UNIVERSITY OF ILLINOIS EXTENSION
College of Agricultural, Consumer and Environmental Sciences

report on
PLANT
DISEASE

RPD No. 1002
September 2005

DEPARTMENT OF CROP SCIENCES
UNIVERSITY OF ILLINOIS AT URBANA

CHARACTERISTICS OF FUNGICIDES USED IN FIELD CROPS

INTRODUCTION

Numerous factors must be understood to get maximum value from fungicide applications. Such factors include the limitations of fungicides, what fungicides do and how such materials work, the reasons why a fungicide may fail, means by which to enhance the performance of such pesticides, and the steps one should take to avoid the development of fungicide-resistant fungal populations.

There are many different fungicides available for use in the field crop market and many more will undoubtedly become available in the future. Although many factors must be considered when deciding which fungicide to use, product cost and efficacy are the primary factors influencing a producer's decision. However, even the most cost-effective fungicide will perform poorly in the field if basic product characteristics are not understood and taken into account.

This document provides information regarding foliar and seed treatment applications and limitations, fungicide terms, resistance management, and fungicide families. It is intended to supplement the pest biology and treatment recommendations found in other University of Illinois Extension publications such as the Illinois Agricultural Pest Management Handbook, Field Crop Scouting Manual, Pesticide Applicator Training Manuals (Field Crops and Seed Treatment), Reports on Plant Disease pest fact sheets (www.ag.uiuc.edu/~vista/rpd.html) and various newsletters (www.ipm.uiuc.edu/bulletin) and websites (www.ipm.uiuc.edu)

SEED TREATMENTS

Fungicide seed treatments (Figure 1) are commonly used to help ensure uniform stand establishment via protecting against seed- and soilborne pathogens. Considered of such great importance in corn stand establishment, fungicide seed treatments are utilized in virtually all corn seed marketed to the producer. Seed treatments have displayed phenomenal success in eradicating seedborne pathogens such as smut or bunt from sorghum, wheat, barley and oats. In addition, seed treatments may be used to suppress root rots in certain crops. Finally, some of the more recent systemic seed treatments can supplement, or provide an alternative to, traditional broadcast sprays of foliar fungicides for certain early season foliar diseases.

Figure 1. Treated corn and soybean seed. (Courtesy: B. Paulsrud, University of Illinois)

For further information concerning fungicides used in field crops, contact Bruce Paulsrud, Extension Specialist in Pesticide Safety Education and Plant Pathology, Department of Crop Sciences, University of Illinois in Urbana-Champaign.

Seed treatments can protect the seed and seedling from attack by certain pathogens. Non-systemic fungicides form a chemical barrier over the surface of the germinating seed. This barrier protects the germinating seed from soilborne pathogens such as pythium. Systemic seed treatments protect young plants from root rot and may offer protection from early foliar diseases.

Typically seed treatments will last only about 10-14 days following planting, with pesticide breakdown most rapid under warm, moist conditions. However, certain active ingredients can protect seedlings for much longer periods when applied at the highest labeled rate. Although the duration of protection may be limited, a delay in infection can reduce stand losses and yield impact. For chronic diseases such as root rots, the earlier the infection takes place, the greater the damage to the plant.

Advantages of Seed Treatments

- Seedborne pathogens are vulnerable. The seedborne phase is often the weak link in the life cycle for many plant pathogens. Using seed treatments to control seedborne pathogens often provides a very effective method for disease control.
- Precision targeting. Seed treatments are not subject to spray drift. Because chemicals are applied directly to seeds, little is wasted on non-target sites such as bare soil.
- Optimum timing. Seeds and seedlings are generally more vulnerable to diseases and insects than mature plants. Applying treatments to the seed allows pesticides to be present when needed most.
- Low dose. Relatively small amounts of pesticides are used in seed treatments compared to broadcast sprays. This reduces the cost and the potential impact to the environment. It also reduces the probability of chemical residues in harvested grain.
- Easy to apply. Seed treatments are relatively easy and cheap to apply compared to broadcast sprays.

Disadvantages of Seed Treatments

- Accidental poisoning. Treated seed looks like food to some animals. Livestock may discover carelessly handled treated seed and may eat that treated material. Birds, pheasants or quail for instance, may consume spilled treated seed. Left in an improper location for storage, treated seed may even pose a threat to young children who may find, handle and eat this colorful stock.
- Cropping restrictions. Much the same as other pesticides, some seed treatments may have significant grazing or rotation crop restrictions.
- Limited dose capacity. The amount of pesticide capable of being applied is limited by how the amount of material will actually adhere to the seed. Seed coating technologies are helping the industry overcome this limitation, however phytotoxicity may still pose a problem.
- Limited duration of protection. The duration of protection is often short due to the relatively small amount of chemical applied to the seed, dilution of the chemical as the plant grows, and breakdown of the chemical.
- Limited shelf life of treated seed. Producing excess treated seed is undesirable because the shelf life of treated seed may be limited. Surplus treated seed cannot be sold for grain. This is a particularly serious limitation for seeds such as soybean, where seed germination and vigor decline relatively fast.
- Phytotoxicity. Pesticide injury to plant tissues is called phytotoxicity. Since seed treatments must exist in high concentrations on the tender tissues of germinating seeds and seedlings, they generally have very low phytotoxicity. A few seed treatments are partly phytotoxic when applied at high rates. Lower germination and/or stunting may occur if application rates are not carefully

controlled. Cracked, sprouted, and scuffed seeds may be particularly susceptible to toxic effects. A few seed treatments may reduce the length of the sprout and, therefore, affect the choice of planting depth.

- Worker exposure. In the course of treating and handling large volumes of seed, workers may be exposed to skin contact with seed treatments must be prevented in the seed treatment process.

