THE ROLE OF SEED TREATMENT IN MODERN U.S. CROP PRODUCTION

A REVIEW OF BENEFITS

CropLife
FOUNDATION

Executive Summary

Farmers must meet an array of demands and challenges every day: growing crops that have minimal disease and insect damage, protecting the environment and providing food for communities across the globe. In modern U.S. agriculture, farmers pursue continuous improvement through new technologies that help them face these obstacles in a sustainable way. This includes the responsible use of crop protection products (insecticides, herbicides and fungicides), applied to the soil, seeds or the growing crop.

Seed treatment specifically refers to the application of chemical products and/or biological organisms to the seed prior to sowing in order to suppress, control or repel pathogens, insects and other pests that attack seeds, seedlings or plants. Seed treatment offers an increasingly precise mode of applying products in the field, and provides a high level of protection against insects and disease while reducing potential exposure of humans and the environment to crop protection products.

Some of the benefits of seed treatment include:

Grower benefits

- Seed treatments contribute to earlier and faster planting, higher plant populations and higher crop yields.
- Farmers achieve maximum protection of crops by planting genetically modified (GM) seed that has been treated with crop protection products.
- Following planting, seed treatments offer effective control against early season, below-ground and above-ground pests and diseases, and reduce the need for additional rescue treatments or replanting of a failed crop.
- Seed treatment protects the seed itself, which has high intrinsic value, and increases the value of the harvested crop through improved yield and significantly higher commodity prices since 2005.

Healthier crops

- Seed treatment offers an effective method of protecting seed from pathogens, insects and other pests, and contributes to the healthy, uniform stand establishment of a variety of crops produced in the U.S.
- Insecticide and fungicide seed treatments contribute to more uniform seedling emergence, healthier plants and significantly reduced insect and disease damage.

Positive environmental impacts

- Seed treatment precisely places the crop protection product on the surface of a small seed, effectively reducing the need to apply products over the entire field.
- Due to its precise application directly to the seed, which is then planted below the soil surface, seed treatment reduces potential off-target exposure to plants and animals.

Precision application

- When applied as a seed treatment, crop protection products increase precision and effectiveness by placing the product exactly where it is needed to protect the germinating seed.
- The precise application of a crop protection product via seed treatment reduces soil surface exposure by up to 90 percent compared to in-furrow applications and up to 99 percent compared to a surface application.
- Polymer seed coatings bind crop protection products directly to the seed, largely eliminating dust exposure to people who handle and plant the seed, as well as to non-target organisms.

Economic impacts

- Seed treatment products, applied to nearly every acre of corn planted in the U.S. in 2011, helped support nearly $80 billion worth of crop value to American farmers.
- The global fungicide seed treatment market is growing at a compound annual growth rate of 9.2 percent and is expected to reach $1.4 billion by 2018.
- The global insecticide seed treatment market is projected to reach $4.2 billion by 2018, growing at a compound annual growth rate of 10.8 percent.

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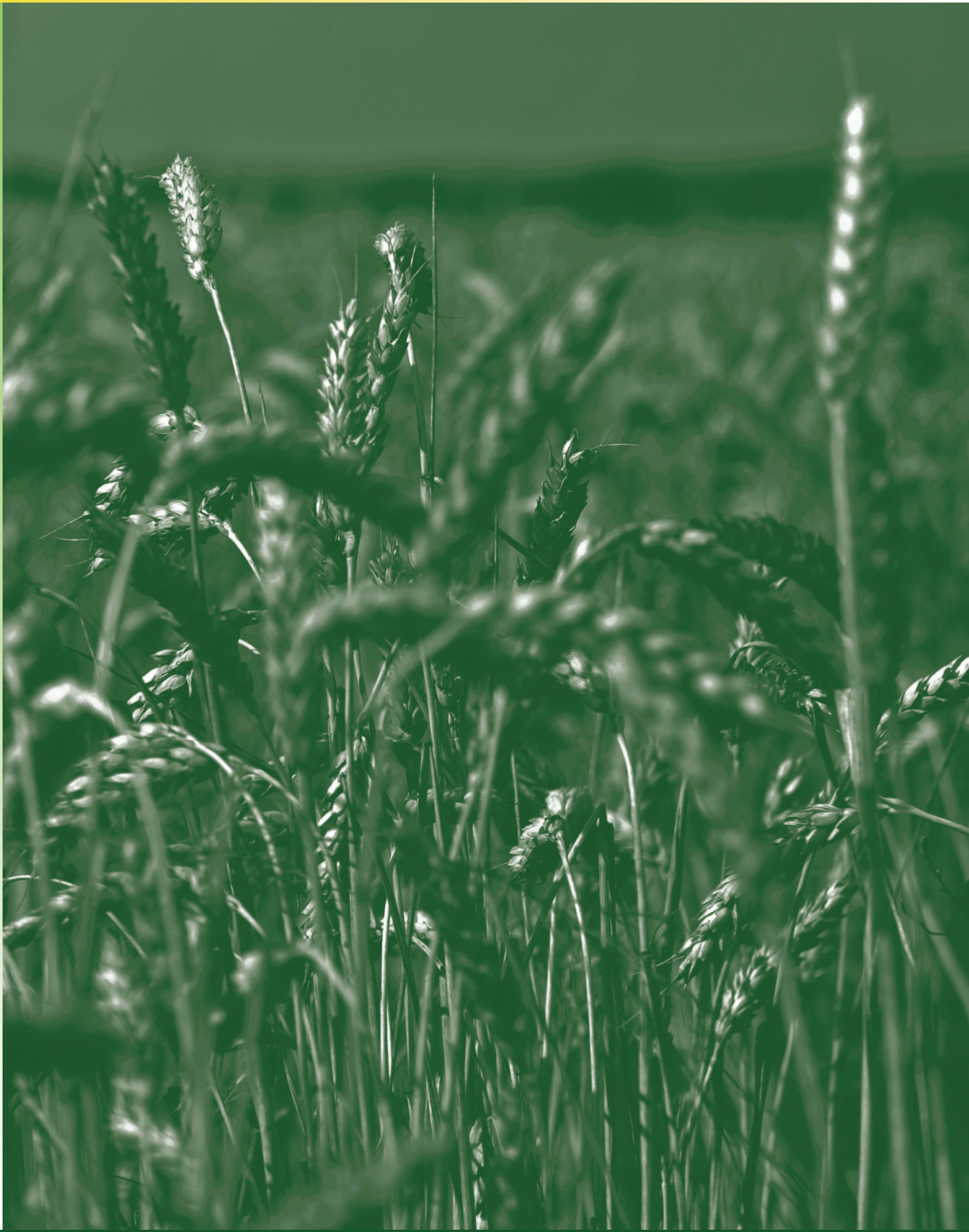

I. A SUMMARY OF SEED TREATMENT BENEFITS

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A. Introduction

Ninety percent of the world's food crops are grown from seed [94]. Seed treatments play a vital role in controlling early season insects and diseases, as well as improving the stand establishment and vigor of the seedling. Other application techniques used to control many pests, including in-furrow applications or early season foliar sprays, are now being replaced with seed treatments by virtue of their residual systemic efficacy.

Seed treatment active ingredients are regulated by the U.S. Environmental Protection Agency (EPA) under the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA). A rigorous, science-based, risk-benefit assessment is conducted by EPA during the registration and development of these active ingredients. After evaluating data from more than 120 scientific tests and determining that the product poses no unreasonable adverse effects on humans or the environment, EPA registers crop protection chemicals for commercialization and use in seed treatments.

A critical success factor for the seed treatment market was the development of a complete protection solution against various plant stressors in a single product that is grower-friendly, crop-friendly and environmentally responsible [94]. Growers want a seed treatment that will be rapidly absorbed by the seed coat and plant roots, which then protects the growing plant throughout its susceptible period of development. Seed treatments are formulated so that they pose no unreasonable adverse effects and act against a broad range of insects and pathogens with minimal environmental impact.

Chemical seed treatments, which are typically manufactured from petrochemical or inorganic raw materials, are classified by pest or discipline as fungicides, insecticides and other chemical seed treatments. In developing new active ingredients for the seed treatment market, manufacturers consider crops that dominate the sales of seed treatments. Certain crops such as soybeans have risen in importance, while others, such as sugarbeets, have declined.

Table 1 demonstrates the growth of the global seed treatment market from 2001 to 2011 based on major crops. Table 2 includes data on global fungicide and insecticide seed treatment sales for selected years.

Table 1. Global sales of seed treatments by crop, 2001 to 2011

Crop	2001 (percent of market)	2011 (percent of market)
Cereals	40.0	29.0
Corn	15.0	25.0
Potato	7.0	5.0
Sugarbeets	6.0	–
Cotton	5.0	9.0
Canola/Rapeseed	5.0	7.0
Soybean	5.0	18.0
Rice	–	5.0
Others	17.0	2.0
Total sales	**$950 million**	**$2.8 billion**

Source: Research and Markets (2013)

Table 2. Global sales of seed treatment by year

Year	Fungicide	Insecticide	Other / Mixture
1994	68%	21%	11% mixture
1997	60%	25%	15% mixture
2012	34%	52%	13% other

Source: Research and Markets (2013), Schwinn F. (1994)

B. Origins of seed treatment practices

Seed treatment practices offer three approaches through biological or chemical control of pests:

- Protectant – protection of the health of the host plant
- Eradicant – curative therapy of an infested host plant
- Disinfectant – destruction of a phase in the life cycle of the pest

The earliest reported use of a seed treatment dates back to 60 A.D., when wine and crushed cypress leaves were used to protect seed from storage insects. The active component in this mixture was likely hydrogen cyanide.

Fungicide seed treatment had a serendipitous beginning in the 17th century, when wheat seed salvaged from a shipwreck near the United Kingdom grew very well. British agronomist and inventor Jethro Tull [113] recorded: "At the following harvest, all the wheat in England happened to be smutty, except the produce of this brined seed, and that was all clean from smuttiness." This finding led to the concept of disinfection by means of seed treatment. Many of the subsequent records of seed-borne organisms relate to diseases known as "bunts" (caused by fungi belonging to the genus *Tilletia*) and "smuts" (caused by fungi in the genus *Ustilago*). It was not until 1755, when Tillet demonstrated that the "bunt" fungus was seed-borne, that seed treatments became more widespread [112].

An important breakthrough in seed treatment occurred in 1807, when Benedict Prevost "discovered that the black smut dust, made up of very small spherical objects, would grow if placed in water" and "…the spores in water taken from a copper pan either did not germinate or died shortly after germination." Following up on this clue, Prevost discovered that as little as four parts per million (ppm) of copper sulfate in water would prevent germination of smut spores [12].

Copper sulfate became the treatment of choice for the next 100 years for the control of smuts in small grains, although the lack of seed germination safety for copper sulfate resulted in poor stands from treated seed.

Formaldehyde was introduced as a replacement for copper sulfate in 1897, but was not widely used until the start of World War I, when copper was needed for war supplies.

Beginning in the 20th century, official seed testing stations were established by the International Seed Testing Association to assess seed purity and quality. The first international rules for testing seed were published in 1928. These rules drew increased attention to seed-borne pathogens and insects of cereals, beans, peas and flax. Lucie Christina Doyer's 1938 "Manual for the Determination of Seed-borne Diseases" became a landmark publication in seed technology [20].

Seed treatment insecticides were first used to control stored-seed insects in the 1940s. In the late 1940s and early 1950s, lindane was developed as a seed treatment for the control of soil insects like wireworm. Additional chlorinated hydrocarbon materials used on seed for soil insect control included aldrin, dieldrin and heptachlor. The systemic insecticide disulfoton was introduced in the 1950s as the first widely used systemic seed-applied insecticide for cotton, which is routinely damaged by early-season foliar-feeding insects such as thrips.

In 1948, a fungicide named captan was discovered, and in 1950 was introduced as a seed treatment. Captan was a broad-spectrum contact fungicide, and was rapidly introduced to a number of crops, including field corn [12]. Captan was applied to seed corn at a rate of 350 to 750 ppm, a high loading of seed treatment fungicide by today's standards. Seed treatment coatings were not used when captan was the standard seed treatment fungicide, resulting in a substantial amount of chemical dust when seed was transferred to a planter.

The next major change in seed treatment products was the introduction of methylmercury, which became available as a liquid in the U.S. in 1948 [59]. This was an inexpensive liquid that rapidly became the product of choice for small grains seed treatment. Mercury treatments remained popular until the 1970s, when they were identified as having potentially toxic environmental and human safety impacts [12].

In the early 1970s, the first systemic fungicide seed treatment technology for the control of both loose and covered smut was registered in the U.S. Carboxin became the new standard seed treatment fungicide for small grains and other crops. Several additional systemic fungicides have received EPA approval in the last 40 years. These deliver a higher degree of smut control and actively protect against additional types of smut [21].

A low-use rate (25 ppm) non-systemic broad-spectrum fungicide, fludioxonil, was registered for corn and other crops in the mid-1990s. Seed treated with this new product had very little dust, moved more easily through commercial seed conditioning plants, where seed is cleaned and refined, and planted through the new pneumatic planters without problems. Within a few years, fludioxonil had replaced captan as the standard seed treatment fungicide on many crops.

In 1994, the first neonicotinoid insecticide was registered with the EPA. The introduction of this new generation of precision seed treatment technology changed the seed industry and growers' appreciation for the importance of seed treatment products. These insecticides, combined with more effective seed treatment fungicides and used with a seed treatment polymer coating, provided a new level of seed and seedling protection. Use of these new seed treatment products resulted in earlier and faster planting, more uniform emergence, higher plant populations, healthier plants, less insect damage and higher crop yield [31].

Biological seed treatments and plant extracts have entered the seed treatment market in recent years and are being used commercially on large amounts of seed. Some have received EPA registration with specific pest control claims, while others are being sold as yield enhancement products or as products that will improve plant health and vigor.

C. Benefits of applying seed treatments

The benefits of seed treatment technologies are numerous and have evolved over time with the introduction of new chemical classes and more advanced equipment. Table 3 compares changes in crop protection and seed that have driven the increased benefits from seed treatment products prior to 1992 and following the introduction of new chemistries and technologies in 1998.

Table 3. Changes in seed treatment

Prior to 1992	After 1998
Old chemistry	Highly active, low-rate chemistry
Imprecise application methods	Better seed treatment formulations
High loading rates	More consistent performance
Exposure concerns	More precise application equipment
Poor handling formulations	Introduction of seed coating

Major benefits of seed treatment include:

Grower benefits
As evidenced by its rapid adoption in the U.S., seed treatment offers considerable benefits for growers and allows them to produce high-quality crops. Seed treatments contribute to earlier and faster planting, higher plant populations and higher crop yields.

Following planting, seed treatments offer effective control against early season, below-ground and above-ground pests and diseases, and reduce the need for additional rescue treatments or replanting.

Seed treatment protects the seed itself, which has high intrinsic value, and increases the value of the harvested crop through improved yield and significantly higher commodity prices since 2005.

Farmers achieve maximum protection of crops by planting GM seed that has been treated with crop protection products.

Healthier crops
Seed treatment offers an effective method of protecting seed from pathogens, insects and other pests, which contributes to high-quality crop production. Broad-spectrum crop protection products used to treat seed control pre- and post-emergence insects and diseases.

Insecticides used as seed treatments provide a healthy, uniform crop by controlling insects. Seed treatments can address insect control at the following times: during storage; to prevent seedling damage; to limit early foliar feeding; and to prevent root damage.

A variety of pests and diseases have the potential to directly influence stand, uniformity, vigor, root health and architecture if not controlled. Seed treatments can address seed and seedling diseases in four different stages, as shown in Table 4.

Table 4. Examples of diseases that are controlled by modern seed treatments

Disease Category	Examples of key diseases
Seed rot	*Aspergillus spp., Penicillium spp., Phomopsis spp.*
Damping-off	*Pythium spp., Rhizoctonia spp., Fusarium spp.*
Post emergence	*Helminthosporium spp., Ustilago spp., Tilletia spp.*
Early onset of root damage and foliar diseases	*Pythium spp., Phytopthora spp., Rhizoctonia spp., Fusarium spp., Helminthosporium spp.*

Positive environmental impacts
Seed treatment precisely places the crop protection product on the surface of a small seed, effectively reducing the need to apply products over entire fields. This reduces potential off-target exposure to crop protection products for both animals and humans.

