



Chemical Classes

FRAC Code 1 • Methyl Benzimidazole Carbamate (MBC) Fungicides

MBC fungicides are registered on many different field crops as both seed-applied and foliar-applied products. These fungicides are effective against a broad range of fungi that cause leaf spots, root and crown rots, stem rots, and powdery mildew, but not rusts. MBC fungicides registered for use on field crops include thiophanate-methyl and thiabendazole (TBZ).

How do they work?

MBC fungicides inhibit tubulin biosynthesis, which interferes with normal cell division (mitosis) in sensitive fungi. MBC fungicides have both preventative and early-infection activity on target fungi.

Where do MBC fungicides move in the plant?

These fungicides have systemic properties, but they cannot move down the plant, so they are more effective when complete coverage of the plant is achieved. Canopy penetration is essential for good control.

What is the risk of fungicide resistance?

The target site for MBC fungicides is β -tubulin. Modification of a single amino acid in a fungus can result in resistance; therefore, the risk of resistance developing to these fungicides is high. Resistance to MBC fungicides was first reported in 1970, and MBC fungicides have lost effectiveness for many important diseases.

FRAC Code 2 • Dicarboximide Fungicides

Dicarboximide fungicides are used on many different types of plants, including field crops, stone fruits, grapes, ginseng, cole crops, some berry, greenhouse, vegetable, field, turf and ornamental crops. Iprodione and vinclozilin are dicarboximide fungicides registered for use on a few field crops.



Sclerotinia stem rot (a.k.a. white mold) of soybean.

D. S. Mueller

These fungicides are highly effective against several different fungal pathogens, including *Alternaria*, *Botrytis*, and *Sclerotinia* spp.

How do they work?

These fungicides interfere with the osmotic signal transduction pathway, which affects germination of spores and growth of mycelium.

Where do dicarboximide fungicides move in the plant?

Some dicarboximide fungicides exhibit locally systemic properties. Depending on product and crop, dicarboximide fungicides may provide protection for 14 to 21 days.

What is the risk of fungicide resistance?

The risk of fungicide resistance is medium to high, so appropriate resistance management strategies should be followed. To minimize the risk, the number of applications should be limited to two or three per crop per season. Where possible, dicarboximide fungicides should be rotated or tank mixed with fungicides from different chemical groups.



Stripe rust of wheat.

C. A. Bradley

FRAC Code 3 • DMI Fungicides

The fungicide group DMIs that contain the triazole fungicides was introduced in the mid-1970s. Several DMI fungicides have been labeled or are in the process of being labeled for use on field crops—including cyproconazole, difenoconazole, fenbuconazole, flusilazole, flutriafol, imazalil, metconazole, myclobutanil, propiconazole, prothioconazole, tebuconazole, tetraconazole, and triticonazole.

DMI fungicides are used on field crops, fruit trees, small fruit, vegetables, and turf. These fungicides are highly effective against many different fungal diseases, especially powdery mildews, rusts, and many leafspotting fungi.

How do they work?

The DMI fungicides inhibit one specific enzyme, C14-demethylase, which plays a role in sterol production. Sterols, such as ergosterol, are needed for membrane structure and function; thus they are essential for the development of functional cell walls. Therefore, these fungicides result in abnormal fungal growth and eventually death.

Each DMI compound may act in a slightly different part of the biochemical sterol-producing pathway. Although the results are similar in various fungi—abnormal fungal growth and death—there are great differences in the activity spectra of these fungicides. For example, triazoles have no effect against spore germination because spores contain enough sterol for the formation of germ tubes. Some spores even have enough sterol to produce infection structures so, in some cases, triazoles may not be effective against infection of the host tissue.

DMI fungicides may be applied preventively or as early-infection treatments. When applied as an early-infection treatment, applications must be made early in the fungal infection process. Some triazole fungicides have antispore properties, which means they inhibit spore production and therefore help to slow disease development. However, if a fungus begins to produce spores on an infected plant, triazole fungicides are then not effective.

Where do DMI fungicides move in the plant?

Although the DMI fungicides don't have the degree of systemic movement of many herbicides, they are locally systemic and more mobile in plant tissues than some fungicides. After application, the active ingredient is readily taken up by leaves and moves within the leaf. Studies have shown that three droplets of a labeled rate of a DMI fungicide applied to a soybean trifoliolate leaf covered the entire leaf within one day. Note, however, that DMI fungicides are not necessarily transported from one leaf to another leaf or from one part of the plant to another part. They also do not move down plants through the phloem. Most DMI fungicides have a residual period of approximately 14 days.

