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The Impact of Beneficial Organisms in Corn Agroecosystems

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by

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Corn is one of the world's, and Nebraska's, most important crops. Millions of acres are planted to corn each year in the Cornhusker State. However, each year there are a plethora of arthropod, weed, and microorganism pests that rob farmers of reaching their maximum yield potential. There are many options available to manage these pests in corn agroecosystems, but one option is often underutilized: beneficial organisms. For each pest, there are a variety of natural enemies that can assist in mitigating the damage caused by pests.

Many beneficial organisms exist, and they can be grouped by the type of pest they target: arthropods, weeds, or pathogens. Natural enemies in each of these groups range from large and conspicuous to microscopic. For example, lady beetles and nematodes can prey upon arthropod pests, ground beetles and certain fungi help control weeds, and some mites and bacteria target plant pathogens.

Beneficial organisms should be one tool used in Integrated Pest Management (IPM) programs. Taking advantage of natural enemies is more important than ever due to pesticide bans and resistance. Conservation biological control, which is readily available and relatively easy to implement, is one way farmers can maximize the impact of beneficial organisms. This method of conserving natural enemies can be achieved by reducing pesticide use or using selective pesticides, conserving and planting vegetation to

supply resources to beneficials, using less-toxic pest management alternatives (e.g., planting Bt corn), and adopting reduced tillage practices such as no-till to preserve essential resources.

One important example that highlights the impact of beneficial organisms in corn agroecosystems is their role in the management of spider mites, which are often a problem in hotter and drier areas. While there are other methods available to manage spider mites, some of these, such as pesticides, can be harmful to beneficial organisms. Therefore, growers and agronomists must consider multiple factors when creating and implementing IPM programs.

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Introduction

Many different crops are grown in Nebraska, including soybeans, wheat, alfalfa, sorghum, oats, millet, dry edible beans, sunflowers, sugar beets, and potatoes. However, one crop seems to rise above the rest: corn. Corn (*Zea mays*) is one of Nebraska's most important crops, with 10.2 million acres planted to corn in 2020 (USDA NASS, 2021). The Cornhusker State ranks third in corn production in the United States behind Iowa and Illinois (USDA NASS, 2021).

Like every crop, corn has its fair share of pests that either directly attack it (e.g., insects and pathogens) or compete with it for valuable resources, including water and nutrients (e.g., weeds). Some of the most important arthropod pests, diseases, and weeds found in corn in Nebraska are listed in Table 1.1. While there are many management options available to combat these pests – such as pesticides and crop rotation – one management tool seems to be often overlooked: beneficial organisms.

Although the term "beneficial" is somewhat subjective, an organism is considered beneficial if it helps reduce the population of a pest. Many people throughout history have recognized the potential of beneficial organisms in pest management, particularly through intentional biological control. Biological control takes advantage of natural enemies, either through conserving existing enemies (conservation biological control) or releasing exotic (classical/importation biological control) or reared (augmentation biological control) enemies, for the purpose of controlling other organisms.

Table 1.1. Examples of pests of corn in Nebraska.

Corn Pest	Scientific Name	Part of Corn Affected
Arthropods[1]		
European corn borer	*Ostrinia nubilalis*	Leaves, stalk, pollen, cobs
Western bean cutworm	*Striacosta albicosta*	Pollen, silks, tassels, ears
Corn earworm	*Helicoverpa zea*	Leaves, silks, ears
Western corn rootworm	*Diabrotica virgifera verifier*	Roots, leaves, silks
Twospotted spider mite	*Tetranychus urticae*	Leaves
Banks grass mite	*Oligonychus pratensis*	Leaves
Diseases[2]	**Causal Pathogen**	
Gray leaf spot	*Cercospora zeae-maydis*	Leaves
Southern rust	*Puccinia polysora*	Leaves
Goss's bacterial wilt and blight	*Clavibacter nebraskensis*	Leaves, stalk
Anthracnose stalk rot	*Colletotrichum graminicola*	Stalk, leaves
Fusarium ear rot	*Fusarium verticillioides, F. proliferatum, F. subglutinans*	Ears
Weeds[3]		
Kochia	*Bassia scoparia*	
Common waterhemp	*Amaranthus tuberculatus*	
Horseweed/marestail	*Erigeron canadensis*	
Common lambsquarters	*Chenopodium album*	
Velvetleaf	*Abutilon theophrasti*	

[1] Wright et al., 2012a; Wright et al., 2012b
[2] Jackson-Ziems et al., 2012; Jackson et al., 2011a; Jackson et al., 2011b
[3] Sarangi & Jhala, 2018

Sailer et al. (1976) discuss the history of biological control and list several relevant dates in the early history of this practice based on many different references. For example, in the year 1200, farmers in China put nests of an arboreal ant, *Oecophylla smaragdina,* in citrus and litchi trees to help manage a stink bug, *Tessaratoma papillosa*. In that same year, ants were also used against date palm pests in Yemen. In 1602, parasitism of a small white butterfly, *Pieris rapae*, by the parasitic wasp *Cotesia glomerata* was recognized. In 1762, the mynah bird, *Acridotheres tristis,* was introduced from India to Mauritius to control the red locust. In 1840, the rove beetle *Ocypus olens* and the ground beetle *Calosoma sycophanta* were used to control earwigs (*Forficula auricularia*) and gypsy moth (*Lymantria dispar dispar*) larvae. In 1888, the lady beetle *Rodolia cardinalis* was shipped from Australia to California to successfully manage the scale insect *Icerya purchasi*.

Although classical and augmentation biological control have been successful in many situations, these forms of biological control are often expensive and unavailable to farmers. However, conservation biological control is readily available to many farmers and relatively easy to implement. Therefore, conserving already-present natural enemies is an important tool farmers use in Integrated Pest Management (IPM) programs. Utilizing multiple pest management options can also help farmers save money, as they rely less on pesticides, which is especially important in the face of pesticide resistance.

There are many beneficial organisms present in corn production systems, including organisms that target arthropod pests, weeds, and pathogens. In this chapter, I will discuss several of these beneficial organisms, their biology, and the pests they help manage. Chapter 2 will explore methods to conserve beneficial organisms and discuss the impact of these organisms on spider mites, a pest of corn found in Nebraska.

Beneficial Organisms That Target Arthropod Pests

There are many arthropod pests found in corn agroecosystems. Fortunately, these pests have many natural enemies that contribute to their management. Some of these beneficial organisms can be easily seen, such as lady bugs and ground beetles. Others, such as predatory mites, are much more inconspicuous. Still others can not be seen with the naked eye, such as nematodes. While these natural enemies are very diverse, each one plays an important role in the biological control of arthropod corn pests.

Lady Beetles

Lady beetles (Coleoptera: Coccinellidae) are some of the most recognizable insects in nature. Although, some lady beetles do not have the red-and-black coloration that many think of when hearing “lady beetle.” Such lady beetles include *Scymnus* and *Stethorus* species, which are smaller and black. However, the best way to identify lady beetles is not by their colors, but by their overall body shape and the patterns on the pronotum and elytra (Cunningham et al., 2007). Larvae are elongate, gray or black, and often have orange markings and soft spines. While many different species of lady beetle exist, some species that are commonly found in corn include (Table 1.2): the seven-spotted lady beetle (*Coccinella septempunctata*), the multicolored Asian lady beetle (*Harmonia axyridis*), the twelve-spotted/pink lady beetle (*Coleomegilla maculata*), the convergent lady beetle (*Hippodamia convergens*), and the thirteen-spotted lady beetle (*Hippodamia tredecimpunctata*) (Park & Obrycki, 2004). In one study conducted in central and western New York, researchers surveyed lady beetles in research and commercial fields of sweet corn. In addition to *C. maculata* and *C. septempunctata*, many other species of lady beetle were recorded in these fields, such as the twenty-spotted lady beetle (*Psyllobora vigintimaculata*), the parenthesis lady beetle (*Hippodamia parenthesis*), and the fourteen-spotted lady beetle (*Propylea quatuordecimpunctata*) (Hoffmann et al., 1997).

Table 1.2. Some common lady beetles found in corn.

Image			
Common Name	Seven-spotted lady beetle[1]	Multicolored Asian lady beetle[2]	Twelve-spotted/pink lady beetle[3]
Scientific Name	*Coccinella septempunctata*	*Harmonia axyridis*	*Coleomegilla maculata*

[1, 2] Photos: Alexander Cunningham (Cunningham et al., 2007)
[3] Photo: Jim Kalisch (Cunningham et al., 2007)

Lady beetles go through complete metamorphosis and therefore have four distinct life stages: egg, larva, pupa, and adult. Cunningham et al. (2007) describe the life cycle of lady beetles, beginning with egg laying. Lady beetles will lay five to 50 bright yellow eggs on vegetation (Figure 1.1). Once the eggs hatch, the larvae eat their eggshells and stay together for about a day. Afterwards, they begin searching for prey. The larvae go through four instars before pupating. After several days, soft-bodied adults emerge, but within a few hours, their exoskeletons harden enough for the insects to walk around. One to two days later, they are able to fly and assume their coloration. After adults feed for a short period of time, they mate, and females lay their eggs. The adults aggregate together and overwinter in leaf litter or other debris. Most lady beetles in Nebraska have one to two generations per year (Cunningham et al., 2007).

Figure 1.1. Lady beetle eggs.

Photo: Dori Porter (Cunningham et al., 2007)

Lady beetle adults and larvae are predators of aphids, but they also prey on mealybugs and other soft-bodied insects. Additionally, *Scymnus* and *Stethorus* (Figure 1.2) species are beneficial for controlling spider mites. *Stethorus* species are known as "mite destroyer beetles." Lady beetles may also feed on pollen or insect eggs. In fact, *C. maculata* can complete development on pollen alone (Michaud et al., 2008; Cottrell & Yeargan, 1998). Abundant pollen in corn fields may divert *C. maculata* from preying on eggs of insects, such as corn earworm (*Helicoverpa zea*) (Cottrell & Yeargan, 1998) and European corn borer (*Ostrinia nubilalis*) (Musser & Shelton, 2003).

Figure 1.2. *Stethorus* beetle preying on mites.

Photo: U. Wyss (Michaud et al., 2008)

In one experiment performed by Musser & Shelton (2003), predation of European corn borer eggs by *C. maculata*, *H. axyridis*, and the insidious flower bug, *Orius insidiosus,* was assessed. In the no choice lab experiment, two temperatures were used:

20°C (68°F) and 27°C (about 81°F). *H. axyridis* larvae could not complete their development on the diet of only European corn borer eggs. On the other hand, *C. maculata* readily developed on these eggs. *H. axyridis* adults also ate significantly fewer eggs than *C. maculata* adults did. The lady beetle adults consumed more eggs at 27°C than at 20°C (Table 1.3).

Table 1.3. Consumption of European corn borer eggs by *C. maculata* and *H. axyridis* at 20°C and 27°C.

Insect	20°C	27°C
	European corn borer eggs eaten/day/insect	
C. maculata adult	6.2 ± 0.8	12.1 ± 0.5
H. axyridis adult	2.4 ± 0.3	3.7 ± 0.7

Adapted from Musser & Shelton, 2003

The researchers in this experiment also looked at rates of predation in the field by pinning European corn borer eggs onto the bottom side of corn leaves. Egg predation was as high as 60%. However, there was a negative correlation between predation and aphid populations. For example, predation was about 10% when aphid populations were the highest. This correlation demonstrates the impact aphids can have on predation rates of other insects in sweet corn (Musser & Shelton, 2003).

In another review paper, Evans (2009) discusses lady beetle predation on insects other than aphids. For example, in addition to preying on eggs of Lepidopteran pests (such as European corn borer, corn earworm, and fall armyworm (*Spodoptera frugiperda*)), many lady beetles also may feed on eggs and young larvae of Coleopteran pests, particularly in the family Chrysomelidae. Some of these pests include Colorado potato beetle (*Leptinotarsa decemlineata*) and alfalfa weevil (*Hypera postica*). Additionally, lady beetles may prey on eggs and larvae of Hymenoptera and Diptera. However, egg, larval, and pupal cannibalism may also occur with lady beetles, especially if other food sources (e.g., aphids and pollen) are limiting.

Lady beetles are available to be purchased in large quantities to be released into different ecosystems, but this isn't recommended, as the beetles will typically fly away due to their instinct to disperse (Cunningham et al., 2007). Instead, lady beetles should be conserved.