Precision application
When applied as seed treatments, crop protection products increase precision and effectiveness by reducing the applications of pesticides applied to the land area. The precise application of a crop protection product via seed treatment reduces soil surface exposure by up to 90 percent compared to in-furrow applications and up to 99 percent compared to a surface application [16]. Seed treatment is a convenient application method in which the crop protection product is applied directly to the target. There is a uniform loading rate of the product for each plant.

Seed treatment is a leading technology in precision agriculture. Not only are seed treatments primarily applied in a closed system, their loading rate per acre is minimal compared to all other types of applications. In addition, with the advent of GM seeds, the industry has focused research on optimizing the seeding rate required to optimize yields.

Improvements to seed treatment equipment
Seed treatment application technology has improved from a gross application of ounces per hundred weight of seed (cwt) to a precise application of milligrams per individual seed. There have been significant improvements in application using equipment designed to apply loading rates of milligrams of crop protection product per seed. Computerized treating systems calculate the total product application rate for each lot of seed, adjust the seed and product flow, and make corrections as necessary for each new lot of seed.

Economic impacts
In addition to providing highly effective protection against pests and disease, seed treatments have a significant economic impact on markets, particularly in the U.S. and Europe [88]. The global seed treatment market was valued at $2.43 billion in 2011. Insecticides accounted for 52 percent of the total market revenue, followed by fungicides, which accounted for 35 percent of revenue. The global fungicide seed treatment market is growing at a compound annual growth rate of 9.2 percent and is expected to reach $1.4 billion by 2018. The global insecticide seed treatment market is projected to reach $4.2 billion by 2018, growing at a compound annual growth rate of 10.8 percent.

The high cost of GM seed is a key factor in the high demand for and growth of chemical seed treatments. As a result, seed treatment is currently the fastest growing agricultural chemicals sector. A bag of stacked trait cotton seed (220,000 to 250,000 seeds) typically carries a technology cost of approximately $300 to $400 per bag.

D. Fungicide seed treatments

A number of fungicide seed treatments have been introduced since the 1930s that offer effective control against many crop pathogens. Table 5 lists active ingredients developed in the last several decades along with their benefits and limitations.

Seed and seedling diseases may be caused by a variety of organisms such as fungi, bacteria, viruses and nematodes. Fungicide seed treatments focus on pathogenic fungi that destroy plant cells and tissues, prevent seed germination, or cause poor development or death of seedlings. Some of these diseases can reduce crop yield substantially, especially on susceptible cultivars. These diseases can also have a significant impact on the plant's root architecture.

Pathogens can be seed-borne or seed-transmitted. Typically, such pathogens develop in seedlings following germination. The infested plant then may become diseased as a seedling or by means of later infection that can cause disease in the mature plant. This causes the newly formed seed to become infested as it matures on the plant. Such seed pathogens infest the seed coat and may be systemic (e.g. bunts and smuts of cereals) or nonsystemic (e.g. *Helmithosporium spp., Fusarium* scab on cereals). Table 6 shows the major seed-borne pathogens that can affect the seven largest global crop commodities.

Table 5. Key fungicide seed treatments introduced since the 1930s

Year	Chemical group/fungicide (FRAC Code)	Attributes
Prior to 1930s	Organic Mercury/ Phenyl Mercury Acetate	+ Inexpensive broad-spectrum protectant - Cancelled in the 1970s
1930s	Dithiocarbamate/ Thiram (M3)	+ Broad-spectrum seed protectant - Irritating to skin
	Aromatic Hydrocarbon/ Pentachloronitrobenzene (14)	+ Active against *Rhizoctonia*, *Sclerotinia* and bunt - Better as a soil treatment versus a seed treatment
1950s	Phthalimides/Captan (M4)	+ Broad-spectrum seed protectant - High loading rate, dust-off
1960s	Oxathin Carboxamide/ Carboxin (7)	+ First systemic seed treatment - Spectrum, for this reason mixed with captan, thiram or PCNB
	Thiophanates/ Thiophanate Methyl (1)	+ Systemic, translocated to new growth - Active on ascomycete and basidiomycete fungi
1970s	Triazole/Triadimenol (3)	+ First seed treatment for air borne disease - Subject to powdery mildew resistance
1980s	PhenylAmides/Metalaxyl (4)	+ Highly effective on oomycete (*Pythium*) and corn and sorghum downy mildews - Subject to fungal resistance
	Triazole/Tebuconazole (3)	+ Broad-spectrum, unique on dwarf bunt
1990s	Phenylpyrrole/ Fludioxonil (12)	+ Broad-spectrum, low rate, long residual - Unstable in light
	Triazole/Difenoconazole (3)	+ Broad-spectrum, unique on dwarf bunt
2000s	Methoxy-Acrylate/ Azoxystrobin (11)	+ Broad-spectrum, especially *Rhizoctonia* and *Fusarium*; some *Pythium* activity
2010s	Pyrazole-MET1/ Sedaxane (39)	+ Excellent activity on *Rhizoctonia*, seed decay - Resistance concerns

Source: Fungicide Resistance Action Committee (2013), Thomson (1997)

Seed that is not infested before planting may be attacked once planted in the soil. *Pythium spp.* may attack seed within three hours of planting. This makes it difficult to develop varieties that have resistance to *Pythium*. Old or damaged seed is more vulnerable as the seed coat leaks exudates that attract pathogens to the germinating seed. This process is further aggravated in cold, wet soils, such as those planted early in the season in soil that has undergone minimal tillage. Damping-off diseases caused by *Pythium, Rhizoctonia* and *Fusarium* are present in all natural soils. Fungicide seed treatments can provide early season protection against soil-borne seedling pathogens. Table 7 shows other major soil-borne pathogens that can affect the seven largest global crop commodities.

New fungicide technology has improved efficacy, requiring less active ingredient than other methods needed to have the same positive effect on combating fungi during the seed's growth, and providing improved pest protection than needed at an equal or higher-use rate.

Several chemistry classes are currently being offered to seed companies as seed treatments. The activity of these chemistries against various diseases is shown in Table 8.

As one example of effectiveness, the emergence of the fungicide metalaxyl improved modern agricultural practices due to its unique efficacy as a seed treatment against *Pythium*. Metalaxyl was registered by EPA in 1983 and is now registered on more than 50 crops across the globe. This efficacy has resulted in the widespread acceptance of metalaxyl and its purified enantiomer, mefenoxam.

Metalaxyl use increased following the growing trend in no-tillage crop production. No-tillage soils remain considerably cooler and wetter for a longer period in the spring, creating favorable conditions for *Pythium spp.*, which will attack slowly emerging seedlings. Treating seed with metalaxyl allows farmers not only to protect their crops, but also plant earlier in the season and optimize the yield potential of crops such as corn and soybeans.

Today's seed treatment market offers pre-mixture products containing combinations of three, four or more fungicides from multiple classes of chemistry and giving both contact and systemic activity with multiple modes of action. This approach allows for a broader spectrum of activity across the fungal classes known to impact seedling stand establishment, resulting in improved plant health. This approach is an excellent form of stewardship in protecting against fungicide resistance.

Table 6. Major seed-borne pathogens in the major commodities

Crop	Seed-borne pathogens
Cereals	*Cochliobilus sativus* *Stagnospora nodorum* *Alternaria spp.* *Microdochium nivale* *Fusarium* *Pyrenophora tritici-repenti* *Tilletia carries* *Ustilago nuda* *Claviceps purpurea*
Corn	*Fusarium spp.* *Penicillium spp.* *Aspergillus spp.* *Bipolaris spp.* *Alternaria spp.* *Rhizopus spp.*
Potato	*Fusarium spp.* *Rhizoctonia solani* *Verticillium dahlia* *Streptomyces scabies* *Colletotrichum coccodes* *Helminthosporium solani*
Soybean	*Phomopsis spp.* and *Diaporthe spp.* *Cercospora kikuchii* *Peronospora manshurica* *Alternaria* and *Fusarium spp.*
Rice	*Pyricularia oryzae* *Helminthosporium spp.* *Bipolaris oryzae* *Curvularia lunata* *Alternaria padwickii* *Fusarium spp .*
Cotton	*Aspergillus flavus,* *Fusarium spp.*
Canola	*Leptosphaeria maculans* *Sclerotinia sclerotiorum* *Alternaria spp.* *Xanthomonas campestris*

Source: American Phytopathological Society Press

Table 7. Major soil-borne pathogens in the major commodities

Crop	Soil-borne pathogens
Cereals	*Gaeumanomyces graminis* - take-all *Pseudocercosporella herptrichoides* - eyespot *Bipolaris sorokiniana* - common root rot *Polymyxa graminis* - soil borne wheat mosaic
Corn	*Gibberella zeae* - stalk rot *Stenocarpella maydis* - *Diplodia* stalk rot *Colletotrichum graminicola* - *Anthracnose* stalk rot *Fusarium moniliforme* - *Fusarium* stalk rot *Macrophomina phaseolina* - charcoal rot *Sphacelo-theca reilina* - head smut
Potato	*Streptomyces scabies* - common scab *Spongospora subterranean* - powdery scab *Phytophthora erythroseptica* - pink rot *Rhizoctonia solani* - black scurf *Colletotrichum coccoides* - black dot *Fusarium sambucinum* - *Fusarium* dry rot *Helminthosporium solani* - silver scurf
Soybean	*Phytophthora sojae* - *Phytophthora* root rot *Fusarium virguliforme* - sudden death syndrome *Sclerotium rolfsii* - southern blight *Phialophora gregata* - brown stem rot *Macrophomina phaeseolina* - charcoal rot
Rice	*Achlya spp.* - water mold *Bipolaris oryzae* - brown spot *Curvularia lunata* - seedling blight *Sclerotium oryzae* - stem rot *Helminthosporium oryzae* - brown leafspot
Cotton	*Thielaviopsis basicola* - black root rot *Glomerrella gossypii* - anthracnose *Fusarium oxysporum* - *Fusarium* wilt *Macrophomina phaeseolina* - charcoal rot
Canola	*Leptosphaeria maculans* - black leg S*clerotinia sclerotiorum* - stem rot *Alternaria alternate* - black spot

Source: American Phytopathological Society Press

Table 8. Spectrum of activity of the major fungicide seed treatments currently in use

Class of chemistry	Relative performance on key fungi (++++ indicates highest level of activity; - indicates no activity)				
	Fusarium	*Rhizoctonia*	Seed rots	*Pythium*	*Phomopsis*
Phenylamide	-	-	-	++++	-
Strobilurin	++	+++	++	++	+
Triazole	+++	+++	++	-	++
Phenylpyrrole	++++	+++	+++	-	+++
Pyrazole	+	++++	+++	-	+

Source: Dyer, et al. (2007), Maude (1996)

Table 9. Major soil and foliar insects

Crop	Soil insects	Foliar insects
Cereals	Wireworm - *Agrotes spp.*	Bird Cherry oat aphid - *Rhaplosiphum padi* English grain aphid - *Sitobion avenae* Greenbug - *Schizaphis graminium* Russian wheat aphid - *Diuraphis noxia*
Corn	Corn rootworm - *Diabrotica spp.* Cutworm - *Agriotis spp.* Grape colaspis - *Colaspis brunnea* Seed corn maggot - *Delia platura* White grub - *Cyclocephala lurida* Click beetle - *Elateridae spp.* Wireworm - *Agriotis spp.*	Aphids - *Aphis spp.* Billbug - *Sphenophorus spp.* Chinch bugs - *Blissus leucopterus* Flea beetle - *Chaetonema pulicaria* Stink bugs - *Euschistus spp.* Thrips - *Frankliniella williamsi*
Cotton	Wireworm - *Agrotis spp.*	Aphid - *Aphis gossyppi* Jassid - *Empoasca spp.* Thrip - *Franklinella spp., Thrips tobaci*
Potato	Wireworm - *Agrotis spp.*	Aphid - *Aphis gossyppi, Macrosiphum euphobiae* Colorado potato beetle - *Leptinotarsa decemlineata* Potato leafhopper - *Empoasca fabae*
Soybean	Wireworm - *Agrotis spp.* Corn rootworm - *Diabrotica spp.*	Aphid - *Aphis glycines* Bean leaf beetle - *Ceratoma trifurcate*
Rice		Green leaf hoppers - *Deois flavopicta* Rice water weevil - *Lissorhoptrus oryzophilus* Stem borer - *Elasmopalpus spp.* Thrip - *Stenchaenothrips spp.*
Canola		Aphid - *Myzus persicae, Brevicoryne brassicae* Cabbage curculio - *Ceutrhynchus rapae* Flea beetle - *Phyllotreta spp., Psylloides chrysocephala* Saw fly - *Athalia rosae*

Source: Morrill (1995)

E. Insecticide seed treatments

Crop production requires knowledge of each crop's agronomic characteristics and a full understanding of the pests that might affect them. Growers must understand a pest's life cycle and the damage that it can inflict upon the crop so that the optimal control measure can be implemented at the optimal time of the season.

The biodiversity of insects that affect crop production indicates the potential for seed treatment insecticides in the future. Many pests have been studied and identified as primary limitations to crop production, as shown in Table 9.

From 1917 to 1920, there were widespread droughts accompanied by outbreaks of grasshoppers. Many native insects such as wireworms, cutworms and wheat stem sawflies started to adapt from native grasses to small grains. Some introduced insect species also became economically important pests of small grains, including the Hessian fly, wheat midge and cereal leaf beetle. Changes in agricultural practices have resulted in changes in insect population densities.

Treating seed with an insecticide became common in the 1940s, long after the establishment of fungicide seed treatments. Prior to the 1940s, the primary insecticide products used were inorganic, such as Paris green (copper acetoarsenite) and arsenic. The ability to manage pests improved with the development of organic insecticides.

Year	Product name/active ingredient	Corn maggot	Wireworm	Thrip	Other insects[a]
Prior to 1976	Lindane/Lindane	*	*		
	Diazinon/Diazinon	*			
	Di-Syston®/Disulfoton	*	*	*	
	Lorsban®/Chlorpyrifos	*	*		
	Orthene®/Acephate			*	
1984	Actellic®/Pirimiphos-methyl				*
1985	Reldan®/Chlorpyrifos-methyl				*
1994	Gaucho®/Imidacloprid	*	*	*	*
1996	Razor®/Cypermethrin	*	*		
1998	Icon®/Fipronil				*[b]
1999	Permethrin/Permethrin	*	*		
2000	Cruiser®/Thiamethoxam	*	*	*	
2003	Poncho®, NipsIt®/Clothianidin	*	*	*	*

Table 10. Historical seed treatment insecticides and their activity against pests

a: Leafhopper, chinch bug, flea beetle, Colorado potato beetle, Hessian fly, fire ant and grape colaspis
b: Rice water weevil

Uses of insecticides as seed treatments started with control of stored product pests. This was followed by the development of lindane as a seed treatment for soil insects, and then by the use of organophosphate chemistries in the 1950s.

Since 1997, a rapid increase in the use of insecticide seed treatments has paralleled an increase in the use of GM seeds and a decrease in in-furrow, granular insecticide treatments. Growers today prefer seed treatments as opposed to banded or broadcast applications.

Table 10 shows insecticide seed treatments introduced in recent decades that have activity against some of the more common insect pests.

The introduction of the neonicotinoid class of insecticide seed treatments (imidacloprid, thiamethoxam and clothianidin) ushered in a large improvement in insect control. Prior to the commercialization of these neonicotinoids, most insecticide products did not persist long enough to provide effective control on a broad spectrum of insects. Neonicotinoid insecticides possess a number of valuable attributes that have led to their increased adoption by growers [31]:

- Neonicotinoids provide broad-spectrum control on a range of insects.
- Neonicotinoids are categorized in the reduced risk category according to EPA. This means that use of these products is considered to have a minimal impact on wildlife species and the environment, when used according to the product label.
- Neonicotinoids possess excellent seed safety as they do not harm germination and growth rates or vigor of treated seeds.
- Safety to handlers during treatment, handling and sowing is improved by the low exposure and toxicological profile.
- Neonicotinoids enhance plant vigor and increase yields.
- The use of neonicotinoids as seed treatments reduces input costs for crop production.

After seeds germinate, neonicotinoid molecules are rapidly taken up by the roots and transported into the cotyledons, young shoots and leaves. The systemic movement, along with a long residual activity in the plant, makes the chemistry ideally suited for use as a seed treatment. Neonicotinoid insecticides control early season insect pests in the critical phase of seedling emergence and during the vulnerable, early growth stages of plant development.

