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Gary W. Witmer
USDA-APHIS-Wildlife Services, gary.w.witmer@aphis.usda.gov

Nathan P. Snow
USDA-APHIS-Wildlife Services, nathan.p.snow@aphis.usda.gov

L. Humberg
USDA-APHIS-Wildlife Services

T. Salmon
University of California Cooperative Extension-San Diego

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GARY W. WITMER, *USDA, APHIS, Wildlife Services, National Wildlife Research Center, Fort Collins, CO, USA*
NATHAN P. SNOW, *USDA, APHIS, Wildlife Services, National Wildlife Research Center, Fort Collins, CO, USA*
L. HUMBERG, *USDA, APHIS, Wildlife Services, Brooklyn, NY, USA*
T. SALMON, *University of California Cooperative Extension-San Diego, San Diego, CA, USA*

ABSTRACT Voles (*Microtus* spp.) are ubiquitous to the northern hemisphere. Numerous species occur in North America and several species cause significant damage of various types: food crops, livestock forage production (e.g., alfalfa), nursery trees, reforestation, orchards, rangeland forage, and damage to lawns, golf courses and ground cover. Much research has been conducted with voles and a number of management options have been developed, including habitat manipulation, rodenticides, traps, repellents, barriers, supplemental feeding, and increased natural predation. However, significant damage still occurs because voles are not easily managed. Voles are small and secretive, prolific, active year-round, able to exploit refugia, and cyclic with periodic irruptions. Currently there are no permanent solutions to managing voles, so long-term monitoring and management of populations is required. We review what is known about voles, the types and extent of damage they cause, advantages and disadvantages of management methods, and some research needs. Research needs include the development of effective repellents, effective rodenticide baiting strategies that minimize nontarget hazards, and cost-effective methods to protect the root systems of woody plants.

KEY WORDS *Microtus*, meadow mice, rodent management, vole, wildlife damage

There has long been controversy regarding the members and taxonomy of the microtine rodents (Carleton and Musser 1984). The group has been classified as being within the family *Cricetidae* (Wilson and Reeder 2005) while others place it within the family *Muridae* (Nowak 1991). When classified within *Cricetidae*, the group has been placed within the subfamily *Arvicolinae* which contains approximately 27 genera, including voles, lemmings, and muskrats (Wilson and Reeder 2005). Species of this group are circumboreal around the northern hemisphere and many are serious pests (Prakash 1988, Witmer et al. 1995). In North America, many of the pest species belong to the genus *Microtus*, commonly called voles or meadow mice. About 7 of the 23 species of *Microtus* cause damage in various parts of North America. In this paper, we review the literature and provide background information on voles and the damage they cause. We also discuss management strategies that can help reduce agricultural damage by voles and new directions for future research.

Ecology of Voles

The biology, ecology, characteristics, and distribution of voles have been summarized by Pugh et al. (2003), O'Brien (1994), and Tamarin (1985). Voles are small, secretive rodents. They have small eyes and ears, short tails, and dark fur. Most species of *Microtus* are $\leq$20 cm in total length and weigh $\leq$75 g. Most species of voles live in colonies. They occupy a variety of habitats, but are mostly associated with grasslands. Voles are semi-fossorial with elaborate burrow systems. Pugh et al. (2003) noted that vole nests are usually only about 12 cm below the surface. The burrows provide shelter from inclement weather and predators, a place to raise young, and a place to store food stuffs. The openings to the burrows are about 4 cm in diameter and are connected by a series of surface runways that are about 2.5–5 cm wide. Careful examination of the runways will often reveal clipped plants and fecal droppings.

Voles are active year-round and have many foraging bouts throughout the 24 hour day. They feed on a variety of plant materials and their feeding preferences shift through the seasons. Succulent grasses and forbs are used when first available in the spring and throughout the summer. From late summer through the fall, seeds are heavily used. During the winter, voles primarily feed on woody species as herbaceous foods are not readily available. Roots and tuberous materials are fed on throughout the year.