There are many seed treatment products available, each with different restrictions, labeled uses, active ingredients, dose rates, additives, or formulation. As with most pesticides, each active ingredient has strengths and weaknesses, which is why many seed treatments consist of one or more active ingredients. The degree of pest control often depends on the dose rate of the active ingredient. Some pests may require higher rates than others to achieve control. Some seed treatment labels give a range of rates and indicate pest control responses that are expected for each rate. The applicator must choose the product(s) and rate appropriate for the crop, anticipated pest problem, and the application equipment.

When evaluating a seed treatment, consider the fact that many pathogens are not adequately controlled with current seed treatment products due to one or more of the following product limitations:

- Pesticides with appropriate activity are not available,
- Little or no systemic activity in the plant tissues,
- Limited or no product movement into the expanding root zone,
- Limited product duration - peak periods for pest protection and pest infection/damage do not significantly overlap, or
- Effective rates may simply be too expensive or may be phytotoxic to the seed or seedling. Where these limitations exist, diseases may be better controlled using genetic resistance, a soil-applied fungicide, a foliar-applied fungicide, or some other management strategy.

Application Equipment for Treating Seed

The principal objective is to thoroughly coat the seed with an appropriate rate of pesticide. Complete coverage is particularly important on weaker seed and on seed with cracked seed coats because they are more susceptible to seedborne and soilborne pests. Too much pesticide may injure germinating seed; too little pesticide is often ineffective.

Commercial seed treating equipment (Figure 2) is designed to apply accurately measured quantities of pesticides to a given weight of seed. Thus, all treaters have two essential components: 1) a seed and pesticide flow control system, and 2) a seed and pesticide mixing chamber(s). There are many different treaters in use and on the market, but for calibration purposes it may be best to categorize them according to how the seed and pesticide is measured (metered) - either mechanical metering or electronic proportional metering.

Figure 2. Commercial seed treatment equipment. (Courtesy: Gustafson LLC)

Regardless of the treatment equipment used, proper operation is critical to effective seed treatment. Poorly maintained or adjusted equipment can damage seed, apply incorrect amounts of chemical, or provide insufficient seed coating. All seed treatment equipment requires regular inspection to maintain the correct ratio of chemical used to the amount of seed treated. Ideally, this needs to be done daily and on a lot-by-lot basis.

FOLIAR APPLICATIONS OF FUNGICIDES

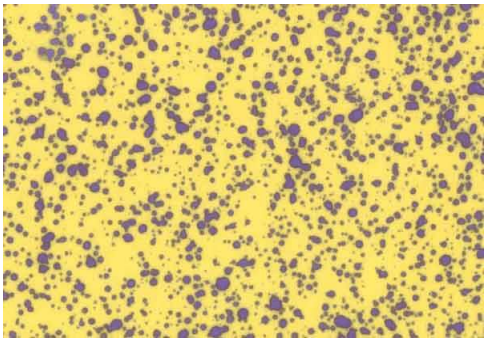

Figure 3. Water sensitive paper showing spray droplet deposition. (Courtesy: S. Bretthauer, University of Illinois)

When making foliar fungicide applications, thorough coverage of the plant is essential. However, canopy penetration typically becomes more difficult as the growing season progresses and the plants become larger and denser. With the right weather conditions many foliar diseases will begin to develop and flourish deep within a dense plant canopy. Thus, penetrating the canopy and providing thorough coverage of the lower canopy is critical. Good spray droplet deposition on the target plant is also important. Spray droplet size has a major influence on coverage, penetration, and deposition (Figure 3). Small spray droplets provide better coverage and tend to deposit well on the target, but if droplets are too small they may fail to penetrate the canopy and deposit within it, or they may drift off target, or volatilize. Droplets that are too large will not deposit as well because they have a tendency to bounce or run off the leaf, which reduces the coverage. The goal of a foliar fungicide application is to create a droplet size that gives a good balance of coverage, penetration, and deposition.

For most fungicide applications, droplets in the 200-300 µm (1 micron = one millionth of a meter) range are ideal. This droplet size range falls within the American Society of Agricultural Engineers (ASAE) standard S-572 fine and medium droplet spectrum categories. Where drift is a concern, an applicator should use a medium droplet spectrum. An applicator can control the droplet spectrum created during an application by selecting and correctly using the proper nozzle. The droplet spectrum created by a nozzle is a function of the nozzle design, orifice size, and operating pressure. In general, nozzles with large orifices produce larger spray droplets, while nozzles with smaller orifices produce smaller spray droplets. As pressure is increased, smaller droplets are created. Using low pressure reduces the amount of small spray droplets. Use a nozzle manufacturer's catalog to select a nozzle size and operating pressure that will create the desired droplet spectrum of medium as well as deliver the required nozzle flow rate in gallons per minute.

Figure 4. Ground sprayer utilizing pulse width modulation technology for drift reduction. (Courtesy: S. Bretthauer, University of Illinois)

For fungicide applications, using nozzles with wide fan angles, such as 110 degrees, is recommended over narrower fan angles. Although hollow cone nozzles can be used to make fungicide applications, they create a great deal of very small, drift prone, droplets that will not adequately penetrate dense plant canopies. Extended-range flat-fan nozzles create smaller droplets in the higher end of their pressure operating range. One must be careful to not exceed the upper pressure limit. Turbo flat fan nozzles also have a wide pressure operating range and can create the desired droplet spectrums for fungicide applications. Turbo flat fan nozzles reduce the amount of driftable fines, which is another advantage fan nozzles when one intends to make fungicide applications.

