in Australia. The level of host resistance (complete, partial, or null) of a plant genotype generally alters the effectiveness of FST. The benefit of an FST is generally realized on susceptible varieties but not partially resistant varieties (Anderson and Buzzell 1982; Dorrance and McClure 2001; Guy et al. 1989; Wang and Davis 1997). Most soilborne pathogens have a broad host range (reviewed by Lamichhane et al. 2017) and a variety resistant to a specific soilborne pathogen may be highly susceptible to one or more other soilborne pathogens existing at the same

Table 4. Literature reports of negative effects of fungicides commonly used for seed treatments on nontarget soil organisms

Fungicide[a]	Crop	Effects observed	References
Fluoxastrobin, fluopyram, tebuconazole, prothioconazole	Wheat	Reduced litter decomposition rate	Zaller et al. 2016
Strobilurin and triazolinthione	Wheat	Reduced surface activity of earthworms	Van Hoesel et al. 2017
Fludioxonil, metalaxyl-M, carboxine, thiram, difeconazole, carbendazim	Soybean	Carbendazim and thiram, regardless of the combined applied insecticide, was the most harmful to *Bradyrhizobium* spp.	Gomes et al. 2017
Benzimidazole, dicarboximide, thiram	Chickpea, pea, and wheat	Population decline of biocontrol agents and their performance with reduced root and shoot biomass and grain yield	Gaind et al. 2007
Metalaxyl, thiram, carbathiin, oxycarboxin, thiabendazole	Chickpea	Decreased number of viable rhizobia on the seed, reduced nodulation and shoot dry matter	Kyei-Boahen et al. 2001
Fludioxonil, mefenoxam, azoxystrobin, thiabendazole, and sedaxane	Maize and soybean	Negative effects on rhizosphere soil microbial communities and endophytic leaf fungal communities	Nettles et al. 2016
Carbendazim, thiram, or carboxin	Soybean	Reduced soybean nodulation	Zilli et al. 2009
Trifloxystrobin, pyraclostrobin, azoxystrobin, fludioxonil, mefenoxam, thiamethoxam, prothioconazole, penflufen, metalaxyl, sedaxane, tebuconazole, and triticonzole	Corn, soybean, and oat	Minimal effect on arbuscular mycorrhiza colonization	Cameron et al. 2017
Carbendazim	Rice, green gram, soybean, and cowpea	Negative effects on fungal endophytes of rice seedlings and suppression of shoot and in all the crops	Vasanthakumari et al. 2019
Azoxystrobin	NST[b]	Azoxystrobin under certain conditions can reduce fungal soil diversity	Adetutu et al. 2008
Azoxystrobin	NST	Reduced microbial populations, negative influences on the activities of urease, protease, and dehydrogenase	Guo et al. 2015
Azoxystrobin	NST	Growth inhibition of organotrophic bacteria, actinomycetes, and fungi; changes in microbial biodiversity; inhibitory effect on the activity of dehydrogenases, catalase, urease, acid phosphatase, and alkaline phosphatase	Baćmaga et al. 2015
Iprodione	NST	Altered microbial communities and elevated dosages of iprodione may potentially affect the microbial community structure and diversity of the soil	Verdenelli et al. 2012
Mefenoxam	NST	Detrimental effects on sensitive populations of fungi	Demanou et al. 2006
Metalaxyl	NST	Repeated use caused negative effects on soil microbial community structure	Wang et al. 2019
Metalaxyl and mefenoxam	NST	Activity of dehydrogenase and the availability of NO_3– were generally adversely affected	Monkiedje and Spiteller 2005

[a] Fungicides were used alone or in combination.

[b] NST: no seed treatments were applied but the fungicides were directly applied to soil to evaluate their effects.

location. Indeed, no benefits of metalaxyl seed treatment were reported in Pythium-resistant cotton cultivars, although seed treatment with carboxin pentachloronitrobenzene for the control of Rhizoctonia-induced damping-off resulted in stand increases of some cultivars in field trials (Wang and Davis 1997). In general, most field crops have low resistance against damping-off pathogens such as *Rhizoctonia* spp. and *Pythium* spp., with resistance to *P. sojae* in soybean a notable exception. Even so, if partial resistance to a soilborne pathogen is present in a crop, the level of partial resistance would likely be insufficient to limit damping-off and seedling root disease if deployed alone, and consequently, use in combination with an FST would be beneficial. Further, recent studies successfully identified forage legumes with a general 'tolerance' to soilborne complexes involving *Pythium irregulare*, *Aphanomyces trifolii*, *Rhizoctonia solani*, various *Fusarium* spp., and >30 races of *Phytophthora clandestina* (Barbetti and You 2017a), which suggests an alternative approach to managing soilborne complexes, although there likely still will be a place for use of FST depending upon the level of tolerance in particular varieties.