Voles have a high reproductive potential. They reach sexual maturity in a few months and females can have 5 or more litters per year with 3–6 (maximum 11) young per litter. Voles are known to reproduce during the winter under snow cover, especially if green foods are available (Negus et al. 1977, Jannett 1984, Johnson 1987). Dispersal by young animals into surrounding areas, including crop fields, often occurs at this time. Overwinter survival depends greatly upon weather severity and food availability.

Vole densities can dramatically vary throughout the year. Also, voles are known to undergo multi-year cycles throughout the northern hemisphere (Stenseth 1999). Cycles of peak densities occur every 3–5 years, but despite intensive research efforts, ecologists are conflicted about what causes them (Krebs 1996, Ylonen et al. 2003). Researchers have suggested the cycles are related to: resource limitation (Ford and Pitelka 1984, Hornfeldt et al. 1986), predation pressures (Korpimaki et al. 1991, Korpimaki and Norrdahl 1998), vegetation cover (Birney et al. 1976), density-dependent season length (Smith at al. 2006), breeding performance (Mihok and Boonstra 1992), defense mechanisms from food plants (Massey et al. 2008), disease outbreaks (Wolff and Edge 2003), and body condition of individuals in a population (Agrell et al. 1992); but not related to stress hormone levels (Boonstra and Boag 1992). Lambin et al. (2006) explained that the reasons for cycles likely differ by geographic region, and multiple reasons should be considered.

Johnson and Johnson (1982) described how the irruptions of vole populations in western USA resulted in damage of agricultural crops, orchards, and rangeland and forest resources. Normally, across a variety of habitats, densities of voles at about 10–100 per ha are common (O'Brien 1994). Densities during these irruptions often reach several thousand animals per ha (Johnson and Johnson 1982, O'Brien 1994). Low densities are common in the winter and spring and then increase substantially through summer and fall due to annual reproduction and recruitment. The annual mortality rates of voles are quite high with 70+% dying within a year of birth (O'Brien 1994). A large variety of mammalian and avian predators prey upon voles and vole survival rates are lowest where abundant, dense cover was not available (Pugh et al. 2003).

Studying Voles

Numerous methodologies have been implemented for studying voles. Radio-transmitters have been widely used to estimate movement patterns and home ranges of voles (Herman 1977, Webster and Brooks 1981, Hansteen et al. 1997, Russell et al. 2007). However, transmitter-carrying voles have shown reduced activity and lower survival from predation (Hamley and Falls 1975, Webster and Brooks 1980), therefore, this may not be the most effective study technique. Thus, researchers have employed other techniques, like tracking voles marked with radioactive material, with success (Godfrey 1954, Miller 1957, Ambrose 1973). Live-trapping with mark-recapture techniques (Getz et al. 2005, Wiewel et al. 2007), live-trapping with timer mechanisms (Drabek 1994), and pitfall-trapping (Boonstra and Krebs 1978) have also been used to access various biological aspects of voles.

Benefits from Voles

We found very few reports of benefits to humans from voles. However, Frischknecht and Baker (1972) reported that voles can be used as a biological control to reduce sagebrush in order to increase grazing productivity in rangelands. Also, voles are an important prey species to numerous species of wildlife, especially raptors (Baker and Brooks 1981). Similarly, the importance of cyclic rodent species, such as voles, have been described by Goszczynski (1977) and Andersson and Erlinge (1977).

DAMAGE

Most reported vole damage centers on agriculture and forestry (O'Brien 1994, Pugh et al. 2003). Voles also cause structural damage (i.e., such as undermining of dikes, levees, and irrigation ditches by burrowing; or gnawing on cables and plastic tubing) and aesthetic damage (i.e., such as destroying lawns, golf courses, and vegetative ground covers). Although voles are susceptible to a number of diseases, they rarely pose a health threat to people, pets, or livestock (Pugh et al. 2003). The cyclic nature of vole populations can impact agricultural fields drastically and quickly. However, reducing the damage sustained by agriculture could be a circular predicament, because Janova et al. (2008) found evidence that the cycles of voles could, in part, be driven by the practices of agricultural production in the Czech Republic.