While some air induction nozzle types are not suitable for fungicide applications, there are several air induction nozzle designs that produce fine and medium droplet spectrums. Air induction nozzles are designed to work at a higher pressure than other flat-fan nozzle designs, and should be operated according to the manufacturer's recommendations. One must make sure that the pump can provide the required pressure when using this type of nozzle. Air induction nozzles also reduce the amount of driftable fines.

Figure 5. Twin nozzle cap with two individual nozzle tips. One set to spray forward in the direction of travel and the other set to spray backwards. (Courtesy: S. Bretthauer, University of Illinois)

Twin spray nozzles (Figure 5) produce two flat-fan patterns, one angled forward in the direction of travel and the other angled backward in the opposite direction. The twin spray design has been shown to increase canopy penetration, a capability deemed important for many fungicide applications. There are two designs available; single tips with two orifices, and modified caps that hold two individual nozzle tips. With the caps, the applicator can choose the type of nozzle to use (such as an air induction tip). The applicator should set the nozzle spacing and boom height to provide the overlap required for the type of nozzle being used. This information can be found in the nozzle manufacturer catalogs.

Sprayers with air-assisted booms have been shown to provide excellent canopy penetration and spray deposition. The airflow from air-assisted booms aids in droplet transportation into the canopy, and increases coverage compared to that achieved with a standard boom. Coverage is especially improved in the middle and lower portions of the plant canopy. Spray droplets smaller than those that are desirable for standard applications can be used because the airflow will deliver the droplets into the canopy and not allow them to be blown off target. Air-assist sprayers also increase spray deposition on the underside of leaves. Some air-assist sprayers use the air to atomize the spray and create the droplets. It is important to match the airflow rate to the plant canopy height and density.

Spray application rates of 10 GPA or higher are recommended for ground applications, and 5 GPA rates are recommended for aerial applications. Do not fail to create the right droplet spectrum when applying at higher rates. By failing to control droplet size, it is possible to increase the GPA but actually decrease the total number of droplets created which would reduce coverage.

Figure 6. An aerial application with an aircraft set up to provide a uniform spray pattern. (Courtesy: D. Gardisser, University of Arkansas).

Aerial applications (Figure 6) are an effective means of applying foliar fungicides. Nozzles are also important for aerial applications, and aerial applicators have excellent control of droplet size. By changing an aerial nozzle's deflector angle or orientation, the droplet size spectrum can be altered. This occurs because of sheer on the spray as it enters high speed air resulting from the aircraft's movement. As droplets enter the fast moving air stream, they can be shattered into smaller droplets. A valuable tool that aerial applicators have to assist in setting up their aircraft is the Aerial Spray Nozzle Models developed by

the USDA ARS Aerial Application Technology research team at College Station, Texas (http://apmru.usda.gov/downloads/downloads.htm). By entering the nozzle type, orifice size, nozzle or deflector angle, pressure, and air speed, the model calculates the droplet spectrum and other valuable information. This allows an aerial applicator to set up the aircraft to create the droplet spectrum required for a specific job.

Agricultural aircraft have the advantage of speed, which can be especially important during severe disease outbreaks or when frequent applications are required. They also have the ability to spray when field conditions are too wet for a ground sprayer. Because they have no physical contact with the crop, they also prevent damage to the crop that may occur when ground sprayers are used, especially later in a growing season. Flying too low can actually increase drift and reduce deposition for aerial applicators. An ideal height for aircraft is often 10 to 14 feet above the canopy. At higher altitudes above the crop, droplets are exposed to the wind more than they should be. At lower heights, droplets can become trapped and carried off in air turbulence created when the aircraft flies extremely close to the canopy. The producer should select an aerial applicator with aircraft setup to provide the correct droplet size in a uniform spray pattern.

COMMON FUNGICIDE TERMS

It is important to recognize that, with rare exception, fungicides do not control diseases caused by bacteria or other pathogens. Fungicides are a sub-group of pesticides which kill or inhibit the growth of fungi. Some experts will argue that fungicides which don't actually kill the fungus (but perhaps inhibit its growth, sporulation, or spore germination) should be called fungistats. Although this distinction has merit, the term fungicide is being used exclusively in this publication.

A variety of terms are used to describe the mobility and activity of fungicides. Examples include protective-contact, local penetrant, local systemic, systemic, translocated. preventative, and curative. These terms are described in this section, along with the practical significance of each.

Protective-Contact Fungicides

These products remain on the surface of plant foliage, protecting it from infection for some period of time. They do not enter the plant tissue (Figure 7). Uniform spray coverage is vital. The length of protection depends on many factors. As with any pesticide, rainfall or irrigation within a few hours after application may wash away much of the pesticide and greatly reduce the protective value. Even after drying on the plant surface, residues continue to be eroded via rain, dew, vaporization, sunlight, etc., thus reducing protection. Furthermore, as the plant tissues expand or are replaced, new tissue is left unprotected. For these reasons, protective-contact fungicides need to be reapplied more often than systemic fungicides. The addition of a spreader-sticker adjuvant to the spray mix may help improve coverage and slow residue loss. As always, carefully read both the fungicide and the adjuvant label to ensure that the proposed tank-mix is legal and safe for the crop.

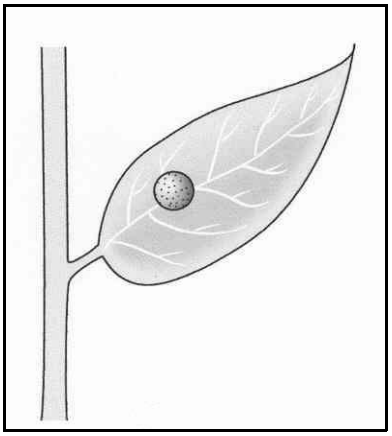

Figure 7. Protective-contact fungicides do not enter the plant.