What is the risk of fungicide resistance?

There are resistance concerns because the fungicide site of action is very specific. Resistance has occurred on other plant pathogens, including some rusts. Some of the DMI fungicides have disappeared from the marketplace because resistance to them developed and they no longer provided any benefit or advantage in a disease control program. Resistance management practices for DMI fungicides should include avoiding repeated applications of DMI fungicides alone in the same season against a high-risk pathogen.

FRAC Code 4 • Phenylamide Fungicides

Phenylamide fungicides are used to control fungi-like organisms known as oomycetes (a.k.a. water molds), such as *Phytophthora* and *Pythium*. These fungicides are often used as seed treatments or in-furrow treatments, and include mefenoxam and metalaxyl.

How do they work?

Phenylamide fungicides inhibit the synthesis of ribonucleic acid (RNA). This affects mycelial growth and the formation of spores and infection structures.

Where do phenylamide fungicides move in the plant?

Phenylamide fungicides exhibit systemic properties. The primary movement of phenylamide fungicides in the plant is upward.



Downy mildew of sunflower.

C. A. Bradley

What is the risk of fungicide resistance?

The risk of resistance to phenylamide fungicides is high. Resistance of the potato late blight pathogen (*Phytophthora infestans*) and the sunflower downy mildew pathogen (*Plasmopora halstedii*) to phenylamide fungicides is common.

FRAC Code 7 • Carboxamide fungicides

Carboximide fungicides registered on field crops include boscalid, carboxin, and flutolanil. Although in the same group, these fungicides differ in their method of application and spectrum of diseases controlled. Boscalid is used primarily as a foliar fungicide with activity against *Botrytis*, *Sclerotinia*, and *Alternaria* species. Carboxin is used primarily as a seed treatment with activity against *Rhizoctonia*, *Tilletia*, and *Ustilago* species. Flutolanil is generally used as a seed treatment or in-furrow treatment to control *Rhizoctonia*.

How do they work?

Carboxamide fungicides inhibit respiration in target fungi. Specifically, the carboxamide fungicides inhibit complex II of fungal respiration.

Where do carboxamide fungicides move in the plant?

Carboxamide fungicides have locally systemic to systemic properties. Movement of carboximide fungicides is translaminar and upwards.

What is the risk of fungicide resistance?

The risk for resistance developing to the carboxamide fungicides is medium. Resistance has been documented for some fungi.

FRAC Code 9 • Anilinopyrimidine (AP) Fungicides

The AP fungicides registered on field crops include cyprodinil and pyrimethanil. These primarily foliar fungicides have activity against *Botrytis* species and a few other fungi.

How do they work?

AP fungicides inhibit the synthesis of amino acids. This inhibits fungal penetration and fungal growth both inside and outside the leaf.

Where do AP fungicides move in the plant?

AP fungicides are systemic with upward movement in the plant. Depending on conditions, crop, and disease, AP fungicides can provide protection for 7 to 14 days.



Loose smut of wheat.

C. A. Bradley

What is the risk of fungicide resistance?

The risk for resistance developing to AP fungicides is medium. Resistance to AP fungicides has already occurred in some *Botrytis* species. To broaden the spectrum of activity and delay the formation of resistance, AP fungicides often are mixed with other fungicides with activity against the targeted pathogen. In addition, there are restrictions as to the number of applications per season.

FRAC Code 11 • Quinone Outside Inhibitors (QoI) Fungicides

QoI fungicides include three fungicide families, strobilurins and two newer families, represented by fenamidone and famoxadone. Strobilurins labeled for use on field crops include azoxystrobin, fluoxastrobin, pyraclostrobin, and trifloxystrobin. These fungicides are used on most field crops, as well as many fruit trees, small fruit, vegetables, and turf. Strobilurins were derived from a naturally occurring compound found in wood-rotting fungi. Fenamidone and famoxadone, however, are synthetic fungicides. These compounds are very effective on a broad spectrum of fungi. The antifungal activity of QoI fungicides is different than other available fungicides.

How do they work?

QoI fungicides act at the quinol outer binding site of the cytochrome bc₁ complex (complex III of fungal respiration). Thus, these fungicides act by inhibiting fungal mitochondrial respiration that stops energy production in the fungus and results in its death.

This group of fungicides should be applied preventively or as early as possible in the disease cycle. They are effective against spore germination and early fungal growth. Once the fungus is growing inside the leaf tissue, QoI fungicides have little or no effect.

