INTRODUCTION
Biological control is a component of integrated weed management (IWM) and may be defined as the reduction of pest (insect, weed, pathogen) populations by natural enemies. Biological control is arguably the least used IWM tactic. However, it may receive increased consideration due to pressure to reduce agriculture intensification and improve environmental stewardship. In agricultural fields, a percentage of germinating weeds survive, produce seeds and deposit new seeds into the soil seedbank. Nevertheless, the actual fate of weed seeds after falling from their mother plants is mostly unknown. Research has proven that a significant number of weed seeds don't make it to the seedbank due to natural mortality factors such as desiccation and being consumed by natural enemies (biological control agents). This reduces the accumulation of seeds entering the soil seedbanks thereby playing a critical role in weed management. The full impact of natural enemies on weed management is undetermined. However, destruction of a large percentage of weed seeds in a field will impact weed density and consequently weed management intensity. As such, biological control should receive greater attention as an IWM tool. To this end, the objective of this article is to bring greater awareness to natural enemies and their contributions to weed management. This is the 6th article of a series on IWM. Initial articles can be found within the Vegetable and Fruit and Headline News newsletter (March, April and May Special Editions).

What is seed predation (granivory)?
Organisms that consume plant seeds are known as granivores or seed predators. Birds, rodents and insects feed on weed seeds. Plant seeds contain high energy reserves that supply plant embryos resources needed to germinate and develop into seedlings. Thus, weed seeds can be an excellent source of nutrients for invertebrates and mammals living in or near agricultural fields. Seed predation can occur on plants (pre-dispersal predation) and after seeds have shed from
plants and fallen to the soil surface (post-dispersal predation). Generally, weed seeds on the surface are more susceptible to insect granivory than buried seeds; and several generalist seed predators contribute to post-dispersal granivory. However, some species are specialist granivores that feed almost exclusively on seeds and rarely animal prey. Others are omnivores which means they eat plant and animal items. Granivores are capable of altering the population dynamics of weeds in agricultural fields and consequently contribute to an IWM program. Nevertheless, the degree to which weed population growth is inhibited by granivory varies among habitats.

**Who are these seed predators?**
Many insects from orders Coleoptera (beetles), Orthoptera (crickets) and Hymenoptera (ants) eat weed seeds after they have fallen to the ground, and several genera of carabid beetles (Coleoptera: Carabidae) have been identified as post-dispersal seed predators. Invertebrate seed predators such as carabid beetles and crickets (Orthoptera: Gryllidae) are key drivers of weed seed destruction and the subsequent reduction of weed emergence. In fact, it was suggested that post-dispersal seed consumption by carabids can limit population growth of weedy plants. In addition to carabids and crickets, harvester ants, birds and rodents such as the wood and white footed mouse are important post-dispersal weed seed predators in natural and agricultural environments within the northern hemisphere. Generally, seed predation caused by rodents or harvester ants is reported to be high compared to when carabids or crickets are the main seed predators. Rodents are highly mobile with a greater home range than carabids. Still, carabids are common seed predators in agroecosystems and are debatably the most studied family of invertebrate with respect to granivory. One of the more common carabid granivores in many agricultural systems is the Pennsylvania dingy ground beetle, *Harpalus pennsylvanicus* (Fig. 1). In North America, the peak activity period of this beetle is believed to occur from August - September which directly coincides with the senescence of many summer annual weeds. The omnivorous field cricket, *Gryllus pennsylvanicus* (Fig. 2) is also well recognized for its ability to consume weed seeds and feeds on a diversity of species within agricultural lands including large crabgrass (*Digitaria sanguinalis*), giant foxtail (*Setaria faber*), velvetleaf (*Abutilon theophrasti*), common ragweed (*Ambrosia artemisiifolia*), and redroot pigweed (*Amaranthus retroflexus*) seeds. In northeastern Spain, the harvester ant, *Messor barbarus* (Fig. 3) is considered a voracious weed seed predator and can contribute to significant reductions in weed abundance in rain-fed cereal fields. Consumption of weed seeds by granivores can influence the composition of the weed community within agricultural fields.
Rates of seed predation