Local Penetrant and Systemic Fungicides

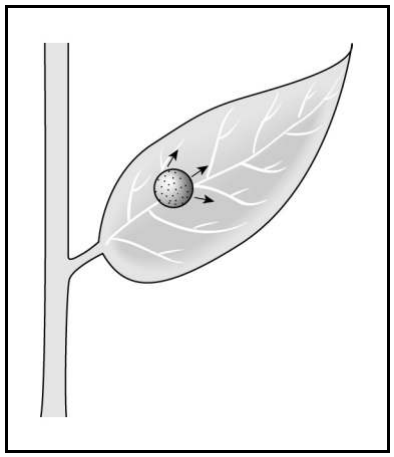

Figure 8. Local penetrant fungicides are absorbed, but remain close to the site of uptake.

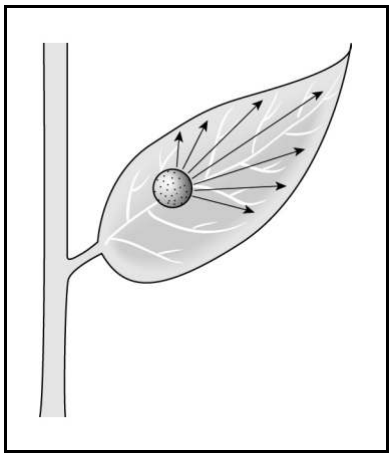

Figure 9. Systemic fungicides currently available in the field crops market only display upward/outward mobility in the plant acropetal translocation).

These products are absorbed into the plant. Some are fairly mobile within the plant, while others are not. Local penetrant (sometimes called local systemic) fungicides are absorbed into the immediate area of application but are not translocated far from the site of uptake (Figure 8). They serve to prevent the development of disease at and near the site of absorption. Systemic fungicides are more mobile than local penetrants. However, the systemic fungicides currently available in the field crops market only display upward/outward mobility in the plant. This upward/outward movement is sometimes referred to as acropetal or apoplastic translocation (Figure 9).

Curative vs Preventative Activity

Fungicides can also be classified according to <u>when</u> they act upon the pathogen. Preventative fungicides prevent the infection and establishment of the pathogen. All fungicides offer some degree of preventative activity. Since protective-contact fungicides do not enter the plant, it stands to reason that they only provide preventative activity.

Some systemic and local penetrant fungicides have “curative” properties, meaning the fungicide has the ability to stop the progress of infections that may have occurred a few hours or days before the application. This “kick-back” or “reach-back” characteristic is useful when responding to infection episodes. However, the effectiveness of even curative fungicides is diminished when an applicator waits too long and disease severity becomes too high.

Supplemental Labeling

As you read various pest management newsletters, you will inevitably note discussions of various types of supplemental pesticide labeling. Sometimes a pesticide company will issue a bulletin or recommendation which slightly modifies (but does not contradict) an existing “Section 3" pesticide label. In other cases, a supplemental label may be issued which substantially expands the scope of an existing label. Following are the types of pesticide labels you are likely to encounter and a brief description regarding their purpose.

- **Section 2(ee)**: Sought when the registrant wants to respond rapidly to a limited range of pest and application issues (e.g., adding a pest, tank-mixing restriction). Thus, the time-consuming process of amending the Section 3 label and introducing it into the market can proceed without inconvenience to the applicator or pesticide company.
- **Section 24(c)**: Sought when a federally registered product is not sufficiently available for an existing or imminent pest problem within a state. This route is often used to provide management options for minor crops.

- **Section 18**: In some cases, a 24(c) label is not practical or can not be obtained. However, a Section 18 label may be sought to manage emergencies such as an outbreak of a new or previously minor pest on a crop for which no registered pesticide is available.

If you wish to use a pesticide as directed by a Section 24(c) or Section 18 supplemental label, you must have a copy of the supplemental label in your possession at the time of use. You can obtain supplemental labels from your pesticide dealer, from the pesticide manufacturer, or from online resources such as www.cdms.net or www.greenbook.net. Remember that these labels specifically state where, how, and for how long the product may be used. For additional information regarding supplemental labels, refer to *Illinois Pesticide Applicator Training Manual 39-13: Demonstration and Research*, University of Illinois Extension, 2001.

RESISTANCE MANAGEMENT

There are many reasons why a fungicide might fail to adequately control disease. Often fungicides "fail" because they are applied too early, too late, too infrequently, at the wrong rate, or too inconsistently to get even coverage on the plants. However, for those times when you know that everything has been done correctly and the performance is poor, consider that you may be dealing with a fungicide-resistant pathogen population.

"Where do fungicide resistant fungal pathogens come from?" One origin is via introduction of resistant types from another area, and the other is through genetic change in the pathogen population in a particular area. Genetic mutations can allow resistant fungi to occur at very low numbers within a fungal population. When a fungicide effectively controls the susceptible members of a species, only those that possess a resistance trait can survive and reproduce. It is important to remember that resistant populations start out in very small numbers. It may take years for you to notice resistant populations, and you may only perceive the problem as a poorer- or shorter-than-expected duration of fungicide protection.

How do you know if you are truly dealing with a fungicide-resistant pathogen population? Several criteria may be used to diagnose the problem:

- The disease was controlled effectively with this fungicide in the past.
- All other causes of fungicide failure have been eliminated (timing, frequency, canopy penetration, environmental, or misapplication problems, and so on).
- Other diseases on the fungicide label (besides the one in question) were controlled effectively.
- The site has a history of continuous use of the same fungicide or other fungicides within the same FRAC Group.