Where do QoI fungicides move in the plant?

Most QoI fungicides are locally systemic. They are absorbed into leaf tissue. If a droplet of fungicide is applied to the top surface of a leaf, it will spread out on the surface of the leaf and even move to the cuticle on the other side of the leaf. Some of these fungicides move up the plant in the xylem. Additionally, some may move as a gas above the leaf and readily rebind to the waxy leaf surface. Most have a residual period of approximately 7 to 21 days.

What is the risk of fungicide resistance?

Because QoI fungicides are active only at one specific site, the risk of fungicide resistance is high. To date, there are more than 20 different plant pathogens that have some level of resistance to QoI fungicides.



Rust of common bean.

C. A. Bradley

FRAC Code 12 • Phenylpyrrole (PP) Fungicides

PP fungicides include fludioxonil, which is used mostly as a seed treatment in field crops with a broad disease control spectrum. Fludioxonil also has limited use as a foliar fungicide on a few crops.

How do they inhibit fungi?

Similar to the dicarboximide fungicides, the PP fungicides interfere with the osmotic signal transduction pathway, affecting germination of spores and growth of mycelium. There is no cross-resistance between the dicarboximide and PP fungicides.

Where do PP fungicides move in the plant?

PP fungicides do not have systemic properties so do not move in the plant.

What is the risk of fungicide resistance?

The risk of resistance developing to PP fungicides is low to medium.

FRAC Code 14 • Aromatic Hydrocarbon (AH) Fungicides

AH fungicides are used primarily as seed treatments on some field crops and include quintozone (a.k.a. pentachloronitrobenzene [PCNB]) and chloroneb. Some AH fungicides can be applied as foliar or in-furrow treatments for control of *Rhizoctonia* and *Sclerotinia*.

How do they inhibit fungi?

The mode of action of AH fungicides is not certain, but it is proposed that AH fungicides interfere with lipid and membrane synthesis in target fungi, which will affect mycelial growth.

Where do AH fungicides move in the plant?

Some AH fungicides have upward systemic activity, and others are redistributed in the plant through a vapor phase.

What is the risk of fungicide resistance?

The risk of resistance developing to AH fungicides is low to medium.

FRAC Code 21 • Quinone Inside Inhibitors (QiI) Fungicides

Currently, the only QiI fungicide commercially available is cyazofamid, which has activity against oomycetes. It is labeled for control of late blight on potatoes.

How do they inhibit fungi?

QiI fungicides inhibit respiration and energy production by affecting the same enzyme as the QoI fungicides; however, they act at the quinone “inside” (Qi) binding site. Studies have shown that although QoI and QiI



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Blackleg of canola.

fungicides act on the same enzyme, they remain in different FRAC classes because the binding sites are sufficiently distinct.

Where do Qil fungicides move in the plant?

Cyazofamid has limited systemic activity and should be applied before the pathogen infects the crop.

What is the risk of fungicide resistance?

The risk of fungicide resistance is medium to high, although no resistance has been detected to date. This is because the fungicide is a single-site inhibitor. General fungicide resistance management guidelines should be followed to delay fungicide resistance development.

FRAC Code 22 • Benzamide Fungicides

The only benzamide fungicides currently labeled for use on field crops is zoxamide, which was first used commercially in 2001. Zoxamide specifically targets diseases caused by oomycetes, like late blight on potatoes and downy mildew on vines and vegetables.

How do they work?

Benzamide fungicides destroy microtubules, which affect mitosis and cell division. This inhibits germ tube and mycelial growth. Zoxamide is the first fungicide that targets microtubule assembly in oomycetes.

Where do benzamide fungicides move in the plant?

Zoxamide is not a systemic fungicide, but does have good residual efficacy.

What is the risk of fungicide resistance?

The risk of fungicide resistance is relatively low. There have been no reports of fungicide resistance to zoxamide, both in the field and in laboratory studies. Zoxamide is sold primarily in mixtures with mancozeb.

FRAC Code 27 • Cyanoacetamide-Oxime Fungicides

Currently, the only cyanoacetamide-oxime fungicide available for use on field crops is cymoxanil. This product is applied as a seed treatment to cut potato seed pieces or as a foliar application to potato plants to control late blight.

How do they work?

The mode of action for cymoxanil is unknown. Cymoxanil is a preventative fungicide with some early-infection activity.



Late blight of potato.

W. R. Stevenson

Where do cyanoacetamide-oxime fungicides move in the plant?