The systemic attribute is also of great value in protecting plants from insect-vector-borne viruses such as barley yellow dwarf virus, potato leafroll virus, bean mottle virus and the bacterium that causes Stewart's wilt, carried by the corn flea beetle.

F. Other seed treatment technologies

Crop protection products dominate the seed treatment market, but other chemicals such as herbicide safeners, nematicides, plant growth regulators and nutritionals are also used as seed treatments. The purpose of these seed treatments is also to protect and enhance the viability of the seed.

Most herbicide safeners are included in the herbicide formulation [2]. For example, sulfonylurea products with isoxadifen or cyrosulfamide are herbicide formulations of more than one chemical product. A seed treatment product containing fluxofenim has long been used to protect grain sorghum against injury from the soil-applied herbicide metolachlor (or s-metolachlor).

Nematicides target and kill nematodes associated with seed and plant emergence. Nematodes are one of the most devastating and common plant pests. With the regulatory issues facing both granular and fumigant nematicides, there has been a great deal of focus on seed treatment uses of nematicidal and nematistatic products. These products can significantly improve plant development. If a seedling can be protected for 40 days after planting, it will often outgrow the damage inflicted by most plant pathogenic nematodes. University research continues to determine the true value of the nematicide seed treatments. Table 11 lists some nematicides that have been introduced and registered for seed treatment use.

Table 11. Registered seed treatment nematicides

Product	Active ingredient	Year of introduction and crop
MeloCon®	*Paecilomyces lilacinus* strain 251	2005 on vegetables
Avicta®	Abamectin	2006 on cotton and 2010 on corn
Aeris®	Thiodicarb + Imidacloprid	2007 on cotton
VOTiVO®	*Bacillus firmus*	2011 on corn and soybeans

Plant growth regulators are plant-hormone-based products that control normal plant functions. Examples include abscisic acid and cytokinin. Over the years, strains of the nitrogen-fixing bacteria *Rhizobia spp.* have been improved, as has the knowledge of their colonization of roots. *Rhizobia* are now applied in conjunction with seed treatment applications to legumes. Part of this new technology is often referred to as "promoter technology." For example, lipo-chitooligosaccharide (LCO) modifies the process by which *Rhizobia* establish symbiosis with the plant that is independent of temperature. Researchers are also focusing on methods to germinate seedlings and improve their uptake of phosphorous in view of future limitations on the availability of phosphorous fertilizers.

Several biological products – native or exotic microbial species that mitigate the effects of insects or diseases – are emerging as stand-alone products or in combination with chemical seed treatments. Most of these products claim to stimulate the natural defenses of the germinating seed to which they are applied. One example is a product comprised of *Bacillus subtilis* and *Rhizobial* inoculum, and sold as a bio-fungicide.

Biological seed treatments are made up of renewable resources and contain naturally occurring active ingredients. The effectiveness of these treatments in protecting the seed and enhancing plant growth is still being extensively researched. Typically, biological products are applied in conjunction with a chemical treatment. The chemical provides early season protection and the biological product offers later season protection after the organism has colonized the plant roots. Biological seed treatments claim to further reduce potential negative impacts on the environment along with pest resistance development. Biological seed treatments are expected to be one of the fastest growing seed treatment sectors in the near future, in part because they are easier to register at EPA [94].

Seed enhancement refers to seed treatments that improve germination, seed growth or accuracy of planting. Seed enhancements include products for priming, pelleting, coating and conditioning of seeds. Today, most seeds are coated with a polymer that is mixed with the seed treatment product or applied to the seed as a final coating. These products are not regulated by EPA as pesticides and do not have pesticidal activity.

Polymers serve a number of functions in seed treatment:

- Improve seed coverage of other seed treatments on the seed surface;
- Aid in the application of biological seed protectants to the seed;
- Aid in conditioning the seed to separate viable and non-viable seed;
- Improve the cosmetic appearance of seed and assist in identifying GM seed;
- Establish a barrier between the seed treatment chemicals and the seed to improve the safety of the seed treatment;
- Reduce friction and abrasion of seeds during storage and planting;
- Reduce dust-off from treated seed so there is less residue in seed bags and from pneumatic planters;
- Improve planter drop of seeds while sowing.

Seed pelleting is the process of coating seeds with inert materials to change their size and shape for improved plantability. It has long been utilized to make individual seeds of certain crops uniform in shape and size and help the planting equipment achieve a more uniform stand and spacing of crop plants in the field. Small and irregularly shaped seeds, such as lettuce seeds, can then be handled as larger, round-shaped pellets.

G. Role of seed companies

Seed companies will not apply a new seed treatment to their seed products without first conducting extensive testing of seed safety. Deterioration of seeds begins at seed maturity and continues until all the seed tissue is dead. This process of deterioration can be influenced by the phytotoxic effects of chemicals applied to the seed. Seed treatments must not reduce the quality of the seed.

Seed quality assessments include genetic, physical, pathological and physiological tests for viability and vigor. The Association of Official Seed Analysts has established several tests of seed vigor including [4]:

- Accelerated aging;
- Cold stress;
- Cool germination;
- Seedling growth rate; and
- Seed viability.

Cold tests and accelerated aging tests are the most common, but each seed company makes decisions on testing to satisfy its own internal standards.

GM seed was first sold in the U.S. in 1996. By 2012, GM crops were grown on more than 170 million hectares around the globe [109]. Many of the major seed companies (Dow AgroSciences, Monsanto Company, DuPont Pioneer and Syngenta Crop Protection) are currently selling GM seed with multiple crop traits including herbicide tolerance and insecticidal properties. Seed treatments are applied to a high proportion of GM seed. This has increased the cost of seed and grower expectations in row crop production agriculture. Growers expect that each seed will produce a healthy seedling and mature plant.

Seed companies require that a seed treatment have a global registration package that covers the countries represented in the major seed markets. Seed may be produced in one part of the world and shipped elsewhere to be sold for planting. By requiring a global registration package, seed companies have the opportunity to establish nurseries and grow-out facilities in both hemispheres of the world, which in turn allows them to raise two crops of seed per year.

H. Development of seed treatment equipment

As with other aspects of application technology, there has been an explosion of automated seed treating systems that achieve precision accuracy in the application of all-in-one products that may include polymers and seed coatings and multiple crop protection active ingredients.

Seed treatment application has generally moved away from batch machines. A batch machine once placed a specific amount of seed (e.g., cwt =100 pounds) in a rotating drum with mixing baffles, where the seed was sprayed with a measured quantity of treatment product. Various sized screen liners could accommodate different types and sizes of seed. The industry has largely moved to continuous coating machines, which accommodate larger amounts of seed (e.g. up to 50,000 pounds of corn seed per hour). The operator can adjust the amount of product sprayed and control phased, sequential applications of multiple products.

Differing numbers of seeds per pound among batches of seed require varying treatment rates if the seed treatment is applied strictly per weight of seed. One pound of soybean seed, for instance, could contain as few as 2,400 seeds or as many as 3,600 seeds. The low rate of application of the neonicotinoid chemistries brought about a major shift in application, from rates of fluid ounces per hundred pounds of seed, to milligrams or less product per individual seed. This shift resulted in seed treatments being viewed as a value-added product by the crop production and seed industries.

The most recent advancement in seed treatment technology is the development of closed systems for both small and large retail operations that make atomized spray applications. Sophisticated electronic controls can apply multiple custom treatments to a batch of seed, minimizing or eliminating the use of water, which can reduce seed quality and germination. The systems limit applicator exposure, adjust rates to the specific size of the seed and permit traceability of treated seed.

I. Conclusions

Seed treatment is a cutting-edge technology for crop protection that provides many benefits to growers and represents one of the most effective tools in precision agriculture. Seed treatments have helped to improve the yields of many different crops by providing the insurance of a uniform stand across a wide variety of soil types, cultural practices and environmental conditions. The technology allows broad-spectrum seed treatment crop protection products to protect seeds from pre- and post-emergent insects and diseases. Seed treatments provide an economical crop input that is applied directly on the seed using highly effective technology. In addition, emerging seed treatment technologies have improved in tandem with more advanced field planting equipment. The significantly lower amount of active ingredient applied compared to alternative applications makes seed treatment environmentally sustainable and further reduces potential off-target exposure to plants and animals.

II. KEY STATISTICS AND SEED TREATMENT SOLUTIONS FOR MAJOR CROPS

Corn
Cotton
Sorghum
Canola
Oat
Wheat
Barley
Potato
Soybean
Sunflower
Sugarbeet
Peanut
Alfalfa
Rice

CORN

Acres Harvested
87.4 million

Yield
123.4 bushels per acre

Crop Value
$79.8 billion

It is estimated that 90 percent of the corn seed planted in the U.S. receives a seed treatment.

Data for 2011.
Source: National Corn Growers Association; U.S. Department of Agriculture National Agricultural Statistics Service; U.S. Department of Agriculture Economic Research Service

Common Pests

- Southern corn billbug
- Southern green/brown stinkbug
- Sugarcane beetle
- Chinch bug and early season aphid
- Corn rootworm
- Wireworm
- White grub
- Seed corn maggot
- Black cutworm
- Flea beetle
- Nematode

Common Diseases

- *Pythium* (Midwest)
- Head smut

Seed Treatment Solutions*

- Clothianidin
- Imidacloprid
- Thiamethoxam
- Combinations of captan, carboxin, diazinon, maneb, or metalaxyl
- Metalaxyl and captan
- Abamectin and *Bacillus firmus*
- Triticonazole

* includes fungicide and insecticide treatments

COTTON

Acres Harvested
10.4 million

Yield
790 pounds per acre

Crop Value
N/A

Data for 2011.
Source: Council for Biotechnology Information; National Cotton Council; U.S. Department of Agriculture Economic Research Service

Common Pests

- Nematode
- Thrip
- Wireworm

Common Diseases

- *Pythium*
- *Rhizoctonia*
- *Thielaviopsis* black root

Seed Treatment Solutions*

- Metalaxyl
- Triadimenol or myclobutanil
- Abemectin and Larvin
- Imidacloprid and thiamethoxam
- Disulfoton

* includes fungicide and insecticide treatments

SORGHUM

Acres Harvested
3.9 million

Yield
54.6 bushels per acre

Crop Value
$1.3 billion

Data for 2011.
Source: U.S. Department of Agriculture
Economic Research Service

Common Pests

- Chinch bug
- Aphid
  (greenbug, yellow
  sugarcane aphid)
- Red fire ant

Seed Treatment Solutions*

- Imidacloprid
- Thiamethoxam
- Fluxofenim

* includes fungicide and insecticide treatments

Canola (Rapeseed)

Acres Harvested
1 million

Yield
1,475 pounds per acre

Crop Value
$357.6 million

Data for 2011.
Source: PG Economics Ltd, UK; U.S. Department of Agriculture Economic Research Service; U.S. Department of Agriculture National Agricultural Statistics Service

Common Pests

- Crucifer flea beetle

Common Diseases

- Seed-borne black leg

Seed Treatment Solutions*

- Benzimidazole
- Dicarboximide
- Morpholine
- Imidacloprid
- Clothianidin
- Thiamethoxam

* includes fungicide and insecticide treatments

SMALL GRAINS

Oat	**Wheat**	**Barley**
Acres Harvested 939,000	Acres Harvested 45.7 million	Acres Harvested 2.2 million
Yield 57.1 bushels per acre	Yield 43.7 bushels per acre	Yield 69.6 bushels per acre
Crop Value $189.3 million	Crop Value $14.3 billion	Crop Value $814 million
Data for 2011. Source: U.S. Department of Agriculture National Agricultural Statistics Service	*Data for 2011. Source: U.S. Department of Agriculture Economic Research Service; U.S. Department of Agriculture National Agricultural Statistics Service*	*Data for 2011. Source: U.S. Department of Agriculture National Agricultural Statistics Service*

Common Pests

- Hessian fly
- Wireworm
- Aphid – vector of barley yellow dwarf virus (BYDV)

Common Diseases

- Dwarf bunt
- Loose smut
- Black point (*Fusarium* scab)
- *Pythium*
- Loose and covered smut
- Dry seed decay

BYDV is the most wide-spread and destructive viral disease of wheat. It can also infect oats and barley.

Seed Treatment Solutions*

- Difenoconazole
- Carboxin
- Imidacloprid
- Triticonazole
- Thiamethoxam
- Imazalil
- Clothianidin
- Metalaxyl

* includes fungicide and insecticide treatments

POTATO

Acres Harvested
1.1 million

Yield
397 cwt per acre

Crop Value
$4 billion

Data for 2011.
Source: U.S. Department of Agriculture
National Agricultural Statistics Service

Common Pests

- Colorado potato beetle

Common Diseases

- Late blight (*Phytophthora* infestans)
- *Fusarium* dry rot

Seed Piece Treatment Solutions*

- Maneb
- Mancozeb
- Cymoxanil
- Flutolanil
- Fludioxonil
- Thiophanate-methyl
- Imidacloprid

* includes fungicide and insecticide treatments

SOYBEAN

Acres Harvested
74 million

Yield
41.5 bushels per acre

Crop Value
$35.7 billion

All current soybean seed treatment fungicide combinations include at least one product that is active against *Rhizoctonia*.

Data for 2011.
Source: PG Economics Ltd, UK; Soy Stats; U.S. Department of Agriculture Economic Research Service; U.S. Department of Agriculture National Agricultural Statistics Service

Common Pests

- Bean leaf beetle – vector of bean pod mottle virus (BPMV)
- Bean leaf beetle
- Thrip
- Three-cornered alfalfa hopper
- Aphid
- Soybean cyst nematode

Common Diseases

- Pod and stem blight
- *Pythium*
- *Phytophthora*
- White mold
- *Rhizoctonia*

Seed Treatment Solutions*

- Carboxin
- Metalaxyl
- Mefenoxam
- Imidacloprid
- Thiram
- Azoxystrobin
- Clothianidin
- Thiabendazole
- Captan
- Abamectin
- *Bacillus firmus*

* includes fungicide and insecticide treatments

SUNFLOWER

Acres Harvested
1.5 million

Yield
1,398 pounds per acre

Crop Value
$589.3 million

Data for 2011.
Source: U.S. Department of Agriculture
National Agricultural Statistics Service

Common Pests

- Pale striped flea beetle
- Sunflower beetle
- Wireworm

Common Diseases

- Downy mildew

Seed Treatment Solutions*

- Azoxystrobin
- Thiamethoxam
- Fenamidone
- Mefenoxam
- Metalaxyl

* includes fungicide and insecticide treatments

SUGARBEET

Acres Harvested
1.2 million

Yield
23.8 tons per acre

Crop Value
$2 billion

Data for 2011.
Source: PG Economics Ltd, UK; U.S. Department of Agriculture Economic Research Service; U.S. Department of Agriculture National Agricultural Statistics Service

Common Pests

- Beet leafhopper – vector of curly top

Common Diseases

- *Aphanomyces*

Seed Treatment Solutions*

- Hymexazol
- Imidacloprid
- Clothianidin
- Thiamethoxam

* includes fungicide and insecticide treatments

PEANUT

Acres Harvested
1.1 million

Yield
3,313 pounds per acre

Crop Value
$1.2 billion

Data for 2011.
Source: U.S. Department of Agriculture
National Agricultural Statistics Service

Common Pests

- Thrip

Common Diseases

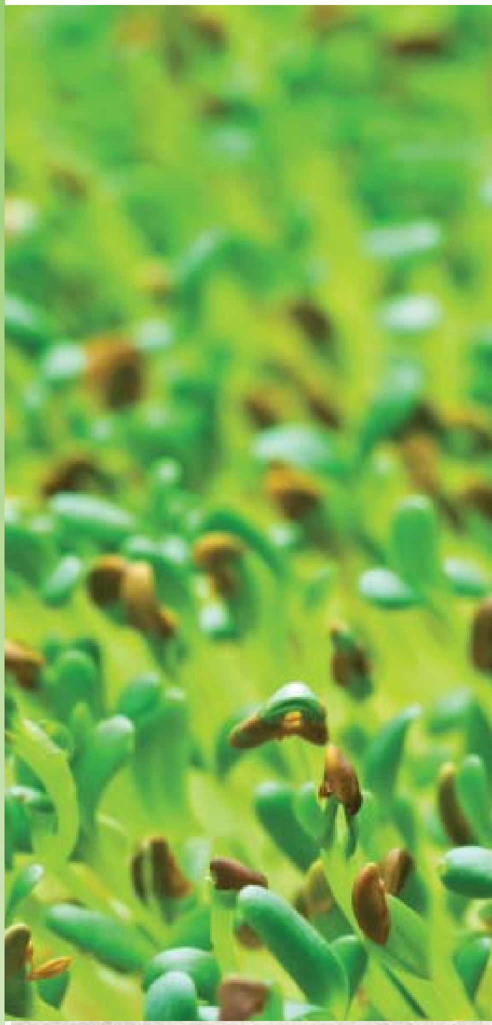
- *Rhizopus*
- *Fusarium*
- *Rhizoctonia*
- *Pythium*