If you answer "yes" to several or all of these criteria, you should suspect resistance; review your observations with a plant pathologist and the fungicide manufacturer representative.

Terms Used When Discussing Fungicide Resistance

When discussing fungicide resistance, the terms can sometimes be confusing. Following are the key terms one should understand.

FRAC: Fungicide Resistance Action Committee, an international, industry-based committee that issues guidance and anti-resistance strategies for different fungicide groups. FRAC organized the existing fungicide active ingredients into target site groups and gave each group a specific code number. For

example, FRAC Group 3 includes the well known DMI fungicides. FRAC Group codes are beginning to be printed on some fungicide labels, which will help in preparing resistance management plans.

Resistance: When a fungicide has little or no ability to control a fungus that should be controlled with that fungicide. Because the term "resistance" may be interpreted as "absolute resistance" or may be confused with host plant resistance, plant pathologists sometimes use the terms "insensitivity" or "tolerance" instead of resistance. However, some experts argue that the term "insensitivity" should be reserved for describing a fungus that is not inherently controlled by a fungicide (e.g. DMI fungicides never did control Pythium or Phytophthora; the pathogens did not change). Regardless of the term used, be cautious when interpreting reports of fungicide resistance. Just because a pathogen population is deemed resistant to a fungicide; it does not necessarily mean it will completely fail to control the pathogen. There are degrees of fungicide resistance.

Cross-resistance: When a fungus is resistant to different fungicides, especially within the same FRAC Group. For example, you would suspect cross resistance if you switched from azoxystrobin to trifloxystrobin and a strobilurin-resistant pathogen was not controlled. Both belong to FRAC Group 11.

Multiple resistance: When a fungus is resistant to fungicides from different FRAC Groups. For example, you would suspect multiple resistance if you treated the previously mentioned strobilurin-resistant population with propiconazole (a FRAC Group 3 fungicide) and found that you still could not control the disease.

Being proactive

Specific recommendations for reducing the potential for development of fungicide resistance include the following:

- The use of fungicides should be integrated into an overall disease and pest management program that includes appropriate cultural practices, host plant resistance, and scouting.
- Apply fungicides when disease first occurs and when predictive models suggest disease is likely to occur.
- Do not use a lower than recommended rate or rely upon curative or late applications.
- Avoid using an active ingredient (or members of the same FRAC Group; see Table 1) more than once per season. For example, there are a number of fungicides with a strobilurin group as the active ingredient, and they all have the same site of action (FRAC Group 11). Thus, exclusive use of different active ingredients within the same FRAC Group is a poor strategy that may promote development of resistant pathogens. If multiple applications are necessary, alternate or tank mix effective active ingredients from different FRAC Groups.
- Monitor the efficacy of all fungicides used and record other factors that may influence fungicide performance and disease development.

FUNGICIDE FAMILIES

The fungicides commonly used in Illinois field crops are listed below in their respective families. Table 1 provides a brief summary of the active ingredient families, trade names, relative resistance risk, and the degree of mobility in the plant. The text boxes that follow provide the same information, but the modes and sites of action are provided in more detail. In addition, general family characteristics are provided such as the primary diseases controlled and whether preventative or curative activity is offered.

Fungicide residual activity (duration of protection) can vary greatly, even within a fungicide family, depending on the target pathogen, environmental conditions, crop growth rate, and fungicide application rate. Your best indication of residual activity is the spray interval which will be found in the Directions for Use section of each fungicide label. In general, seed treatments are effective for 10-14 days following planting, contact foliar fungicides often provide protection for about 7-14 days, and systemic foliar fungicides may provide protection for 10-21 days.

Similarly, human and environmental toxicity concerns can vary greatly within a fungicide family and for different formulations. Acute toxicity warnings are based on the active ingredient as well as the inert ingredients used in the formulation. For example, an EC (emulsifiable concentrate) formulation will typically have more serious human hazard statements on the label compared to other formulations of the same active ingredient. You can get an indication of the toxicity concerns from the signal word (for example, Danger, Warning, or Caution) on the pesticide label. To protect yourself and the environment, read and observe the specific human and environmental hazard statements found in the Precautionary Statements section of each pesticide label. For detailed acute and long-term effects of specific pesticides, see the product's Material Safety Data Sheet (MSDS) or the U.S. EPA's registration website (http://cfpub.epa.gov/oppref/rereg/status.cfm?show=rereg).

In general, fungicides are comparable to other widely used pesticides in acute human toxicity. In terms of environmental hazards, it is important to recognize that many (both old and new) fungicides are toxic to fish and aquatic invertebrates. In addition, some fungicides, such as azoxystrobin, can damage certain apple and crabapple trees. For these reasons, drift control and observing set-backs are important even with fungicides.

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Table 1. Fungicide Resistance Action Committee (FRAC) Group, Fungicide Names, Resistance Risk, and Mobility for Fungicides Used in Illinois Field Crops*.