Seed predation rates are highly variable and can be influenced by several mutually inclusive factors such as the species of seed and granivore, size or sex of the granivore, weather, availability of other foods as well as seed features (e.g., size, biomass, odor). These particulars may also impact granivores’ seed preferences. Field conditions are also pertinent with respect to seed predation rates. For example, site estimations of seed losses due to seed predators have ranged from 20% for barnyardgrass (*Echinochloa crus-galli*) and lambsquarters (*Chenopodium album*) (Figs. 4a, b) in a chisel plow system to 88% for giant ragweed (*Ambrosia trifida*) in no-tillage corn. In Iowa, a study was conducted to investigate the impact of seed predation on giant foxtail by spreading seeds on the soil surface in standing corn during late September. In the subsequent field season, the field was planted to no-till soybean and foxtail emergence was monitored throughout the season. Areas in the field where seed predators were excluded resulted in a nearly 50% increase in giant foxtail densities. In a study in Ontario, mice consumed 10 to 22% of the available barnyardgrass and common lambsquarters seeds in no-till corn and soybean fields; and in Oregon, 99.8% of redroot pigweed, barnyardgrass and common lambsquarters seed rain in alfalfa fields were consumed by field mouse (*Peromyscus* spp.). Some of the variation in amount consumed may also be related to seed depth. For example, seed burial depths of 0.5 or 1.0 cm reduced redroot pigweed and giant foxtail seed consumption by two carabid species but the larger carabid, Pennsylvania dingy ground beetle was not influenced by burial depths. However, some carabids are capable of detecting weed seeds buried in the soil and can use visual, tactile and olfactory cues for detecting seeds. In a greenhouse study, consisting of redroot pigweed, velvetleaf and giant foxtail seed, the carabid, *Anisodactylus sanctaecrucis* (Fig. 5) reduced total weed emergence by 15%, and northern field cricket females and males decreased weed emergence by 16 and 5%, respectively. In field experiments, vertebrate access to velvetleaf seeds reduced emergence from 4 to 9% and invertebrate access reduced emergence 4 to 6% across field sites. Vertebrate access to giant foxtail seeds reduced emergence 3 to 7%, and invertebrate access reduced emergence 4 to 13%. These wavering results suggest that predation of weed seeds by vertebrates and invertebrates reduces weed emergence but their influence on the weed community will vary from miniscule to significant.
Measuring seed predation
In some instances, researchers or farmers may be interested in the level of seed predation in a field or plot. A common method used to quantify seed predation involves lightly attaching weed seeds to sandpaper or a similar material and placing the seed cards in the field. Cards can be retrieved in a day or two and the percentage of seeds removed recorded. Weed seeds may also be placed in small dishes of finely sieved soil from the field site and sunk into the ground so that seeds are at soil level or just below. This method will provide an estimate of seed predation under more natural conditions. If the interest is solely in invertebrate seed predators such as insects, it may be necessary to enclose a wire mesh around the sandpaper or dish so that invertebrates have access while preventing entrance by rodents and other vertebrates. One limitation of measuring seed predation using these methods is it does not provide information regarding what's removing the seeds. Spy cameras may be set up to obtain this information. Additionally, pitfall traps (Fig. 6) can be used to determine which invertebrate seed predators are active in a field. These traps are generally used to capture ground dwelling arthropods and typically consist of a container (e.g., plastic cup) buried into the ground with its rim at surface level or just below. Mobile insects fall inside and cannot get out. The cup can be filled with soapy water, which breaks the surface tension and ensure individuals that enter the container sink. A cover may be placed over the top to keep out wildlife and prevent traps from overflowing due to rainfall.

Do granivores have food preferences?
In the field, preferences of granivores for different species of weed seeds are poorly understood. However, when given a choice, seed predators often feed preferentially on one species over another. Moreover, seed preference depends on the species of weed and granivore. Research in Iowa found that carabids have a clear partiality for waterhemp (*Amaranthus tuberculatus*) over velvetleaf, giant foxtail and lambsquarters seeds. In a separate study, seed preference trials were conducted with four common insect granivores: northern field cricket, Pennsylvania dingy ground beetle, common black ground beetle, *Pterostichus melanarius* (Fig. 7a) and Allard’s ground cricket, *Allonemobius allardi* (Fig. 7b). Seed predation of 10 commonly used cover crop species (e.g., small grains, legumes and mustards) and three weed species were tested. All four granivores readily consumed cover crop seeds. However, cover crops with hard seed coats and seed hulls such as hairy vetch and barley were less preferred. Another seed preference study involving three species of common ground beetles: *Amara aenea*, *Pterostichus melanarius* and *Allonemobius allardi*.
Anisodactylus sanctaecrucis, and Pennsylvania dingy ground beetle and the northern field cricket showed variation in “taste” among species. Some species consumed more redroot pigweed compared with giant foxtail seeds and all species consumed fewer velvetleaf than redroot pigweed and giant foxtail seeds. However, when seed biomass was considered, some granivores that consumed less velvetleaf seeds ate similar or greater amounts compared to other weeds with respect to seed biomass. The fact that granivores ate different families of cover crop seeds suggests that they pose a risk to crop seeds. However, seed size and depth of planting minimize risks of most crop losses to seed predators. Still, small-seeded legumes and grasses are at greater risk for predation losses if broadcast seeded during conditions that are hospitable to granivores. However, if most cover crop or crop seeds are planted under the soil surface, this should minimize losses.