Types of Damage

In the course of their winter foraging activity, voles can cause substantial damage to berry bushes, orchards, woody ornamentals, Christmas tree plantations, and reforestation efforts (Askham 1992). The bark and vascular tissues of trees in fruit orchards across North America sustain significant damage from voles (Askham 1990, Sullivan et al. 2000). Damage to woody species may not be readily noticed because the roots are gnawed over time and stem girdling often occurs under snow cover.

Voles are often implicated in damage to certain field crops such as alfalfa, grains, soybeans, and sprouting corn. Several researchers have described the substantial loss in corn yield and other crops that can occur when vole and other rodent populations are large (Clark 1984; Hines 1993, 1997; Hygnstrom et al. 1996, 2000; Hines and Hygnstrom 2000). Clark (1984), Johnson and Johnson (1982), and O'Brien (1994) describe the nature of vole damage and give examples of substantial economic losses to apple and alfalfa production. Voles and other rodents can dig up seeds, although damage often involves foraging on the newly-emergent seedlings several weeks after planting (Hines and Hygnstrom 2000). In some cases, these rodents cause significant damage to root vegetables (e.g., carrots, sugar beets, and potatoes) especially in small gardens that border good vole habitat. During peak density years, voles may deplete forage intended for livestock on pastures and rangeland.

Much of the damage in no-till crops in the Midwestern and Pacific Northwestern portions of the United States occurs to sprouting plants in the late winter or spring (Clark and Young 1986, Johnson 1986, Witmer et al. 2007). Based on estimates of vole food requirements and densities, Grodzinski et al. (1977) surmised that voles had little impact on winter wheat production during low population years and that only 2–3% of the crop was destroyed in periods of high density. Conversely, Witmer et al. (2007) found damage levels of up to 9% in winter pea fields during a low vole density period with damage appearing to occur mostly during winter under snow cover. Johnson (1987) suggested that high levels of damage can occur by voles in no-till fields during high population densities.

High vole densities can attract raptors to airports resulting in an increase in bird-aircraft strike hazards (Witmer and Fantinato 2003). When vole populations are controlled at airports, raptor use of the area and the number of bird strikes both decline (Robert Johnson, Kansas City International Airport, unpublished data).

Economics of Damage

The physical impacts from voles in agriculture and forestry industries can have high economic costs (Askham 1992, O'Brien 1994, Pugh et al. 2003). For example, the cyclic fluctuations of the levant vole (*M. guentheri*) in middle-eastern countries resulted in more that 50% decline in yield of cereal and fodder crops, and up to a 16–25% lose of alfalfa yield (Wolf 1977). Also, in Washington State (USA), Askham (1988) reported a production decrease in a large apple orchard of 36% during a 2-year period of an extremely high population of montane voles (*M. montanus*). Therefore, controlling for voles is often implemented, but can have high costs to reach desired levels of damage reduction (Byers 1984).

MANAGEMENT

Voles and their damage pose many management challenges. Reviews of management and control have been conducted by Byers (1985) for orchards, Askham (1992) for silviculture, and Pelz (2003) and Witmer and VerCauteren (2001) for agriculture fields. The traditional approaches to vole population and damage management have relied on direct reduction of the vole population using rodenticide baits or rodent traps, and the reduction of habitat carrying capacity for voles by habitat manipulation (Johnson and Johnson 1982, Clark 1984, O'Brien 1994). Today, many approaches focus on management efforts that are environmentally benign (Singleton et al. 1999, Pelz 2003). These techniques have had varying degrees of success. Importantly, managers must consider the location, species, and type of damage before choosing an effective management strategy. Each method has advantages and disadvantages, and generally using an integrated pest management (IPM) approach will involve several methods woven into an effective damage reduction strategy (Table 1; Witmer 2007). Most cooperative extension county offices or state agricultural universities have booklets available on rodent control specific to particular species and areas.