FRAC Group code and name [target site of action]	Common name	Trade names	Resistance risk	Mobility
1. Methyl benzimidazole carbamates [mitosis: ß-tubuline assembly]	thiabendazole	LSP, in Rival	High	Systemic (upward)
	thiophanate-methyl	Topsin-M	High	Systemic (upward)
3. Demethylation inhibitors (DMI) [C14-demethylation in sterol biosynthesis]	difenoconazole	Dividend	Medium	Systemic (upward)
	imazalil	Flo-Pro IMZ, in Raxil MD Extra	Medium	Systemic (upward)
	myclobutanil	Laredo	Medium	Systemic (upward)
	propiconazole	Bumper, PropiMax, in Quilt, in Stratego, Tilt	Medium	Systemic (upward)
	tebuconazole	Folicur, in Gaucho XT, Orius, in Raxil.	Medium	Systemic (upward)
	tetraconazole	Domark	Medium	Systemic (upward)
	triadimenol	Baytan	Medium	Systemic (upward)
4. Phenylamides [RNA polymerase I]	mefenoxam (=metalaxyl-M)	Apron XL LS, in Maxim XL, Ridomil Gold	High	Systemic (upward)
	metalaxyl	Allegiance	High	Systemic (upward)
7. Carboximides [complex II in fungal respiration (succinate-dehydrogenase)]	carboxin	in Prevail, Vitavax	Medium	Systemic (upward)
11. Quinone outside inhibitors (QoI) [complex III of fungal respiration: ubiquinol oxidase, Qo site in mitochondria]	azoxystrobin	Dynasty, Protégé, Quadris, in Quilt, in SoyGard.	High	Systemic (upward)
	pyraclostrobin	Headline	High	Local penetrant
	trifloxystrobin	in Stratego, Trilex	High	Local penetrant
12. phenylpyrroles [MAP protein kinase in osmotic signal transduction]	fludioxonil	Maxim 4FS, in Maxim XL	Low to Medium	Contact-protective
14. Aromatic hydrocarbons (chlorophenyls, nitroanilines) [lipid peroxidation (proposed)]	PCNB	in Prevail, Terra-Coat LT-2N, in Vitavax-PCNB	Low to Medium	Contact-protective
M3. dithiocarbamates [multi-site contact activity]	mancozeb	Dithane, Manzate, Penncozeb	Low	Contact-protective
	maneb	in Enhance Plus	Low	Contact-protective
	thiram	Thiram, in many products	Low	Contact-protective
M4. phthalimides [multi-site contact activity]	captan	Captan, in many products	Low	Contact-protective
M5. chloronitriles (phthalonitriles) [multi-site contact activity]	chlorothalonil	Bravo, Echo, Equus	Low	Contact-protective

* Fungicide labels change frequently; check product labels and consult with manufacturers for current registration and crop use information.

FRAC Group 1 (methyl-benzimidazole carbamates)	
Example active ingredients and trade names:	• thiabendazole (Seed: LSP, in Rival.) • thiophanate-methyl (Foliar: Topsin-M)
Primary fungi controlled (read individual product labels for limitations)	Leaf spots/blights, non-oomycete seed/seedling rots, sclerotinia white mold, and smuts/bunts.
Protection characteristics:	Mobility: Acropetally systemic (upward/outward mobility) Preventative and curative activity
Resistance concerns:	High risk.
Mode or site of action on pathogen:	Brief: Disrupts cell division thus reducing developmental rates and inhibits needed processes in the plant resulting in death. Detailed: Disrupt ß-tubuline assembly, which among other things, blocks mitosis, the process by which a parent cell splits in two resulting in two, genetically identical daughter cells. The process starts with the duplication of DNA/chromosomes during what is termed "interphase." Following duplication, chromosomes condense into what might best be termed "easily moved packages" (a process termed "prophase"). Next, these "chromosome packages" align in a "cell-central" column, a process called metaphase. In the next step, called anaphase, the duplicated chromosome pairs are "split apart" and one of each pairs is pulled to either end of the cell. Finally, in telophase, the cells split down the middle, forming two daughter cells with identical genetic characteristics. The movement of chromosomes to the central column in metaphase and then to each end of the cell in anaphase is accomplished by cellular structures called microtubules. Microtubules are long chains made up of repeated units of a molecule called tubulin. Microtubules attach to chromosomes and then push them to the central column by adding tubulin molecules (lengthening the chain) and then pull them to each end of the cell by subtracting tubulins (shortening the chain). Benzimidazoles bind to tubulins, blocking the cell's ability to change the length of microtubules and, hence, to move chromosomes. In short, metaphase is compromised which affects all the necessary steps of mitosis (cell division) thereafter. This may arrest cell division. Alternatively, compromised mitosis may "short circuit" cell division and the cell may divide without a normal anaphase, often producing a daughter cell with too many or too few chromosomes.

FRAC Group 3 (de-methylation Inhibitors [DMIs]) (Note: Most of these active ingredients belong to the "triazole" sub-group, but some of them [such as imazalil] do not.)	
Example active ingredients and trade names:	• difenoconazole (Seed: Dividend) • imazalil (Seed: Flo-Pro IMZ, in Raxil MD Extra, in RTU-Vitavax Extra) • myclobutanil (Foliar: Laredo) • propiconazole (Foliar: Bumper, PropiMax, in Quilt, in Stratego, Tilt) • tebuconazole (Seed: in Raxil; in Gaucho XT; Foliar: Folicur, Orius) • tetraconazole (Foliar: Domark) • triadimenol (Seed: Baytan; in RTU Baytan-Thiram)
Primary fungi controlled (read individual product labels for limitations)	Fusarium head blight (wheat scab), leaf spots/blights, non-oomycete seed/seedling rots, powdery mildew, rusts, and smuts/bunts.
Protection characteristics:	Mobility: Acropetally systemic (upward/outward mobility) Preventative and curative activity
Resistance concerns:	Medium risk.
Mode or site of action on pathogen:	Brief: Death via inhibited cell growth. Death via compromised "poor filtering" membrane, which allows substances to enter and accumulate in the cell. Other essential processes are inhibited as well also resulting in death. Detailed: Inhibits enzymes needed to form sterols (lipids), which are intimately tied to phospholipids in the cell membrane. (Note: Sterols are located between certain phospholipids in the cell membrane – much like mortar between blocks in a wall. There they aid in various functions such as decreasing the permeability of the membrane. Sterol production is thus an important step in the process of cell membrane formation and is essential for securing the integrity of the cell membrane.)
FRAC Group 4 (phenylamides)	
Example active ingredients and trade names:	• mefenoxam = metalaxyl-M (Seed: Apron XL LS, in Maxim XL; Soil: Ridomil Gold) • metalaxyl (Seed: Allegiance FL and LS; in SoyGard; in Prevail)
Primary fungi controlled (read individual product labels for limitations)	Oomycetes (pythium and phytophthora).
Protection characteristics:	Mobility: Acropetally systemic (upward/outward mobility) Preventative and curative activity
Resistance concerns:	High risk. However, selection pressure is low since metalaxyl or mefenoxam are used primarily as seed treatments. A 2001-2002 survey of *Phytophthora sojae* isolates from Illinois soybean fields revealed no practical level of resistance to metalaxyl or mefenoxam.
Mode or site of action on pathogen:	Brief: Death likely via disrupted protein formation resulting in reduced rates of cellular development and inhibited cellular metabolism. Detailed: Disrupt RNA polymerase, an enzyme, which is needed to form ribonucleic acid (RNA). In the cell, deoxyribonucleic acid (DNA) provides the blueprint for proteins in the fungus. However, DNA is stored in the nucleus, and proteins are made outside of the nucleus, in the cytoplasm, by cellular machines termed ribosomes. The information in the DNA is transferred from the nucleus to the ribosomes via an RNA intermediary. Disrupting RNA polymerase disrupts RNA formation and therefore disrupts gene expression. Literally, the fungus cannot make proteins, meaning that it cannot grow and maintain itself.