Ground Beetles

Ground beetles (Coleoptera: Carabidae) are another group of important generalist predators that are found in most agricultural settings. Ground beetles are dark colored, shiny, or iridescent and large with slender legs and ridged wing covers. Their head, which is smaller than their thorax, has threadlike antennae. Many ground beetles are nocturnal and they can be found running across the soil surface, in cracks in the soil, or under leaves or debris. They rarely fly (Mahr, n.d.a). Most larval feeding occurs under the soil surface (Michaud et al., 2008).

Many species of ground beetle are present in agroecosystems. In one three-year study conducted in South Dakota, 24,750 ground beetles were captured in a transgenic corn-soybean cropping system, representing 57 species (French et al., 2004). Three species accounted for 81% of beetles captured ("dominant" species): *Cyclotrachelus* *alternans*, *Harpalus pensylvanicus*, and *Pterostichus permundus* (Table 1.4). Six other "abundant" species accounted for 14% of beetles captured (Table 1.4). There were no significant differences between the number of dominant beetles caught in corn fields compared to soybean fields.

Table 1.4. Species and percentage of ground beetle captured in a transgenic corn-soybean cropping system in South Dakota.

Species	Percentage	Combined Percentage
Dominant species		
Cyclotrachelus alternans	36.2	~81%
Harpalus pensylvanicus	26.6	
Pterostichus permundus	18.0	
Abundant species		
Bembidion quadrimaculatum	3.6	~14%
Brachinus ovipennis	1.0	
Calosoma calidum	0.8	
Cicindela punctulata	3.8	
Poecilus chalcites	1.7	
Poecilus lucublandus	3.8	

Adapted from French et al., 2004

In another study from Iowa, researchers studied ground beetle assemblages in conventional (corn/soybean) and diversified (corn/soybean/triticale-alfalfa/alfalfa) crop rotation systems (O'Rourke et al., 2014). *Poecilus chalcites* (Figure 1.3) comprised greater than 70% of beetles captured across all cropping treatments.

Ground beetles undergo complete metamorphosis. Eggs are laid on aboveground objects or in cavities made in the soil. Species may lay a few to hundreds of eggs (Mahr, n.d.a). There are three larval instars, which may either burrow in the soil or live in debris. Ground beetle larvae are usually predaceous. Usually, there is only one generation per year. However, some species need more than one year to complete their development. Larger adult ground beetles can live two to four years. Most species overwinter as adults in the soil or in sheltered sites (Mahr, n.d.a).

Figure 1.3. *Poecilus chalcites*.

Photo: Iustin Cret (Roth et al., 2021)

Ground beetles feed on many different insects, including fly maggots and pupae, rootworms, caterpillars, grubs, earthworms, adults of other beetles, and other small soil-dwellers and soft-bodied insects (Michaud et al., 2008; Mahr, n.d.a). Some species may feed on leaf tissue and seeds. They are voracious feeders and consume their body weight in food daily (Mahr, n.d.a). Regarding their impact on pest populations, there is relatively little information available, despite many of these beetles having been captured during surveys. In one study, approximately 80% of cutworm larvae (Lepidoptera: Noctuidae) were consumed by *Pterostichus* beetles within 20 minutes (Epstein et al., 2001). Due to ground beetle numbers and how much they consume, they likely help to significantly control pest populations in many situations (Mahr, n.d.a). Therefore, they should be conserved as much as possible.

Lacewings

Lacewings (Neuroptera: Chrysopidae and Hemerobiidae) are another important group of beneficial insects found in corn fields. Adults have large, lacey wings (hence, the name), protruding eyes, threadlike antennae, and slender abdomens. When at rest, they hold their wings over their abdomen in a tent-like fashion. Green lacewings (Chrysopidae) tend to be larger than brown lacewings, measuring just under 2 cm (3/4 inch) long. Brown lacewings (Hemerobiidae) are usually smaller than green lacewings, measuring about 0.5-1 cm (1/5 to 2/5 inch) long. Larvae are alligator-shaped and have sickle-like mandibles (Figure 1.4). Lacewings are primarily nocturnal. Several species occur in field crops, but one of the more common species is the common green lacewing (*Chrysoperla carnea*) (Figure 1.5) (Michaud et al., 2008).

Figure 1.4. Lacewing larvae.

Photo: E. Prado (Michaud et al., 2008)

Figure 1.5. *Chrysoperla carnea* adult.

Photo: Francesco Schiavone (CABI, 2021)

Figure 1.6. Green lacewing egg on a corn leaf.

Photo: Callie Braley

Lacewings go through complete metamorphosis. After mating, brown lacewing females lay their eggs directly onto vegetation, while green lacewing females lay their white, oval eggs on thin stalks that are attached to vegetation (Figure 1.6). A female lacewing can deposit over 200 eggs (Hodgson & Trina, 2008). Eggs are laid on stalks to avoid cannibalism by lacewing larvae and predation by other insects. The way eggs are laid may aid in identification of a green lacewing species (e.g., relative length of stalk, single eggs versus a group of eggs, in a line or spiral) (Michaud et al., 2008). Eggs are laid in areas where there will likely be abundant prey. For example, I have seen many lacewing eggs on the lower leaves of corn plants, where aphids can usually be found. Eggs are laid in the spring and larvae emerge in four to five days (Hodgson & Trina, 2008). Larvae go through three instars before pupating (Griffith & Gardiner, 2016). The time between larvae and adult is two to three weeks, and the entire life cycle is about one month (Hodgson & Trina, 2008). During the growing season, at least two generations can be produced (Hodgson & Trina, 2008). In the fall, pupae overwinter in silky, round cocoons that are protected by vegetation (Griffith & Gardiner, 2016). Adults will emerge in early spring.

All lacewings are predaceous as larvae, but not all adults are predaceous (Michaud et al., 2008). However, all species of brown lacewing are predaceous as adults (Griffith & Gardiner, 2016). Green lacewing adults that are not predaceous will feed on nectar, pollen, and aphid honeydew (Griffith & Gardiner, 2016). Some species of green lacewing larvae will also cover themselves with plant matter to camouflage themselves from predators (Griffith & Gardiner, 2016). Lacewing larvae are voracious predators that prefer aphids and are known as “aphid lions”. They will also consume other soft-bodied pests including mites, thrips, mealybugs, leafhoppers, whiteflies, and insect eggs. They will use their mandibles to pierce prey and consume their contents. Larvae can consume up to 200 soft-bodied insects per day (Griffith & Gardiner, 2016).

Lacewings are available commercially, but the success and usefulness of releasing these beneficial insects for augmentative biological control has been limited due to lack of important information such as habitat preferences (Michaud et al., 2008). Effective marketing, the training of customers, and the cost of rearing larvae are also issues of producing and selling lacewings (Tauber et al., 2000). If purchased, the insects are usually shipped as eggs and should be immediately distributed due to the larvae's cannibalistic nature (Michaud et al., 2008). Already-existing lacewings can be conserved, as well. Another important note is that lacewings may have tolerance to some insecticides, such as pyrethroids (Grafton-Cardwell et al., 2017).

Thrips

Thrips (Thysanoptera) are minute and slender insects and many species are pests of various crops (Table 1.5), including western flower thrips (*Frankliniella occidentalis*) and onion thrips (*Thrips tabaci*). However, there are species of thrips that are considered beneficial due to their predatory nature on pests, such as the aforementioned thrips or mites. These beneficial species include banded (or banded-wing) thrips (*Aeolothrips* spp.), black hunter thrips (*Haplothrips mali*), *Franklinothrips* (*Franklinothrips orizabensis, F. vespiformis*), and six-spotted thrips (*Scolothrips sexmaculatus*) (Bethke et al., 2014). The most beneficial thrips in corn is the six-spotted thrips. Banded thrips tend to be associated with non-grass plants (Progressive Gardening, 2018), black hunter thrips are typically found in deciduous fruit trees (WSU, n.d.), and *Franklinothrips* can be found on low growing plants and shrubs, including some vegetables and fruits like cucumber, kidney bean, and melon (Mao et al., 2018).

Six-spotted thrips (Thysanoptera: Thripidae) adults (Figure 1.7) are about 3 mm (1/8 inch) long. Adults, pale yellow to whitish in color, have long, hairlike fringes on the margins of their wings. When at rest, three dark spots are clearly visible on each white forewing. Larvae are translucent white to yellowish.

Figure 1.7. Adult six-spotted thrips.

Photo: Jack Kelly Clark (UC IPM, n.d.a)

Table 1.5. Some common pest thrips, their host plants, and their adult appearance.

Common Name	Scientific Name	Host Plants	Adult Appearance
Bean thrips	*Caliothrips fasciatus*	Beans, occasionally other legumes	Blackish body with white wing bands
Citrus thrips	*Scirtothrips citri*	Mainly citrus and blueberries	Light orangish yellow to white body
Greenhouse thrips	*Heliothrips haemorrhoidalis*	Mainly perennials with thick, broad leaves (e.g., avocado, azalea)	Black body with pale wings
Onion thrips	*Thrips tabaci*	Mainly vegetables (e.g., garlic, onion)	Yellow to dark brown body
Western flower thrips	*Frankliniella occidentalis*	Many herbaceous ornamentals, vegetables, and fruits, some shrubs and trees	Thick, bristle-like hairs at tip of abdomen; abdomen extends beyond wing tips at rest; various colors

Adapted from Bethke et al., 2014

Thrips' metamorphosis is between incomplete and complete. They hatch from eggs, have two larval instars, prepupa, pupa, and then become adults. Eggs are laid in plant tissue and hatch almost immediately (UC IPM, n.d.b). During the growing season, it takes six-spotted thrips about 10 days for eggs to develop into adults. When prey is abundant and temperatures are warm, six-spotted thrips can produce many generations per year (UC IPM, n.d.b).

Six-spotted thrips mostly prey upon spider mites and their eggs, and they can be found on most any plant that has spider mites. Plants from which these thrips have been collected include: avocado, cotton, corn, grape, hops, soybeans, and many others (Gilstrap et al., 1995). Some specific examples of mite prey include the twospotted spider mite and Banks grass mite (Gilstrap, 1995). However, these thrips may also feed on phytoseiid mites, which are beneficial (Gilstrap, 1995). While these thrips feed on all stages of spider mites, they prefer immatures (UC IPM n.d.b). Adults can consume about 60 mites per day, while larvae consume about 10 mite eggs, larvae, or nymphs per day (UC IPM, n.d.b).

Overall, six-spotted thrips are beneficial for several reasons (Gilstrap, 1995), as they:

- Prey on a wide range of species
- Have a wide range of host plants
- Can be predatory and reproductive within a wide range of temperatures
- Consume large numbers of prey (but require relatively few prey to survive)
- Have a high searching capacity (and is effective at searching at low prey densities)
- Are well synchronized with their prey
- Produce relatively high numbers of eggs for each prey killed

There are very few options available to purchase these thrips, if at all. Therefore, these beneficial insects should be conserved.

Predatory Mites

Many species of mites (Acari) are phytophagous and thus are considered pests (e.g., twospotted spider mite, Banks grass mite), but there are also many mite species that are predatory towards phytophagous mites and other pests. These predatory mites tend to be larger than spider mites and measure ca. 0.5 mm long. They have long legs suited for rapid movement and are shaped differently than pest mites. Many predatory mites are in the family Phytoseiidae (Mesostigmata), but there are also beneficial mites in other families, including Ascidae (Mesostigmata), Cheyletidae (Trombidiformes), Tydeidae (Trombidiformes), and many others (Gulati, 2014). Some specific species within Phytoseiidae include: *Phytoseiulus persimilis*, *Galendromus occidentalis*, *Neoseiulus californicus*, and *Amblyseius swirskii* (Gulati, 2014). In Nebraska, the most important predatory mite is *Neoseiulus (=Amblyseius) fallacis* (Figure 1.8) (Wright et al., 1993). This mite is pear-shaped and pale brown or straw-colored. They also do not have dark pigmentation characteristic of pest mite species (Wright et al., 1993).

Figure 1.8. *Neoseiulus fallacis* adult attacking a phytophagous mite.

Photo: Natures Good Guys (n.d.)

Mites go through incomplete metamorphosis. The life stages are: egg, larva, two nymphal stages (protonymph and deutonymph), and adult. After hatching, the larva will have six legs, but the remaining stages will have eight legs. *N. fallacis* females lay one to five eggs per day, and a total of 26 to 60 eggs over their lifetime (Natures Good Guys, n.d.). The eggs hatch in two to three days, and development from egg to adult takes anywhere from three days (at 32°C/90°F) to nine days (at 21°C/70°F) (Natures Good Guys, n.d.). In the fall, adult females enter diapause in response to short days. Under optimal conditions, populations can undergo a 20- to 50-fold increase in two weeks (Natures Good Guys, n.d.).