Seed Treatment Application

The time interval between treating and sowing seed should be minimized to avoid negative effects on seed germination and/or seedling emergence and to reduce risk of phytotoxicity. Long-term storage of treated seeds slowed time to and rate of emergence as well as coleoptile length of winter wheat (Purchase et al. 1992). Because time at planting is often limited, on-farm seed treatment may not always consider the required time interval, especially when farmers have to treat a high volume of seed. The relative effectiveness of seed treatments depends upon the on-farm method of application (Barbetti 1981). Poor application of FST is counterproductive because high seed coverage increases producer returns compared with low seed coverage (Poag et al. 2005). As storage time of treated seeds increases, there is a higher risk of phytotoxicity (Khaleeq and Klatt 1986), although the level of phytotoxicity depends on the type of chemistry used. In this paper, we emphasize the need to reduce the time interval between seed treatment and sowing wherever possible, and to ensure effective application methods are used.

Seed Quality

FST will not compensate for poor seed quality. Seed produced under stressed conditions or those with mechanical injury, that are shriveled and or have low germination rates may still have poor stand establishment even with fungicide treatments (Barnard and Calitz 2013; Fahad et al. 2017). Seed size may also compromise FST efficacy, especially for crops characterized by bigger seed size, as smaller seeds may germinate but they usually establish poorly. Therefore, other good agronomic practices such as using pathogen-free seed, selecting resistant/tolerant cultivars, improving soil drainage, and maintaining optimal fertilizer, likely compliment FST.

Precision Planting of Treated Seed

Use of precision farming can greatly reduce negative impacts of FST and improve profitability of FST. Precision farming, also known as prescribed farming, is the use of inputs only where and when they are needed (Schimmelpfennig 2016). Currently, farmers sow fungicide treated seeds over the entire field even though problematic areas of the field, where an FST can provide benefits for farmers, may constitute a small fraction of the field. Nevertheless, it is becoming popular for fungicides to be applied to the seed as part of a seed pelleting process that facilitates precision planting, especially in row crop farming. Recent advancements in multihybrid planter technology should enable treated seed to be planted in areas of fields with a history of stand establishment problems thus reducing input costs and fungicide exposure per unit area. Stevens et al. (2018) reported use of ILeVo (a.i.) seed treatment only in management zones with a history of soybean sudden death syndrome resulted in a net profit of US$78 per acre compared with a loss of US$15 per acre when seed treated with ILeVO was planted across the entire field. This underscores the importance of precision sowing, which not only reduces input costs and nontarget impacts of seed treatments but maximizes overall profitability of the crop by minimizing yield loss in areas where pathogens are most prevalent.

What is the Future for Fungicide Seed Treatment?

Past research on FST focused on short-term economic benefits, based on the search for more effective pesticides that could improve crop stand and yield, without considering environmental problems in the long term due to the use of treated seeds. However, there has been great progress in recent years regarding the availability of science-based information on benefits and risks relating to FST. Consequently, the general public is more aware of health and environmental issues and that more people are looking for information related to potential benefits versus risks of using treated seeds. At the same time, it is surprisingly difficult to find information on various aspects of FSTs. This difficulty could be due to the lack of a close collaboration between public research and the seed industry, and the generation of public knowledge on the benefits versus risks of FST should increase in the future. This knowledge should facilitate judicious use of fungicides, which seems to be a more pragmatic option for field crops than searching for alternatives to FST. This is because certain seed technologies such as seed priming is predominantly applied commercially to high value and small volume seeds lots (e.g., vegetables or some industrial crops such as sugar beet), which are unlikely to be generally feasible for lower-value broad acre crops. Indeed, scale and cost versus benefits of these technologies remains an issue for broad acre crops and needs further investigation and better definition. Future use of FST may differ markedly around the world. Disparate regulations related to FST in various countries; multiplicity of soil types, environmental conditions, and production practices; diversity in seedborne and soilborne pathogens that might be the target of FST; and disparate resources available to farmers as well as contrasting philosophies regarding pesticide use around the globe, all affect FST. In the E.U., evolving pesticide legislation has led to the ban of a large number of previously available pesticides that were often used as seed treatments. According to the updated data of the E.U. pesticide database (file updated on 23 February 2018), following the regulation 1107/2009/EC, 493 pesticides have been approved for renewal, 827 have not been approved, 27 are pending approval, and 20 have been banned from use. With regard to fungicides used in seed treatments, the European Commission has set phase-out schedules for the following fungicides: benzimidazole, carbamate, carbendazim dicarboximide, and iprodione, following the decision not to renew their E.U. approval (The EU pesticide database, https://ec.europa.eu/food/plant/pesticides_en). This change in legislation clearly highlights a need to urgently seek more sustainable forms of seed treatments that are both efficacious and cost effective; the latter is important for field and forage crops given their comparative low value compared with crops farmed in intensive horticulture. Use of precision planting will also have a role in reducing nontarget effects of FST as well as reducing costs and preserving yield.