FRAC Group 7 (carboxamides)	
Example active ingredients and trade names:	• carboxin (Seed: Vitavax; in Prevail)
Primary fungi controlled (read individual product labels for limitations)	Non-oomycete seed/seedling rots, and smuts/bunts.
Protection characteristics:	Mobility: Acropetally systemic (upward/outward mobility) Preventative and curative activity
Resistance concerns:	Medium risk.
Mode or site of action on pathogen:	Brief: Death via energy depletion/starvation. Possible buildup of reactive intermediates, due to inhibited respiration, resulting in cell damage and death. Detailed: Disrupts electron transport thus inhibiting respiration in the mitochondria. Most cellular energy is produced by cellular generators called mitochondria. Carboxamides block a molecule in mitochondria called "complex II." In the mitochondria, one energy source is a molecule called FADH2. Mitochondria produce energy by transferring electrons from FADH2 to complex II and then from complex II to another complex, called complex III, and finally to another complex, called complex IV. Complexes II, III, and IV span a mitochondrial membrane. The movement of negatively charged electrons through the complexes and across the membrane pulls positively charged protons across the membrane as well (because positive charges are attracted to negative charges). The buildup in protons on one side of the membrane creates a gradient. In order for this gradient to be remedied - i.e. in an effort to create an equilibrium - protons must pass back through the membrane. While doing so, they pass through and turn a cellular turbine (in a manner analogous to modern power plants) in the membrane to generate ATP - i.e. cellular energy - necessary for the fungus/organism in question to survive. Disrupting "Complex II" disrupts electron transport from FADH2. This in turn halts proton movement and reduces the mitochondria's ability to procure energy.

FRAC Group 11 (quinone outside Inhibitors, or "strobilurins")	
Example active ingredients and trade names:	• azoxystrobin (Seed: Dynasty, Protégé, in SoyGard; Foliar: Quadris, in Quilt) • pyraclostrobin (Foliar: Headline) • trifloxystrobin (Seed: Trilex; Foliar: in Stratego)
Primary fungi controlled (read individual product labels for limitations)	Leaf spots/blights, non-oomycete seed/seedling rots, powdery mildew, and rusts.
Protection characteristics:	Mobility: Varies in this family but azoxystrobin is deemed acropetally systemic (upward/outward mobility) Mainly preventative activity
Resistance concerns:	High risk. A single letter change in the DNA code of certain fungi has been deemed all that is necessary to develop strobilurin resistance.
Mode or site of action on pathogen:	Brief: Death via energy depletion/starvation. Possible buildup of reactive intermediates, due to inhibited respiration, resulting in cell damage and death. Active ingredients in this family are synthetic variations of molecules found in saprophytic fungi. Detailed: Disrupts electron transport thus inhibiting respiration in the mitochondria. Most cellular energy is produced by cellular generators called mitochondria. Strobilurins block a molecule in mitochondria called "complex III." In the mitochondria, one energy source is a molecule called NADH. Mitochondria produce energy by transferring electrons from NADH to complex I and then from complex I to another complex, called complex III, and finally to another complex, called complex IV. Another energy source, noted earlier in this publication, is a molecule called FADH2. Mitochondria also produce energy by transferring electrons from FADH2 to complex II, then to complex III, and finally to complex IV. Complexes I, II, III, and IV span a mitochondrial membrane. The movement of negatively charged electrons through the complexes and across the membrane pulls positively charged protons across the membrane as well (because positive charges are attracted to negative charges). The buildup in protons on one side of the membrane creates a gradient. In order for this gradient to be remedied - i.e. in an effort to create an equilibrium - protons must pass back through the membrane. While doing so, they pass through and turn a cellular turbine (in a manner analogous to modern power plants) in the membrane to generate ATP - i.e. cellular energy - necessary for the fungus/organism in question to survive. Disrupting "Complex III" disrupts electron transport from NADH and FADH2. This in turn halts proton movement and reduces the mitochondria's ability to procure energy.