Seed Treatment Solutions*

- Thiamethoxam
- Captan
- Trifloxystrobin
- Thiophanate-methyl
- Metalaxyl
- PCNB
- Carboxin

* includes fungicide and insecticide treatments

ALFALFA



Acres Harvested
19.2 million

Yield
3.4 tons per acre

Crop Value
N/A

Data for 2011.
Source: U.S. Department of Agriculture National Agricultural Statistics Service

Common Diseases

- *Phytophthora*
- *Pythium*

Seed Treatment Solutions*

- Metalaxyl
- Mefenoxam

* includes fungicide and insecticide treatments

RICE

Acres Harvested
2.6 million

Yield
7,067 pounds per acre

Crop Value
$2.7 billion

Data for 2011.
Source: U.S. Department of Agriculture
National Agricultural Statistics Service

Common Pests

- Rice water weevil
- Grape colaspis

Common Diseases

- *Pythium*

Seed Treatment Solutions*

- Metalaxyl
- Thiamethoxam
- Mefenoxam
- Clothianidin

* includes fungicide and insecticide treatments

LARGE SEEDED VEGETABLES

Common Pests

- Corn flea beetle – vector of Stewart's wilt
- Bean leaf beetle
- Cucumber beetle – vector of bacterial wilt
- Seed corn maggot

Common Diseases

- Bacterial wilt
- Stewart's wilt

Seed Treatment Solutions*

- Imidacloprid
- Thiamethoxam

* includes fungicide and insecticide treatments

SMALL SEEDED VEGETABLES

Common Pests

- Onion maggot
- Leafy vegetable insects

Common Diseases

- Early season soil pathogens

Seed Treatment Solutions*

- Cyromazine
- Thiamethoxam

* includes fungicide and insecticide treatments

III. SEED TREATMENT EVOLUTION AND CROP CASE STUDIES

A. Overview of seed treatments

The use of seed treatments, such as the application of fungicides and insecticides directly to the surface of the crop seed, is increasing rapidly throughout the world. This form of precision seed application provides a high level of pest protection and growth enhancement to crops by achieving results in the soil, where many pest problems occur.

Precision seed treatments are integral components of integrated pest management (IPM), which "… is a sustainable approach to managing pests by combining biological, cultural, physical, and chemical tools in a way that minimizes economic, health, and environmental risks" [1]. The advantages of seed treatments include their ease of use, precise placement of pesticides in the root zone of the growing plant and the immediacy of their effects after sowing. Without the use of seed treatments, current farming practices would be considerably less sustainable and economical.

Additional types of seed technologies include inoculants, plant extracts, biological products, seed-applied herbicide safeners, seed treatment polymers and plant growth regulators.

B. How seed treatment technologies work

1. Reducing need for crop inputs

By replacing broad-area crop sprays with precise applications of crop protection products to the seed itself, farmers can avoid spray drift and drastically lower the application rates of crop protection products on a per unit area basis. For example, applying a crop protection product as a seed treatment exposes only about 50 square meters per hectare of soil to the pest control material. An in-furrow application exposes about 500 square meters per hectare of soil surface to the pest control material. Applied as a broadcast spray to the entire field, 10,000 square meters per hectare of soil surface would be exposed to the pest control material. In this example, seed treatment reduces soil surface exposure by 90 percent compared to in-furrow applications and 99.4 percent compared to a surface application [16].

The total amount of pest control material applied to the land is also substantially less when using precise seed treatment, since many seed treatment fungicides are used at rates of less than 1 gram of active ingredient per hectare (less than 0.40 grams per acre).

2. Disease management

Pathogenic seed-borne fungi are frequently found on or in seeds and can result in lower germination or produce a number of plant diseases, collectively known as "smut" [62]. Many fungicide seed treatments have contact activity; that is, if a seed treatment fungicide comes in contact with a particular fungus, the fungus will die or its growth will be inhibited [67]. Contact fungicides are effective against seed-borne fungi that are located on the seed surface. Certain fungi, like loose smut of cereals, are inside the seed. The use of systemic fungicide seed treatments, which are absorbed into the seed or seedling during the germination process, are effective in controlling internal infections [67].

Soil-borne fungi that live in the soil and attack the seed or young seedlings soon after planting can kill the plant or reduce its vigor [81]. They attack the young root system or the sprout as it makes its way to the soil surface. Contact fungicides coated on the seed create a protective barrier in the soil that slows or stops the soil pathogens from attacking the seed. Systemic fungicide applications are needed to protect the seedling, from planting through emergence, by being absorbed by the seed or seedling and moving into the developing plant tissue, thus extending the time of disease control. The concentration of the crop protection product in the seedling, along with the sensitivity of the fungi to the active ingredient, determines how long the disease control lasts.

In cold, wet soil, slow seedling emergence allows other fungi to attack the seed and seedling. Seed corn companies have improved their fungicide seed technologies by using new active ingredients and/or multiple fungicides. Systemic fungicides effective against *Pythium*, which attacks when the soil is cold and wet, have allowed growers to plant corn and soybeans earlier in the growing season. Earlier planting time extends the planting season and often improves crop yields.

3. Pest management

Seed treatments cannot by themselves offer complete protection for agricultural crops, but they do offer a first line of protection against many pests that limit crop stand and yield. Seed treatments are valuable forms of pest management, but they may need to be followed by additional crop protection measures, unless pest and disease activity is restricted to the early stages of crop growth [101].

Today's growers must contend with high populations of many different insects that attack seeds, seedlings and developing plants, both below ground and above ground. Contact insecticides applied to the seed before planting form a protective barrier around the seed and root zone, and can be highly effective against soil insects such as wireworms or seed maggot, even at low rates of application [123].

Systemic insecticides that move into the plant – either directly through water intake, during germination or through root uptake – control insects such as aphids, thrips, flea beetles, leaf hoppers, bean leaf beetles and many other foliar feeding insects. These products require the insect to feed on the plant in order to be effective. The insecticide moves from the site of absorption (seed or root) into the plant and is effective in the newly forming leaves and roots. As target insects feed on the leaf, they ingest the insecticide and either die or become inactive and stop feeding. Beneficial insects that do not feed on the plant are not directly affected by a systemic seed treatment insecticide; however, the population of beneficial insects may build up more slowly due to a potential reduction in their food source [51].

The period of effective control for a systemic insecticide depends upon the dose applied to the seed and the sensitivity of the insect to the product. The concentration of the seed treatment insecticide in the plant declines as the plant grows; eventually, the insecticide is diluted in the plant to a no-effect level.

In recent years, seed treatments that reduce nematode damage to corn, cotton and soybean crops have been introduced. These products include active ingredients from classical chemical control, biological control and plant extracts. They are designed to reduce early season nematode damage and allow seedlings and young plants to be as healthy and vigorous as possible.

4. Polymers

Seed treatment polymers, which help bind product to the seed and create a protective barrier, play a critical role in the success of seed treatment active ingredients. Polymers are either mixed with the seed treatment product or applied to the seed as a final protective material. Without highly effective polymers, many seed treatment materials could not be used.

Polymers serve multiple important functions in seed treatment:

- Improve the treating and coverage of seed by the active ingredient;
- Bind the precise dose(s) of the crop protection product(s) to the seed;
- Minimize abrasion of seeds during the treatment process, handling, storage, and planting to reduce loss of active ingredient and formation of contaminated dust;
- Reduce friction of seed, allowing it to move more easily through conditioning facilities and planting equipment;
- Improve the cosmetic appearance of seed; and
- Make the seed more consistent in size and shape to improve planting efficiency and accuracy.

Today, with high quality polymers, less total dust occurs on treated seed than on untreated seed. Twenty-five years ago, dust-off of seed treatment fungicides between treating and planting was 30 percent or more. Pneumatic planting systems used by today's grower would result in unacceptable levels of chemical dust-off if seed treatment polymer seed coatings were not used.

Treating corn seeds without using a good polymer system can result in uneven movement of seed through planting equipment, seed skips in the furrow and double-planted seed in current corn planting systems. Polymers eliminate these planting problems and allow seed to flow through planters at a more uniform rate.

Polymers contribute to increased vigor and more effective planting for various crops:

Sugarbeets Seed singulation refers to the separation of a single seed from a pool of seeds before planting. Raw sugarbeet seed is jagged and irregular in shape, resulting in poor singulation of the seed and inconsistent seed spacing during planting. For many years, the standard practice was to plant sugarbeet fields to a higher field population, then thin the stand to the desired population using hand labor or a mechanical thinning device. Today, growers can plant encrusted or pelleted sugarbeet seed at the desired stand and spacing [32].

Encrusting surrounds the seed with a thick coat without changing its shape. For sugarbeet seeds, encrusting is defined as adding a coating to the seed that is minimum 30 percent by weight of the raw seed [32, 96]. Use of seed encrusting improves planter accuracy, establishes a protective barrier between the seed and seed treatments that may not be safe on raw seed, and improves application accuracy of all seed treatment products [96].

Pelleting sugarbeet seed adds a coating mixture that is 200 percent of the weight of the raw seed [32]. Although it is a more costly procedure, pelleting offers the same benefits as encrusting, but changes the shape of the seed [32]. Making the seed round and uniform in size and shape further improves planter accuracy.

Alfalfa The small size of alfalfa seed along with its shallow planting depth makes it more susceptible to poor stand establishment. A seed coating of 8 to 34 percent of the seed weight is common in the alfalfa seed market. Treated seed produces a better stand than raw seed under adverse growing conditions. Major improvements in the coating process have occurred in the past five years. New polymers, micro nutrients and bio-enhancers are being used in alfalfa seed coatings. Super-hydration polymers keep the seed moist during the germination process and also help to bind the seed enhancement products to the seed [105].

Small-seeded vegetables Carrot seed ranges in size from 181,000 to 545,000 seeds per pound [30]. Celery seed ranges from 908,000 to 1,135,000 seeds per pound. These seeds are very valuable, so growers cannot afford to waste any seed in their planting systems. It is nearly impossible to take these incredibly small seeds and plant them as raw seed. Pelleting of small seeds with inert materials to change their shape and size improves singulation [29, 95].

There are two basic components in the pelleting process: bulking material and a binder. Crop protection products can be placed in or on the pellet instead of being applied directly to the seed. For some products that may damage seed germination, a seed pelleting barrier may reduce seed safety concerns [95]. Pellet ratios vary for a given seed type. Lettuce pellets range, on a seed-to-pellet weight ratio, from 1-to-17 up to 1-to-35. The higher ratio product is valuable for growers who plant at a faster tractor speed [95].

Large seeded vegetables "Super sweet" hybrids of sweet corn, popular among consumers, have light-weight, shriveled seeds that make accurate planting and even plant spacing quite challenging. In a Brazilian study, pelleting sweet corn seed from high-sugar varieties to increase seed volume by 37 percent reduced both double-seed drops and seed-planting gaps by approximately 90 percent, compared to raw seed. [19]

5. Inoculants

Rhizobia are living bacteria that fix atmospheric nitrogen on roots of legume plants and have a limited life on seeds. A portion of the nitrogen formed on the root is used directly by the plant, and the remaining nitrogen becomes available for the crop planted the following year [35]. Colorado State University Extension notes, "The relationship between the legume and *Rhizobia* is symbiotic, or mutually beneficial. The bacteria invade plant root hairs and multiply in the outer root tissue. The plant forms tissue that acts as a protective enclosure around the bacteria. The plant also supplies energy to the bacteria from photosynthesis. For their part, the bacteria convert nitrogen gas to ammonia in the nodules" [22].

Because these beneficial bacteria have a limited life when applied to the seed, *Rhizobia* seed inoculation has historically occurred just before planting the seed, and was not considered to be a seed treatment method. New seed treatment materials can extend the shelf life of *Rhizobia* to several months, and *Rhizobia* are now a standard part of many seed treatment packages. The application of a build-up coating that includes *Rhizobia* extends the life of the *Rhizobia*.

Applying *Rhizobia* bacteria to soybean seed can convert 53 to 265 pounds of atmospheric nitrogen per acre to ammonia [22]. Many *Rhizobia* products can be applied to soybean seed along with fungicide or insecticide seed treatments. Soybean *Rhizobia* usage has become more common, especially among seed dealers and agricultural cooperatives.

An alfalfa crop can produce up to 308 pounds of nitrogen per acre, and inoculating an alfalfa field only costs $1 to $5 per acre [22]. Seed treatment places *Rhizobia* in the exact location in the soil to grow with the alfalfa seedling.

C. Seed treatment as a precise delivery method

Farmers, growers and other agricultural producers who must control weeds, diseases, insects and nematodes are trained in the proper application of crop protection products, as mandated by FIFRA. Every effort is made to apply crop protection products to seeds at the correct rate and minimize the product's impact on the environment.

A large amount of grain is treated each year with a stored-grain insecticide that is approved for this use. This is not considered seed treatment. When a crop protection product is applied to the seed, it is rendered unfit to legally enter the grain market [70]. To guarantee that seed treated with a seed treatment pesticide does not enter the food chain, the EPA requires that an approved dye be added to the treated seed, marking it with an unnatural color [117]. This dye requirement is only for seed treatments using an EPA-registered pesticide, and is not applicable for seeds treated with inoculants, stored-grain insecticides approved for food and feed use, some biological materials and other non-pesticide products.

Applying crop protection products to seed is vastly different than a field application. Commercial seed treating facilities utilize the newest technologies to assure the accuracy of application of seed treatment products. Seed treatments are typically applied directly to the seed in closed treating systems. Seed treatment products are atomized in mixing chambers to apply an even coating to the entire surface of each seed. Lab analysis of randomly selected samples verifies both total application of product and individual seed application.

Computerized treating systems calculate the total product application rate for each lot of seed, adjust rates of the seed and chemical flow and make corrections as needed before each new seed lot. Batch treatment of a finite amount of seed in a closed chamber allows for a phased application of multiple products as the seed spins in a revolving chamber.

Many seeds are sold by count instead of weight, but seeds are treated according to weight, based on product density. The number of seeds per pound is determined for each lot of seed. Most seed treatment labels indicate application rates per seed for improved accuracy.

The precision technology provides farmers and growers with a highly accurate and uniform application of seed treatment products to provide optimum crop protection, plant population and plant spacing in the field.

D. Factors influencing the growth of seed treatment technologies

The Food and Agriculture Organization of the United Nations (FAO) estimates that global food production will need to nearly double by the year 2050 in order to feed an expected population of nine billion people, who expect an increasing standard of living [23]. Seed treatment products will be a necessary tool in achieving this level of crop production.

Global sales of seed treatment products in 1997 were estimated at about $700 million [5]. Seed treatment products, applied to nearly every acre of corn planted in the U.S. in 2011, helped support nearly $80 billion worth of crop value to American farmers. By 2018, it is estimated that the global fungicide seed treatment market will reach $1.4 billion [88].This type of growth does not happen unless a number of major factors converge.

1. Farms and production demands

Agricultural commodity prices were low from 1993 to 2006.The marketing year average price for a bushel of field corn was $2.33 over the 14-year period. Soybean prices, over the same period, averaged $5.83 per bushel [115, 116].With low prices and reduced profit margins, growers were forced to minimize input costs and increase production.

In 1900, almost one million farms produced half of all agricultural products that were sold in the U.S. This number decreased to 76,000 farms by 1987 and only 33,000 farms by 2007. Farm operations with at least $1 million in sales more than tripled from 1982 to 2007. Farms with sales below $1 million in 2007 were, on average, losing money [77]. In 2001, growers with sales totaling $250,000 or more made up 7.2 percent of all producers and farmed 33.5 percent of all the available farmland. By 2010, this same group represented 10.3 percent of all growers who farmed 48.4 percent of all the land [116].