Predatory mites typically are associated with plant feeding mites, but they can help regulate other pests, such as western corn rootworms and wireworms (*Agriotes sordidus*). In one lab study by Prischmann et al. (2011), researchers looked at consumption rates of immature rootworms by six non-phytoseiid soil-dwelling mite species: *Gaeolaelaps* sp. (Laelapidae), *Macrocheles insignitus* (Macrochelidae), *Glyptholaspis* (= *Holostaspis*) *americana* (Macrochelidae), *Eviphis ostrinus* (Eviphididae), *Gaeolaelaps* (*Hypoaspis*) *aculeifer* (Laelapidae), and *Stratiolaelaps scimitus* (Laelapidae) (formerly *Hypoaspis miles*). Although rootworms were a sub-optimal food source for the mites, all species fed upon the rootworms to some degree. Several mite species had detrimental effects on larvae survival and two species had negative impacts on egg densities. Prischmann et al. (2011) concluded that it is unlikely that any one species of mite tested would have a major impact on control of rootworms, but collectively, these generalist soil-dwelling mites may have an important role in managing rootworm larvae populations. In another recent study, Pasquier et al. (2021) studied the predation capacity of three non-phytoseiid soil-dwelling predatory mite species (*Stratiolaelaps scimitus*, *Gaeolaelaps aculeifer* and *Macrocheles robustulus*

(Macrochelidae)) on immature western corn rootworms and wireworms in a lab setting. Eggs of these pests were never consumed, but all three mite species attacked the first instar larvae of both pests.

While these studies have shown how non-phytoseiid predatory mites can be of importance, phytoseiid mites have many advantages over other predatory mites due to abundant availability, high fecundity, dispersal rate, good searching ability, high degree of prey specificity, and adaptability to different ecological niches (Gulati, 2014). Different species of phytoseiid mites also have different life styles (Table 1.6), ranging from specialized predators of certain mites to specialized pollen feeders. *Phytoseiulus persimilis* is a Type I mite and thus is desirable as a potential biological control agent. For example, Pickett et al. (1987) released *P. persimilis* by aircraft onto field corn for the purpose of controlling spider mites in Texas. *Phytoseiulus persimilis* established at least small colonies in each of the three study sites, but only had an impact on spider mite densities at one site.

Type II, III, and IV mites can also be used in biological control programs (McMurty & Croft, 1997), even though they are not specialized predators. In fact, generalist predators are more likely to survive at low prey densities than specialized predators, as they can also feed on pollen, plant exudates, and honeydew (McMurty & Croft, 1997). Therefore, there are benefits to using all types of phytoseiid mites. It’s also important to note that, in general, specialized spider mite predators (e.g., *P. persimilis*, *N. fallacis*) prefer to prey on eggs, whereas generalist predators (e.g., *G. occidentalis*, *N. californicus*) show no prey-stage preference or preferred larvae (Blackwood et al., 2001).

Table 1.6. Life styles of phytoseiid mites.

Life Style	Description	Representative Mite(s)
I	Specialized predators of *Tetranychus* species	*Phytoseiulus* species
II	Selective predators of tetranychid mites	*Galendromus*, some *Neoseiulus*, few *Typhlodromus* species
III	Generalist predators	Some *Neoseiulus*, most *Typhlodromus,* *Amblyseius* species, etc.
IV	Specialized pollen feeders/generalist predators	*Euseius* species

Information from McMurty & Croft, 1997

Neoseiulus fallacis is a Type II phytoseiid mite. They eat an average of about 15 spider mites per day (Wright et al., 1993). They survive, reproduce, and develop best when *Tetranychus* species are present (Pratt et al., 1999). Pratt et al. (1999) studied prey-food types of *N. fallacis*, including twospotted spider mites, other spider mites, other mites, eriophyid mites, insects, pollen (including corn), and other food sources such as honeydew. The mites thrived best on *Tetranychus* species and reproduction, survival, and development were lower on non-tetranychid food, although nearly all prey-food types led to better results than no food. *Neoseiulus fallacis* is available commercially, but commercial biological is not cost effective. Furthermore, there are several factors that can affect survival of *N. fallacis*, including soil surface type (e.g., clod, grass, gravel), management practices (e.g., mulching), amount of ground cover, and environmental conditions (Jung & Croft, 2000). Hot and dry conditions (which are often present in western Nebraska) negatively affect *N. fallacis* survival.

If growers choose to release predatory mites, they should be aware that releasing these mites may not significantly reduce pest mites in their corn fields (Messenger et al., 2000). The appropriate species for the area and time of year should be chosen. Timing and release rate should be correct, as well. Releases should also be made before serious spider mite outbreaks occur. Additionally, predatory mites occur naturally in corn fields. Therefore, conservation of these predatory mites may be a less expensive pest management option compared to augmentative biological control.

Minute Pirate Bugs

There are many species of predatory "true" bugs, including damsel bugs, big-eyed bugs, assassin bugs and, as I'll discuss in this section, minute pirate bugs. These insects use their piercing-sucking mouthparts to skewer prey, inject enzymes to digest their internal organs, and drink their liquified body contents (Michaud et al., 2008). Pirate bugs are in the family Anthocoridae in the order Hemiptera. Several minute pirate bugs, also called minute flower bugs, are in the genus *Orius.* They are 2-5 mm (1/12 to 1/5 inch) long and black and white. Other species in the genus *Anthocoris* are 3-5 mm (1/8 to 1/5 inch) long and black, brown, or purplish. There are many other genera of minute pirate bugs, as well. Adult minute pirate bugs can be distinguished from most other true bugs by the absence of apparent veins or cells near the tip of the forewings (UC IPM, n.d.c).

Figure 1.9. The insidious flower bug (*O. insidiosus*) feeding on whitefly nymphs.

Photo: Jack Dykinga (USDA ARS, 2020)

One species of minute pirate bug, the insidious flower bug (*Orius insidiosus*) (Figure 1.9), has been studied extensively and can be found in Nebraska. These insects are very small in size, measuring about 3 mm (1/8 inch) long. Their bodies are oval-shaped, flattened, and their wings are positioned flat over the body. They are mostly black, but have a gold stripe across the back and white wing tips that extend past the abdomen.

Minute pirate bugs undergo incomplete metamorphosis. They develop through three life stages: eggs, nymphs, and adults. Adult females lay 80 to 100 eggs throughout their lifetime (Green, n.d.). Eggs are often laid in plant tissue with the round top protruding and will hatch four to five days later. Nymphs are brown, orange, reddish, or yellowish in color, teardrop-shaped, and wingless. They develop through five instars and become larger with each molt. The oldest nymphs have wing pads and wings develop on their final molt. During warm weather, development time from egg to adult is about three weeks (UC IPM, n.d.c). Adults overwinter in protected places (e.g., plant debris). They become active again in March or April and fly until October. Several generations are produced per year (UC IPM, n.d.c).

Minute pirate bugs may become a nuisance in the fall, as they bite the exposed skin of humans. However, they do not feed on human blood or inject saliva or venom, although some people develop redness or a welt. Minute pirate bugs are omnivorous, feeding on plant sap and flower juices. They are not pests, but are predaceous throughout their lives (Green, n.d.). They are highly mobile, active predators and are one of the first predaceous insects to begin feeding early in the growing season (UC IPM, n.d.c). These beneficial insects are partial to thrips (Michaud et al., 2008) and spider mites, but they will also feed on leafhoppers (Green, n.d.), aphids, psyllids, small caterpillars, whiteflies, and insect and mite eggs (UC IPM, n.d.c).

Musser and Shelton (2003) looked at the predation of European corn borer eggs by several generalist predators, including *O. insidiosus*. *Orius insidiosus* readily completed development on a diet of European corn borer eggs. In the no choice portion of the experiment, each *O. insidiosus* ate about 2 eggs per day at both 20°C (68°F) and 27°C (about 81°F). However, the presence of corn leaf aphids and corn pollen reduced egg predation. Kiman and Yeargan (1985) studied the development and reproduction of *O. insidiosus* reared on different diets including pollen, green beans, tobacco budworms (*Chloridea virescens*), soybean thrips (*Sericothrips variabilis*), and/or twospotted spider mites. It successfully completed nymphal development on just pollen, but development was significantly faster on diets that contained arthropod prey compared to no-prey diets. Fecundity was also higher on diets that contained tobacco budworm eggs. Isenhour et al. (1989) found that predation on corn earworm and fall armyworm larvae by *O. insidiosus* may be enhanced by prey feeding on Lepidoptera-resistant corn genotypes.

Although minute pirate bugs are available for purchase, in most outdoor situations, releasing these insects is unlikely to control pests (UC IPM, n.d.c). These beneficials also are common in corn, soybeans, and other crops, so conserving them can have important pest management impacts.

Parasitoids

Immature parasitoids feed in or on the body of their hosts, which kills the host. The adults are usually free-living and the females search for suitable hosts for their offspring. Two important groups of parasitoids are: parasitic wasps (Hymenoptera) and tachinid flies (Diptera) (Michaud et al., 2008). Insects in both of these groups undergo complete metamorphosis and can be found in field crops.

Almost all insects are attacked by at least one species of parasitoid wasp. These wasps have also been used in many successful classical biological control programs. For example, in the early 1900s, two wasps, *Eriborus terebrans* (Ichneumonidae) and *Macrocentrus cingulum (=grandii)* (Braconidae), were introduced into the United States to help control European corn borer (Shelton, n.d.). These species have been recovered from European corn borer larvae in Nebraska (Clark et al., 1997). While many species of parasitoid wasps are large and colorful, most of the economically important species are small and unostentatious, such as those that target aphids (Figure 1.10) (Michaud et al., 2008). Some species are solitary (one larva per host) and others are gregarious (multiple larvae per host).

Figure 1.10. Parasitoid wasp attacking an aphid.

Photo: U. Wyss (Michaud et al., 2008)

Parasitoid biology is different than many other insects. Reproduction is usually sexual, but most females can manipulate the sex of their offspring by controlling egg fertilization. Unfertilized eggs produce males and fertilized eggs produce females (arrhenotoky). Females typically oviposit eggs into a host, where the larvae will feed, develop, and pupate (endoparasitism). In some situations, eggs are laid externally on the host, where the larvae feed (ectoparasitism). Females may also use their ovipositor to deliver venom to immobilize or paralyze a host or to simply puncture a host and feed on its body fluids. Some species allow the host to continue normal development and growth after oviposition.

Tachinid flies are also important parasitoids. There are more than 1,000 species in North America, and all have a parasitic lifestyle (Michaud et al., 2008). Appearance may vary considerably between species, but most resemble house flies (although size can differ quite a bit) and have bristled bodies. Many moth and butterfly larvae and beetle adults and larvae are attacked by these flies (Michaud et al., 2008; Mahr, n.d.b). One example is *Lydella thompsoni* (Figure 1.11), which was introduced into the United States to help control European corn borer (Shelton, n.d.; Mahr, n.d.b).

Figure 1.11. *Lydella thompsoni* adult.

Photo: Jim Kalish and Tom Hunt (Capinera, 2005)

Most tachinid species are solitary, but some species are gregarious. The vast majority of tachinids are endoparasites, as well. In many tachinid flies, eggs will mature within a female that then will lay eggs that hatch immediately (Mahr, n.d.b). Usually, females lay an egg on the surface of a host's cuticle. The hatching larva then bores into the host's body and develops internally. In other cases, the egg may be consumed by the host when it feeds. The host may either be killed in the adult stage or – more commonly – in the pupal stage (Michaud et al., 2008).

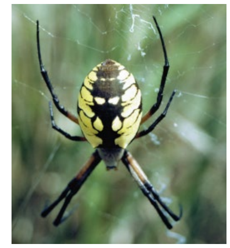
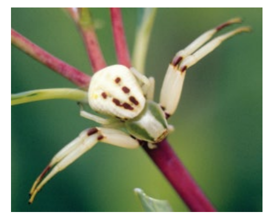
Many parasitoids can produce several generations per year, but this is often dependent on their host. While some parasitoids are commercially available, such as the small wasp *Trichogramma ostriniae* (Trichogrammatidae), that attacks European corn borer, many parasitoids are not, so conservation of these beneficial insects should be considered.

Spiders

Spiders (Araneae) are important generalist predators in agroecosystems, and many consider their presence to be an indicator of good ecosystem health. There are many species of spiders in Nebraska, but they can be broadly categorized by their hunting strategies: trapping their prey, sitting and waiting for prey, or actively hunting prey. Table 1.7 lists several spiders found in Nebraska corn fields. Additionally, Seymour et al. (2016) is a great resource for identifying many different spiders in Nebraska.