Monitoring

The importance of pest population monitoring or "scouting" as a component of IPM has received considerable attention in recent years (Matthews 1996). This certainly applies to vole populations because of their high reproductive potential and because once high densities (≥200/ha) are achieved, substantial damage is generally inevitable. A variety of methods have been developed for monitoring vole populations: use of live- or snap-traps along grids, use of apple slices or other food removal methods, and the counting of active colonies per acre (Tobin et al. 1992; Tobin and Richmond 1993; Hines 1993, 1997; Clark 1994; Hines and Hygnstrom 2000; Witmer and VerCauteren

Table 1. Methods to reduce damage by voles.

Population Management	Habitat Management	Other Approaches
Rodenticide baits	Eliminate vegetative cover	Physical barriers
Fumigants	Manage or remove refugia	Repellents
Traps	Disrupt burrows	Frightening devices
Encourage predation	Plant unpalatable vegetation	Supplemental feeding
	Endophytic grasses	Fertility control
	Crop/tree species/variety selection	

2001). Vole populations should be monitored in late winter or early spring, after snow-melt, and again just prior to planting. Managers and landowners should look for fresh trails in the grass, burrow openings, droppings, and evidence of feeding. They should pay particular attention to adjacent fallow areas that have heavy vegetation because voles can build up in these areas and quickly invade agricultural fields. Some general guidelines indicate that vole population or damage management activities may be required if trap success is ≥10% or if ≥12 active colonies per ha are observed (Witmer and VerCauteren 2001).

Habitat Management

Habitat manipulation has long been used as a way to lower the carrying capacity for voles. Voles need tall, protective vegetative cover and researchers have noted the importance of grassy areas to voles and other rodents (Randall and Johnson 1979, Witmer et al. 2007). Several researchers have also noted the importance of grassy borders as refugia for rodents and the need to manage the refugia to help reduce the influx of rodents into crop fields during growing seasons (Clark 1984, Edge et al. 1995, Martinelli and Neal 1995, Chambers et al. 1996, Witmer et al. 2007). Perhaps the most important approach for preventing rodent damage to crop fields is lowering the carrying capacity for rodents in agricultural fields and refugia surrounding fields. The refugia provide harborage for rodents when crop fields are inadequate to support many rodents and also sustain voles during lows in their population cycles. Management actions can include mowing, burning, grazing, plowing, herbicide application, and the use of rodenticides (Witmer and VerCauteren 2001, Brown et al. 2004). Also, normal farming practices can reduce vole populations in fields, such as mowing, mulching, harvesting and plowing. However, plowing was the only effective farming strategy found for reducing common voles in Germany (Jacob 2003). But, also in Germany, Jacob and Hempel (2003) found that reducing vegetation height quickly reduced the home range size of voles by 42%, and likely increased the amount of predation risk for voles. Mowing should be combined with removal of plant residues and those residues can provide good cover and travel corridors for voles (Witmer and Fantinato 2003, Witmer et al. 2007). Combining habitat management with another form of management (e.g., see section on Biological Control) may also be an effective strategy for maintaining low numbers of voles. Various methods of habitat management are especially useful in no-till agriculture fields, because without tilling, intact burrow systems and crop residues are maintained, and surrounding areas provide suitable habitat for rodents (Witmer et al. 2007). Therefore, the potential exists for substantial increases in rodent populations with subsequent crop damage (Johnson 1987, Bourne 1999).

Crop selection is another consideration for agricultural producers that may be experiencing vole damage, because some crop species or varieties may be less susceptible to damage by voles and other rodents (Witmer et al. 1995, Witmer and Fantinato 2003). This is also true for reforestation situations where types of tree species are important. Additionally, planting large seedlings can help assure the trees achieve large size quickly, becoming less prone to vole and other rodent damage (Askham 1992).