The average price of corn and soybean from 2007 to 2010 was nearly 80 percent higher than the average price from the previous 14 years [116].The average price for corn increased to $4.30 per bushel, while average soybean prices rose to $10.34 per bushel over the 4-year period. The average yield of soybeans increased by one-third from 1993 to 2010, while the average yield of corn increased 52 percent during the same period of time [115, 116]. The development of biofuels, especially ethanol, from field corn and other crops increased the demand and improved prices for grains.

The large number of American farmers nearing retirement age, along with reduced numbers of young people involved in farming has also forced growers to increase the size of their operations. This movement to larger-scale operations resulted in major implications for seed treatments.

In an effort to get more seed in the ground during the optimal planting window, growers began purchasing planting equipment that could handle larger-scale operations. In 1970, a grower using a four-row planter could plant 40 acres per day if the soil had previously been prepared. With the introduction of more advanced machinery, a grower using a 36-row planter today expects to plant 945 acres per day [77].

Growers have adjusted planting schedules in order to take advantage of prime weather and soil conditions for optimum crop production. Springtime cold fronts, with heavy rain followed by cooler temperatures, typically move across the Midwest during April and early May. These weather conditions favor *Pythium* activity in the soil and infection of seed and seedlings. Growers minimize the risk of poor crop yields resulting from springtime diseases by planting earlier and utilizing fungicide seed treatments.

2. Conservation tillage practices

The cost of fuel needed for crop production doubled from 2001 to 2006 and nearly tripled between 2001 and 2008 [116]. Growers responded to higher fuel costs by converting more acres to no-till or reduced-till farming practices and planting herbicide-tolerant seed.

Reduced tillage practices save fuel by decreasing the number of trips across the field with the tractor while improving soil quality, reducing soil erosion and increasing the useful life of equipment.

These changes in tillage practices saved time and fuel, but resulted in soil conditions that could be detrimental to crop seedling growth and survival. Conservation tillage and no-till practices typically leave more than 30 percent of soil covered with crop residue. Reduced-till systems leave 15 to 30 percent of the soil covered with residue [37]. Soil that is covered with crop residue stays cold and wet longer than clean, plowed soil, adding to the stand establishment issues caused by *Pythium* and other seed- and soil-borne pathogens, and also creating a protective environment for some soil insects such as wireworms and white grubs [77]. No-till fields can also have more early emerged weeds that are attractive to black cutworm moths laying their eggs [84]. Seed treatments can control or reduce damage caused by all of these pests.

3. Fertilizer applications

The cost of nitrogen fertilizer, the most expensive cost in the production of certain crops such as corn, increased along with the cost of fuel [115]. Growers responded to higher fertilizer costs by reviewing their fertility programs in order to optimize fertilizer applications and increasing their efforts to achieve maximum yield potential. Corn requires large amounts of nitrogen fertilization, so growers raised their expectations for corn stands, uniformity and yield potential. Producers observed the improvement in stand, plant health and yield when they planted seed that had been treated with a high performing fungicide and a neonicotinoid insecticide.

4. Value of GM seed

The introduction of GM seed added immense value to seed, but the GM seed purchased in 2010 cost more than twice as much as non-GM seed purchased in 2001 [115]. Growers understood the value of the biotech traits, but with the increase in cost, expectations also increased. In the 1960s, most growers expected that at least 85 percent of the planted corn seed would emerge as seedlings; it was common for some seeds to rot and others to be destroyed by insects. Today, growers expect a nearly 100 percent stand of corn under most growing conditions, even though the seed is being planted in a harsher environment. The seed industry is marketing superior quality seed compared to 50 years ago. The combination of improved seed varieties developed through modern breeding techniques along with effective seed treatments provides the grower the best stand possible. Replanting a field where crop emergence is poor because of disease or insect pest conditions is no trivial matter; the seed is very costly; fuel, equipment and labor costs are significant; and wasted weeks cut into crop yields substantially. Seed treatment is essential to protect the significant investment in high quality seed.

5. Industry engagement

Three factors within the industry propelled the rapid growth of seed treatments: effective products, new approaches to marketing and improved seed treating equipment.

Seed treatment fungicides have consistently offered high value to the seed industry and growers since the introduction of the first systemic product in the 1970s. Each of the newly developed fungicide products increased industry and grower awareness of the role seed treatments would play in the future. When neonicotinoid insecticides were introduced as seed treatments in 1994, they ushered in a new era of farming practices and market growth.

Prior to the introduction of neonicotinoid insecticides, seed treatments were generally sold as low-cost insurance products. The seed industry considered seed treatments a "cost of goods" that reduced their net profit for the sale of a bag of seed. The marketing team at Gustafson LLC, anticipating the value of imidacloprid for sorghum, designed a program prior to its introduction in 1994 that made seed treatment a profit center for the seed industry. Imidacloprid was intended to replace a granular insecticide growers were purchasing for the control of chinch bugs on sorghum. The value stream that was being given up by the agricultural chemical dealer from the sale of the granular insecticide would now be captured by the seed industry. The seed company had money tied up in inventory and needed to upgrade their treating equipment to apply imidacloprid accurately. Training their sales group on the value of the product was also required, as was educating growers on this new delivery system for insect control. This new profit stream began the industry's conversion from considering seed treatments as "cost of goods" to value-added products.

The profits from seed treatment were usually shared with seed dealers. To prevent unnecessary storage of seed from year-to-year and discarding unsold seed, dealers began treating seeds at their dealership as they were being loaded into growers' seed tenders. Seed dealers made a profit from treating while giving their customers a seed that held up to early season stress. This change in marketing seed treatments resulted in benefits for seed treatment suppliers, seed companies, dealers and growers.

The first seed treatment insecticides were designed to be used at a specific application rate per seed for a given insect to be controlled, and they were substantially more expensive than any previous seed treatment. It was imperative that each seed receive the correct amount of active ingredient. High-tech batch treating equipment was developed for use with specialty seeds and rapidly installed in corn treatment facilities for the application of high rates of insecticides. At the same time, high capacity equipment that treated seed by weight rather than by volume replaced old systems that required constant attention and adjustments to maintain accuracy. An updated line of equipment was developed to allow retail dealers to treat with similar accuracy that was achieved at commercial facilities.

The seed industry has shifted to more accurate, high capacity closed systems. Without the profit center coming from seed treatment products, funds would not have been available for upgrading facilities with state-of-the-art equipment to apply precise, effective seed treatment technologies.

E. Crop case studies: common pests, diseases and seed treatments

Seed treatments ensure that many crops in the U.S. are protected from harmful pests and diseases that can severely inhibit healthy growth and cause massive stand losses. In many cases, the severity of a certain disease or pest depends on environmental factors such as soil conditions, weather and planting dates. The case studies in this section reference various research trials and reports that have been conducted across the U.S. The seed treatment options discussed within each crop case study provide differing degrees of protection relative to application rates and targeted use.

1. Field corn

a. Insect pests

Neonicotinoid insecticide seed treatments are convenient, relatively safe to seed, have very low human toxicity and are effective against a large number of insect pests. Nearly all of the non-organic corn seed in the U.S. is treated each year with some rate of neonicotinoid insecticide. Before neonicotinoid seed treatment insecticides became available, many insect pests were controlled with in-furrow granular insecticides applied at rates up to 1 pound per acre, or not controlled at all.

Neonicotinoid insecticides target a wide range of insects, specific to the geographic location where the seed is planted. Corn growers in North Carolina use a seed treatment insecticide at planting rather than a granular insecticide to control Southern corn billbug. In the South, growers need to control Southern green and brown stink bugs and sugarcane beetles. Southwest corn growers may need to control chinch bugs or early season aphids. Growers in the Midwest may use seed treatment insecticides for corn rootworm control on refuge-in-a-bag systems, which contain both traited and non-traited seeds, or for rootworm control on refuge acres. All U.S. growers may be concerned about crop damage and yield loss from insects such as wireworms, white grubs, seed corn maggots, black cutworms, flea beetles and early season thrips.

When neonicotinoid-treated corn seed was planted into corn fields with high wireworm populations, one study found that final plant stand was increased by 18 percent and yield was increased by 12 percent [61]. Depending on the application rate and the insect pest, insect numbers or insect damage from stink bugs and sugarcane beetles can be reduced by 50 to 98 percent [100]. Corn rootworm damage to corn roots is normally reduced by one point on the 0-to-3 point scale. The data clearly demonstrate the effectiveness of these seed treatment insecticides against many of the major pests of field corn, and at rates of only 10 to 40 grams of active ingredient per acre, compared to 454 grams (1 pound) per acre that had been applied as a granular insecticide.

Research conducted by The University of California, Berkeley demonstrates that neonicotinoid materials induce changes in plants at the gene level that result in disease control, improved plant health and enhanced stress tolerance, especially under drought conditions. According to the report, "Under changing climatic conditions, reliable methods of improving stress tolerance (e.g., to pathogens, drought or heat) become even more critical, as is the need for a mechanistic underpinning for any treatment employed" [24].

b. Nematodes

Most nematodes that feed on corn are native to the U.S. Many of these species can also live on native grasses and crops such as soybeans and alfalfa, so field rotation will not decrease nematode populations [114]. At least 120 different species of plant-parasitic nematodes are known to feed on corn around the world, with more than 60 species present in North America [76]. A survey completed by the University of Illinois from 2009 to 2010 found that "over two-thirds of the soil samples contained populations of lesion nematodes that were above threshold for moderate risk of damage" [73].

Some granular insecticides reduce corn nematode populations, but with the use of transgenic corn seed for corn rootworm control, fewer growers apply granular insecticides at planting. In the last decade, some granular materials that were used to reduce nematode damage in corn have been removed from the marketplace. Two seed treatment products that combine an insecticide with a product that has activity against early season nematode damage have been introduced for corn in recent years. One of these products is a traditional chemical product while the other uses a biological as the control agent. Growers now have tools to evaluate the need for these new seed treatments and determine yield benefits under specific field conditions and nematode populations.

c. *Pythium*

Prior to the introduction of systemic seed treatment fungicides in the 1970s, much of the land prepared for planting corn was moldboard plowed and had little crop residue on the soil surface at planting time. Most growers did not start planting corn until the first of May, after the black soil had warmed from the springtime sun. The combination of delaying planting in warm soil resulted in corn seedling emergence in 5 to 7 days after planting. Seed corn was relatively inexpensive and an 85 percent stand of corn was considered acceptable (85 percent of the planted seeds germinating and surviving).

Today, however, the beginning of the field corn planting season has moved from the first of May to April 10 or earlier, particularly in the Midwest. Corn seed is now being planted into cold, wet soil with heavy crop residue. The number of days from planting until emergence for early planted corn is often 14 days or more, which provides diseases like *Pythium* extended time to infect seedlings.

Pythium species that attack corn seeds in the Midwest are mostly active when the soil temperature is between 50 and 60 degrees F and the soil is saturated with water, so that zoospores can “swim” to the germinating seed or seedling and infect the plant. *Pythium* survives in plant residue or as zoospores in the soil. The severity of *Pythium* attack depends upon the amount of *Pythium* that is in the soil as well as the intensity of environmental stress [67].

Several seed treatment products have been introduced in the last 30 years to help control *Pythium* damage and improve planting accuracy and crop health.

In 1980, field corn seed was treated with captan fungicide that often included an insecticide for stored grain insects. The results of a large testing program in 1981 revealed that captan seed treatment increased corn yields by about 10 percent compared to untreated seed [82].

The fungicide metalaxyl was first used as a corn seed treatment in 1990, and by the mid-1990s was part of nearly all corn seed treatments. It was applied at a rate of only 20 ppm when added to a captan treatment. This lower rate was adequate for the early season control of *Pythium*.

Today, either metalaxyl or mefenoxam is used as the standard seed treatment for *Pythium* protection and combined with broad-spectrum fungicides to insure protection across the known seedling disease complex of corn, including *Fusarium spp.* and *Rhizoctonia*.

d. Head smut

Field corn head smut (caused by fungi in the genus *Ustilago*) can be devastating to corn growers in a number of major corn growing states. Head smut can only be managed with resistant varieties and the use of a seed treatment fungicide. The disease is mostly found in drier states west and south of Nebraska but has also been identified in Minnesota, Iowa, Indiana, Ohio and New York.

Head smut is primarily considered a soil-borne disease, but it can also be carried and spread by seeds. The fungus overwinters in soil and infects seedlings early in the season. In the early 1980s, the triazole family of highly systemic fungicide seed treatments was discovered and used to reduce head smut infections and increase yields [101]. These fungicides were used on corn seed planted into fields where growers had previously observed head smut. Today, fungicide seed treatments are applied to corn seed as a means of preventing the spread of the disease to uninfected fields.

2. Cotton

a. Nematodes

Seed treatment materials are becoming one of the last available options in reducing yield losses of cotton due to nematodes. Plant-parasitic cotton nematodes have been found in every cotton growing area in the U.S. The major nematodes that attack cotton are the root-knot, reniform, lance and sting nematodes.

Since 2006, three seed treatment products have been introduced to cotton growers to help reduce yield losses resulting from nematode damage to cotton crops. A Texas trial completed in 2011, in a field infested with high numbers of root-knot nematodes, demonstrated the benefits of using these new seed treatments. The trial included six total treatments. Treatment one contained a complete fungicide package, but no insecticide, while treatment two contained the same fungicide package and an insecticide. The remaining four treatments included products to reduce nematode damage. The seeds treated with products to reduce nematode damage yielded 73 to 123 more pounds of cotton lint per acre than the fungicide control and 58 to 108 pounds of additional lint compared to the insecticide control [97].

b. Thrips

Thrips are the smallest insects to attack cotton, but they can reduce lint production by more than 100 pounds per acre. Cotton is more susceptible to thrips injury than other row crops due to the slow growth of its terminal bud during the first seven to 10 days after emergence. The terminal bud contains tissue that will eventually develop into true leaves and fruiting structures. Thrips prefer to feed on this slow-developing bud, and the damage they cause shows up as the plant grows. Leaves of a plant that has been heavily attacked are crinkled and distorted. Once the cotton plant develops the first three to four true leaves, it grows much faster and develops more tolerance to thrips. Early-planted cotton is more susceptible to thrips damage since the plant grows at a slower pace and the immature thrips require more time to reach the pupa stage [55].

Both seed treatment insecticides and granular in-furrow insecticides are effective against early season thrips. Foliar spray insecticides are also effective against thrips, but close scouting of the field and timely application of the spray is required. Results of long-term research show that treatments are more effective in preventing yield loss from thrips damage when applied at planting [55]. Planting-time treatments can also have an effect on other early season pests like cutworms and early season aphids.

The effectiveness of insecticides was historically measured by the number of live insects found on a crop after treatment, but with the introduction of neonicotinoid insecticide seed treatments, the effectiveness of insecticides is based on insect damage rather than insect numbers. It is common to observe live thrips on cotton plants grown from neonicotinoid-treated seed, but these insects may not be feeding on and damaging the plant.

c. Seedling diseases: *Pythium, Rhizoctonia* and *Fusarium*

Of all diseases that cause diminished lint production in cotton grown in the U.S., seedling diseases are the most damaging. It is estimated that 27 percent of lint loss from 1991 to 2000 was caused by seedling diseases. Common pathogens of cotton are *Pythium*, *Rhizoctonia* and *Fusarium*, and environmental conditions at planting time are important factors in their severity [90].

Pythium is a major cause of pre-emergence damping off of cotton [72]. *Pythium* requires excess soil moisture in order to "swim" to the seed or seedling and infect the plant. Cold, wet soils favor the disease, along with heavy soil that contains high levels of organic matter.

Rhizoctonia is the most common cause of post-emergence damping off of cotton under stressful growing conditions. Stresses that slow the emergence and early growth of a cotton plant increase the *Rhizoctonia* infection and severity. Infected plants develop a red-colored lesion at the soil line that can girdle the stem and kill or weaken the plant [72].

A number of different *Fusarium* species attack cotton and other crops. These species are quite varied in how they affect plants, but generally cause the most negative effects when a seedling is under stress, since species attack slowly. Seed treatments have direct activity on some species of *Fusarium* and can reduce damage by controlling other diseases that might weaken the seedling.