Spiders prey on a variety of insects. For example, orb-weaver spiders prey on flies, moths, grasshoppers, beetles, bees, wasps, and mayflies, while crab spiders typically feed on flies, bees, wasps, and small butterflies (Seymour et al., 2016). Many of these beneficial spiders are not available to purchase commercially. Therefore, conservation is an important pest management tool in agroecosystems.

Table 1.7. Examples of spiders found in Nebraska corn fields.

Hunting Type	Group	Family	Example Species
Prey trapping	Web-spinners (e.g., garden spiders, orb-weavers)	Araneidae	 Yellow garden spider, *Argiope aurantia*
Sit-and-wait	Crab spiders	Thomisidae	 Whitebanded crab spider, *Misumenoides formosipes*
Hunting	Jumping spiders, wolf spiders	Salticidae, Lycosidae	 Bold jumper, *Phidippus audax*

Information and photos from Seymour et al., 2016
Photos: Jim Kalisch

Microorganisms

There are many groups of beneficial microorganisms: fungi, bacteria, viruses, protozoans, and nematodes. Although these organisms are very small and hidden from view, many are entomopathogenic and target insects. Therefore, they are beneficial and can have a significant impact on pest populations.

One of the most well-known microorganisms is the Gram-positive, soil-dwelling bacterium *Bacillus thuringiensis*, which has been utilized in biopesticides and genetically engineered (GE) crops. *Bacillus thuringiensis* is ubiquitous (Martin & Travers, 1989) and there are many subspecies and strains that target different hosts (e.g., Lepidoptera, Coleoptera, Diptera). The pathogenicity of this bacterium is due to crystalline (Cry) protein toxins called delta endotoxins. Essentially, these toxins are released in an insect's midgut and dissolve in this alkaline environment. The toxins then become active and create holes in the gut wall that allow the bacteria to access the hemolymph – or insect's blood. Death occurs due to starvation, as the insect is unable to eat and digest food, and septicemia.

Entomopathogenic fungi are also important in managing pest populations. *Metarhizium* and *Beauveria* are two genera that contain insect-attacking fungi. *M. anisopliae* and *B. bassiana* (Figure 1.12) are the best-known species in each genus, respectively. Both are ubiquitous in soil and have been used for biological control of insects.

Figure 1.12. European corn borer infected with *Beauveria bassiana*, seven to 10 days.

Photo: Keith Weller (USDA ARS, 2016a)

Another fungus that targets spider mites is *Neozygites floridana*. This naturally occurring fungus is favored by average daily temperatures below approximately 29°C (85°F) and relative humidity above 90% (Wright et al., 1993). Several cool, damp days occurring together will give this fungus an opportunity to infect and kill spider mites. Mites that are infected become brown and shriveled and die quickly.

Attempts to induce epizootics in pest populations by releasing bacterial or fungal microbes often fail due to stringent environmental requirements for infection and growth (Michaud et al., 2008). Often, when suitable conditions arise, direct human assistance is not needed. However, conservation of these organisms is one way we can assist in their pest management.

Nematodes can also target insect pests, although, it's important to note that many nematodes are phytophagous and are pests. There are two types of insect-targeting nematodes: parasites that that infest and primarily starve a host and entomopathogenic nematodes that have obligate associations with bacteria. These bacteria produce toxins that disable and kill the host. They also decompose host tissues. The nematodes feed on the bacteria and decomposed tissues. Two entomopathogenic nematodes include *Steinernema* species (associated with *Xenorhabdus* species) and *Heterorhabditis* species (associated with *Photorhabdus* species). For example, *H. bacteriophora* actively searches for and attacks white grubs (Figure 1.13) and other insects, while *S. carpocapsae* targets armyworms, cutworms, and other insects via a sit-and-wait strategy (UC IPM, n.d.d).

Figure 1.13. Healthy and *Heterorhabditis bacteriophora*-infected white grubs.

Photo: UC IPM (n.d.d)

Some entomopathogenic nematodes are produced and sold commercially for control of foliar and soil insects. For example, several studies show the effectiveness of *Heterorhabditis bacteriophora* for managing western corn rootworm (Toepfer & Toth, 2020; Toepfer et al., 2008). Nematodes are usually applied as either a spray suspension or a soil drench, but survival and efficacy rates depend on soil type and moisture availability (Michaud et al., 2008). Nematodes are killed by light and heat, so applications should be made in the evening (UC IPM, n.d.d). Some nematodes are also ubiquitous in soil and may be compatible with insecticides. Therefore, conserving these beneficials can be an easily-implemented pest management practice.

Beneficial Organisms That Target Weeds

While arthropod pests directly damage crops, weeds typically reduce crop yield through competition for important resources such as light, water, and nutrients. Many farmers also pride themselves on having clean, weed-free fields. With many weeds (e.g., kochia and common waterhemp) becoming resistant to herbicides like glyphosate, it's becoming increasing important to understand and utilize other weed management methods. Luckily, there are several beneficial organisms that target weeds and their seeds, including ground beetles, certain weevils, and some microorganisms.

Ground Beetles

While many ground beetle species are predaceous towards other arthropods, some species are well-known weed seed predators (Table 1.8). Menalled et al. (2007) documented some of these species in their study from Michigan (Table 1.8). These beetles' olfactory abilities may play a large role in their detection of weed seeds. In one experiment from Canada, Kulkarni et al. (2017) studied the response of three omnivorous carabid species to imbibed and unimbibed weed seed odors. Seeds included those from rapeseed/canola (*Brassica napus*), wild mustard (*Sinapis arvensis*), and field pennycress (*Thlaspi arvense*). All ground beetle species did not discriminate between seeds that were unimbibed, but they did discriminate between imbibed seeds. The researchers concluded that odors of weed seeds can help carabids find and recognize seeds of some weed species.

Table 1.8. Some species of ground beetles that act as weed seed predators and their relative abundance in no-till systems in Menalled et al. (2007).

Ground Beetle Species	Relative Abundance in No-Till Systems in Menalled et al. (2007)
Agonum muelleri	–
Anisodactylus merula	–
Anisodactylus sanctaecrucis	1.5%
Amara aenea	7.9%
Amara cupreolata	–
Amara littoralis	–
Harpalus affinis	0.2%
Harpalus pensylvanicus	3.7%
Harpalus rufipes	–
Pterostichus melanarius	1.0%

Ground beetles are also able to detect weed seeds buried in soil, although consumption of buried seeds is less than consumption of non-buried seeds. In a greenhouse study by Kulkarni et al. (2015), females of three carabid species consumed more volunteer canola seeds compared to males. Additionally, all beetles consumed more seeds that were scattered on the soil surface than seeds that were buried up to 4 cm. However, there was evidence of seed consumption at all depths. For example, in 72 hours, *P. melanarius* females consumed about 37 canola seeds at a depth of 0 cm and about 4 canola seeds at a depth of 4 cm. Another study also found that weed seed burial depths of 0.5. or 1.0 cm (0.2 or 0.39 in) reduced consumption of some weed seeds by smaller carabids (White et al., 2007).

Ground beetle seed predation is also influenced by tillage and vegetational diversity. A Maine study of the effects of tillage on weed seed predators found that rotary tillage and moldboard plowing reduced the activity density of weed seed predators 52% and 54%, respectively (Shearin et al., 2014). Although, chisel plowing was similar to the undisturbed control. Menalled et al. (2007) also found that activity of seed-predating ground beetles were over three times higher in no-till systems compared to both conventional and organic systems. Regarding vegetation diversity, Pavuk et al. (1997) studied ground beetle activity density and composition in vegetationally diverse corn agroecosystems over two years. In one year of the study (the previous year was one of severe drought), activity density was significantly greater in broadleaf weed treatments compared to grassy weed or corn monoculture treatments. Community similarity was generally high for all treatments. Pavuk et al. (1997) suggest ground beetle species respond differently to vegetational diversity, perhaps due to suitable prey availability and microclimate preferences.

Although weed seed predation by carabids is influenced by a variety of factors, these beetles can be very effective in reducing many different weed seeds. Some of these include seeds from redroot pigweed (*Amaranthus retroflexus*), giant foxtail (*Setaria* *faberi*), velvetleaf, shepherd's purse (*Capsella bursa-pastoris*), European field pansy (*Viola arvensis*), Canada thistle (*Cirsium arvense*), and canola. However, ground beetles do have preferences regarding which weed seeds to consume. For example, in one study, three species of carabids consumed fewer velvetleaf seeds than redroot pigweed and giant foxtail seeds (Table 1.9) (White et al., 2007). In the same study, weed emergence of these three weeds was recorded. One of the ground beetles decreased total weed emergence by 15% (Table 1.9).

Table 1.9. Mean number of weed seeds consumed by three carabid beetle species in a 48-hour feeding-choice study and carabid beetle effect on combined weed emergence.

	Seeds Consumed (no.)			Weed Emergence (%)	
Species	Velvetleaf	Redroot pigweed	Giant foxtail	Beetles present	Beetles absent
A. aenea	2	32	33	38	41
A. sanctaecrucis	4	78	40	25	40
H. pensylvanicus	7	89	60	34	39

Adapted from White et al., 2007

Petit et al. (2014) also found that carabids preferred the seeds of European field pansy and shepherd's purse over other weed seeds (e.g., wild buckwheat, *Fallopia convolvulus*). Additionally, Honek et al. (2003) found that carabids generally preferred Canada thistle seeds and consumption rates increased with body size. However, small carabids preferred seeds of shepherd's purse and consumption rates were not related to their size. For both kinds of seed, the average daily consumption rate was 0.33 mg seeds mg body mass^{-1} day^{-1} for all carabid species tested. The researchers also stated that predation of weed seeds on the ground in arable fields can be as high as 1,000 seeds m^{-2} day^{-1}.

Ground beetles are abundant in agroecosystems and play and important role in reducing weed seeds and arthropod pests. Thus, conservation of carabids is likely to prove beneficial.

Weevils

One weed that has been the target of several biological control programs is musk thistle (*Carduus nutans*) (Figure 1.14). This weed was introduced into the United States from southern Europe and western Asia in the mid-1800s. Although this weed is currently not considered to be noxious, it has spread throughout the United States and is difficult to manage over large areas. It is typically a biennial, as it overwinters in the rosette stage and bolts the second year in late spring. A single plant can produce approximately 20,000 seeds (Gupta et al., 2019).

Figure 1.14. Musk thistle, *Carduus nutans*.

Photo: Gupta et al. (2019)

Two insects that have be utilized for the control of musk thistle include the musk thistle flower head weevil (*Rhinocyllus conicus*) and the musk thistle rosette weevil (*Trichosirocalus horridus*). These weevils (Coleoptera: Curculionidae) are native to Europe and were introduced and released in different areas of the United States in the late

1900s. They are compatible with each other, as they target different parts of musk thistle plants and therefore do not compete.

The flower head weevil (Figure 1.15) is about 6 mm (1/4 inch) long and undergoes complete metamorphosis. Adults congregate on bolting musk thistle plants in mid-May to mid-June. There, they feed on the rosettes, mate, and lay eggs on the flower buds. Each female lays an average of 100 eggs during her lifetime (Puttler & Bailey, 2001). In about six to eight days, the eggs hatch and the larvae burrow into the flower and interfere with seed production and viability. As many as 40 larvae have been found per terminal head (Puttler & Bailey, 2001). Some flower heads may prematurely turn brown due to the number of larvae feeding on it or in the stem below. It takes about a month for larvae to complete their development and begin pupation, which lasts another one to two weeks. Adults emerge in June or July and seek overwintering sites in ground litter, wooded areas, and under new musk thistle rosettes. These weevils produce one generation per year (Roeth et al., 2012).

Figure 1.15. Musk thistle flower head weevil, *Rhinocyllus conicus*.

Photo: Mike Quinn (Quinn, 2015)

The rosette weevil is about 3 mm (1/8 inch) long and goes through complete metamorphosis. In early October, adults emerge from aestivation. They feed on the underside and center of musk thistle rosettes, which causes the plant to die or produce multiple stems, but reduce seed production. Mating occurs and eggs are laid in rosettes in late fall. The adults overwinter and resume laying eggs in the early spring of the following year until the beginning of May. The eggs hatch and larvae burrow into the growing center or crown bud. Their feeding eventually creating a necrotic area that is noticeable by spring. This feeding can kill a musk thistle plant or cause the plant to produce fewer, smaller flower heads that contain less seed. Larvae feed for six to eight weeks, pupate in the soil, and adults emerge in June. These weevils produce one generation per year (Roeth et al., 2012).

