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PROFILES

Slug (Mollusca: Agriolimacidae, Arionidae) Ecology and Management in No-Till Field Crops, With an Emphasis on the mid-Atlantic Region

Margaret R. Douglas[1] and John F. Tooker

Department of Entomology, The Pennsylvania State University, 101 Merkle Building, University Park, PA 16802.
[1]Corresponding author, e-mail: mrd276@psu.edu.

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ABSTRACT. As acreage of row crops managed with conservation tillage increases, more growers are encountering slugs, elevating their importance as crop pests. Slugs can eat virtually all crops and they inflict most of their damage during crop establishment and early growth in the spring and fall. This damage tends to be most severe under cool, wet conditions, which slow crop growth and favor slug activity. These mollusks are particularly troublesome within the Chesapeake Bay watershed where conservation tillage is strongly encouraged to minimize agricultural run-off into waterways that lead to the Bay. Slugs are challenging to control because of the limited number of management tactics that are available. We consider the species of slugs that are commonly found in mid-Atlantic field crop production and discuss their natural history, ecology, and some of the factors limiting their populations. We conclude with cultural, biological, and chemical management options, particularly for corn production, and suggest elements of a potential integrated management program for slugs.

Key Words: *Deroceras reticulatum*, slugs, no-till farming

Slugs have been one of the most serious pests of crops grown in no-tillage systems since these conservation-based farming practices first were adopted in North America (Gregory and Musick 1976). Slugs thrive in the low-disturbance, residue-rich environments characteristic of no-till fields, and now with no-till farming practiced on >88 million acres (35.5%) of U.S. cropland (Horowitz et al. 2010), slugs have become a prominent pest in parts of the United States with high no-till adoption rates. For instance, in a recent Pennsylvania survey, over 80% of no-till growers identified slugs as their most challenging pest problem ($n = 61$, J. Tooker, unpublished data). Heavy and perennial slug damage can even convince some frustrated growers to return to tillage to control their heavy slug populations (Willson and Eisley 1992, Hammond et al. 1996, J.F.T., unpublished data).

One area of heavy no-till adoption has been the mid-Atlantic region, where no-till farming has been encouraged to limit agricultural run-off into streams and other bodies of water that flow into the Chesapeake Bay (USDA-NRCS 2011). In Pennsylvania in 2009, for example, 58% (1.2 million acres) of corn (*Zea mays* L.), soybeans (*Glycine max* (L.) Merrill), barley (*Hordeum vulgare* L.), wheat (*Triticum* spp. L.), and oats (*Avena sativa* L.) were farmed without tilling (USDA-NASS 2009). In particularly cool and wet years, like 2009, much of this acreage can be at risk for slug damage, but it has been estimated that slugs cause stand reductions and yield loss on ≈20% of no-till acres annually (J. Whalen, personal communication. Consistent with this, 20% of growers in our survey indicated that they experience trouble with slugs every year, and an additional 47% see significant slug damage every 2–3 yr.

Compounding the ongoing challenge posed by slugs is a limited understanding of slug ecology across the region and, beyond tillage, a paucity of reliable slug control tactics. Growers have access to just a few active ingredients that are labeled against slugs, and many growers rely on homespun solutions that are not very well evaluated. Here, we review the natural history and ecology of slugs with a focus on mid-Atlantic field crops, discuss the available scouting and management options, particularly for corn, and highlight areas in need of research.

Description of Species and Life Cycles

Slugs are close relatives of snails—essentially snails without a shell. They are legless, soft-bodied creatures with four front tentacles, two that carry the eyes and two that operate like antennae. Slugs also have a covering of slimy mucus all over their bodies. In addition to the mucus on the outside of the body, when slugs travel they secrete mucus from the pedal gland, located at the anterior end of the animal (South 1992). This mucus aids in slug locomotion and leaves behind a characteristic "slime trail" that can be a valuable clue of their presence. Different species vary in color and pattern, but all are various earth tones such as gray, brown, or orange. Again varying by species and age, slugs can range in size from a few millimeters to several centimeters.

Over 15 slug species occur in the mid-Atlantic United States (Pearce 2008), but only four appear to be common in field crops: *Deroceras reticulatum* Müller, (gray garden, or gray field, slug, Fig. 1); *Deroceras laeve* Müller (marsh slug, Fig. 2); *Arion subfuscus* Draparnaud (dusky slug, Fig. 3); and *Arion fasciatus* Nilsson (banded slug, Fig. 4). Although some of these species are not commonly associated with damage, *D. reticulatum* appears to be the most economically important, often occurring in the largest numbers and most often associated with crop damage (Hammond and Byers 2002). This is a medium-sized (up to 5-cm long), light to dark gray slug that produces sticky, white mucus when disturbed (an identifying characteristic of this species). It often has a mottled appearance, though pattern can vary greatly. *Deroceras reticulatum* appears to be native to western Europe, where it is a common pest of agricultural crops (Kerney and Cameron 1979), but has been introduced to most parts of the world, frequently becoming a serious pest in areas of introduction, including North America where it was established by 1843 (Chichester and Getz 1969). *Deroceras reticulatum* appears particularly well-adapted to crop fields. It seems to have less restrictive water requirements than many slug species so it can survive better in crop fields, where it also encounters less competition from other slug species (South 1992). Moreover, *D. reticulatum* is less common in natural habitats (Chichester and Getz 1973).