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Jay Ram Lamichhane

Dr. Jay Ram Lamichhane is a research scientist at INRAE, France. He earned a B.S. (cum Laude) and an M.S. (cum Laude) in agronomy in 2005 and 2007, respectively, at Tuscia University, Viterbo, Italy. He then earned a Ph.D. (best ranked) in plant pathology in 2011 and worked as a postdoc fellow for over two years at the same university before moving to France in 2013. He worked for a year as visiting postdoc fellow at Plant Pathology Research Unit, INRA, Avignon. From 2014, he was involved within the scientific coordination of Europe-wide IPM networks called ENDURE (http://www.endure-network.eu/) and C-IPM (http://c-ipm.org/), both aiming to foster IPM in European agriculture. Dr. Lamichhane has worked on etiology, epidemiology, and management of diseases caused by bacterial and fungal pathogens on horticultural, fruit, and nut tree crops. In September 2017, he was hired by INRA into a tenured position to work on abiotic and biotic factors, cropping practices, and their interactions affecting field crop establishment. He thus works at the interface between agronomy, plant pathology, soil science and soil microbial ecology using both experimental and modeling approaches. Dr. Lamichhane serves as co-editor-in-chief of the international journal Crop Protection. He has authored or co-authored over 60 publications in peer-reviewed international journals with scientists worldwide, published several book chapters, congress proceedings, and co-supervised several Ph.D. students.

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Dr. Mingpei You has more than 25 years of plant disease research experience, not only across diverse crops in Australia and China, particularly oilseed Brassicas and forage legumes, but also across rice, horticultural, and forestry diseases. She is widely recognized internationally for her research into etiology and epidemiology and in developing better integrated disease management. Her research has a strong emphasis on identifying novel host resistances against a wide range of soilborne and foliar fungal and oomycete pathogens. She has particular expertise in defining the temporal and geographic changes occurring with soilborne pathogen complexes and the effects of environment on such changes. She has also conducted critical research into better defining and improving our understanding of pathogen sub-specific variation at both the phenotypic and molecular levels, and on defining key drivers influencing host-pathogen interactions. She has unique skills in relation to the application of statistics to plant disease data and has published more than 80 refereed scientific papers in the last decade.

Véronique Laudinot

Véronique Laudinot is an extension advisor working at the chamber of agriculture of the Vosges, a French department of the Grand Est region. She is also involved at the national level chamber of agriculture network. She obtained a Master's degree in agronomy in 1991 from Agro Paris Tech. Since 2008, she has engaged in different activities related to the national action plan "Ecophyto," which aims to reduce the use of conventional pesticides in French agriculture. Her activities are focused on advising and training farmers involved within the network DEPHY FERME as well as supporting extension personnel in their evolution of training practices (CASDAR national groups: "conseillers demain," CASDAR Changer, and CASDAR Phyto'El). She is author or co-author of numerous articles in popular science journals and periodical reviews targeted to extension advisors. She often gives seminars on the potential of reducing reliance on conventional pesticides using agronomic tools and practical experiences. Currently, she is leading a 6-year project called FAST, related to the network DEPHY EXPE, that aims at assessing technical, economic, and environmental performances of cropping systems without chemical seed treatments.

Martin J. Barbetti

Prof. Martin Barbetti is recognized internationally for his numerous contributions over many years to crop protection research. His contributions focus mainly on providing a better understanding of the epidemiology and management of a wide range of foliar and soilborne pathogens across a diverse array of broad-acre and horticultural crops. His findings have been widely adopted to improve disease control. Martin comes from a farming background and was a plant pathologist at the Department of Primary Production and Regional Development Western Australia before he joined the University of Western Australia in 2004. A major focus of his research has been on diseases of oilseed Brassicas and forage legumes. He has more than 30 years of experience researching diseases of oilseed and vegetable Brassicas, forage and crop legumes, cereals, and a diverse array of horticultural crops. Practical findings from his research have greatly helped growers to improve their disease management procedures. He has published >270 refereed scientific papers across a wide range of crop-pathogen combinations, and a similar number of extension and conference articles. He has an extensive track record in building collaborations across international (e.g., India, China, Europe, and Africa) and national research institutions, including academia, government, and farmers, as evidenced by the large number of co-authored publications arising from these connections.

Jean-Noël Aubertot

Dr. Jean-Noël Aubertot is an INRAE research director. He is an agronomist specialized in crop protection. He studied fundamental physics and graduated from Paris University with a Master's degree in oceanography, meteorology, and environmental physics. He graduated from INA-PG (currently AgroParisTech University) with a Ph.D. in agronomy in 1998. He has a strong background in modeling, with experience designing and using models from different scientific fields: epidemiological models, ecological models, population genetic models, crop models, etc. For 20 years, his main research area has been the analysis and modeling of the impacts of cropping practices on pest development (mainly on diseases of arable crops). Since 2007, he has coordinated the INRA/CIRAD IPM network. He regularly participates to the ENDURE Executive Committee meetings and organizes international summer schools on a regular basis. He coordinated many national projects and was the leader of the methodological workpackage of the European Project PURE (2011–2015). He was involved in two major French national expertises on pesticide reduction ("Pesticides, Agriculture and the Environment", Aubertot et al., 2005; "Usages et alternatives au glyphosate dans l'agriculture française" Reboud et al., 2017). Since 2011, he is the president of the Scientific and Technical Support Committee for the National Coordination Cell in charge of the Farm and Experimental Networks of the French national action plan for pesticide reduction.

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