In Nebraska, only the flower head weevil is well established across the state (Roeth et al., 2012). Many studies have also focused on just the flower head weevil and its success. For example, one study published in 1975 documented the first success of musk thistle control by the flower head weevil (Kok & Surles, 1975). One hundred adults were released in 1969 at a site in Virginia. Six years later, musk thistle density had been reduced by 95%. In 1974 and 1975, approximately 90% of the thistles had been attacked by the weevil and more than 10% of the terminal heads had aborted. The only heads that had not been severely infested were the later-blooming, smaller ones. Additionally, eggs and adults were found 32 km (19.88 mi) from the original release site.

In a two-year study from central Nebraska, McCarty and Lamp (1982) musk thistle seed heads were sampled just after flowering. During the first week, several weevils per head were recorded (Table 1.10). The thistles at the weevil-infested sites also produced significantly less seed than the non-infested site in both years (Table 1.10). However, heads that bloomed later during flowering had less than one weevil per head and many viable seeds were still produced at the infested sites.

Table 1.10. Weevil incidence in musk thistle heads blooming during the first week and reduction in seed production at infested sites compared to non-infested sites.

	Weevil Incidence (weevils per head)	Reduction in Seed Production (%)
1978	6.7	28
1979	28.0	78

Information from McCarty & Lamp, 1982

The rosette weevil and its success has also been studied. Roduner et al. (2003) evaluated the success of both the flower head and rosette weevils in Oklahoma by determining infestation of musk thistles. Flower head weevils had been released in 34 counties by 2001, whereas rosette weevils had been originally released in six counties in 1998. Flower head weevils were recovered from 30 of 34 counties; rosette weevils were recovered in three of the six original release counties, plus one county where no releases were made until 2001. Twenty-five percent or more of the sites were considered well infested in 63% of the counties and thistle densities had been reduced by 25 to 90% in 13 counties. In sites where both weevil species had been released, thistle density reductions occurred faster than in sites where only flower head weevils had been released. The researchers concluded that head weevils are established in Oklahoma and are effectively reducing musk thistle populations; rosette weevils are also established in several of the original 1998 release areas.

Both the flower head and rosette weevils have played an important role in managing musk thistle. However, these weevils can also attack native, non-target *Cirsium* thistles in Nebraska. There are five native *Cirsium* thistles in the state (Table 1.11). Louda et al. (2005) have shown that the flower head weevil can significantly impact one of these species: Platte thistle. Due to this, Pitcher's thistle (*Cirsium pitcheri*), a closely related, rare, and threatened thistle found in parts of the Midwest, may also be negatively affected (Louda et al., 2005). The impact on wavyleaf thistle has also been documented by Louda et al. (2005). Therefore, one must consider both the benefits and drawbacks to utilizing these weevils. Like all biological control agents, these insects are more likely to become well-established in areas with large infestations of the problem pest (Roeth et al., 2012). Fractured landscapes also prevent expansive establishment of biological control agents. Although, if a landowner is willing to learn how to develop high populations of biocontrol agents, such as these weevils, biological control can be successful.

Table 1.11. Native thistles in Nebraska.

Common name	Scientific Name
Tall thistle	*Cirsium altissimum*
Platte thistle	*Cirsium canescens*
Flodman's thistle	*Cirsium flodmanii*
Yellowspine thistle	*Cirsium ochrocentrum*
Wavyleaf thistle	*Cirsium undulatum*

Other Arthropods

Apart from the flower head and rosette weevils, many insects and other arthropods have been utilized for the control of weeds. For example, several insects are permitted for release in the United States to control common St. John's wort (*Hypericum perforatum*), an aggressive weed from Europe and Asia (Winston et al., 2012). Two of these insects are *Chrysolina quadrigemina* and *Chrysolina hyperici*. These beetles (Coleoptera: Chrysomelidae), which are native Europe and Asia, target leaves and flowers. Another insect that targets leaves and flowers is *Aplocera plagiata* (Lepidoptera: Geometridae), native to Northern Europe. *Zeuxidiplosis giardi* (Diptera: Cecidomyiidae) from Europe acts as leaf galler. Finally, *Agrilus hyperici* (Coleoptera: Buprestidae) is stem and root miner. However, non-target effects have been seen with several of the biological control agents. Many of them attack goldwire (*Hypericum concinnum*), a native plant found in California. Winston et al. (2012) provide a great resource about these agents as well as common St. John's wort and other *Hypericum* species.

Other examples of arthropods used for the control of weeds include the musk thistle tortoise beetle (*Cassida rubiginosa*) (Roeth et al., 2012), the stem-mining weevil (*Hadroplontus litura*) (Sciegienka et al., 2011) and the Canada thistle gall fly (*Urophora cardui*) (Colorado Dept of Ag, n.d.) for Canada thistle, and the bindweed gall mite (*Aceria malherbae*) for field bindweed (*Convolvulus arvensis*) (Figure 1.16) (KSU Dept of Entomology, 2018). Several biological control agents show great potential to control weeds, especially when used with other weed management practices. For example, in one lab study, bindweed gall mites reduced both field bindweed shoot and root biomass up to 50% (Boydston & Williams, 2004). Additionally, combining these mites with either 2,4-DB or

Figure 1.16. Field bindweed (*Convolvulus arvensis*) plant (top) and leaves (bottom).

Photos: Callie Braley

glyphosate reduced field bindweed root biomass more than the mites or herbicides alone (Boydston & Williams, 2004). Despite the potential of some biological control agents and their commercial availability, some agents are limited in field settings. Several are also not well-established, nor have they been widely distributed. For example, even though field bindweed occurs throughout the United States, the bindweed gall mite has been widely distributed in only a handful of states (KSU Dept of Entomology, 2018). One of the first successful establishments of this mite was in Texas, documented by Boldt & Sobhian (1993). McClay et al. (1999) also documented mite establishment in southern Alberta and Montana.

Microorganisms

Microorganisms can also be useful to control certain weeds. Although there are many different types of microorganisms, fungi are the dominant group used for weed biological control agents. Viruses, bacteria, and nematodes are rarely used, if at all, as many plant pathogens lack sufficient host specificity to be considered safe. Rusts (Basidiomycota), a group of fungi belonging to the Pucciniaceae family, are one of the more commonly used fungal groups due to their host specificity, high reproduction rate, and ease of dissemination. Two examples include *Puccinia carduorum* for musk thistle and *Puccinia punctiformis* for Canada thistle. *Puccinia carduorum* becomes active around the time musk thistle starts to bolt. About one week after inoculation, white blister-like flecks appear on the thistle. These develop into brown pustules up to 3 mm (1/8 inch) in diameter after two to three days, and within two weeks, spores are produced. Leaves that are infected may become yellow and die (Roeth et al., 2012). *Puccinia* *punctiformis* also causes yellow speckling on the leaves of Canada thistle. In late spring to early summer, fungi on diseased shoots will cross with other nearby fungi and the spores will turn a rusty red-brown color (Colorado Dept of Ag, n.d.). Wind-blown spores will infect neighboring thistle plants throughout the summer. In late summer or fall, diseased stems die. Leaf tissue from these stems falls on emerging rosettes, where the fungus can quickly move to the roots where it will overwinter (Colorado Dept of Ag, n.d.). However, the effectiveness of *P. punctiformis* is variable. In one study, up to 86% of fall-inoculated rosettes gave rise to at least one systemically diseased shoot the following spring (Berner et al., 2013). However, the mean percentage of rosettes giving rise to diseased shoots was approximately 30% (Berner et al., 2013).

Numerous other fungi have been used in efforts to control various weeds (Table 1.12), but not many have been successful in the long term. For example, BioMal, made from *Colletotrichum gloeosporioides* f.sp. *malvae* for the control of mallow (*Malva* spp.), is no longer commercially available due to a narrow market and difficult production. Even fewer bacterial plant pathogens (Table 1.12) have been researched and successfully implemented. Even so, some bacteria show promise as biological control agents. *Pseudomonas syringae* pv. *tagetis* is one such example, which attacks Canada thistle. This bacterium may be even more effective at controlling this thistle when combined with the stem-mining weevil. Sciegienka et al. (2011) researched the interactions between these two biological control agents and glyphosate on the growth of Canada thistle. They found that the relationship between the biocontrol agents and the herbicide was mostly additive. In addition, the interaction between the two agents indicated that applying the pathogen prior to releasing the weevil larvae could be more deleterious to Canada thistle compared to a late application.

Table 1.12. Examples of microbial biological control agents in North America.

Bioherbicide Agent	Target Weed	Intended System
Fungi		
Colletotrichum gloeosporioides f.sp. *aeschynomene*	Northern jointvetch (*Aeschynomene virginica*)	Rice, soybean
Colletotrichum gloeosporioides f.sp. *malvae*	Round leaf mallow (*Malva pusilla*)	Wheat, rye, barley, canola, sunflower, soybean, oats, etc.
Colletotrichum orbiculare	Spiny cocklebur (*Xanthium spinosum*)	Pasture and field crops
Colletotrichum truncatum	Hemp sesbania (*Sesbania exaltata*)	Field crops
Phoma chenopodicola	Common lambsquarters (*Chenopodium album*), others	Field crops such as corn and sugarbeet
Alternaria destruens	Dodder spp. (*Cuscata* spp.)	Alfalfa, peppers, blueberries, etc.
Bacteria		
Pseudomonas fluorescens strain D7	Downy brome (*Bromus tectorum*)	Field crops

Adapted from Harding & Raizada, 2015

As previously mentioned, many microbial biological control agents have not been successful in the long term. Furthermore, several agents are difficult to produce and targeted markets are too narrow. Thus, very few are available commercially. Naturally occurring pathogens can be conserved, however.

Beneficial Organisms That Target Plant Pathogens

There are many plant pathogens that affect corn, including various fungi, bacteria, and viruses. Many of these may seriously reduce yields if left untreated. Therefore, it's important to be aware of the many different natural enemies of plant pathogens, including arthropods, such as beetles and mites, and other microorganisms, such as certain fungi, bacteria, and nematodes.

Arthropods

Some insects act as fungivores, feeding on mycelia, fruit bodies, or spores of fungi. Among these insects, the most species-rich taxa are Coleoptera and Diptera (Schigel, 2012). However, most fungivorous Dipterans target certain mushrooms, while many Coleopterans attack fungi that utilize wood (Schigel, 2012). Several beetle families that feed on fungi include Erotylidae, Endomychidae, and some species in Tenebrionidae. For example, pleasing fungus beetles (Erotylidae) feed on a wide variety of fungi, but each species seems to be specific to a particular group of fungi (Skelley, 2021). Some species feed on fungi found on dead trees and stumps, while others feed on fungi found on dead roots and logs (Skelley, 2021). Most research of beetle fungivory has been based on basidiomycete fungi that produce large fruit bodies and the beetles associated with them (Schigel, 2012). Studies regarding associations of Coleoptera with ascomycete, minute, and microscopic fungi are lacking.

Herbivorous insects may also feed on plant pathogenic fungi for their own benefit (e.g., greater nutrient consumption), but these microbes are rarely included in studies on plant-herbivore interactions (Eberl et al., 2020). Regardless, consumption of microorganisms by herbivores may be much more widespread than commonly believed (Eberl et al., 2020).

Several mites are also fungivorous. Species in Terpnacaridae, Grandjeanicidae, Micropsammidae, and other families are primarily particulate-feeding fungivores (Walter, 1988). Species in Alicorhagiidae are omnivorous. One example is *Alicorhagia fragilis*, which consumes more fungi when other prey (e.g., nematodes) are not available (Walter, 1988). This mite (and other species in Alicorhagiidae) is widespread and inhabits soil and leaf litter, but is under-studied (Pfliegler & Bolton, 2016).

Many arthropods feed on nematodes, as well. Beetle larvae, fly larvae, diplurans, symphylans, centipedes, and mites can prey upon nematodes (Kiontke & Fitch, 2013). In grassland ecosystems, symphylans and mites are the most important arthropod predators of nematodes (Kiontke & Fitch, 2013).

Although many arthropods may feed on fungi and other microbes, little research has been done regarding the consumption of microorganisms by arthropods in field settings. Therefore, the impact of these arthropods is unknown.