Endophytic grasses offer a potential method to reduce vole populations. The fungi in endophytic grasses produce alkaloids that are known to reduce herbivory. Endophytic fescue and perennial rye grasses may reduce rodent carrying capacity, but further investigation is needed (Fortier et al. 2000). Witmer (2004) found a lower abundance of small mammals on endophytic grass fields than non-endophytic. Endophytic grass fields could be maintained around agricultural fields or at sites such as airports. One of the difficulties with this approach, however, is that a near monoculture of the endophytic grass species must be maintained at the site. Other species of unpalatable plants may offer a similar approach to lowering the rodent carrying capacity of a site. For example, meadowfoam (*Limnanthes macounii*) is a native herbaceous plant of the Pacific Northwest that seems to be unpalatable to many rodents (Gary Witmer, USDA, APHIS, Wildlife Services, unpublished observation).

However, managers should consider that unmanaged habitats tend to support the highest densities of small mammals which, in turn, support various predator species that depend on small mammals (Aschwanden et al. 2007). Therefore, any manipulation of refugia habitats to reduce vole populations should be restricted to the most crucial areas where significant damage is occurring or expected to occur. Some areas should be left unmanaged to help support biodiversity. Also, reducing vole populations and damage can be problematic on some conservation lands where severe habitat management is not an option (Lee Humberg, personal observation). In high public visibility areas, there may be socio-political pressures to not use certain methods such as rodenticides, snap-traps, or management methods that lessen the aesthetics of the landscape.

Supplemental Feeding

Voles have been found to switch their feeding from agricultural crops and orchards to suitable alternative foods; given the alternative foods are more palatable (Sullivan and Sullivan 1988). Broadcast whole or cracked corn, or soybeans have been used as a supplemental food source to reduce damage by voles, especially in no-till corn and soybean fields, (Hines and Hygnstrom 2000, Hygnstrom et al. 2000). These can be applied at a rate of about 125. 5 kg per ha at the time of planting or several weeks post-planting, depending on when serious damage is anticipated. It also appeared that rodent damage to seedlings in reforestation efforts can be reduced by using sunflower seeds (Sullivan and Sullivan 1982) or alfalfa pellets (Sullivan et al. 2001) during the winter when most woody plant damage occurs. However, these efforts have not always been particularly effective on some sites (Sullivan and Sullivan 1988, Sullivan et al. 2001).

An issue of using supplemental feeding to reduce damage by rodents is that the addition of nutritious food may increase the survival and reproduction rate of the rodents. Desy and Thompson (1983) demonstrated this effect in a field study in Illinois. However, the addition of supplemental food did not prevent the population crash of this cyclic vole population a year later.

Exclusion and Barriers

Excluding voles from large areas is often difficult and rarely practical. However, wire-mesh barriers placed both above- and below-ground for gardens and around individual trees have been useful in certain situations (O'Brien 1994). It is important that individual barriers around trees do not damage the tree bark or its root system or cause any growth problems or deformities. This approach to protecting individual plants or clumps of plants is more effective and economical than fencing entire gardens or fields (Marsh et al. 1990), and is especially effective for reducing damage to seedlings (Zimmerling and Zimmerling 1998). Barriers made of metal, plastic, and wire mesh that were approximately 25 cm high were effective in reducing damage in a pen trial, and even more effective in combination with a repellent (Witmer et al. 2001). Pelz (2003) suggested that some barriers stop movements of voles, especially when placed in combination with poison bait stations. However in a field trial, Witmer et al. (2007) found that 25-cm-tall metal barriers extending above and below ground were not effective at excluding voles from areas of no-till agriculture areas. Rodents can burrow under barriers or get over them by climbing the tall crop plants as they grow higher than the barriers. It is also difficult and costly to maintain barriers in agricultural fields because of all the activity with large farming equipment and vehicles.