Deroceras laeve (Fig. 2) looks similar to *D. reticulatum* but is often darker, occasionally being nearly black, and produces clear, watery mucus when disturbed (an identifying characteristic of this species). As an adult, it is smaller than *D. reticulatum* (up to 2.5 cm). Historically, *D. laeve* had a holarctic distribution so it evolved in North America, but this species also has been moved worldwide and some populations in the United States appear to have been introduced

Fig. 1. Gray garden slug (*Deroceras reticulatum*) (photo: Margaret Douglas, PSU).

Fig. 2. Marsh slug (*Deroceras laeve*) (photo: Margaret Douglas, PSU).

Fig. 3. Dusky slug (*Arion subfuscus*) (photo: Nick Sloff, PSU).

from Europe and elsewhere (South 1992). It has a very wide habitat range, including crop fields and gardens, as well as a variety of natural habitats including moist woodlands and marshy areas (Getz 1959, Chichester and Getz 1973). In most cases it does not appear to reach the high population densities of *D. reticulatum* in field crops of the mid-Atlantic, though it can be a significant pest in some settings, including greenhouses and irrigated vegetable production (Godan 1983, South 1992).

Fig. 4. Banded slug (*Arion fasciatus*) (photo: Nick Sloff, PSU).

Arion subfuscus (Fig. 3) is a large (up to 8 cm) tan, brown, or even orange-looking slug that produces orange mucus upon disturbance (an identifying characteristic of this species). It also appears to be native to western Europe, but is more common in northern portions of Europe, and has been introduced to many countries where it is an occasional crop pest (Kerney and Cameron 1979, South 1992). In Pennsylvania, it is more common in crop fields in western counties. *Arion subfuscus* is now thought to be a cryptic species complex containing at least two distinct species, *A. subfuscus s.s.* and *A. fuscus*, which can only be distinguished on the basis of genital characteristics (Pinceel et al. 2004, 2005). Both species are present in the northeastern United States (Barr et al. 2009).

Arion fasciatus (Fig. 4) is a medium-size slug as an adult (up to 5 cm), has a dark lateral band extending down each side of the body, and on the dorsal side often has a thin, dashed white line, which is faintly evident near the tail of juveniles. Like *A. subfuscus*, *A. fasciatus* appears to be introduced to the United States from western and northern Europe, but confusion between it and two other similar-looking species (*A. silvaticus* and *A. circumscriptus*) limits the reliability of historic records and distribution maps (Kerney and Cameron 1979). *Arion fasciatus* can be distinguished from these two other species by the presence of a yellowish or orangish band below each lateral body band (Chichester and Getz 1973). That being said, the species status of these three closely-related taxa remains in flux (Geenen et al. 2006). *Arion fasciatus* is often easy to find in mid-Atlantic crop fields, particularly preplanting in spring, but rarely appears to be associated with crop damage.

All slugs are hermaphrodites, but their mating systems are species-specific and can be quite complex. Genetic data suggest that *D. reticulatum* is predominantly outcrossing, usually mating with other individuals to reproduce, whereas other species of pest slug may be more prone to self-fertilization (McCracken and Selander 1980). Mating, egg-laying, hatching, and development are not well synchronized even within a single species, so slugs of various stages of development can be found at many times of year. This makes slug activity difficult to predict, but generally speaking slugs are most active and damaging April-June and then again in September and October (Godan 1983). Spring-time damage often can be caused by newly hatched *D. reticulatum*, which appears to have a more synchronized life cycle in this region than some other species. In central Pennsylvania, a large portion of the population seems to overwinter as eggs. In Ohio, both eggs and adults of *D. reticulatum* have been reported to overwinter, though it appears that the newly hatched juveniles are still responsible for most crop damage in spring (Hammond et al. 1996). In Delaware, adults and juveniles of *D. reticulatum* are both present in the spring.

Although it was unclear before 2010 whether adults or hatchlings are most responsible for crop damage in spring, recent surveys indicate that juveniles appear to cause the most damage (J. Whalen, personal communication).

Slug eggs are small, gelatinous spheres or ovals found under residue or in the soil (Fig. 5). The eggs often are found in clumps but also may occur singly. These eggs tend to hatch in Pennsylvania in early to mid-May, which is about the time when corn and soybean are in vulnerable seedling stages. *Deroceras reticulatum* juveniles, which resemble adults but are smaller, grow through the spring and summer, emerging at night and during rains and usually hiding during the day, mature in the late summer or early fall, mate, and lay eggs in the fall. It is often mature slugs of *D. reticulatum* that are responsible for damage to fall-planted small grains, forages, and cover crops. Eggs from these individuals overwinter and hatch the next spring.