Microorganism Modes of Action

There are several different mechanisms microorganisms use against plant pathogens (Table 1.13) (Köhl et al., 2019; Pal & Gardener, 2006) that either directly or indirectly inhibit plant pathogens. We can utilize these microorganisms to either reduce plant pathogen numbers, protect infection courts on plants, and/or reduce disease severity. Reducing plant pathogen numbers involves the destruction of pathogen inoculum or the prevention of its formation (Cook, 1985). Protecting plants' infection courts involves establishing non-pathogenic or mildly virulent microorganisms on the surface of plants to preempt or inhibit plant pathogens (Pat & Gardener, 2006). Plants can also be protected by using non-pathogenic or mildly virulent microorganisms to induce resistance (Cook, 1985).

Fungi

Fungi can act as antagonists against other fungi, nematodes, and bacteria. They can also parasitize other fungi as well as nematodes. Through induced resistance, fungi can help protect host plants against fungi, bacteria, and viruses.

When fungi parasitize other fungi, it is known as mycoparasitism. Some common mycoparasites include *Pythium* species (such as *P. oligandrum*), *Trichoderma* species, *Coniothyrium minitans*, and *Sporidesmium sclerotivorum*. Each of these have been considered for use as biological control agents. However, in the United States, many registered fungal agents are used for managing fungal diseases in vegetables and ornamentals, but not in field crops (van Lenteren et al., 2018).

Table 1.13. Some modes of action microorganisms use against plant pathogens.

Mode of Action	Definition	Acts On/Against
Antagonism	Direct inhibition of pathogen; microbe grows outside pathogen and doesn't rely on pathogen as immediate nutrient source	Pathogen and environment
1. Preemptive exclusion (competition)	Microbe deprives pathogen of a critical resource	
2. Antibiosis	Microbe produces a chemical factor (e.g., lytic enzymes, toxins) that harms the pathogen	
Parasitism	Exploitation of pathogen as a resource (i.e., nutrient source); microbe exists inside pathogen; kills slowly	Pathogen
Predation	Consumption of pathogen by microbe of equal or larger size; pathogen killed or immobilized quickly	Pathogen
Induced Resistance	Invoking of plant defenses by pathogenic or non-pathogenic microbe	Host plant
1. Cross protection	Infection by avirulent or mildly-virulent virus strain; enhances plant to exhibit enhanced resistance to virulent virus strain	Plant pathogenic viruses
2. Induced resistance	Herbivore feeding triggers plant response that leads to inhibition of subsequent feeding by herbivores	Herbivorous insects
3. Systemic acquired resistance (SAR) *"salicylic acid dependent pathway"*	Infection by a pathogen leads to other leaves being more resistant to subsequent infection by pathogens	Biotrophic pathogens
4. Induced systemic resistance (ISR) *"jasmonic acid/ ethylene dependent pathway"*	Root colonization by plant growth promoting rhizobacteria leads to enhanced resistance to pathogens in leaves	Necrotrophic pathogens

Information from Pat & Gardener, 2006; G. Yuen (personal communication), 2021

Nematophagous fungi attack nematodes in a variety of ways. Some trapping fungi attack nematodes by using adhesive knobs or hyphae or non-constricting rings while other fungi use constricting rings. Endoparasites use spores and egg/cyst parasites use hyphae. Different genera also have different attack devices used against nematodes (de Freitas Soares et al., 2018). Some fungi form traps only when they sense the presence of nematodes via pheromones (Kiontke & Fitch, 2013). Certain fungi also have nematicidal activity on plant parasitic nematodes in the genera *Pratylenchus*, *Xiphenema*, *Tylenchorhynchus*, *Helicotylenchus*, *Hoplolaimus*, and *Longidorus* (de Freitas Soares et al., 2018), nematodes that commonly feed upon corn in the Midwest (Tylka, 2007). *Metarhizium anisopliae* and *Beauveria bassiana* also have activity on plant parasitic nematodes. For example, *B. bassiana* negatively affects the southern root-knot nematode, *Meloidogyne incognita* (Figure 1.17) (de Freitas Soares et al., 2018), which can feed on corn. Furthermore, *Trichoderma* species are widely used against plant parasitic nematodes in greenhouses (de Freitas Soares et al., 2018). Endoparasites are unable to infect plant parasitic nematodes, as the spores are too large to pass through nematodes' stylets.

Figure 1.17. A juvenile root-knot nematode, *Meloidogyne incognita*, penetrating a tomato root.

Photo: William Wergin and Richard Sayre (USDA ARS, 2016b)

Bacteria

Bacteria can act as antagonists against fungi, nematodes, and other bacteria. They can also parasitize fungi and nematodes. Additionally, they can impact fungi, bacteria, and virus infection through induced resistance.

Bacteria in the *Bacillus* genus are good examples of microorganisms targeting other microorganisms. *Bacillus* species inhabit many different habitats and, in general, have a broad spectrum of antagonistic activity against plant pathogenic fungi (e.g., *Fusarium* species, which can cause root rot in corn), bacteria, and viruses (Fira et al., 2018). For example, *Bacillus* lipopeptides can have a strong impact on plant pathogens through direct antibiosis (Fira et al., 2018). In the United States, several *Bacillus* species are registered biological control agents for managing various diseases (van Lenteren et al., 2018). Some have been proven to be efficient in biological control against plant pathogens (Borriss, 2015). However, some strains of *Bacillus* (e.g., *B. pumilus* BG34) may negatively affect plant stand when used as seed treatments, especially in comparison to fungicide seed treatments (Bradley, 2008). In addition, some *Bacillus* species can be used for nematode management (van Lenteren et al., 2018). One example is *Bacillus firmus* for control of the southern root-knot nematode (Terefe, 2009).

Apart from *Bacillus*, other bacteria are also used for the management of plant pathogenic microorganisms. For example, *Pseudomonas chlororaphis* 63-28 targets *Pythium* species, *Rhizoctonia solani*, and *Fusarium oxysporum* (van Lenteren et al., 2018). *Pasteuria nishizawae* Pn1 is also registered in the United States for control of *Heterodera* and *Globodera* nematodes (van Lenteren et al., 2018). Another example is *Pasteuria penetrans*, an obligate bacterial parasite of root-knot nematodes, which has been used in biological control (Pal & Gardener, 2006). Researchers in one study looked at both *P. penetrans* and *Paecilomyces lilacinus*, a fungus, for the control of the southern root-knot nematode (Dube & Smart Jr, 1987). They found that *P. penetrans* and *P. lilacinus* each negatively affected root-knot nematodes. However, root-knot nematode control was more effective when both were used together.

Nematodes and Viruses

Most nematodes are microbial feeders, feeding on bacteria and/or other nematodes (Kiontke & Fitch, 2013). Nematodes can help reduce pathogen biomass as well as stimulate plant host defenses (Pal & Gardener, 2006). Furthermore, nematodes reduce populations of plant parasitic nematodes in virtually all soils (Khan & Kim, 2007). However, the importance of nematodes in biological control is unknown. Several orders of predatory nematodes have been studied, but it is inconclusive whether they are effective biological control agents of plant parasitic nematodes (Khan & Kim, 2007).

Viruses can parasitize bacteria as well as affect other viruses via induced resistance. Regarding biological control, their importance in targeting fungi and nematodes is unknown. When viruses parasitize bacteria, they are known as bacteriophages, or simply phages. The infection of bacteria occurs in aquatic environments, such as ponds, water-filled soil pores, and water films on leaf surfaces, thus, no vector is needed for dispersal or penetration of bacteria (Gill & Abedon, 2003; G. Yuen, personal communication, 2021). Bacteriophages are also very host specific. Each phage can only infect certain strain(s) of a bacterial species. There are only a limited number of bacteriophages and other viruses registered as biological control agents for managing pathogens (van Lenteren et al., 2018). For example, the bacteriophage for *Xanthomonas campestris* pv. *vesicatoria*, the causal agent of bacterial spot disease of pepper and tomato, is registered in the United States. The effectiveness of this bacteriophage is greatly reduced due to its lack of residual activity on plants (Balogh et al., 2003). Although, certain formulations (e.g., powerdered skim milk plus sucrose) can increase the longevity of these phages, thus increasing their effectivity (Balogh et al., 2003).

Conclusion

It is clear that while many different pests attack and damage corn, there are also a variety of natural enemies, from lady beetles to nematodes, that attack these pests. Many people, both today and throughout history, have observed and utilized the pest management capabilities of beneficial organisms. Some of these organisms are commercially available, but all beneficials can be conserved via conservation biological control. Therefore, this readily available and easy-to-implement tool should be used alongside other management tactics in IPM programs.

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CHAPTER 2: CONSERVATION OF BENEFICIAL ORGANISMS IN CORN AGROECOSYSTEMS

Introduction

There are many beneficial arthropods and microorganisms present in corn agroecosystems. These organisms play an important role in pest management, and utilizing them in IPM programs is more important than ever. Due to increased awareness of the potential harmful effects of pesticides, many pesticides have been banned or their use restricted in the United States and throughout the world (Pesticide Action Network International, 2021). For example, the United States Environmental Protection Agency (EPA) recently announced a ban on chlorpyrifos, an organophosphate insecticide. According to some studies, chlorpyrifos may have adverse effects on children's health (Mie et al., 2018). Several other pesticides are on a watchlist due to their acute or chronic toxicity and/or environmental impacts (UTZ, 2015). Furthermore, even though the EPA is confident that the food we eat is safer than ever (EPA, 2021), chemophobia and the importance of 'natural' food influence the acceptability of pesticides and agricultural biotechnology (Saleh et al., 2021). Personal experiences with pesticides also play a role in acceptability (Coppin et al., 2002).

Additionally, dependence on pesticides has also led to resistance. In Nebraska, resistance to glyphosate has been reported in kochia, common waterhemp, horseweed, and other weeds (Sarangi & Jhala, 2018). Other examples in Nebraska include western corn rootworm resistance to Cry3Bb1 and mCry3A proteins and western bean cutworm resistance to the Cry1F protein used in transgenic corn (Meinke et al., 2014; Coates et al. 2020). Additionally, resistance to the quinone outside inhibitor (QoI) fungicides has been found in *Cercospora sojina*, the fungal pathogen that causes frogeye leaf spot in soybean (Mane et al., 2020).

Pesticide resistance has led to the “pesticide treadmill” (Figure 2.1), the cycle of pesticide application leading to pesticide resistance, causing farmers to use even more pesticides. Dependence on pesticides is also based on other factors, such as the “promotional failure” of pesticide alternatives (Hu, 2020). Hu (2020) states that if alternatives could be successfully implemented, dependence on pesticides would not have persisted for such a long time. Many farmers are also using practices that can promote pesticide use, such as continuous cropping and no-till. According to a survey by Sarangi and Jhala (2018), approximately 61% of total farmed or scouted areas in Nebraska are under no-till production.

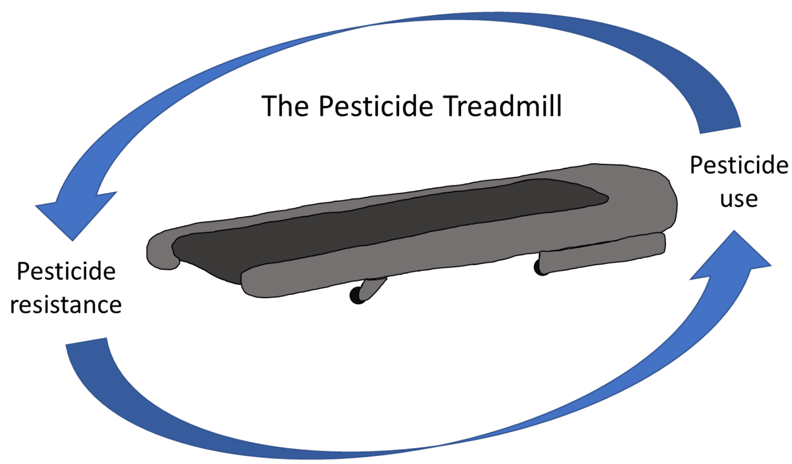


Figure 2.1. A simple depiction of the pesticide treadmill.

Due to these factors, it is imperative that growers are aware of the beneficial organisms that may be present in their corn fields, the pest management services these beneficials can provide, and methods to conserve these organisms. In this chapter, the conservation of beneficial organisms in corn production systems will be discussed. In addition, it will also address the use of beneficial organisms in an IPM program to manage spider mites in corn, common arthropod pests found in western Nebraska.