Abiotic and biotic factors impacting seed predation
In the field, the intensity of seed predation by invertebrates varies during the course of a year. One source of this variation is fluctuations in ambient temperature. Granivorous insects (field crickets, ground beetles, ants, etc.) are most active during the growing season when temperatures are favorable for cold-blooded species. The highest rates of seed predation tentatively occur in late summer and early fall coinciding when weed seeds are shedding off of plants. Mammalians such as rodents, which cache seeds for later consumption and birds are active year-round. In contrast, carabids hibernate in winter and have a reduced home radius than rodents and birds and typically do not cache seeds. Still, during the cropping season, it is ill advised to have rodents visiting a field due their droppings and their propensity to feed on produce. The rate of seed predation typically increases as a crop canopy develops within a field. A closed canopy typically provides greater refuge for predators. Thus, they are more likely to colonize fields with more “protected covering”. As such, predation rates in crops such as wheat and barley are expected to be higher during the early crop cycle compared to crops such as corn and wide row soybean with open canopy. Howbeit, later in the season, after canopy closure, seed predator activity is expected to pick up in these fields and reach levels similar to those in small grains.

In addition to seasonal trends and crop spacing, there are abiotic factors such as weather that can impact seed availability to granivores. For example, hard rain droplets may force seeds to enter the soil profile; and during winter, seeds may enter the soil by falling into cracks due to freezing/thawing cycles. In addition, fluctuations in ambient temperature may affect seed predation. The effect of temperature on seed consumption was investigated using two carabid seed predators, strawberry seed beetle, Harpalus rufipes and metallic green ground beetle, Harpalus affinis (Fig. 8a) and dandelion, Taraxacum officinale (Fig. 8b) as a model system. Test individuals were kept at one of six constant temperatures between 10 and 28°C (50 and 82°F) and provided a...
surplus of seeds. Seed consumption by both beetle species increased with temperature. Interestingly, the increase differed for males and females of the metallic green ground beetle. Indicating that the influence of temperature on seed consumption will vary according to species and sex. Other factors impacting seed predation include seasonal population fluctuations of granivores, phenological changes in granivore’s lifecycle, trophic interactions with other organisms, presence of alternative food sources and seed distribution pattern on soil surface.

**Enhancing weed seed predation in arable landscapes:**

**Heavy tillage.**
Farmers may consider adopting practices that will augment granivores in their fields. To this end, certain husbandry practices may prove inhospitable to weed seed predators while others make field conditions more alluring and congenial. For example, seed predators are quite capable of locating seeds on the soil surface; and once seeds move into the soil profile that threat of predation is significantly lowered. This suggests that production practices that allow seeds to remain on the soil surface makes them more vulnerable to granivory. To this end, tillage can be disruptive to weed seed predators. Heavy tillage can cause direct mortality of granivores and destroy food and habitat resources required for their survival. Tillage can reduce adult activity, oviposition rate and immature stages of carabids. Furthermore, tillage can bury the majority of seeds at depths where predation is minuscule. A study in Spain found that decreasing soil disturbance promoted a more regular nest distribution of harvester ants known for their seed removal ability. Recommendations for enhancing weed seed predation services on-farm include delaying fall tillage following harvest and in the spring. This tentatively allows greater weed seed losses due to predation by maximizing the period that weed seeds are available on the soil-surface. Further, some carabids breed in the fall. As such, the greater weed coverage and resources in the fall may provide a more optimal refuge, egg laying site and food during this period. Moreover, spring tillage can threaten populations of carabid larvae. Conversely, if these delays result in a greater deposit of weed seeds in the seedbank, the positive benefits of seed predation conservation may be surpassed.