Despite this general pattern, it is apparent that *D. reticulatum* eggs often can be found throughout the year, and some areas will see in early autumn a significant hatch of eggs and damage from juveniles (South 1992). It may appear that this fall hatch is the result of a second generation, and some areas of Europe see a second generation. However, it is more likely that it is a result of eggs laid during spring and early summer by individuals that survived the winter and resumed activity in spring (Hunter and Symonds 1971). The maximum life span of *D. reticulatum* is 12 mo or so and the shortest generation time would be at least 6 mo because eggs can take anywhere from 2 to 5 mo to hatch under field conditions (South 1992). Individual *D. reticulatum* can lay several hundred eggs in their lifetime (Port and Port 1986).

The life cycles of the other slug species common in mid-Atlantic crop fields also are reported to be annual (South 1992), but in mid-Atlantic states they are not synchronized with *D. reticulatum*. *Deroceras laeve* and *A. fasciatus* appear to overwinter more often as adults or juveniles rather than eggs because large individuals of these species are common in early spring (M.R.D., unpublished data). This matches the observation that *D. reticulatum* adults were fairly sensitive to winter cold in Ontario, whereas *D. laeve* was quite tolerant (Rollo and Shibata 1991). Adults of *Arion subfuscus* were reported to die in summer in central New York (Beyer and Saari 1978). Some *Arion* species have been reported to live as many as 2 yr, particularly if they are unsuccessful at finding a mate (South 1992). As with *D. reticulatum*, populations of these other species can be significantly influenced by hard winters, which can kill adults and juveniles, but thick snow packs can insulate slugs against the cold and allow more to survive the winter.

Despite a basic understanding of slug life cycles, regional variation in slug phenology is poorly documented. Improved monitoring efforts, particularly for *D. reticulatum*, could help growers and pest managers better anticipate and manage slug damage, for instance by timing crop planting in spring to avoid periods of greatest slug activity.

Host-Plant Species and Damage

Slugs can feed on a wide range of host-plant species and are well known as agricultural pests. In no- and reduced-tillage field crop production, they are considered serious pests of many crop species, including wheat, barley, oats, rye (*Secale cereal* L.); corn, soybeans, tobacco (*Nicotiana tabacum* L.); canola (*Brassica napus* L. or *Brassica rapa* L.); alfalfa (*Medico sativa* L.); and other cereals and leguminous forages (Godan 1983, Hammond and Stinner 1987, South 1992, Barratt et al. 1994, Cook et al. 1996, Hammond et al. 1999, Byers 2002). Most slug-induced crop damage occurs within a month of planting when crops are vulnerable seedlings (Byers et al. 1983, South 1992). Slugs damage crops by feeding on the seed, resulting in plant mortality before emergence and poor crop stands, and then damage seedlings as plants emerge from the ground (South 1992). Slugs feed by scraping with their radula on the surface of their food, which can include seeds, roots, stems, leaves, and flowers.

In corn and many small grains, slugs scrape strips in the leaves, leading first to window-pane damage, and then to leaf shredding (Fig. 6). In soybeans, slugs create craters in cotyledons (Fig. 7), then ragged holes in leaves, but cause plant mortality by killing the apical meristem. Similar ragged holes to those seen on soybeans are seen on slug-damaged canola, alfalfa, and other broadleaf crops (Fig. 8). There are reports of complete defoliation of some crops, including tobacco, under extreme population densities (Godan 1983). Slime trails, often associated with slug damage, can be used to confirm the presence of slugs in a field. Seedlings are especially at risk when the seed furrow or slot is left open, creating dark, cool slug "highways" leading right to the next seedling. For potatoes and some horticultural crops (e.g., grapes), slugs can even vector diseases, but this phenomenon does not appear to have been reported for field crops (South 1992).

For many crop species, the economic impact of slug feeding has been hard to quantify. For corn, plants can outgrow apparently heavy damage with little yield loss. However, a given amount of slug damage can correspond to more or less yield loss depending on weather conditions during and after slug feeding (Byers and Calvin 1994). For soybeans, damage can be quite severe if slugs reduce plant populations (Barratt et al. 1994), but so long as slugs do not kill seedlings, soybeans can withstand significant defoliation without suffering significant yield loss (Hammond 2000). In forages, slugs can kill seedlings during establishment, contributing to lowered yields in the establishment year (Byers and Templeton 1988). Through selective feeding, slugs also can decrease the amount of legumes in mixed forage stands, leading to a less desirable grass- or weed-heavy mix (Byers 2002). For cereals, slug-thinned stands often have increased tillering, mitigating yield losses (South 1992), though yield losses can be significant under high slug densities (Barratt et al. 1994).

A large body of literature has tried to clarify slug, and particularly *D. reticulatum*, feeding preferences (reviewed in South 1992). Much of this research, however, provides only limited information because

Fig. 5. Slug eggs in the soil (photo: Nick Sloff, PSU).

Fig. 6. Slug damage to corn (photo: Margaret Douglas, PSU).

Fig. 7. Juvenile gray garden slug (*Deroceras reticulatum*) on soybean (photo: Nick Sloff, PSU).