FRAC Group 12 (phenylpyrroles)	
Example active ingredients and trade names:	• fludioxonil (Seed: Maxim 4FS, in Maxim XL)
Primary fungi controlled (read individual product labels for limitations)	Non-oomycete seed/seedling rots.
Protection characteristics:	Mobility: contact-protectant Preventative activity
Resistance concerns:	Low to medium risk.
Mode or site of action on pathogen:	Brief: Death likely via cell lysis (i.e. rupturing of the cell membrane). Haphazard osmotic pressure regulation leads to increasingly erratic osmotic pressure applied internally and/or externally to the cell membrane. Such pressure eventually compromises the cell membrane, rupturing it, resulting in cell death. Detailed: Disrupt osmotic signal transduction. Such products specifically inhibit MAP kinase proteins. These proteins, and other similar proteins involved in "signal transduction," are the means by which a cell monitors the environment. When such proteins are "turned on" by environmental conditions, they signal the cell to produce appropriate response materials. In short, signal transduction proteins allow the cell to respond to external and internal conditions. For instance, dehydrated cells would be stimulated to accumulate fluids, whereas fluid uptake would normally be blocked in turgid cells. In the case of MAP kinase, such proteins are used to monitor those signals/conditions that influence osmotic pressure within the cell. MAP kinase proteins "detect irregularities" in cellular osmotic pressure and "signal" the cell to adjust water intake (i.e. adjust osmotic pressure) accordingly. Disruption of MAP kinase proteins inhibits the cell's ability to detect osmotic irregularities and thus inhibit the signal for needed, appropriate changes in osmotic pressure. Compromised osmotic signal transduction likely leads to erratic, or even non-existent, osmotic pressure regulation in the cell, which may eventually rupture or dehydrate the cell, killing it.

FRAC Group 14 (aromatic hydrocarbons [chlorophenyls, nitroanilines])	
Example active ingredients and trade names:	• PCNB = pentachloronitrobenzine (Seed: in Prevail, Terra-Coat LT-2N, in Vitavax-PCNB)
Primary fungi controlled (read individual product labels for limitations)	Non-oomycete seed/seedling rots, and smuts/bunts.
Protection characteristics:	Mobility: contact-protectant Preventative activity
Resistance concerns:	Low to medium risk.
Mode or site of action on pathogen:	Brief: Broad site of action. Death likely via cell lysis (i.e. rupturing of the cell membrane) due to massive damage incurred by the cell membrane. Detailed: Affects lipids possibly via lipid peroxidation. In lipid peroxidation, a free radical reacts with a lipid by removing an electron from the lipid. The removal of that electron results in the production of additional free radicals. Since lipids are an integral part of the cell membrane, the free radical-lipid reaction eventually damages the cell membrane. Damage to the membrane would be roughly similar to damage caused by such herbicides as paraquat (which also results in the formation of free radicals which cause massive damage to cell membranes).

FRAC Group M3 (dithiocarbamates)	
Example active ingredients and trade names:	• mancozeb (Seed: Grain Guard; Foliar: Dithane, Manzate, Penncozeb) • maneb (Seed: in Enhance Plus) • thiram (Seed: in many products)
Primary fungi controlled (read individual product labels for limitations)	Leaf spots/blights, non-oomycete seed/seedling rots, rusts, and smuts/bunts.
Protection characteristics:	Mobility: contact-protectant Preventative activity
Resistance concerns:	Low risk.
Mode or site of action on pathogen:	Brief: The FRAC list states that such materials have “multi-site” activity. Death results from the disruption of various processes within the cell thus resulting in retarded cell development, growth, etc. Death likely also via energy depletion/starvation due to an inhibited respiration process. As more and more processes are disrupted, a “critical point” is passed for the fungus and the fungus expires. Detailed: Likely interferes with oxygen uptake, likely interferes with function of enzymes, and likely disrupts numerous other processes. (Note: Many sulfur-containing enzymes are important in amino acid synthesis – and therefore influence protein synthesis and cell development. A host of other processes in the plant are greatly dependent upon sulfur-containing enzymes. Sulfur containing enzymes and oxygen are both intimately tied to various parts of the respiration process).

FRAC Group M4 (phthalimides)	
Example active ingredients and trade names:	• captan (Seed: Captan, in many products)
Primary fungi controlled (read individual product labels for limitations)	Non-oomycete seed/seedling rots.
Protection characteristics:	Mobility: contact-protective Preventative activity
Resistance concerns:	Low risk.
Mode or site of action on pathogen:	Brief: The FRAC list states that such materials have "multi-site" activity. Death likely results from the disruption of various processes within the cell thus resulting in retarded cell development, growth, etc. As more and more processes are disrupted, a "critical point" is passed for the fungus and the fungus expires. Detailed: Most periodicals state that this material affects many different sites of action. Possibly inhibits a host of fungal enzymes.

FRAC Group M5 (chloronitriles or phthalonitriles)	
Example active ingredients and trade names:	• chlorothalonil (Foliar: Bravo, Echo, Equus)
Primary fungi controlled (read individual product labels for limitations)	Leaf spots/blights.
Protection characteristics:	Mobility: contact-protective Preventative activity
Resistance concerns:	Low risk.
Mode or site of action on pathogen:	Brief: Death results from the disruption of a broad range of various processes within the cell (respiration would be on example). Additional/possible mortality due to inhibited production of cellular components, which would retard cell development, growth, etc. Detailed: Chlorothalonil reacts with thiols (compounds in the plant containing sulfur and hydrogen). (Note: Many sulfur-containing enzymes play an important role in amino acid synthesis – and therefore influence protein synthesis and cell development. A host of other processes in the plant are dependent upon sulfur-containing enzymes. Sulfur containing enzymes are tied to various parts of the respiration process – including the "Complexes" that procure energy from NADH and FADH2).