Cymoxanil has local systemic activity. It penetrates rapidly and when inside the plant, it cannot be washed off by rain. Cymoxanil has relatively short persistence so its period of action improves when combined with other fungicides.

What is the risk of fungicide resistance?

The risk of fungicide resistance is low to medium; however, repeated use of cymoxanil may lead to fungicide resistance. Therefore, it is required that cymoxanil as a foliar spray be tank mixed with another protectant fungicide with a different mode of action. As a seed treatment, cymoxanil must be combined with other fungicides that have registered seed treatment uses in potatoes.

FRAC Code 28 • Carbamate Fungicides

The only carbamate fungicide available is propamocarb hydrochloride, which is labeled for use against potato early and late blight. The mode of action is different compared to other oomycete fungicides, so it provides an option against strains that have developed resistance to other fungicides. Propamocarb also is available for use on certain vegetables, turf, ornamentals and some greenhouse grown plants.

How do they work?

Carbamate fungicides disrupt the formation of fungal cell walls by interfering with synthesis of phospholipids and fatty acids. They also affect mycelial growth, spore production and germination.

Carbamate fungicides are protectant fungicides with systemic activity. They should be applied before infection when conditions are favorable for disease development.

Where do carbamate fungicides move in the plant?

Carbamate fungicides are absorbed by roots and leaves and are transported upwards in the plant.

What is the risk of fungicide resistance?

Fungicide resistance risk for carbamate fungicides is low to medium. It is recommended that these fungicides are rotated with different groups of fungicides that control the same pathogens, or to use tank mixtures with fungicide from a different group, including the multi-site activity fungicides. Another precaution to minimize fungicide resistance is to use propamocarb no more than three times per season.



W. R. Stevenson

Early blight of potato.

FRAC Code 29 • Oxidative Phosphorylation Uncoupler Fungicides

Currently, the only oxidative phosphorylation uncoupler fungicide available for field crops is fluazinam, which only is labeled for use against late blight on potatoes. Fluazinam has been shown to control some mites as well.

How do they work?

These fungicides act by inhibiting energy production. Unlike the QoI fungicides, respiration continues but the energy is not converted to a usable form, eventually leading to cell death. Fluazinam inhibits spore germination and the formation of infection structures.

Fungicide applications should begin when weather conditions favor disease development, because it works best as a preventative fungicide with little early-infection activity.

Where do oxidative phosphorylation uncoupler fungicides move in the plant?

Fluazinam is a protectant fungicide and has no systemic activity so thorough coverage is needed.

What is the risk of fungicide resistance?

Resistance is a major concern for most fungicides that affect energy production; however, the risk of fungicide resistance developing for uncouplers is low. Despite being used for several seasons with up to 10 applications per season and no mixture partners, there is no indication of a change in sensitivity of the late blight pathogen. Still, it is recommended not to rely exclusively on one product for pest control so fluazinam should be rotated with different groups that control late blight.

FRAC Code 30 • Organo Tin Fungicides

Fentin hydroxide (triphenyltin hydroxide) is the only fungicide in this class that is registered for use on field crops. It is used to control *Cercospora* leaf blight on sugar beet and early blight and late blight on potato.

Care must be taken when applying because combinations with some pesticides (especially emulsifiable concentrate insecticides), micronutrients, spreaders, stickers, surfactants, or buffering agents, can increase phytotoxicity. Triphenyltin hydroxide carries the signal word “DANGER” and is a restricted use fungicide.

How do they work?

The organo tin fungicides disrupt oxidative phosphorylation, which inhibits respiration in target fungi.



M. F. R. Khan

Cercospora leaf spot of sugarbeet.

Where do organo tin fungicides move in the plant?

This group of fungicides is not systemic.

What is the risk of fungicide resistance?

The risk of fungicide resistance developing is low to medium, although resistance in the *Cercospora* leaf spot fungus of sugar beet has been documented.

FRAC Code 32 • Heteroaromatic Fungicides

Heteroaromatic fungicides are used to control oomycete pathogens such as *Aphanomyces* and *Pythium*. Hymexazol, the only current fungicide registered for use on field crops in this class, is used as a seed treatment to control soilborne pathogens on sugarbeet.

How do they work?

Hymexazol affects targeted pathogens by inhibiting nucleic acid synthesis.

Where do heteroaromatic fungicides move in the plant?

Hymexazol has upward systemic properties.

What is the risk of fungicide resistance?