Fig. 8. Slug damage to canola (photo: Margaret Douglas, PSU.)

feeding assays often use leaf disks, detached leaves, or crushed leaves that have been incorporated into agar (e.g., Cates and Orians 1975, Dirzo 1980, Rathcke 1985, Molgaard 1986, Cook et al. 1996), with the exception of a few studies using whole plants (Kozlowski and Kozlowska 2004). Living plants are better able to mobilize defenses in response to herbivory and perhaps fend off some slug feeding, but confining slugs to live plants and quantifying the amount of damage can be challenging. Plant architecture may also be quite important to slug preferences in a field setting, as slugs tend to feed heavily on leaves near the soil surface (M.R.D., unpublished data). Nevertheless, existing preference work appears to indicate that *D. reticulatum* prefers plant species in Fabaceae, Brassicaceae, Asteracaeae, and cultivated cereals (South 1992). In some experiments, *D. reticulatum* preferred clover species (*Trifolium pretense* L., *T. repens* L.) and weedy plant species such as narrowleaf plantain (*Plantago lanceolata* L.), dandelion (*Taraxacum officinale* L.), shepherd's purse (*Capsella bursa-pastoris* L.), and lamb's quarters (*Chenopodium album* L.), suggesting that slightly weedy fields, or fields deliberately underseeded with a preferred clover species, might help limit crop damage by providing slugs alternative food sources (Cook et al. 1996, 1997; Peters et al. 2000, Brooks et al. 2003). Experiments conducted in wheat indicate that slightly weedy fields or intercropping might reduce slug damage (Cook et al. 1997, Brooks et al. 2005). Further studies are needed to see if these strategies would apply to other row crops (i.e., corn and soybeans). In pastures and old fields, slugs are strong drivers of plant community composition because they preferentially feed on seedlings of certain species (Peters et al. 2000).

Within crop plant species, oats appear less palatable than barley, which is preferred less than rye and wheat, perhaps because of host-plant chemistry (Duthoit 1964, Godan 1983, South 1992). Alfalfa and red clover are preferred over bird's-foot trefoil (Byers and Bierlein 1982). Some plant species show intraspecific variation in susceptibility to slug feeding and chemistry may also explain these patterns (South 1992, Peters et al. 2000). Certain potato varieties, for instance, are less susceptible to slugs than others, perhaps because of the higher levels of trypsin inhibitors they produce (Port and Port 1986). Similarly in oilseed rape, slug damage is inversely related to concentrations of glucosinolates in young seedlings (Glen et al. 1990). In wheat, however, 12 varieties similarly were preferred by *D. reticulatum* (Cook et al. 1996). Slugs, and *D. reticulatum* in particular, appear capable of "learning" because they can avoid unpalatable plant varieties after limited exposure (Gouyon et al. 1983).

In addition to live plants, pest slugs also have been documented to eat fungi, plant residue, and occasionally one another or other invertebrates (Pallant 1972, Fox and Landis 1973, Jennings and Barkham 1975, Beyer and Saari 1978, Lundgren et al. 2006). The *Arion* species in particular are thought to feed more heavily on fungi (Chichester and Getz 1973, Beyer and Saari 1978). Slugs also can survive on soil organic matter (Miles et al. 1931). The extent to which slugs feed on these alternative foods in field crops is unknown, but may be important in fully understanding slug population dynamics and relationships with crop plants. For instance, slug feeding activity may hasten decomposition and thereby alter soil nutrient dynamics (Theenhaus and Scheu 1996).

Scouting

Economic thresholds are not available to guide slug control decisions for most crop species. One research effort established EILs (EIL) for slug damage to corn seedlings in wet and dry years, but associated economic thresholds were not developed (Byers and Calvin 1994). The EIL for corn ranged from 2 to 20% leaf area removed in a warm, wet year, and from 39 to 59% leaf area removed in dry years, depending on the value of the crop and the cost of the control tactic (Byers and Calvin 1994). The variability in this EIL makes it difficult to implement, but reemphasizes the point made above that slug damage to crops can be difficult to quantify in part because plants have most of the growing season to recover from sublethal damage. In general, many crop species can recover from significant defoliation during early vegetative stages. Corn hybrids appear capable of withstanding at least 40% defoliation during early growth without reductions in yield (Vorst 1986). In soybeans, 50% defoliation of the first unifoliate leaflets caused only minor yield loss, whereas 50% defoliation of the first trifoliate leaflets caused no yield loss at all (Hammond 2000). More concerning are stand reductions caused by heavy slug feeding (Hammond 2000), most likely to occur in dicotyledonous crops where the growing point is prone to slug grazing.

Despite the lack of economic thresholds to help prevent economic loss, scouting for slugs is still useful because it can help identify areas with large slug populations and identify fields at risk. Farmers tend to know which of their fields historically have been troubled by slugs, but it has been our experience that slug populations in many fields catch farmers by surprise. Estimating absolute density of slugs usually requires soil sampling (South 1964, Hunter 1968), and unfortunately is labor-intensive and impractical for farmers or crop consultants.