Seed treatment fungicides have been vital components for cotton growing operations. From 1993 to 2004, 214 research trials were planted across all cotton growing regions by the National Cottonseed Treatment Program. In 120 of these trials (56 percent), one or more of the fungicide seed treatment combinations provided a statistically significant increase in stand compared to untreated seed ($P=0.05$) [90].

d. *Thielaviopsis* black root

Thielaviopsis can only be controlled with the use of seed treatments. This disease is more prevalent in clay soils than sandy soils and is more severe when the soil is cold and wet. *Thielaviopsis* is commonly found in Texas, Mississippi, New Mexico and the San Joaquin Valley of California [72]. Soil populations of *Thielaviopsis* have been shown to be closely related to disease severity [90].

Prior to the introduction of two fungicides in the 1990s, growers could only manage this disease in affected cotton growing areas by adjusting planting dates to reduce the likelihood of disease attack accentuated by climatic stress. Results of a two-year study planted at the Shafter California Research Center, where *Thielaviopsis* is present in the soil, demonstrated the value of using a seed treatment that is active against the disease. The most effective seed treatment combination, including a fungicide that is active against *Thielaviopsis*, produced a 65 percent increase in plant stand compared to untreated seed. Treatments containing a fungicide active against this disease increased stands by 7 to 15.5 percent compared to fungicide combinations that did not contain a *Thielaviopsis*-active fungicide [40].

3. Sorghum

a. Chinch bugs

Chinch bugs overwinter as adults in grasses and begin feeding on sorghum when temperatures approach 70 degrees F. Both adult and immature chinch bugs suck plant juices from sorghum stems and leaves. High chinch bug populations rapidly damage young sorghum plants and can stunt the growth of or weaken older plants [15].

Imidacloprid, a neonicotinoid insecticide seed treatment active ingredient, is more effective than traditional granular insecticides in controlling chinch bugs in sorghum. Growers rapidly adopted the use of imidacloprid when it was introduced in 1994 after observing greater convenience, lower toxicity than granular insecticides that were being used and activity against many insect pests.

Neonicotinoid seed treatment insecticides move into sorghum through the root and translocate upward into the developing seedling. As chinch bugs feed on plants, they ingest a toxic level of insecticide and die. With a low seeding rate of 2 to 10 pounds per acre for sorghum, the amount of seed treatment insecticide (2.3 to 11.4 grams of active ingredient per acre) is very low compared to granular materials (454 grams per acre).

b. Aphids

Several types of aphids feed on sorghum. The species known as greenbug and the yellow sugarcane aphid cause the most damage. Both inject toxins into the plant as they feed. Greenbug-resistant varieties of sorghum are available, but greenbug biotypes constantly change, resulting in only partial protection [107]. Greenbugs populations can increase twenty-fold in one week if not controlled [15].

Yellow sugarcane aphids and greenbugs feed on young sorghum seedlings and can significantly damage the plant by delaying maturity, increasing lodging and decreasing yield. Sugarcane aphids that feed on very young plants for a week or less can cause permanent damage. As sorghum plants grow, they become more tolerant to aphid feeding.

Neonicotinoid insecticides are highly systemic and very effective against aphid damage. The aphid must feed on the treated plant in order for the insecticide to take effect. Beneficial insects that do not feed on the plant are not directly affected by the systemic seed treatment insecticide [51].

c. Red imported fire ants

Red imported fire ants affect many crops in the Southern U.S., but are especially damaging to sorghum. Texas sorghum growers have experienced severe damage from this pest since 1980. The red fire ant thrives in reduced tillage soil conditions. Burndown herbicides applied to reduced tillage sorghum acres remove the fire ant food supply, forcing them to feed on sorghum seeds or young seedlings. These ants damage sorghum by feeding directly on seed embryos or carrying seeds back to their nest. Dry soil conditions after planting favor the ants in two ways: first, sorghum seeds and seedlings grow more slowly and extend the period of time for ants to damage the crop; and second, granular soil-applied insecticides are often less effective when the soil is dry [10].

A research trial in Louisiana was conducted from 1994 to 1996, comparing two soil-applied insecticides to a no-insecticide control and seed treated with a neonicotinoid insecticide. Both soil insecticides and the seed treatments significantly improved final plant stands. The soil-applied insecticides increased final stand by 40 to 43.5 percent, while the neonicotinoid seed treatments more than doubled the final plant stand [10].

d. Grass-type weeds

Weed competition, especially from grass-type weeds, is a significant factor in reducing sorghum yields. Grass herbicides for use on corn and soybean fields were introduced in the late 1960s and mid-1970s. Alachlor and metolachlor were very effective in controlling grass weeds. Sorghum producers were hopeful these herbicides could be used in sorghum fields. Unfortunately, sorghum is sensitive to both of these herbicides, so they could not be used [131].

Herbicide safeners for sorghum seed were developed in the early 1980s. These safeners are applied as seed treatments to selectively protect the crop from herbicide damage while the weeds are killed.

Greenhouse and field trials conducted at Kansas State University demonstrated that safeners were generally effective in preventing herbicide injury to twenty-grain sorghum hybrids throughout three years of testing [131].

Sorghum growers continue to use herbicide safeners in their efforts to maximize yields. These safeners are used in combination with seed treatment fungicides and insecticides to create optimal seed treatment packages.

4. Canola

a. Crucifer flea beetle

Approximately 90 percent of U.S. canola acres are planted in the Northern Plains of North Dakota and Minnesota, where the crucifer flea beetle is prevalent. This insect produces one generation per year and overwinters as an adult in leaf litter of shelterbelts or grassy areas around canola fields. In the spring, when the temperature rises above 57 degrees F, the beetles feed on volunteer canola and weeds, waiting for newly planted canola to emerge. The greatest crop damage occurs during the first two weeks after the seedling appears. During this time, the beetles feed on the cotyledons, leaf tissue and growing tip, often killing the young seedling [48].

Prior to the introduction of neonicotinoid insecticides, growers scouted canola fields daily from the start of seedling emergence and decided if the field needed to be sprayed with a foliar-applied insecticide. Spray applications had to be scheduled around wind and rain conditions. If they sprayed too early, additional flea beetles entered the field, requiring a second insecticide application. Neonicotinoid insecticide seed treatments for canola protect the plant as the seedling begins to grow. As flea beetles begin to feed on the plant tissue of a seedling grown from treated seed, they ingest the insecticide and die. The protection normally lasts through the critical seedling phase of the canola, but growers should scout fields for flea beetles that enter after the seed treatment protection has diminished. Growers obtain crucifer flea beetle protection for canola by using only 9 to 18 grams of active ingredient insecticide per acre, depending on seeding rate.

b. Seed-borne black leg

Black leg of canola is caused by the fungus *Leptosphaeria maculans,* which can reduce yields by up to 50 percent. The fungus was first reported in Saskatchewan, Canada in 1975. Two original pathogenicity groups were identified, but additional groups were discovered in 2003 and 2004. In 1991, an annual survey in North Dakota found black leg in all canola fields surveyed.

Although the infection rate may be low, seed infected with black leg can introduce the disease to clean fields. Not all seed treatment fungicides are effective against the black leg fungus, but several materials will drastically reduce or eliminate the fungus infection. Seed treatments are an effective tool for preventing disease spread.

Black leg-resistant hybrids should be used when black leg is identified in a production field, although resistant varieties may not be sufficiently effective against the pathogenicity groups that were identified in 2003 and 2004. Foliar fungicide sprays also help reduce yield loss [58]. A 3 to 4 year rotation to non-host crops is recommended for fields with a confirmed, aggressive black leg pathogenicity group present [75].

5. Small grain cereal

Small grains were the focus of the very first use of seed-applied materials many centuries ago and today are grown in every region of the U.S. Many small-grain producers depend on seed treatments today to maintain profitable operations. The pests that attack the crops differ from area to area, but small-grain seed treatment is recognized as a valuable agronomic tool in every part of the country.

a. Affects all three small grains

i. Aphids and barley yellow dwarf virus—A number of viral diseases are transmitted by insects, especially aphids. Barley yellow dwarf virus (BYDV) is the most widespread and destructive viral disease of wheat. It can also infect oats and barley. More than 20 aphid species can transmit the disease, depending on where the crop is grown. With this wide host range, the reservoir of BYDV is fairly large. Cool temperatures (50 to 65 degrees F) and wet conditions favor the spread of this virus [125]. Yield losses, which can reach 35 percent, are greatest if infection occurs in the fall for winter wheat [7].

Neonicotinoid insecticide seed treatment moves into the plant as the seed germinates and offers aphid control for 6 to 8 weeks after emergence, depending on the rate of application and environmental conditions.

A 1996 study conducted on oats and winter wheat by researchers at the University of Illinois demonstrated that the neonicotinoid seed treatment insecticide imidacloprid reduced the percentage of BYDV-infected plants for all rates of application tested. The highest application rate provided the highest level of control. Oat yields were more than doubled in an inoculated trial with a moderately susceptible variety. Yields were always numerically higher for treated plots compared to the untreated control, but the yields were statistically significant for the susceptible variety and the inoculated, tolerant variety. When the seed treatment insecticide was used, there was a yield increase of 21 percent for a susceptible variety that was inoculated. The non-inoculated plots that received the insecticide seed treatment yielded 14 percent more than the insecticide-free checks for the four varieties tested [28].

A two-year study at the University of Missouri, "Impact of Aphids Species and Barley Yellow Dwarf Virus on Soft Red Winter Wheat," demonstrated the value of combining a systemic seed treatment insecticide with a foliar insecticide application [134]. In this study, untreated seed was planted and compared to seed that received a neonicotinoid insecticide. Additional treatments from the trial included: use of an insecticide foliar spray every 28 days to keep the plot totally free of aphids; use of a single insecticide foliar spray in the fall; use of an insecticide foliar spray in both the fall and spring; use of a seed treatment plus a fall insecticide foliar spray; and use of a seed treatment with both a fall and spring foliar spray. On average for the two years, the insecticide spray every 28 days increased yields by 17.8 percent. The foliar insecticide spray in the fall only increased yields by 6.4 percent, while the fall and spring spray produced 14 percent more grain than the untreated control. Seed treatment by itself increased yields by 4.4 percent, but when a fall foliar spray was added to the seed treatment, the yields increased 11 percent. Combining the seed treatment with both a fall and spring spray provided a 17.5 percent yield increase. This total combination was 3.5 percent more than two foliar sprays, and was only 0.3 percent less than the aphid free control.

ii. Wireworms—There are many species of wireworms in the U.S. Wireworms mature from the larval stage into click beetles. Adult click beetles can live up to one year, while the larval stage may survive up to seven years [87]. Reduced tillage soil creates an ideal environment for wireworms [84]. Wireworms were once considered a major agricultural pest but became less of a concern after World War II with the introduction and wide usage of chlorinated hydrocarbon, organophosphate and carbamate insecticides. Some of the more persistent insecticides like heptachlor have been reported to control wireworms for up to 13 years [122].

Seed treatment insecticides have long been used to control wireworms in small grains. Heptachlor and lindane were used as seed treatments by growers for many years, and were very effective in reducing wireworm damage. With the removal of these products from the market, neonicotinoid insecticides have become the major seed-applied insecticides for wireworm control. These products reduce wireworm damage, but may cause inactivity rather than death when used at low application rates. Some trials demonstrated that wireworms treated with an insecticide remained inactive for up to 301 days and then recovered [122].

Wireworm trials completed at Montana State University in 2008 demonstrated the benefits of seed treatment insecticides on spring wheat and spring barley [108]. Stands from seeds treated with the most effective insecticide were nearly double that of the untreated control, and yields increased by 25 percent.

iii. *Fusarium* scab—*Fusarium* head blight, also known as scab or *Fusarium* scab, infects small grain seed as the plant flowers, during periods of rainy weather or heavy morning dew. If the weather is warm and wet after infection occurs, the seed becomes shriveled. Using a fungicide seed treatment can improve stand and vigor of seedlings grown from infected seed [62].

Incidences of *Fusarium* scab began to increase in the mid-1980s for two reasons: first, the fungus that causes *Fusarium* scab is a very common corn pathogen, and there was an increase in farming operations that produced both corn and wheat during this period of time; second, growers were adopting reduced tillage and no-till farming systems that increased the levels of crop residue on soil and created preferable conditions for seedling diseases. Wheat sown in a field with corn residue on the soil surface may have had two to three times the scab problem compared to wheat planted into a field without corn residue [27].

iv. Black point—Black point of wheat and barley can be caused by a number of fungi resulting in seed discoloration [18]. Black point infection can occur from heading to maturity under warm and very humid conditions. Black point-infected seed may have a low germination, and, if the seed grows, the developing roots may become infected by the fungi in the seed. Several contact and systemic fungicides, used either alone or in combination, are effective against organisms associated with this disease complex [62].

v. Loose smut—Small grain producers depend on seed treatments to control many diseases, including several types of smut [98, 59].

Loose smut is a yield-reducing disease of oats, wheat and barley that is caused by a different species in each crop: *Ustilago tritici* in wheat; *Ustilago nuda* in barley; and *Ustilago avenae* in oats. For all three crops, spores that form on the panicle or spike are spread by the wind to nearby, healthy plants. The spores land on the stigma of open flowers, germinate and penetrate into the developing seed. When the infected seed is planted and begins to germinate, the loose smut mycelium infects the new plant. Since the infection lives inside the seed germ, it is impossible to control with contact fungicides.

Hot water treatments were the only way to reduce loose smut infection levels prior to the introduction of carboxin as a small grains seed treatment in the 1970s. Carboxin provided seed companies and growers their first chance to control loose smut with a seed treatment. Today, there are a number of systemic fungicide seed treatments available that will give total or near-total control of loose smut [62, 59].

vi. *Pythium*—*Pythium* was not considered a serious pathogen of wheat until growers changed their production practices. Wheat in the Pacific Northwest region had been grown in a winter wheat/fallow rotation for many years. In that rotation, the wheat was planted early into a warm, optimal moisture topsoil, and developed deep roots and many tillers before winter.

As growers tried to increase their productivity in the 1960s, wheat was planted every year in areas that received adequate rain fall to support the crop. Growers at this time were also shifting to reduced tillage or no tillage practices. Planting wheat every year forced the new crop to be planted later in the fall into cold, wet soils, and combined with the reduced tillage systems, resulted in slower emergence and smaller plants at the beginning of winter. These fields often had symptoms of root disease damage.

A multi-year research study completed in the late 1970s and early 1980s identified one or more species of *Pythium* as the main pathogen causing stand loss. This study also found that *Pythium* reduced or eliminated the development of fine hair roots, diminished plant vigor and delayed the maturity of wheat and barley. Researchers also demonstrated that using systemic fungicide seed treatments produced plants that were similar in health to ones grown in fumigated soil where the *Pythium* population had been dramatically reduced [14]. Due to the use of low-cost, low-use rate fungicide seed treatments, growers can continue to implement conservation tillage practices.

vii. Dry seed decay—Dry seed decay occurs when seed is planted into very dry soil such as that found in more arid parts of the U.S. Under dry soil conditions, seeds absorb the moisture that is available but not enough to allow them to germinate. However, the seed moisture content is favorable for storage fungi that rot the seed. The main fungus involved in dry seed decay is *Pencillium*, and infected seeds often appear blue in color. A number of seed treatment fungicides are effective against this disease, and enilconazole is the most favorable option [59].

b. Specific to wheat

i. Hessian fly—The Hessian fly is one of the most destructive pests of wheat and often causes yield losses of 50 percent or more in Kansas [44]. In 2009, entire wheat fields in Kansas were destroyed by the pest. This pest was first introduced into the U.S. during the American Revolutionary War, when Hessian soldiers imported straw bedding that carried the insect. It was first observed in Long Island, N.Y. in 1779 [8].

The Hessian fly has two or more life cycles per year depending on its location. One life cycle occurs in the fall, and is predictable from year to year, allowing growers to plant wheat after a “fly-free date,” as determined by entomologists [8]. By waiting for the fly-free date to start planting, wheat may grow with lower yield potential. In Southern parts of the U.S., planting around the fly-free date is not an effective method of control [9]. Recent research work by Kansas State University discovered that Hessian flies often persist well after the fly-free date [44].