Conserving Beneficial Organisms

Reduced and Selective Pesticide Use

One of the best ways to conserve beneficial organisms is to reduce the use of pesticides. Many beneficials are sensitive to pesticides. Therefore, reducing the use of these chemicals can promote populations of beneficial organisms. One example of this is seen in Ellsbury et al. (1998), where ground beetle populations were compared across varying crop rotation and chemical input (high, managed, and low) treatments. The relative abundance of one beetle, *Harpalus pensylvanicus*, was highest in the low-input plots. Carabid diversity and species richness was also high in the managed plots, which suggested that greater abundance and diversity was encouraged by reduced chemical inputs as compared to the high-input plots.

Many pesticides today are used prophylactically as “insurance” against potential pests. For example, corn seed is often treated with neonicotinoids. Neonicotinoids are broad-spectrum insecticides, and they are the most widely used class of insecticides worldwide. In the United States, between 79% and 100% of corn acres were treated with neonicotinoids in 2011 (Douglas & Tooker, 2015). While these insecticides are useful in fields where early-season insect pests, such as wireworms, white grubs, flea beetles, and chinch bugs (Wilde et al., 2007), are an issue, these insecticides aren’t always useful. In one five-year field study from Canada, researchers observed no significant differences in yield or plant stand between neonicotinoid-treated and untreated corn or soybeans (Labrie et al., 2020). The researchers concluded that, due to very low levels of pest-associated pressure and damage, neonicotinoid seed treatments were useful in only a small percentage of cases and therefore should not be used prophylactically (Labrie et al., 2020).

Prophylactic use of pesticides is not only unnecessary in many cases, but it can also be harmful to beneficial organisms directly or indirectly. Many of these pesticides are broad-spectrum and can directly harm natural enemies. These pesticides can also kill or harm non-pest organisms, such as arthropod decomposers, that act as alternative prey for generalist predators. Pearsons and Tooker (2021) conducted a three-year field study in no-till corn and soybean fields to determine the impact of the prophylactic use of neonicotinoid seed treatments and broadcast applications of lambda-cyhalothrin, a pyrethroid, on arthropod decomposers. Neonicotinoid seed treatments reduced both springtail (Collembola) and millipede (Diplopoda) densities, while the pyrethroid reduced soil mite and millipede densities. Both insecticides also reduced the decomposition of plant litter by greater than 10%. The authors concluded that, based on their results, repeated and widespread use of prophylactic insecticides is likely to cause several negative effects on alternative prey, plant residue breakdown, and nutrient cycling in field crops.

Another study from Brazil compared the prophylactic use of insecticides with IPM and biological control strategies in soybeans (de Freitas Bueno et al., 2011). Even though pest infestation rates were higher in the IPM and biological control treatments compared to the prophylactic insecticide treatment, crop productivity was similar among treatments. The authors stated that the use of IPM remains the best alternative for pest management in soybean fields, as the prophylactic use of insecticides does not result in higher productivity.

Broad-spectrum pesticides are commonly used, but they can be used in a selective manner, as well, such as using them to spot treat specific areas. Another option to conserve beneficial organisms is to use selective pesticides that are less harmful to natural enemies than broad-spectrum pesticides. Each selective pesticide affects natural enemies differently. The same pesticide can also affect one group of natural enemies more or less than another group. For example, beetles, parasitic wasps, and predatory mites are very susceptible to pyrethroids, but lacewings are naturally more tolerant (Grafton-Cardwell et al., 2017).

Some selective insecticides include indoxacarb and spinosad. One study found these insecticides were less toxic to several predators (i.e., two species of lady beetle and the insidious flower bug) in sweet corn than lambda-cyhalothrin (Musser & Shelton, 2003). Other insecticides that show promise regarding selectivity, but need to be studied further, include the diamides (e.g., chlorantraniliprole) and imidacloprid (Gentz et al., 2010). One advantage of these is that both chlorantraniliprole and imidacloprid are synergistic with certain entomopathogenic nematodes (Gentz et al., 2010). This means that the combined use of the insecticide and nematodes is more effective than each method used alone. However, imidacloprid, a neonicotinoid, also may cause issues with several natural enemies and pollinators. In one Australian study, the acute and long-term effects of several selective insecticides (e.g., indoxacarb, spinosad, imidacloprid) were compared to a broad-spectrum insecticide (chlorpyrifos) on three predatory insects (Cole et al., 2010). Apart from chlorpyrifos, imidacloprid generally caused the greatest negative effect on the predators. Although, the method used to apply neonicotinoids can influence its selectivity. For example, imidacloprid is poorly selective for predators when used as a foliar spray, but selectivity is greatly improved when applied as a seed dressing (Albajes et al., 2003).

Pesticides, especially those used prophylactically, can be a great tool when used appropriately: at the right rate, time, and place. They can be an important part of IPM programs alongside biological control agents (Gentz et al., 2010), such as seen with glyphosate and the stem-mining weevil and *Pseudomonas syringae* pv. *tagetis* for control of Canada thistle (Sciegienka et al., 2011). Through their study, Sciegienka et al (2011) showed that there was a mostly additive relationship between the biological control agents and glyphosate. However, overdependence on pesticides can lead to avoidable problems, such as unnecessary expenses and resistance. Therefore, fields should be assessed individually to determine if a pesticide application is required. Factors to consider on a field-by-field basis should include, but are not limited to: the history of a pest, pest density, and the presence of pesticide resistance and natural enemies.

Vegetation Management

Creating or conserving habitats for beneficial organisms may encourage growth of their populations by providing alternate food sources and overwintering sites. One example of this is the creation and use of beetle banks. These banks are strips or berms planted with native vegetation that support beneficial organisms, including predaceous ground beetles. These are often planted around or within crop fields. Filter strips, which are used to reduce sediments and contaminants from runoff, can also provide refuge for beneficial organisms. Both omnivorous and carnivorous ground beetles can be found in this permanent vegetation. In one study, omnivorous species were primarily captured in filter strips flanking a field and weed seed removal was greater in the strips compared to in the field (Menalled et al., 2001). Even though weed seed predation was higher in the filter strips, the authors concluded that habitat management is indeed a feasible way to conserve beneficial organisms.

Even simple field borders can support abundant and diverse beneficials. In one study from Iowa, ground beetle activity in corn fields was compared between fields with hedgerow or grassy borders (Varchola & Dunn, 2001). The study's results indicated that both complex and simple field borders can encourage populations of carabids during the majority of the growing season. For example, early in the season, hedges appeared to be more important compared to grass edges.

Temporary vegetation, such as cover crops, can also serve as a refuge and food source for beneficial organisms. According to one survey, farmers in Nebraska that grow cover crops often drill cereal rye (*Secale cereale*), either alone or in mixtures with radish (*Raphanus sativus*) or hairy vetch (*Vicia villosa*), following soybeans and field corn (Oliveira et al., 2019). However, it is important to note that beneficial organisms may be exposed to pesticides indirectly through cover crops. For example, neonicotinoid seed treatments on crop seeds can enter interseeded cover crops such as cereal rye and hairy vetch, which is a newly discovered route of exposure for beneficials (Bredeson &

Lundgren, 2019). Therefore, consideration for potential interactions with natural enemies should be taken into account when contemplating using pesticides.

Another factor to consider when conserving and/or planting vegetation in or around fields is the potential to harbor pests. Some pests, such as spider mites, overwinter in native grasses or broadleaf plants bordering fields. Grasshopper (Orthoptera) eggs are also laid in undisturbed soils surrounding fields, although dense grass stands can reduce oviposition (Fielding, 2011). Thus, a grower should consider both the benefits and risks when establishing vegetation in or around his or her fields.

Other Methods of Conservation

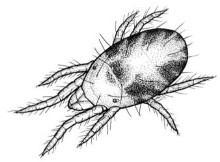
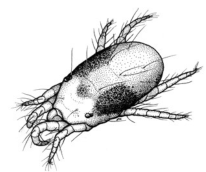
While two primary methods of conserving beneficial organisms are the reduced/selective use of pesticides and the establishment of vegetation, there are several other ways farmers can conserve beneficials. One such method that also allows farmers to control pests is to use Bt and/or glyphosate-resistant corn. Bt corn is less toxic to several insect predators compared to broadcast applications of broad-spectrum insecticides (Musser & Shelton, 2003). In one study, Bt corn actually controlled lepidopteran better than lambda-cyhalothrin (Musser & Shelton, 2003). When looking at the percent of ears infested at harvest, Bt corn also controlled aphids better than lambda-cyhalothrin due to predators being eliminated by the insecticide (Musser & Shelton, 2003). In another study from Nebraska, researchers found that Bt, glyphosate-resistant, and combined Bt and glyphosate-resistant corn hybrids had no significant effects on insidious flower bug population abundance compared to a glyphosate-resistant corn hybrid treated with insecticides (Palizada et al., 2014). Bourassa et al. (2010) also suggest, based on their research, that glyphosate-resistant corn has little impact on overall ground beetle fauna.

Adopting conservation tillage or no-till practices can help conserve beneficial organisms, as well. However, these practices may promote pesticide use, as tillage is not used for managing weeds. Therefore, growers rely more on herbicides. These types of tillage also leave more residue on the soil surface. Residue can harbor plant pathogens, such as those that cause gray leaf spot and Goss's wilt in corn. Although, residue can create refuge for some beneficials, such as *Trichoderma* species, which attack fungal and nematode pathogens (Meriles et al., 2006). Additionally, disturbing the soil as little as possible will leave more weed seeds on the surface, allowing weed seed predators to easily consume them. This is especially important after recent weed seed dispersal (Sarabi, 2019). When used, tillage buries weed seeds at various depths, which may reduce seed predation by beneficials. Kulkarni et al. (2015) found that ground beetles consumed more seeds scattered on the soil surface than seeds buried at any depth. Therefore, conservation tillage and no-till practices may promote beneficial organism populations in various ways.

Beneficial Organisms: One Tool to Combat Spider Mites

Spider mites often cause problems in corn, especially in the drier areas of the western Great Plains. Two spider mite species common in Nebraska are the twospotted spider mite and Banks grass mite (Table 2.1). These pests can be identified by using a hand lens or magnifying glass. While both mites can damage corn by piercing plant cells with their mouthparts and sucking out the juices, twospotted spider mites tend to be more troublesome due to their feeding patterns and broader resistance to miticides.

Table 2.1. Banks grass mite compared to twospotted spider mite.

	Banks grass mite	Twospotted spider mite
Appearance	 Relatively elongated body; dark green pigment spots on either side extending down length of body	 Relatively rounded body; dark green pigment in two distinct spots on middle third body
Webbing	Produces spider-like silk webbing	Produces spider-like silk webbing (typically more than Banks)
Host Range	Almost exclusively grasses	Many grass species, soybeans, fruit trees, vegetables, ornamentals
Timing	Appears earlier in the season	Appears mid- to late-season
Location on Crop	Early infestation on lower leaves, moving upward on plant later	Infestation begins randomly in canopy, can expand to entire plant
Overwintering Location	Primarily the crowns of winter wheat and native grasses	Primarily alfalfa and other broadleaf plants along field borders
Insecticide Susceptibility	Moderately susceptible to many miticides	Has developed resistance to some products

Drawings (Jim Kalisch) and information from Wright et al., 2020a

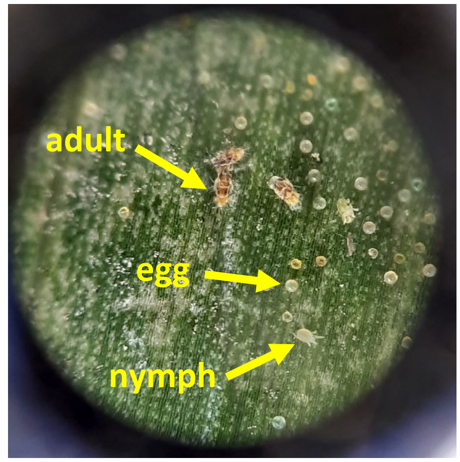


Figure 2.2. Banks grass mite adults (dead), nymphs, and eggs on the underside of a corn leaf (magnified 20X).

Photo: Callie Braley

Spider mites undergo incomplete metamorphosis. Their life stages include: egg, larva, two nymphal stages, and adult. The adults are about 0.45 mm (0.018 inch) long. Both twospotted and Banks grass mites overwinter as females. In the spring or summer, mites crawl or are carried by wind to corn fields (Wright et al., 1993). The drying of surrounding vegetation influences mite movement into corn, e.g., mites move into corn fields once neighboring winter wheat or grasses begin to dry. Once in corn fields, the mites deposit small, round eggs on the underside of corn leaves. Prevailing winds often lead to damage first appearing on the south and west edges of fields. In three to four days, the eggs hatch, and it takes another five to 10 days for mites to begin producing eggs (Wright et al., 1993). All mite stages will be present at the same time (Figure 2.2). Generation times depend on temperature and are usually 10 to 20 days (Peairs, 2014). Wright et al. (1993) state that seven to 10 generations may occur during the growing season. Under laboratory conditions, Banks grass mite populations have been shown to increase 70-fold in one generation (Peairs, 2014).