A number of less-intensive techniques can provide insight into relative slug populations. Specialists in Ohio recommend scouting for adults in fall to identify potential problem fields and to get a relative idea of population size, which can help predict spring populations (R. Hammond, personal communication). In spring before seeding, slug eggs and overwintered slugs can be found by looking under crop residue, especially on mild days soon after rain. Another approach to find slugs is to place artificial shelters in the field, such as roofing shingles (Fig. 9), old boards, wet cardboard, or anything that will create a dark, cool, moist environment. An evaluation of artificial shelters made from various materials concluded that black roofing shingles wrapped in aluminum foil were most effective shelters for assessing populations of *D. reticulatum*, *D. laeve*, and *A. fasciatus* (Schrim and Byers 1980). Several days after putting shelters out, slugs

Fig. 9. Roofing material used as an artificial slug shelter (photo: Margaret Douglas, PSU).

can be found under the shelters during the day. Because shelters can warm up in the heat of the day, it is best to check them in the morning or evening to have maximum potential for detecting slugs (Hommay et al. 2003). Once crops have emerged, slugs can be found by inspecting crops in the evening with a flashlight. With all of these methods, it is important to look closely because juvenile slugs can be very small. Also in early spring, the absence of juvenile slugs could signal not that slug populations are low, but rather that they have not yet hatched from their eggs. Regular scouting can help identify when egg hatch is to be expected.

To more widely document slug populations, extension specialists and educators in mid-Atlantic states recently have made an effort to standardize sampling protocols. We have settled on widely available white rolled roofing (Owens Corning, Toledo, OH; color Shasta White), which are cut into 1 by 1 foot pieces by using a reciprocating saw and utility blade. The white color helps reflect sunlight, keeping them cooler than darker shingles. Shingles then are placed randomly in the field. We move residue aside and have shingles rest directly on the soil where they can better act as artificial shelters. Although shingle traps are a crude sampling technique, our ongoing research indicates that the number of slugs beneath shingles is roughly correlated with damage to corn and alfalfa seedlings in Pennsylvania, and the strength of this relationship can be improved by increasing the number of shingles and averaging the number of slugs found under shingles on multiple dates.

Overall, priority for slug scouting should be given to: 1) fields with a history of slug problems, 2) fields with abundant surface residue, and 3) fields that are low-lying, with heavy soil, or both. Significant slug populations are most likely to materialize when a mild winter is followed by a wet spring. Wet falls may also foster high slug populations the next spring, because abundant soil moisture encourages egg-laying (Willis et al. 2008). Scouts should pay closest attention to new crop growth on successive scouting periods to determine if plants are outgrowing slug damage. Finally, the weather forecast can help inform slug management decisions. If mild, wet, and cloudy weather is expected, slug damage will likely continue and crop growth will be slow, whereas warm and dry conditions are likely to favor plant recovery over slug activity.

Environmental Influences

Slugs are quite sensitive to a range of environmental and biological factors. They are most active and damaging in periods of mild and wet weather. Optimal conditions for *D. reticulatum* are between 17 and 20° C (63–68° F) and 100% RH, and activity tends to increase when air temperatures drop below 21° C (70° F; Godan 1983, South 1992). Slugs can, however, remain active during colder temperatures and slug feeding, though not much movement, can occur as low as 1° C (34° F; Mellanby 1961). Slugs also can survive several hours of freezing and recover well enough to lay eggs if returned to a preferred temperature (Godan 1983). At high temperatures (27–35° C [81–95° F]), slug activity is substantially inhibited by water loss, but slugs can deal with high temperatures and associated water loss in the following ways (Godan 1983). First, slugs, which are ≈80% water, are able to tolerate water loss as high as 50% of their mass, and they can reabsorb water directly through their skin when it becomes available. Second, some slug species have a limited ability to thermoregulate at high temperatures and maintain body temperatures that are considerably cooler than prevailing air temperatures. Third, at high temperatures slugs of the same species tend to huddle together, a tactic presumed to reduce water loss to individuals in the bunch. Finally, slugs can seek shelter from high temperatures by traveling deeper into the soil. Slugs often are found in association with orchardgrass and other bunch-forming grasses (South 1965). Given the sensitivity of slug populations to precipitation and temperature, perhaps it is not surprising that slug populations are expected to shift dramatically with global climate change. For scenarios developed for the United Kingdom, areas prone to slug damage would gain some relief under future climatic conditions, whereas areas not typically associated with slugs seem likely to develop significant slug populations (Willis et al. 2006).

In addition to reducing activity with high temperatures, slugs have an even stronger sensitivity to changes in light intensity (Godan 1983). Slugs are nocturnal and emerge to feed on aboveground plant material after dusk and then return at dawn to shelters under plant residue, rocks, and under the upper soil layers, among other sheltered locations. Rainfall can override this daytime hiding, often causing them to become active during the day (South 1992). During evening, slugs tend to have periods of greater activity. *Deroceras reticulatum* is most active 4–6 hr after dark and then again around three or 4 a.m.; *D. laeve* is most active around 6 a.m. (Godan 1983).