The risk of fungicide resistance is not known. However, hymexazol has a broad spectrum of activity.



Common rust of corn.

D. S. Mueller

FRAC Code 33 • Phosphonate Fungicides

Organic phosphate compounds, including fosetyl-aluminum, are systemic fungicides that have preventative and early-infection activity against oomycete diseases, including *Phytophthora* and *Pythium* root and crown rot and downy mildews.

How do they inhibit fungi?

Phosphonate fungicides act by inhibiting spore germination and blocking development of mycelium. These fungicides also enhance the plant's own natural defense systems against diseases.

These fungicides are most effective when applied prior to disease development, but they do have some early-infection activity. These fungicides can be applied when plants display early disease symptoms. These fungicides should be applied to actively growing plants.

Where do phosphonate fungicides move in the plant?

These compounds are rapidly absorbed through the plant leaves or roots, with translocation both up and down inside the plant. These fungicides are

the only fungicides that are fully systemic. The systemic activity creates a complete barrier of protection while preventing wash-off.

What is the risk of fungicide resistance?

These fungicides have a low risk of fungicide resistance developing. However, fungicide resistance may occur if these fungicides are used repeatedly.

FRAC Code 40 • Carboxylic Acid Amide (CAA) Fungicides

CAA fungicides are systemic fungicides that are effective against oomycetes. Currently, the only CAA fungicide labeled for use on field crops is dimethomorph, which controls late blight on potatoes and downy mildew on grapes and vines.

How do they work?

CAA compounds affect the formation of cell walls. CAA fungicides should be applied just before the onset of infection or when first visible signs of disease occur within the field or nearby.

Where do CAA fungicides move in the plant?

CAA fungicides move up the treated plant stem and into growing leaves. They also have anti-sporulant activity, which helps prevent the spread of diseases.

What is the risk of fungicide resistance?

The risk of fungicide resistance in potato late blight pathogen is low to medium. Resistance has not been found on this pathogen; however, resistance has been found in the grape powdery mildew pathogen. It is recommended that this fungicide be alternated with other modes of action for management of potato late blight. Also, mixtures with multi-site fungicides may be used to reduce risk of resistance development.

FRAC Code M • Multi-Site Activity Fungicides

Multi-site activity fungicides are applied to the leaf and stem surfaces and are considered protective or preventive fungicides. Multi-site activity fungicides have a broad spectrum of disease control activity. Multi-site activity fungicides approved for use on field crops include inorganic compounds (copper and sulfur), dithiocarbamates (mancozeb), and chloronitriles (chlorothalonil).

How do they inhibit fungi?

They inhibit fungi on the plant surface so the fungus will not be able to infect the plant. Contact fungicides affect multiple biochemical sites in fungi; they kill fungi by overwhelming them with poisonous materials.



Anthracnose of common bean.

C. A. Bradley

They should be applied preventively. Multi-site activity fungicides do not affect fungi once they have infected the plant.

Where do multi-site activity fungicides move in the plant?

These fungicides remain on the plant surface and do not penetrate into the plant. They remain active only as long as the fungicide remains on the plant surface in sufficient concentration to inhibit fungal growth, usually 7 to 14 days.

On plant surfaces, contact fungicides are sensitive to environmental conditions like rainfall and solar radiation, unlike systemic fungicides, which are absorbed into the leaf after application (once the residue has dried) and are not affected by rain wash-off and solar radiation. A general rule of thumb for the effect of rain on washing off protectant fungicides follows:

- Less than one inch of rain since the last spray will not significantly affect residues.
- One to two inches of rain will reduce the residue by half.
- Over two inches of rain since the last spray will remove most of the spray residue.



Ascochyta blight of chickpea.

C. A. Bradley

What is the risk of fungicide resistance?

Resistance to multi-site activity fungicides is low. Multi-site activity fungicides are a part of fungicide resistance programs. If multiple applications of fungicides are needed, the benefit of including a multi-site activity fungicide is not to eliminate the use of other fungicides with higher risk of resistance, but to reduce the number of applications of higher risk fungicides made in any one year. This may extend the number of years a higher risk fungicide can be used, but it does not prevent the eventual selection of fungicide resistant pathogens.



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Photos

Photos of diseases represent those that are targeted by fungicide applications, depending on specific conditions for each field.

Cover photos

Top left – Canola field (C. A. Bradley)

Top right – Wheat field (C. A. Bradley)

Bottom left – Corn field (D.S. Mueller)

Bottom right – Flax flower (C.A. Bradley)

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