No-till or reduced tillage systems increase the amount of volunteer wheat in fields and result in greater Hessian fly populations. Growers have two options in controlling Hessian fly in a reduced tillage system: plant after the fly-free date, which may not be effective; or use a seed-applied insecticide that will only work for 3 to 4 weeks after planting. The optimal control of Hessian fly involves a combination of removing volunteer wheat, waiting for the fly-free date and using a seed treatment insecticide [44].

ii. Common bunt of wheat—Common bunt of wheat is a smut that forms bunt balls in the heads of infected plants. At harvest, the bunt balls are crushed and many thousands of teliospores are released. These spores smell distinctly like rotting fish, so the disease is commonly known as “stinking smut.” The spores that are released at harvest spread to clean grain or fall to the ground where they can remain viable for 10 years.

Many contact seed treatment products control the seed-borne inoculum, but not infection from the soil-borne inoculum. Today, systemic fungicide seed treatments effective against wheat smuts are also effective against the soil-borne inoculum [59].

iii. Dwarf bunt—Dwarf bunt is only a problem of winter wheat and only present in climates where snow cover lasts for extended periods of time. Most infections come from soil inoculum, but seeds also carry spores to clean fields. The spores can remain functional for long periods of up to 10 years. Winter wheat planted into infested soil becomes infected during the winter, when temperatures are between 37 and 46 degrees F. Infected plants tend to grow substantially shorter than normal plants. With heavy disease infection, yields can be reduced by 50 percent [41].

The long period of time between planting and infection for winter wheat severely reduces the value of seed treatments in defending against dwarf bunt. In 1994, difenoconazole was registered. This product delivers near-complete control of dwarf bunt and remains the only effective product in the market [59].

iv. Foliar diseases: Powdery mildew, *Septoria* and rust—Season-long disease control is challenging for winter wheat since the crop is planted and emerges in the fall, but is not harvested until the following summer. Foliar disease infections can be controlled in the fall with seed treatments, but infections can still occur the following spring if climatic conditions favor disease development. If a foliar disease develops in the fall and is not controlled, it can rapidly move to new leaves as they develop. This is the case for powdery mildew, *Septoria* and rust, each of which can cause major yield losses. The largest yield losses occur from spring infections that last through the reproductive stage of the plant.

A number of systemic fungicide seed treatments have been introduced since 1989 that give some degree of control for these diseases from planting through fall growth. Use of a seed treatment followed by a foliar fungicide spray can provide the best total disease control [13]. Most or all fungicide seed treatments that have activity against foliar diseases also have activity against some smut diseases.

d. Specific to barley

i. Barley stripe—Barley stripe is a seed-borne disease that only affects barley and can cause significant yield loss. Spores are produced on infected leaves and carried by the wind to nearby developing seed heads. Seed infection only happens in the field [38]. The seed infection is usually found as mycelium within the husk tissue. Only systemic seed treatments have activity against this disease [59].

6. Cut potato seed pieces

Growers in the U.S. commonly plant cut potato tubers to propagate a crop, whereas whole potatoes are planted in other parts of the world. In order to reduce the pounds of potatoes planted per acre (normally 1,200 to 2,600 pounds per acre), seed potatoes are cut into seed pieces that normally range from 42 to 85 grams each before planting.

a. Colorado potato beetles

Since the middle of the 20th century, Colorado potato beetles have developed resistance to 52 different insecticides, in all of the major insecticide classes. This beetle is widely regarded as the most important insect defoliator of potatoes [3]. One beetle can consume 40 square centimeters of foliage per day as a larva and nearly 10 square centimeters per day as an adult [4].

Adult Colorado potato beetles overwinter in the soil or in nearby grassy areas, windbreak or wooded areas. Adults begin leaving their winter sites about the same time potato plants begin to emerge. They feed for a short period of time and then mate [86].

Systemic neonicotinoid insecticide seed piece treatments are effective against adults and larvae, but are ineffective when summer adults emerge from pupation. Growers use insecticides with a different mode of action against summer adults and their offspring, helping to slow the beetle's resistance to insecticides [86].

b. Late blight

Phytophthora infestans, also known as late blight, was responsible for the potato famine that ravaged Ireland and spread to American potato fields in the early 1840s [121]. Once late blight is in a field, it spreads rapidly from plant to plant. The source of the first inoculum may have been volunteer potatoes, but with more aggressive strains now identified in diseased fields, it is unlikely that an infected tuber would have survived to send up a viable sprout. Current research points to contaminated seed pieces mixed with healthy seed pieces as the most likely source of late blight being introduced into production fields.

Late-blight-infected seed pieces usually rot and do not form plants. Mycelium from a diseased tuber can infest a healthy tuber during cutting and handling of seed potatoes [53].

Not all potato fungicide seed treatments are active against late blight, and if a seed treatment that does not control late blight is used with infected potatoes, the amount of late blight could increase in the field. The use of fungicide seed treatments that control other fungal pathogens but not late blight also results in an increase of the disease. These secondary fungal diseases are oddly beneficial in that they can cause infected seed pieces to rot, rather than produce a stem that carries the late blight to the soil surface. Fungicide seed piece treatments that have activity against late blight need to be applied to the seed immediately after cutting, and the seed should be planted as soon as possible after cutting to reduce further spread of the disease. Seed treatments should not be used as a means of rescuing late blight-infested seed lots, but as a tool to reduce the chance of late blight developing in a healthy seed lot [43, 85].

c. *Fusarium* dry rot

Fusarium dry rot is one of the most harmful diseases for potatoes, since it affects both tubers in storage and cut seed pieces at planting [128]. Cutting a potato creates an “open wound” that exposes the crop to diseases, especially *Fusarium* dry rot. Under optimal conditions, this “wound” can suberize in about 5 to 6 days and keep *Fusarium* dry rot from infecting the plant. However, it takes 2 to 3 weeks for a cut potato to completely suberize [93]. If *Fusarium* dry rot does infect the cut seed piece, it can kill sprouts and reduce yields by 25 percent. In addition to the direct effect of dry rot, bacterial soft rot will often colonize dry rot lesions, resulting in the complete rotting of the seed piece [128]. Fungicide seed treatments prevent *Fusarium* dry rot as well as additional diseases such as silver scurf and *Rhizoctonia*.

7. Soybean

a. Bean leaf beetles and bean pod mottle virus

Bean leaf beetles are the main transmitters of Bean Pod Mottle Virus (BPMV), so both the pest and disease often occur together in the same field [17]. BPMV can reduce yields, discolor harvested seed, produce a symptom known as “green stem” and increase pod and stem blight infections.

Bean leaf beetles have two life cycles per year, with the second generation overwintering as adults. A portion of the second generation population acquires the virus prior to overwintering. These beetles can both acquire and transmit BPMV after a single bite of infected plant tissue. In the spring, the beetles feed on alfalfa or other wild hosts and then move into emerging soybean fields. The beetles feed on the emerged cotyledons and first true leaves, infecting the plant as they feed. The earliest planted soybean fields typically attract the most beetles [17].

Seed-applied neonicotinoid insecticides control overwintering bean leaf beetles and reduce the amount of BPMV infection as well as the amount of discolored seed at harvest. Foliar sprayed insecticides also control both the first and second generations of bean leaf beetles, but it may require several sprays in the spring to achieve sufficient control. Combining an insecticide seed treatment for control of overwintering bean leaf beetles along with a foliar spray to control the first generation of bean leaf beetles provides the highest overall control of BPMV [17].

b. Southern soybean insects

Growing soybeans in the Mississippi Delta requires the control of a number of insect pests including bean leaf beetles, grape colaspis, thrips, grubs and three-cornered alfalfa hoppers. Seed-applied neonicotinoid insecticides reduce damage from all of these pests. More than 100 research trials planted in Arkansas, Louisiana, Tennessee and Mississippi from 2003 to 2008 had a 79 percent positive net return on investment. Overall, soybean yields increased about 3.5 bushels per acre across all trials. When early planted soybeans were evaluated separately, the average yield increased to about 6.5 bushels per acre. Researchers observed improved plant vigor when the insecticide was applied to the seed, which led to increased plant stand [89].

c. Aphids

The soybean aphid is a relatively new pest in the U.S. When aphid populations get above threshold, substantial yield losses occur. Systemic neonicotinoid insecticides are active against overwintering aphids, but their direct activity is limited to about 3 or 4 weeks unless planted near an aphid overwintering site. The seed treatment does not hurt beneficial insects that feed on aphids [78]. As these insecticides lose activity, aphids do not reproduce as rapidly as normal. This combination of early season aphid control, reduced aphid reproduction rates and the presence of beneficial insects can keep aphid levels below threshold for 65 days or longer.

d. Soybean cyst nematode

Soybean cyst nematode (SCN) was first discovered in the U.S. in North Carolina in 1954, and has since spread to nearly all soybean producing states. The main symptom of SCN is yield losses, which can be as high as 80 percent and represent millions of bushels [49]. Yield losses ranging from 15 to 30 percent have been reported with no visible symptoms that SCN was damaging plants [127].

SCN-infected plants show symptoms of sudden death syndrome (SDS) and brown stem rot earlier in the year compared to plants that are not infected with SCN [114].

Two soybean seed treatments have been introduced in the last few years as tools to reduce the damage caused by SCN. These products are a combination of fungicide, insecticide and nematode materials as a total seed treatment package.

e. Pod and stem blight

In Iowa alone, it was estimated that only about 3 percent of soybean seed was treated in 1999, while more than 50 percent was treated in 2009 [133]. There were some years when a large amount of commercial soybean seed was treated due to pod and stem blight. Pod and stem blight develops in soybean fields during the growing season, particularly in warm, humid weather conditions [66]. The disease can travel from the stem of the plant to the pod and seed as the crop matures, especially if the harvest of the mature crop is delayed.

Treating infected seed with a fungicide seed treatment, especially a systemic fungicide like carboxin, substantially improves seed germination and produces better stands and healthier plants in the field than untreated seed.

Pod and stem blight presents less of a threat to the seed industry today than it did 30 years ago now that foliar fungicides are available to reduce field infections. Most soybeans are harvested as soon as they are mature with modern harvesting equipment, also reducing the likelihood of infection.

f. *Phytophthora*

Phytophthora root rot of soybeans has been a concern for many decades. *Phytophthora* is a problem in soil above 60 degrees F that becomes saturated soon after planting. This disease survives in crop residue and infects the root. When conditions are favorable, root rot causes damping off of young seedlings or death at any time during the growing season. Resistant soybean varieties are available, but there are many pathotypes of this disease and the genetic resistance is specific to each pathotype. Partial resistance has also been developed that is effective against all *Phytophthora* pathotypes, but it is only expressed after the first true leaves have emerged [66].

Planting soybeans earlier in the spring, before the soil has warmed to 60 degrees F, reduces the incidence of this disease. However, problems can still occur when the soybean season is delayed as a result of climatic conditions.

With the introduction of metalaxyl as a seed treatment in 1981, soybean growers had their first tool to fight *Phytophthora*. Combining metalaxyl with a seed that had resistance to a large number of *Phytophthora* pathotypes improved the odds of obtaining an adequate plant stand, even in wet soil conditions. Today, planting soybean seeds containing partial resistance to *Phytophthora*, along with a metalaxyl or mefenoxam seed treatment, provides effective control against the disease.

g. *Pythium*

When metalaxyl was registered with the EPA as a seed treatment in 1981, *Pythium* was not considered a serious pathogen of soybeans. However, growers moving to earlier planting dates and reduced tillage practices resulted in greater *Pythium* occurrences in the past 30 years. Soybean producers in the Midwest plant their crops earlier in the year to maximize yields, but colder springtime soil and rain create a favorable environment for *Pythium*, which is active from 50 to 60 degrees F [64]. Reduced or no-till farming practices maintained these cold temperatures due to the greater amount of crop residue on the soil surface.

Metalaxyl and mefenoxam seed treatment fungicides are currently available and provide high levels of systemic control of most *Pythium* species. Several additional seed treatment fungicides offer some level of protection against *Pythium*.

h. *Rhizoctonia*

Rhizoctonia root rot can be a pathogen for many different crops and is most damaging to crops that are under stress. *Rhizoctonia* infects young seedlings and can either kill or weaken plants. The seedling infection can expand to the root system and cause plant death later in the growing season [66]. The disease survives on crop residue or in the soil, and corn/soybean crop rotations utilizing a no-till system favor this disease. While *Rhizoctonia* normally does not devastate soybean stands, some researchers believe it reduces yields each year since it is present in most fields.

A number of seed treatments have some degree of activity against *Rhizoctonia*, and several seed treatment fungicides developed since the mid-1990s are highly effective. All current soybean seed treatment fungicide combinations include at least one product that is active against *Rhizoctonia*.

i. White mold

White mold of soybeans infects plants during the flowering period when fields are cool and wet. This disease, once present in a field, can survive for several years.

Seeds can carry white mold to fields that were previously free of the disease. While the number of soybean seeds carrying white mold may be very low, the disease can rapidly develop and spread once it has entered a field [68].

Most seed treatment fungicides have some level of activity against seed-borne white mold, but differences exist in the level of control among products [68]. In 1996, only 8 percent of all soybean seeds were treated, and there was a much greater possibility for white mold to spread [71]. Today, a high percentage of soybean seeds are treated, and the risk of white mold spread has diminished.

8. Sunflower

a. Pale striped flea beetles

The pale striped flea beetle has been observed within a very large geographic area, but has not been extensively studied since it seldom causes serious damage to most crops. This insect inhabits a wide range of crops and weeds. The adult overwinters under soil clods and crop residue.

Although pale striped flea beetles do not significantly damage most crops, they can be very harmful to sunflowers and cause significant stand losses. Adult beetles become active in the spring and feed on alfalfa and weeds. In June, they move to emerging sunflower seedlings and feed on the cotyledons, leaves and hypocotyls of young sunflower plants. This feeding causes the seedling to wilt and die. Sunflower plants develop greater tolerance from flea beetles when they reach the four-leaf stage. The pale striped flea beetle moves very quickly and is difficult to count when fields are being scouted for damage [47].

Treating sunflower seeds with a systemic neonicotinoid seed treatment insecticide reduces damage from pale striped flea beetles by up to 75 percent [47].

b. Sunflower beetles

Sunflower beetles feed exclusively on sunflowers. Adults closely resemble Colorado potato beetles and are sometimes confused with these pests. Sunflower beetles have only one generation per year and overwinter as adults in soil. Adult beetles emerge from the soil in the spring, at about the same time sunflowers emerge, and feed on the first true leaves. Adults feed for about eight weeks. The most yield damage typically occurs from larvae feeding on the above-ground plant parts [47].

Treating sunflower seeds with systemic neonicotinoid insecticides can control adult sunflower beetles. The highest concentration of systemic insecticides is found in the cotyledons and first true leaves of treated plants. Insecticide dilution occurs as additional leaves form, affecting the length of pest control. Reducing the overwintering population of adult sunflower beetles results in fewer females laying eggs and less larval damage.

c. Wireworms

Wireworms are more prevalent in fields where grasses have been growing, including small grains. Approximately 40 percent of all sunflowers in the U.S. are grown in North Dakota or South Dakota, where small grains are typically part of the crop rotation and there is a high likelihood that wireworms will be present.

Wireworms live near the soil surface early in the growing season and move deeper into the soil as the temperature warms and it becomes less moist. Most damage to crops occurs during the spring. Sunflowers can receive the most damage when wireworms feed near the soil surface at planting and during the seedling stage. Heavy wireworm infestations can require growers to replant part or all of a field. Decisions on how to treat for wireworms must be made prior to planting since there are no rescue treatments for wireworm damage [47].

Several seed-applied insecticides are very effective against wireworm damage. Systemic neonicotinoids can protect against wireworm damage as well as damage from other insect pests.

d. Downy mildew

Downy mildew is a common disease that affects sunflowers in all of the Northern Great Plains states where they are grown. This disease has both systemic and secondary infection symptoms, and systemic symptoms are the most devastating. Systemic infections of sunflower seedlings occur in fields infested with downy mildew when the soil is cool and water-saturated.

Downy mildew can survive for up to 10 years in the soil. The downy mildew fungus infects through the developing roots and normally kills the young plant. Control of this disease is complicated by the presence of 12 different races of downy mildew that were identified in North Dakota in 2009. Three of these races make up 75 percent of the total population of downy mildew in North Dakota. Some of these races have become resistant to seed treatment fungicides, so it is necessary to complete periodic field surveys for downy mildew. Planting downy-mildew-resistant hybrids is an important management tool, but is not sufficient by itself due to the shifting downy-mildew races in the field [25].