One of the first indications of spider mite feeding is a yellow or whitish spotting of the upper leaf tissues. As mites develop and reproduce, their colonies, which are on the underside of leaves, become larger (Figure 2.3) and spread on the plant. Severely infested and damaged leaves will be killed prematurely. Effects on corn yield are most severe when mites feed on leaves at or above the ear level (Wright et al., 1993). Corn yields may be reduced due to poor seed fill. Additionally, plant dry down may be accelerated.

Figure 2.3. A large colony of Banks grass mites on the underside of a corn leaf.

Photo: Callie Braley

Many factors contribute to mite infestations (Peairs, 2014), including:

- Host drought stress
- Elevated temperatures
- Low rainfall and humidity
- Lack of natural enemies
- Insecticide use
- Adequate moisture for alternate hosts during the previous growing season

Based on these factors, there are several ways to manage spider mites in corn. One of the most important methods to managing spider mites is to manage natural enemies, mostly through conservation.

Managing Spider Mites with Beneficial Organisms

There are many beneficial organisms that target spider mites in corn agroecosystems. According to Peairs (2014), 35 natural enemy species from 15 families of insects, mites, and spiders have been associated with spider mites on corn. Those discussed in Chapter 1 are listed in Table 2.2.

Table. 2.2. Beneficial organisms in corn agroecosystems that attack spider mites.

Common Name	Family	Group
Lady beetles; primarily "mite destroyer beetles"	Coccinellidae	Arthropods
Lacewings	Primarily Chrysopidae; Hemerobiidae	
Thrips	Thripidae, etc.; primarily six-spotted thrips	
Predatory mites	Phytoseiidae, etc.	
Minute pirate bugs	Anthocoridae	
	Neozygites spp.	Fungi

In Nebraska, the most important natural enemies of spider mites are predatory mites, the mite destroyer beetle, six-spotted thrips, and minute pirate bugs (Wright et al., 1993). In addition, lacewing eggs and larvae can often be found in spider mite colonies (Figure 2.4). In certain situations, a fungus may also help manage spider mite populations.

Predatory mites look similar to spider mites, but they are a bit larger, more teardrop-shaped, yellower, and do not possess the dark pigmentation seen in Banks and twospotted mites. The most important predatory mite in Nebraska is *Neoseiulus (=Amblyseius) fallacis*, which is a phytoseiid mite. These mites can eat approximately 15 mites per day (Wright et al., 1993). Other phytoseiid mites can eat up to about 25 eggs per day (Xiao et al., 2013). Thus, these mites can significantly contribute to spider mite control when and where conditions are favorable. Hot and dry conditions negatively affect *N. fallacis* survival (Jung & Croft, 2000). These conditions are often present in western Nebraska, so *N. fallacis* will not be abundant in this area of the state.

Figure 2.4. Lacewing larvae in a Banks grass mite colony (top) and green lacewing eggs near a Banks grass mite colony (bottom).

Photos: Callie Braley

Mite destroyer beetles (*Stethorus* spp.) are small black lady beetles about 1.5 mm (1/16 inch) long. They lay eggs in active mite colonies and the gray, cylindrical larvae (Figure 2.5) feed on mite eggs. They can eat up to eight mites per hour (Wright et al., 1993) and up to 75 mites per day (UC IPM, n.d.). Relative humidity does not significantly influence the activity of some *Stethorus* species, such as *S. punctillum* (Rott & Ponsonby, 2000). However, temperature can significantly affect activity. Rott and Ponsonby (2000) found that *Stethorus punctillum* activity increased at both 25°C (77°F) and 30°C (86°F) compared to 20°C (68°F). Therefore, many *Stethorus* species can thrive in the hot and dry areas of Nebraska.

Figure 2.5. *Stethorus picipes* larva feeding on twospotted spider mites.

Photo: Jack Kelly Clark (UC IPM, n.d.)

The six-spotted thrips is important in managing spider mites, as well. Both immature and adult thrips feed within mite colonies and can consume approximately 60 mite eggs per day (Wright et al., 1993). Six-spotted thrips are a “gift from nature” (Gilstrap, 1995) and are very beneficial for many reasons. One important reason is that they are adaptable to varying environmental conditions. For example, they can develop and oviposit over a wide range of temperatures, from about 20°C (68°F) to 41°C (106°F) (Gilstrap, 1995), which makes them very important in western Nebraska.

Minute pirate bugs (*Orius* spp.) may also prey upon spider mites as both immatures and adults and are often found in corn fields (Pickett & Gilstrap, 1986; Pickett, 1985). These insects actively search for prey. Both nymphs and adults can consume 30 or more spider mites per day (Patterson & Ramirez, 2017).

Other effective insect predators of spider mites that are found in certain corn-producing areas (e.g., Texas) are predatory gall midges (Diptera: Cecidomyiidae), such as *Feltiella macgregori* (Pickett & Gilstrap, 1986; Pickett, 1985) and *Feltiella acarisuga* (Xiao et al., 2013). Xiao et al. (2013) showed that *F. acarisuga* is a highly effective predator on twospotted spider mite eggs, as these larvae can consume up to 50 eggs per day. However, these species are not important in many parts of Nebraska due to their environmental preferences. For example, relative humidity below 60% negatively affects the reproduction and survival of *F. acarisuga* (Gillespie et al., 2000).

Figure 2.6. Female twospotted spider mite killed by *Neozygites floridana*.

Photo: Trandem et al., 2015

In addition to arthropod natural enemies, spider mites may also be controlled by fungi in the *Neozygites* genus. Both *N. floridana* and *N. adjarica* are known to infect spider mites (Figure 2.6) (Wright et al., 1993; Dick & Buschman, 1995). However, certain weather conditions must be present for these fungi to be effective. For *N. floridana*, relative humidity should be above 90% and average daily temperatures below 29°C (85°F) (Wright et al., 1993). For *N. adjarica*, eight to 10 hours per day of relative humidity above 80% can promote epizootics (Dick & Buschman, 1995). These conditions do not occur in drier areas, such as western Nebraska. In areas where these conditions do exist, several cool, damp days occurring together will promote growth and activity of these fungi. Another interesting phenomenon is that twospotted spider mite males prefer *N. floridana*-killed females over live healthy females (Trandem et al., 2015). This interaction likely enhances transmission of the fungus, further promoting its biological control capabilities.

These beneficial organisms play a very important role in the management of spider mites. The presence of multiple beneficials may also maximize spider mite control (Brødsgaard & Enkegaard, 1995). Furthermore, several of the above natural enemies (e.g., certain lady beetles, predatory mites, and minute pirate bugs) can feed on alternative foods, such as pollen. This means these beneficials can continue surviving in the absence of spider mites. Some beneficials are also available for purchase, but this method of biological control is not cost effective (Peairs, 2014). Therefore, conservation of existing natural enemies is crucial, which can be done through the reduced/selective use of pesticides and provisioning and/or modifications of habitats and food sources.

Other Methods to Manage Spider Mites

While utilizing beneficial organisms is important for managing spider mites, they may not be able to keep mite populations in check. Thus, they should be used as one tool in an IPM program for spider mites. Other ways to manage spider mites include proper irrigation, hybrid selection, and miticide/insecticide applications.

Dry, hot weather favors spider mite reproduction, and some natural enemies do not do well under these conditions (e.g., *N. fallacis* and *Neozygites* spp.). These conditions can also lead to drought stress in corn, especially in plants grown in sandy soils. It has long been known that drought stress can further promote spider mite development (Chandler et al., 1979; Gill et al., 2020). Higher leaf temperatures are associated with drought-stressed plants (Gill et al., 2020; Perring et al., 1986), and leaf/canopy temperatures are significantly correlated with spider mite numbers (Perring et al., 1986). Perring et al. (1986) found that Banks grass mite abundance rapidly increased in response to elevated leaf and canopy temperatures (due to reduced irrigation). If available, irrigation can reduce this stress, helping plants to better tolerate spider mites. Adequate irrigation reduces leaf and canopy temperatures, thus slowing mite reproduction and reducing numbers of spider mites (Perring et al., 1986). Adequate irrigation may also slow the rate of spider mite increase (Chandler et al., 1979), which helps beneficials to better keep up with them. Irrigation itself will not reduce mite densities, however (Peairs, 2014).

Selecting drought-tolerant corn hybrids is another management option for spider mites. Conventionally-bred drought-tolerant corn was introduced in 2011, while genetically engineered drought-tolerant hybrids were introduced in 2012 and widely available in 2013 (McFadden et al., 2019). In Nebraska in 2016, over four million acres of drought-tolerant corn were planted, equivalent to 42% of the state’s corn acreage (McFadden et al., 2019). These hybrids can maintain or exceed yields compared to nondrought-tolerant corn (McFadden et al., 2019) while reducing overall plant stress, thereby mitigating damage from spider mites.

One other common management practice for spider mites is the application of miticides and/or insecticides. Treatment thresholds are based on how many leaves are infested and damaged (Wright et al., 1993) and if spider mite colonies are present and mites actively reproducing (Wright et al., 2020b). However, spider mite damage may look similar to other issues, such as drought stress or disease. Therefore, the actual presence of spider mites should be confirmed before treating. Sometimes fields only have spider mite "hot spots," so the entire field does not need to be treated.

There are several products that may be used for spider mite control in corn (Table 2.3). Mites must come into contact with the pesticide, which can be difficult due to their location on the underside of corn leaves. In addition, not all pesticides kill mite eggs. Some products that have activity against eggs and immature mites include Zeal, Oberon, and Onager. If a product that is ineffective against eggs is used, reinfestation is likely to occur approximately one week to 10 days after pesticide application. If reinfestation is severe, a second application may be necessary. Growers and/or agronomists should thoroughly examine a field five to seven days after treatment to evaluate the effectiveness of a pesticide application. Preventative miticide treatments, such as propargite, spiromesifen, and etoxazole (Ostlie & Potter, 2012), may also be used before spider mites reach economically important levels.

Nearly all synthetic insecticides have detrimental effects on spider mite predators. Due to this, many spider mite infestations may be caused by insecticide applications targeted at other corn pests, such as western bean cutworms and western corn rootworm beetles (Peairs, 2014; Wright et al., 2020b). Some insecticides (e.g., carbaryl) may also stimulate mite reproduction or favor spider mites by increasing nitrogen levels in leaves (Godfrey, 2011). Therefore, growers and agronomists should consider multiple factors before deciding to treat spider mites with pesticides, including the number of plants infested, forecasted weather conditions, the presence of plant stress and natural enemies, and forecasted and historical mite problems (Peairs, 2014).

Table 2.3. Spider mite control products for use in corn.

Chemical Name	Products	Targeted Stages
Mode of action class 1B; organophosphate		
Dimethoate	Dimethoate 4E, 4EC, 400, Dimate 4E, 4EC	Adults
Mode of action class 3A; pyrethroid		
Bifenthrin	Bifenture 2E, Brigade 2E, Discipline 2E, Fanfare 2E, Sniper 2E, Tundra 2E	Adults
Mode of action class 10B		
Etoxazole	Zeal	Eggs and immatures
Mode of action class 12C		
Propargite	Comite	Adults
Mode of action class 23; tetronic and tetramic acid derivatives		
Spiromesifen	Oberon	Eggs and immatures
Hexythiazox	Onager	Eggs and immatures
Combination Products		
Zeta-cypermethrin and bifenthrin	Hero	Adults
Chlorpyrifos and bifenthrin	Tundra Supreme	Adults

Information from Wright et al., 2020b

Conclusion

Managing spider mites in corn can be problematic, but developing an IPM program that uses multiple tactics, including reliance on beneficial organisms, will be most effective. Utilizing beneficial organisms in corn and other crops is becoming increasingly important due to pesticide bans and resistance. Conservation biological control is a relatively easy way for growers to maximize the pest management benefits of natural enemies. Conserving beneficials can be achieved several ways, including the reduced and/or selective use of pesticides, the establishment of vegetation in or surrounding fields, the use of alternative pest management options (e.g., Bt hybrids), and the adoption of reduced or no tillage. As seen with spider mites, natural enemies are capable of significantly reducing pest populations. Additionally, beneficials provide even better pest control when used alongside other cultural management practices (e.g., water/stress management) as a part of an IPM program.

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