**Conservation tillage.** Decreasing tillage intensity is a feasible strategy to enhance weed seed predators. However, reduced labor costs together with increased soil protection may be the main reasons for increased conservation tillage (minimum- and no-till) adoption. Still a potential negative outcome of switching from conventional to conservational tillage early on is a marked increase in weed pressure. Over time, this trend will reverse and there will be less weeds in conservation especially no-till systems provisionally due to less weed seed recruitment to the weed seedbank. Seed predation may contribute to weed pressure decline over time in no-till fields, because most weed seeds are disseminated on the soil surface where they are available to seed predators. A greenhouse study showed that some carabid species will dig down a couple of centimeters to obtain weed seeds and a few may go after deeper buried seeds. However, the vast majority of weed seeds consumed by carabid ground beetles were on the soil surface. Further, findings in the greenhouse study may not adequately represent their behavior in a field environment. Similar to carabid seed feeders, rodents have been found to be important seed feeders in no-till, but not in conventional till systems.

Adopting no-tillage or strip-tillage practices that reduce soil disturbance between crop rows may serve as a refuge for overwintering carabid larvae that can feed on weed seeds in the subsequent crop. Pennsylvania dingy ground beetle are strong dispersers as adults. However, they very rarely oviposit in disturbed habitats. Further, immature carabid stages (larvae) may suffer high mortality
in tilled soil. The results also show seed predation by carabids differed markedly between surface-scattered and buried seeds, as well as among beetle species and between sexes. These studies were conducted under controlled greenhouse conditions and thus, fieldwork is needed to validate findings and quantify seed predation under field conditions. Still it is safe to proclaim that cultural management strategies that promote carabid larval success could increase weed seed management.

**Crop manipulation.** Similar practices used to increase crop competitiveness with weeds may enhance the activity density of granivores. For instance, planting crops at narrower row spacing may attract granivores earlier as they become more active in closed canopy conditions. Similarly, increasing plant density should provide a comparable response. Thus, any practice that results in rapid canopy closure should make conditions more hospitable to granivores. To this end, increasing seeding rates of the crop, using narrow row spacing, reducing intra-row spacing of seeds and transplants, planting primed, larger and more vigorous seeds, and planting transplants as opposed to direct seeding should all make the field environment favorable to seed predators earlier during the crop cycle. If these crop manipulation tactics provide crops a competitive edge over weeds and concomitantly augment the number of seed predators, this should reduce the number of weeds that reach maturity, shed seed and subsequently increase the ratio of seed predators to weed seeds reaching the surface.

**Vegetation manipulation.** It is well known that neighboring landscape can be manipulated to influence the composition of natural enemies in adjacent fields. When neighboring landscape is manipulated to augment natural enemies in agricultural fields, this is commonly called conservation biological control. Research has shown that landscape context (e.g., proximity to field edge) influences invertebrate seed predator numbers and weed seed predation rates. In Spain, it was suggested that seed predation by harvester ants and granivorous rodents can be improved through ecological infrastructures, such as adding field edge vegetation. Further, perennial habitats such as grassy field boundaries congruous to crop fields can influence the in-field abundance of carabids. Other vegetation bordering crop fields that are capable of hosting granivorous invertebrates as well as mammals include hedgerows, grass strips and herbaceous vegetation. Thus, living vegetation is a critical resource needed by seed predators. To this end, incorporating vegetation that can serve as oviposition sites and refuges for overwintering larvae, can also serve as corridors for their movement into and feeding on weed seeds in neighboring crops. For example, mark-recapture and pitfall trapping experiments have shown that the carabid seed predator, *H. rufipes* has a clear preference for habitats with vegetative cover to fallow sites. When released in plots with vegetative cover and fallow plots, *H. rufipes* was twice as likely to be re-captured in their starting plots if released in vegetated vs. fallow plots. Further, weed seed predation is positively associated with vegetative cover. The enhanced vegetation diversity may also result in a greater recruitment of natural enemies to control pests within the crop canopy.

**Organic practices.** Conversion to organic farming can initially elicit increased production of weed seeds. However, organically managed land generally has more seed predators such as birds, carabid beetles and mice. Notwithstanding, an increased rate of natural weed seed losses on organic land may help sustain weed populations at acceptable levels if a diversity of other weed management tools is sufficiently being used. However, increases in predation rates on organic farms may take several years before noticeable changes occur. One factor contributing to less seed predators on conventional farms may be pesticides, which can be harmful to granivores. Field studies have shown positive effects of conservation and organic agriculture on seed-eating
carabids. For example, a study was conducted on 111 farmers’ fields to determine the key carabids eating pansy, *Viola arvensis* seed. It was noted that 17 and 18% of the transect samples taken from fields under conservation and organic management, respectively, contained high seed predation, compared to only 2% of samples collected from conventionally managed fields. In another study investigating the impact of organic farming on weed seed predation, a comparison was made between eight organic and conventional mixed cropping fields in New Zealand. Removal rates of seeds recorded after 48 h of exposure, showed that 17% of seeds in organic fields were removed compared with 10% in conventional fields. Further, higher seed losses occurred at organic field edges and in areas with medium-dense plant cover. Adopting organic practices may enhance the rate of seed predation; however, seed predators alone are not capable of maintaining weeds at non-damaging levels.