Slug populations and activity are also strongly influenced by soil types. Slugs are more common on heavy, wet, infrequently tilled soils, and problematic slug species, like *D. reticulatum* and *A. subfuscus*, prefer lightly alkaline or neutral soils (Godan 1983). In these heavy soils, slugs exploit holes and gaps to move within soil and can follow these passages several centimeters below the soil surface, allowing them to find shelter when necessary, but also access seeds and newly emerged seedlings (Godan 1983, South 1992). Open seed furrows are ideal habitats for slugs and allow them clear access to an abundance of seeds in a sheltered, often moist environment. Slugs can do particularly well in soils with 3% organic matter or greater, because they can feed on organic matter (Godan 1983).

Given their need for a dark, moist microclimate, it is not surprising that slugs and their damage are most common where crop residue is heaviest. Slugs gain shelter from thick residue and can severely damage crops planted into these environments, so farming practices that result in higher levels of residue are likely to increase the amount of damage inflicted by slugs (Hammond and Stinner 1987). It is worth noting that since 1990 corn yields in Pennsylvania have increased an average of 0.28 Mg ha^{-1} yr^{-1}; therefore, the amount of stover left after grain harvest also has increased considerably (Grover et al. 2009), potentially contributing to increased troubles with slugs. Management tactics that reduce soil residue have potential to decrease the amount of slug damage.

Natural Enemies and Biological Control

Slugs are preyed upon by a variety of vertebrate and invertebrate natural enemies. Vertebrate predators include frogs, toads, and some snakes (garter snakes, *Thamnophis* spp.; South 1992); however, it is unlikely that the population densities of these predators are large enough to influence slug populations in agricultural fields. Birds, including poultry, especially ducks and geese, and starlings (*Sturnus vulgaris*), can eat large numbers of slugs (South 1992, Allen 2004), but some of these species also can cause significant damage to newly sprouted field crops.

Although these vertebrate predators contribute to slug control, it appears that arthropod predators hold greater potential to suppress slug populations in crop fields. Arthropod predators of slugs include ground beetles (Carabidae), rove beetles (Staphylinidae), firefly larvae (Lampyridae), marsh flies (Sciomyzidae), harvestmen (Opiliones), wolf spiders (Lycosidae), and centipedes (Chilopoda) (Barker 2004). Certain species of carabid beetles (e.g., Figure 10) appear to be the most significant of these predators in crop fields. For instance in the United Kingdom, the carabid *Pterostichus melanarius* Illiger aggregated in areas of high slug biomass, and ELISA-based gut analysis confirmed that these beetles are significant slug predators (Symondson et al. 1996, Bohan et al. 2000). The potential for ground beetles to suppress slug populations and prevent plant damage also has been amply demonstrated in mesocosm studies (e.g., Asteraki 1993, Oberholzer et al. 2003). However, the significance of arthropod predators to slug suppression in North American crops under field conditions has been little explored. In a recent study in Kentucky strawberries (*Fragaria* × *ananassa*), two of 13 species of carabids (323 individuals screened) tested positive for presence of slug DNA in their guts in a low slug year (Eskelson et al. 2011). Further studies are needed to identify significant slug predators in North America and their possible contribution to slug management (Thomas et al. 2010).

The influence of predators on slugs is reflected in some slug behaviors. For example, slugs appear capable of detecting the presence of ground beetle species that regularly consume slugs, presumably via olfactory cues, and alter their behavior by becoming less active (Armsworth et al. 2005). Under attack, slugs produce copious quantities of defensive mucus, which can gum up the mouthparts of arthropod predators (Mair and Port 2002). Other defense behaviors include "tail-wagging", descending on a mucus thread (similar to many lepidopteran larvae, Gotwald 1972), and occasional autotomy of the tail (Pakarinen 1994).

Of potential slug parasites and pathogens, the most well-known are parasitic nematodes. Ambient levels of slug infection by nematodes are quite low in the United States, and it has even been suggested that release from nematode enemies may be one factor favoring the invasion of North America by European slugs (Ross et al. 2010). In Europe, the species *Phasmarhabditis hermaphrodita* (Rhabditidae) has been extensively studied and formulated into a biological molluscicide (Nemaslug) that is now sold in 14 countries (Rae et al. 2007). This nematode is able to infect a range of slug species including *D. reticulatum* and *D. laeve*, as well as some but not all slugs in the Arionidae (Grewal et al. 2003). Similar to many entomopathogenic nematodes, this species enters its host as an infective juvenile and is associated with bacteria that are thought to be largely responsible for its pathogenicity (Tan and Grewal 2001a,b). In addition to causing mortality, infection with this nematode rapidly inhibits slug feeding, enhancing its effectiveness in preventing crop damage (Glen et al. 2000). Because *P. hermaphrodita* is not known to occur naturally in the United States, legislation currently prevents its sale here (Rae et al. 2007). If it were available in the United States, its high price and short shelf life would likely stifle its economic use in field crops, as it has in Europe (Glen and Symondson 2003), although future improvements may overcome these challenges. Bacteria and other pathogens may be important natural enemies of slugs, but have been studied little (Raut 2004).