When metalaxyl was registered with EPA as a fungicide seed treatment, it was immediately adopted as a major tool for the control of downy mildew in the northern Great Plains. This fungicide was very effective, and for a number of years, downy mildew of sunflowers was not a concern for sunflower producers. Mefenoxam was also registered for downy mildew when it was introduced to the market in the early 1990s. Both mefenoxam and metalaxyl have the same mode of action, and heavy use of these products resulted in resistance by some races of downy mildew that could not be controlled with increased application rates. Researchers have identified a few seed treatment fungicides that offer varying degrees of protection against this devastating soil pathogen. Combining disease-resistant seed with the best seed-applied fungicides can help protect sunflower crops from systemic downy mildew [25].

9. Sugarbeet

a. Beet leafhopper and curly top

Curly top of sugarbeets is caused by a virus that occurs primarily in the arid growing regions of the Western U.S. The virus is transmitted by the beet leafhopper and can infect more than 300 different plant species, including a number of vegetable crops. In 1935, curly-top-resistant sugarbeet varieties became available. Although these varieties serve as the primary control of curly top, the resistance is not complete and the level of disease severity has increased with some of the newer, more popular varieties. Another disease, *Rhizomania* of sugarbeets, has become a bigger threat to the industry than curly top, so seed that is resistant to *Rhizomania* has become more valuable. It is difficult to have resistance to both diseases in the same seed [104].

In Idaho, research trials conducted from 2005 to 2009 evaluated neonicotinoid insecticide seed treatments for the control of beet leafhoppers and resultant reduction in curly top incidences. In some of these trials, additional insects were present, including leafminers, black bean aphids and sugarbeet root aphids. Data was gathered for all insect pests in these trials along with total sugarbeet root yield and recoverable sugar. Data from the multiple years, multiple locations and multiple varieties clearly demonstrated a consistent reduction in curly top as well as a reduction in the number of infested plants when neonicotinoid insecticides were used as a seed treatment. Not surprisingly, both root yield and recoverable sugars were consistently greater for the insecticide treated plots. This data was consistent across varieties with different levels of curly top resistance [103, 104].

b. *Aphanomyces*

Aphanomyces root rot of sugarbeets, also known as black root, is one of the most prominent diseases of sugarbeets worldwide. This soil-borne disease does not affect initial stand establishment but can cause severe stand loss several weeks after the plant emerges. Disease infection can occur from 65 to 90 degrees F, but the optimum temperature for infection is about 78 F. Near-saturated soil also encourages *Aphanomyces* infections [32].

The U.S. is one of the top four sugar-producing countries in the world, and sugarbeets have an important role in sugar production. Without a control method for *Aphanomyces*, sugarbeet production in some parts of the U.S. would be threatened. Cultural practices offer limited help in reducing stand and yield losses for fields infested with the disease [32].

A fungicide, fenaminosulf, was registered as a seed treatment for sugarbeets in 1974 for the control of *Aphanomyces*. This inexpensive and effective product was used until inventories were consumed following the product's cancellation in 1984. Without fenaminosulf, sugarbeet growers had no chemical control method available to protect crops from this serious disease [32].

In 1995, hymexazol fungicide was registered with EPA as a seed treatment. It was first discovered in the 1960s, sold under the trade name Tachigaren®, and quickly became the standard treatment for sugarbeets outside the U.S. [33].

The fungicide hymexazol can only be used to treat seed that is either pelleted or encrusted. Hymexazol seed treatment adds $20 to $28 per acre to production costs. The product's use has grown over the years and continues to be the only fungicide available for the control of *Aphanomyces* root rot of sugarbeets [32].

10. Peanut

a. Thrips

Thiamethoxam was recently labeled with EPA as a seed treatment for peanut seed. The first commercial use of this product for controlling early season insects occurred in 2012. Thrips are the leading early season pests in many peanut production areas. A field trial completed in 2009 in Virginia compared the effectiveness of thiamethoxam seed treatment, a no-insecticide control and two in-furrow granular insecticides. All insecticide treatments were effective in reducing thrips damage and numbers. The thiamethoxam treatment performed similar to the granular insecticides. The in-furrow products improved yields, as did the thiamethoxam systemic seed treatment insecticide [34]. Currently, thiamethoxam is the only systemic seed treatment insecticide registered for application to peanut seed.

b. Seedling diseases: *Rhizopus, Fusarium, Rhizoctonia, Pythium*

Peanut growers rely heavily on fungicide seed treatments for obtaining acceptable plant populations and yields. Peanuts are susceptible to many seed-borne and soil-borne, pre-emergence and post-emergence damping off diseases that can reduce peanut stands by 50 percent or more. Pathogens that result in stand loss include *Rhizopus*, *Rhizoctonia*, *Pythium*, *Aspergillus niger* and *Cylindrocladium*. Every case study reviewed for this report recommended that all peanut seeds be treated with a fungicide for control of seedling diseases [106, 11].

Trials conducted 30 years ago demonstrated 18 percent lower stands when untreated peanut seed was planted, compared to treated seed. There was also a 33 percent increase in tomato spotted wilt virus (TSWV) in the untreated plots [99]. A 12-year study found that the use of seed treatments on peanuts resulted in an average 36 percent yield improvement compared to untreated seed [99].

An Alabama Polytechnic Institute Ag Experiment Station Leaflet from 1948 states: “Poor stands of peanuts which cut growers’ profits may be caused by one of several conditions. Seed rot, however, is one of the most common causes of poor stands.” The Leaflet also reports on research conducted in 1946 where treating peanut seed with a fungicide increased stands by up to 79 percent [130].

11. Alfalfa

a. *Phytophthora* and *Pythium*

Phytophthora and *Pythium* are seedling diseases of alfalfa that can reduce initial seedling establishment as well as increase post-emergence stand loss. Alfalfa seedling diseases cause more damage if cold and wet conditions occur soon after planting. Alfalfa is often planted early in the spring and replanting is usually not an option if the plant population is low. Seed that has resistance to *Phytophthora* is available, but this resistance may not prevent stand loss. Both systemic seed treatments metalaxyl and mefenoxam are effective in controlling seedling attack by *Phytophthora* and *Pythium*. The majority of alfalfa seed in the U.S. is now treated with one of these two products [69].

12. Rice

a. Rice water weevil

The rice water weevil is the most destructive rice insect pest in Louisiana. Both the adult and larva feed on the rice plant, but larval damage to the roots is the most destructive. Rice water weevil infestation begins when a rice field is flooded, since egg laying depends on the presence of standing water. The larval stages of the rice water weevil are spent underground. Heavily infested fields can have as many as 2,000 larvae per cubic meter of soil. Damage to the rice root caused by the rice water weevil results in less plant growth, shorter plant height and decreased yields. Yield losses of up to 25 percent have been recorded in research plots. Sampling from commercial fields indicates a 5 to 14 percent yield loss [102].

Rice growers were without suitable insecticides for the control of rice water weevil until 2004, but three seed-applied insecticides have since received EPA registration for use on rice. All three of these products were included in a 2009 rice study completed at three locations in Arkansas. Soil samples were taken at each location, and rice water weevil counts were made. The fungicide control sample averaged 25 weevils per core, while samples from the applied insecticide samples ranged from three to eight weevils depending on product and rate. All seed-applied insecticides evaluated in this study produced a statistically significant reduction in weevil numbers compared to the fungicide control [57].These three insecticides give growers an environmentally responsible means of controlling this harmful pest [102].

b. *Pythium*

Pythium is a major cause of reduced rice crops stands, particularly in Arkansas. Stand establishment problems occur frequently in the state, especially for early planted rice when soils are cool and wet after planting. There are some rice varieties that have demonstrated levels of *Pythium* resistance. Data from a series of rice seed treatment trials planted in 2011 showed an improvement from the use of metalaxyl seed treatment in every trial for a variety susceptible to *Pythium*. These trials were planted at three locations and included multiple planting dates at some locations. The varieties that had some level of resistance to *Pythium* either responded to metalaxyl for only one planting date/location, or not at all. Adding a seed-applied insecticide or a combination insecticide and fungicide seed treatment failed to improve stand more than using metalaxyl alone. This data demonstrates that *Pythium* was the major pathogen causing stand loss in these trials [91].

c. Grape colaspis

Grape colaspis, also known as lespedeza worm, is arguably the most common insect pest of rice in Arkansas. This very small grub overwinters in the soil and prefers legumes such as soybeans and lespedeza as its primary host. It is common practice in the mid-Southern region of the U.S. to rotate crops from either soybean or lespedeza to rice, so grape colaspis larvae frequently feed on rice seedlings in this region [118].

If a rice crop is infested by grape colaspis, it will emerge with a good stand but will quickly begin to thin. It may appear as if the crop has only minor damage, but the damage continues as the grubs feed for 3 to 4 weeks.

Three insecticides have been registered for application to rice seed in recent years. All three of these products have activity against both grape colaspis and water weevil. Results of a 2009 rice study completed in Arkansas demonstrated that grape colaspis larvae were reduced anywhere between 8 to 83 percent depending on the seed treatment insecticide and rate of application [6].

13. Large seeded vegetable

a. Cucumber beetles and bacterial wilt

Spotted cucumber beetles and striped cucumber beetles spread a bacterium, *Erwinia tracheiphila*, which is responsible for bacterial wilt in cucumbers, muskmelons, pumpkins and squash. The bacterium causes these crops to wilt and eventually die. It overwinters in the digestive system of the beetle and is spread from plant to plant during springtime feeding. Contaminated insect excrement is the source of the bacteria. Plant infection occurs through stomata or wounds in the plant caused by beetle feeding. Beetles ingest more bacteria as they feed on infected plants and continue to spread the disease [63].

Striped cucumber beetles overwinter in Northern climates and emerge in late April, while spotted cucumber beetles migrate north during the spring [120]. Striped cucumber beetles inflict more damage to Northern vine crops since they overwinter in protected areas near production fields. Most damage caused by these beetles is from the spread of bacterial wilt. There is no way to control bacterial wilt of vine crops other than controlling the infected cucumber beetles. At planting time, in-furrow insecticide treatments and neonicotinoid insecticide seed treatments reduce cucumber beetle numbers and the percentage of plants infected with bacterial wilt [39].

b. Seed corn maggot

The seed corn maggot was introduced to the U.S. in the mid-1800s and spread throughout most of the country. These insects overwinter as pupae in the soil, and in the spring adults emerge as flies. Large swarms of seed corn maggot flies often appear in freshly worked fields. Adults mate within two to three days after emerging and lay their eggs in soil with abundant, decaying organic material. Larvae spend their brief, three-week life cycle in soil, feeding on seeds, seedlings and other decaying material. Seedlings are more susceptible to seed corn maggot attack during wet, cold springs when germination and seedling emergence occurs slowly. Due to their short life cycle, larvae may no longer exist in fields by the time growers observe stand problems [123].

Dry bean growers in North Dakota experienced severe infestations of seed corn maggot in recent years when the weather was cold and wet after planting. Seed corn maggots attack dry bean seeds and prevent sprouting or weaken seedlings. There is no rescue treatment for seed corn maggots, but an insecticide seed treatment or soil insecticide used at planting can prevent infestation [46].

A research trial at the University of Wisconsin during the 2003 growing season evaluated several seed treatment insecticides for the control of seed corn maggots attacking snap beans. All seed treatment insecticides tested reduced the damage from seed corn maggots. Final stand counts significantly improved for all of the seed treatment insecticides in the late planted trial. Yields increased for all of the seed treatment insecticides compared to the no-insecticide control, but only the neonicotinoid seed treatments produced statistically significant yield benefits. The increased yields may have been the result of foliar insect control offered by the systemic insecticides [132].

c. Corn flea beetles and Stewart's wilt

Stewart's bacterial wilt of sweet corn was first identified in 1897 by F.C. Stewart, and was initially known as "the sweet corn disease of Long Island." Over the years it has been called Stewart's bacterial wilt or just Stewart's wilt. Stewart's wilt can affect sweet corn, field corn and field corn inbred seedlings. The disease is transmitted by corn flea beetles [83].

Genetic resistance exists in some sweet corn hybrids. Resistant lines display little or no yield loss if Stewart's wilt infection is delayed until the plant has reached the three to five leaf stage. Hybrids with moderate resistance can avoid serious yield loss if the infection is delayed until plants have reached the five to seven leaf stages. In general, there will be a 90 percent yield loss for each incidence of Stewart's wilt [79].

The corn flea beetle lives in areas east of the Rocky Mountains. Corn flea beetles feed on a number of hosts but appear to prefer grasses. Adult beetles overwinter in litter, crop residue and field margins. Cold winters can dramatically reduce adult flea beetle numbers. Adult beetles that survive the winter feed on weeds and move to emerging corn seedlings. There are three or more generations of flea beetles each year [74].

Applying neonicotinoid systemic insecticides to sweet corn seeds reduces incidences of Stewart's wilt by killing overwintering adult flea beetles as they begin to feed on treated corn seedlings. Use of neonicotinoid-treated sweet corn reduced the incidence of Stewart's bacterial wilt by 50 to 83 percent in 17 field studies planted in Illinois during 1998 and 1999. Trials completed from 2000 to 2003 in Illinois demonstrated a 41 to 94 percent reduction in Stewart's wilt in nearly every trial [79].

d. Bean leaf beetles

Bean leaf beetles overwinter as adults, so mild winters increase the likelihood of their survival. Mild winters in the Northern Midwest during the last decade have increased the population of bean leaf beetles and damage to snap beans. Foliar insecticides can be used to control bean leaf beetles; however, the beetles move into snap bean fields over a prolonged period of time, so using a foliar insecticide with a short residual activity may not provide the necessary control. Systemic neonicotinoid insecticides have been registered for use on snap bean seeds in recent years. Both foliar insecticides and systemic neonicotinoid insecticides provide excellent early season control of bean leaf beetles [124].

14. Small seeded vegetable

Crops classified as small seeded vegetables include onions, table beets, radishes, leafy greens, cabbages, cauliflower and many other vegetables [110].

Very few pounds of small seeded vegetable seed are required in order to produce an adequate quantity of these crops each year. In 2013, approximately 1.7 billion pounds of corn seed were planted to produce the number of corn acres in the U.S., and more than 4 billion pounds of soybean seeds were planted. In comparison, 10,500 to 70,000 pounds of cabbage seed were needed to plant all of the cabbage acres in the U.S. [29]. Although the market for vegetable crop seeds is small, the value of the seeds is very high, as is the potential liability for treating them.

The high cost of vegetable seed, the small amount of seed by weight needed to supply the entire market, the small volume of product needed to treat that seed and the high cost of registering a pesticide for use on a single crop all impact the economics of providing seed treatments for vegetable crops. Recent innovations in pricing seed treatments on a cost per 1,000 seeds rather than cost for treating 100 pounds of seed have created greater value for growers of small seeded vegetables and made it possible for registrants to support these crop uses [52].

New small seeded vegetable seed treatment products are entering the market and small seeded vegetable growers will be able to enjoy the convenience and efficacy from the use of seed treatments as these new programs develop.

a. Onion maggot

Onion maggots and seed corn maggots can be devastating to onions, causing 70 to 100 percent crop loss. Onion growers in New York, Michigan and Wisconsin routinely encounter this pest. Chlorpyrifos, a granular insecticide active ingredient, and cyromazine, a seed treatment insecticide, have historically been used to control onion maggots. For heavy onion maggot infestations, growers use both of these products together. Some of the new seed treatment products for onion maggots reduce damage to the same level that is achieved when chlorpyrifos and cyromazine are used together [36]. Onion maggots are notorious for developing resistance to insecticides. It is important that growers follow all guidelines for preventing or slowing resistance build-up [36].

b. Leafy vegetable insects

A seed treatment containing three fungicide active ingredients and the insecticide thiamethoxam, was recently developed for treating lettuce and other leafy vegetables. This seed treatment will control aphids for 45 to 50 days and leafhoppers for 35 to 40 days.

c. Seedling diseases

Small seeded vegetables are susceptible to early season soil pathogens that cause seed and seedling damping off. Use of seed-applied fungicides for control of these seedling diseases is recommended [110]. A new product containing three separately registered seed treatment fungicides can be commercially applied to cabbage, broccoli, cauliflower, carrot, onion, tomato and pepper seeds for control of seed and seedling diseases [45].

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