**Summary**

Biological weed control is arguably the least thought of component of IWM. Howbeit, seed predation is responsible for a significant source of weed mortality on arable land. Thus, seed predators can benefit farmers by reducing weed seedbank deposits and consequently weed pressure that they face in subsequent crops. However, rates of seed predation are inconsistent and the lack of complete knowledge of factors supporting and limiting seed predation reduces its acceptance in IWM programs. Still, similar practices used to support other IWM tools such as actions that lead to faster crop canopy closure and enhanced vegetative cover can concomitantly be used to enhance the activity density of weed seed predators. Moreover, some common seed predators in agroecosystems, such as carabids have been well studied for their potential as biological control agents and it is well known that practices which reduce soil disturbances are more hospitable to carabids. **Financial support for the publication of this article is via USDA NIFA AFRI CARE and EIPM grant award numbers 2016-68008-25079 and 2017-70006-27171, respectively.**

**Bifenthrin receives 2020 Section 18 for control of BMSB on Apples Peaches and Nectarines**

**May 21, 2020**

The registered products, Brigade WSB (10% bifenthrin, EPA Reg. No. 279-3108) manufactured by FMC Corporation; and Bifenture EC (25.1% bifenthrin, EPA Reg. No. 70506-57) and Bifenture 10DF (10% bifenthrin, EPA Reg. No. 70506-227), both manufactured by UPL NA Inc. may be applied. Applications must be made post-bloom, by ground only, at a rate of 0.08 to 0.2 lb. active ingredient bifenthrin (a.i.) per acre; no more than 0.5 lb. a.i. per acre may be applied per year; multiple applications may be made at a minimum of 30 day intervals; a restricted entry interval (REI) of 12 hours and pre-harvest interval (PHI) of 14 days must be observed.

All applicable directions, restrictions, and precautions on the EPA-registered product labels, as well as those outlined on the section 18 use directions referenced in your request, must be followed.

These exemptions expire October 15, 2020.
To help minimize exposure to pollinators, the following statement on the application timing must be observed: "Do not apply this product until after petal fall."

To mitigate risks to aquatic organisms, section 3 product label requirements must be strictly followed. For ground applications (the only method allowed under this exemption) a 10 ft vegetative buffer strip, or a 25 ft buffer zone is required between the site of application and adjacent bodies of water. Recommendations on the section 3 product labels regarding droplet size, wind direction and speed, temperature inversions, and other factors affecting off-site drift or runoff of bifenthrin must also be carefully followed.

In addition, the following statements from the section 3 labels are reiterated:

*This pesticide is extremely toxic to fish and aquatic invertebrates. Use with care when applying in areas adjacent to any body of water. Do not apply directly to water, to areas where surface water is present or to intertidal areas below the mean high water mark. Do not make applications when weather conditions favor drift from treated areas. Drift and runoff from treated areas may be hazardous to aquatic organisms in neighboring areas. Do not contaminate water when disposing of equipment wash waters.*

*This product is highly toxic to bees exposed to direct treatment or residues on blooming crops or weeds. Do not apply this product or allow it to drift to blooming crops or weeds while bees are foraging the treatment area.*

This is the ninth year that emergency exemption requests have been made for the uses of bifenthrin on apple, peach, and nectarine. An IR-4 petition to support a section 3 registration is currently undergoing review within EPA.

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**Vegetable & Fruit News**

A timely publication for the commercial vegetable and fruit industry available electronically in 2020 from April through October on the following dates: April 16, May 14, June 11, July 9, August 13, September 10 and October 29 (Special Research & Meeting Edition).

*Published by the University of Maryland Extension Focus Teams: 1) Agriculture and Food Systems; and 2) Environment and Natural Resources.*

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**Article submission deadlines for 2020 at 4:30 p.m. on:**

April 15, May 13, June 10, July 8, August 12, September 9 and October 28 (Special Research & Meeting Edition).

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