Fig. 10. *Chlaenius tricolor*, a slug-eating beetle (photo: Ian Grettenberger, PSU).

Management Options

Unfortunately, management options for slugs are limited. Moreover, recognized tactics occasionally are ineffective; therefore, an integrated management approach that relies on several control tactics is preferred. Most growers who experience slug problems are committed to no-till or reduced-till practices, so although tillage certainly will help control slugs, it may not be an option. Nevertheless, it is clear that tactics that reduce the amount of surface residue will decrease slug populations. For example, shallow disking (three inches deep) in spring can significantly decrease slug populations (J.F.T. and S. Duiker, unpublished data). It is possible that vertical tillage also can provide some relief from slug populations, but we are not aware of empirical work addressing this issue. In addition to providing good habitat for slugs, no-till fields also can harbor improved natural enemy populations when compared with tilled fields (Witmer et al. 2003); therefore, although no-till fields are prone to slug damage, their stability holds potential to maximize the contribution of predators to improve slug control. These invertebrate predators can be conserved by increasing crop diversity and by using insecticides sparingly (e.g., banding insecticides directly over the row rather than broadcasting it over the entire field) in accordance with integrated pest management (IPM) principles (i.e., use insecticides only when justified economically). Indeed, slug populations have been found to surge after an insecticide application in no-till alfalfa, perhaps because of negative impacts on natural enemies (Grant et al. 1982).

Because older crop plants are not as susceptible to slug feeding as young plants, several management tactics aim to foster early plant growth to get crops growing as quickly as possible to try to "outrun" the slug threat. Early planting may give crops a jump on slugs if crops emerge and have significant growth before eggs hatch in large numbers. For instance, early planting in spring can reduce slug damage to new forage stands in Pennsylvania (Byers and Templeton 1988). In contrast to planting early, some growers have tried planting later, after soils are dried and warmed. This approach is meant to encourage quicker germination and growth by the crop during the time when slugs are already active. The choice of early or late planting likely will vary by region, depending on the timing of slug egg hatch relative to crop planting dates. Also, using row cleaners on the front of planters to move crop residue away from the row allows sunlight more access to the soil, increasing soil temperatures and improving crop emergence. However, it has been observed in Ohio that corn fields planted with row cleaners can still have significant slug injury, particularly when slug populations are large because individuals only have to travel a short distance ($<$15 inches) from the residue to reach crop plants (R. Hammond, personal communication). Growers further can contribute to better early growth by selecting crop varieties that are rated "excellent" for emergence and seedling vigor. Good agronomic practices such as ensuring seed slots are closed can mitigate some slug damage. The choice of crop rotation (Hammond and Stinner 1987) and cover crop (Vernava et al. 2004) also may influence slug populations and subsequent damage; however, more research is needed in these areas.

Few chemical controls are available for slugs. Many insecticides, like chlorinated hydrocarbons or organophosphates, do not appear to be toxic to slugs, show inconsistent molluscicidal activity, or require a very large dose to have any influence (Henderson and Triebskorn 2002). Carbamate insecticides, however, can have activity against slugs, and some compounds appear to provide control of slug populations in some settings. Methiocarb has been formulated as a bait, and is used for slug control under the tradename Mesurol in nonfood crop settings such as ornamental production in nurseries and greenhouses (South 1992, Henderson and Triebskorn 2002). Methiocarb was the primary slug control material in the United States in the 1980s, and is still widely used in Europe, but is no longer labeled for field crop use here (R. Hammond, personal communication). Thiodicarb (tradename: Larvin) was also briefly labeled for use in soybeans (R. Hammond, personal communication). Carbaryl (tradename: Sevin) has been effective when formulated as a bait, but is ineffective when applied as a spray (South 1992), and does not appear to be labeled for use on slugs in row crops. Another carbamate, methomyl (tradename: Lannate LV), currently is being explored as a slug control option. In 2010, DuPont (Wilmington, DE) issued in Delaware, Maryland, Pennsylvania, Virginia, and West Virginia a "2(ee) Recommendation" under the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA) for its use in corn and soybeans against slugs, but little efficacy work has been completed thus far. Research conducted in Virginia in 2011 should provide more information (J. Whalen, personal communication). Methomyl is known to be toxic to a range of invertebrates and also can alter the behavior of some soil dwelling invertebrates, including earthworms (Pereira et al. 2009). Neonicotinoid seed treatments, although apparently not lethal to slugs, have shown mixed effects on slug feeding behavior. In the United Kingdom, a clothianidin-based seed treatment (Deter) is registered in cereals to protect seeds from hollowing by slugs and thereby improve stand establishment. Nonetheless, once seedlings have emerged, neonicotinoids do not appear to reduce slug feeding on leaves (Rose and Oades 2001) and may in some cases even increase slug feeding (Simms et al. 2006).

Despite the molluscicidal activity of some insecticides, the primary active ingredient used against slugs is metaldehyde, which is typically formulated into baits (e.g., Deadline products). Metaldehyde was first developed as a fuel for camp stoves, and in ≈1934 its molluscicidal activity accidentally was discovered in South Africa (Henderson and Triebskorn 2002). Metaldehyde-based baits quickly were adopted as slug control products because of their selectivity and they still dominate the market (Bailey 2002). There is little doubt that metaldehyde-based baits are effective in controlling slug populations, but a major concern is that most of the baits are somewhat water soluble and rain can diminish their efficacy (Bailey 2002). Additional efficacy issues can arise from crop plants being more attractive than the baits and because individual slugs can stop eating before they receive a lethal dose of metaldehyde (Bailey 2002). Some growers have considered applying baits at planting, but because planting date can coincide fairly closely with slug egg hatch in spring, it is important to ensure that juveniles are present before baits are applied or the baits will lose their effectiveness before the eggs hatch (Hammond et al. 1996). Metaldehyde also is toxic to vertebrates, but recent formulations of metaldehyde-based baits have incorporated mammalian repellents and smaller pellet size, making them less risky to mammals (Bailey 2002). Nevertheless, reports of metaldehyde poisoning (e.g., to dogs) appear to be common in areas where metaldehyde is used regularly (Bailey 2002), although it seems that most cases of poisoning involve animals getting into bags or finding spills on the ground rather than when the product is used according to directions (i.e., broadcast in fields; R. Hammond, personal communication).

The focused nature of metaldehyde-based baits may be a benefit to integrated slug management because it allows natural enemies (and other beneficial species like earthworms) to persist in agroecosystems when chemical intervention is necessary (Büchs et al. 1989). Although methiocarb and other insecticides can negatively influence populations of some natural enemy species, including carabids and staphylinids (and earthworms) (Bailey 2002), metaldehyde baits have not been reported to cause similar mortality. Pellets based on iron phosphate (e.g., Sluggo products) also are available and are approved by the Organic Materials Review Institute (OMRI) for use in organic systems. These products also are expensive, so use on the large scale typical of field crops may be too costly to be practical. At present, slugs are rarely a problem in organic field crop production because continuous no-till is unusual in these cropping systems, and tillage is likely to prevent significant slug problems in this region.

Because slug control can be frustrating, some growers have experimented with home remedies. Chief among these is spraying crops at night when slugs are actively feeding with nitrogen solutions, which act as a contact poison and burn slugs. A common approach is to use a 30% urea-based nitrogen solution, mix it with an equal amount of water, and apply 20 gallons per acre. This tactic is typically repeated a few nights in a row to reach as many slugs as possible and to maximize its effectiveness, and despite potential for burning crop leaves with the high concentration of nitrogen, growers that use this approach believe that the benefits from decreased slug populations outweigh the cost of temporary foliar damage. It should be noted however that there is a wide range of opinion on the efficacy of nitrogen sprays; some growers rely on them whereas others do not believe they are useful (R. H., personal communication). One factor that can undermine this technique is windy conditions that cause slugs to seek shelter out of the reach of nitrogen sprays. Growers using this technique should spray on calm, mild nights when slugs are most likely to be feeding on crop foliage.

Other growers will try to control slugs by putting dry ammonium sulfate over their crop rows, generating a salty band that may exclude slugs. Keep in mind that any use of nitrogen or ammonium sulfate needs to comply with a farm's nutrient management plan. Some farmers with slug problems will choose to use salt-based formulations of herbicides rather than other options with the hope that they might kill or repel slugs. We are not aware of any work evaluating this approach.

It appears safe to say that there is not a "silver bullet" for slug problems in no-till crop fields. Many of the tactics discussed above provide some relief under certain circumstances. This inconsistency is problematic; in fact, it is one of the most frustrating features of slug management communicated to us by growers. But inconsistencies can be decreased by employing, in the tradition of IPM, many tactics in concert. For example, we always recommend scouting for slugs to determine where they are problematic. This seems obvious, but our experience is that people infrequently scout for slugs until damage occurs. Even if slugs annually plague certain fields, scout these fields, possibly in fall, but definitely in spring to determine the size of the populations present. Consider the amount of residue the field will have at the time of planting. In fields with a lot of residue, reducing the amount of residue may be prudent if it fits within a grower's management philosophy. If residue is abundant and slug populations are present, take steps at planting to ensure the crop has the best chance to get up out of the ground quickly.

For instance in corn, consider using row cleaners to move debris away from the row. Also, use hybrids rated excellent for emergence and early season vigor, and even a pop-up fertilizer to maximize early season plant growth. Spiked closing wheels may provide some help by ensuring a well-closed seed furrow and good seed-to-soil contact. If in the past these tactics have not seemed to help much, consider adding another tactic, like banding ammonium sulfate over the crop row. If slug populations develop and damage threatens plant survival and stand establishment, be ready to protect your crop with molluscicides. But rather than treating entire fields, consider using metaldehyde-based baits or nitrogren sprays in just the effected areas. No matter the approach, keep records of the growing conditions and what worked. Good records will help refine the most effective approaches to manage slug populations in no-till fields.

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