Broadleaved trees guarded with rigid plastic tubes that were at least 25 cm tall and pushed into the ground did not sustain damage from voles, whereas shorter guards contained some damaged trees (Davies and Pepper 1989). Davies and Pepper (1989) also found that using chemical weed control in a 1 meter diameter swath as a barrier around a tree reduced the incidence and severity of damage. Other types of barriers such as a circle of pea gravel around seedlings to discourage burrowing to the root system are being investigated (Gary Witmer, USDA, APHIS, Wildlife Services, personal communication). This is particularly important because much damage to seedlings and orchard trees occurs from voles burrowing to the root system and damaging it. Normally, once signs of the damage are noticed by growers, the trees have already received substantial damage.

Biological Control

Voles have many predators, many of which are birds of prey (Pugh et al. 2003). Also, weasels (*Mustela* spp.) and other mammalian predators are known to prey heavily on voles. Modifying sensitive areas (e.g., agricultural fields, pastures, and orchards) to support higher numbers of predators has had varying success for reducing vole populations (Sullivan and Druscilla 1980, Askham 1990, Pelz 2003). To increase raptor use of the areas, nest boxes and artificial perches can be added; whereas, to increase use of the area by mammalian predators, hay bails or other types of protective cover can be added (Witmer et al. 2008).

Research is underway in the area of wildlife fertility control (e.g., Miller et al. 1998), but it will probably be years before a registered commercial product is available for any species of rodent. Early studies with voles looked at the compounds diethylstilbestrol (German 1985) and indomethacin (Seeley and Reynolds 1989) with promising results. Fertility control in rodent species that are continuous breeders poses technical difficulties, cost-effectiveness issues, and nontarget issues (Tyndale-Biscoe and Hinds 2007, McLeod et al. 2007). There has been some preliminary investigation of the ability of altered light cycles to influence vole reproduction (Haim et al. 2004). This study in Israel found that flashes of light throughout the night reduced reproduction in voles and affected their thermoregulatory system. They suggested that this method may help regulate population size and help avoid vole population irruptions.

Managers and crop growers often raise the question of using a species-specific disease to control rodent populations in their fields. Technical difficulties, public concerns, and legal-regulatory issues suggest that this will not be an option in the near future in the USA (Witmer 2007).

Repellents

Some chemical repellents are registered for vole damage control, but these are only partially effective and not practical over large areas. EPA-registered vole repellents contain the active ingredient capsaicin or thiram (O'Brien 1994). Additionally, the use of repellents on food crops is usually restricted or not allowed. Some researchers have suggested, however, that predator odors (e.g., from urines, feces, or anal glands) may help exclude rodents from areas, although success rates are dependent upon cover availability and other factors (Sullivan et al. 1988, Merkens et al. 1991). Some electronic and magnetic devices have appeared on the commercial market, but these have not been found effective in eliminating rodents from fields or buildings (Timm 2003). Witmer et al. (2001) showed that various repellents did reduce vole breaches of barriers and food consumption, including blood meal, capsaicin, castor oil, coyote urine, quebracho, and thiram. However, high concentrations of the repellents were needed. Salatti et al. (1995) showed that the herbicide Casoron also was a potential repellent. Voles in Central Asia were mainly attracted to food via the odor of the plants (Fan et al. 1992), thus an effective odorous repellent could significantly reduce feeding.

Trapping

Snap-traps can be used to reduce vole populations, but are labor-intensive and also not very practical over large acreages. They are used mostly for population monitoring and for research purposes. However, they can be used where the use of rodenticides are not desirable or allowed, such as in backyards or garden areas. Traps should be placed throughout the area of active vole colonies with a trap spacing of about 3–10 m between traps. Peanut butter, oatmeal, or apple slices make excellent baits for many species of voles. Often, no bait is needed because voles will trigger the trap as they pass over it while running along their runway. Snap-traps should be placed at right angles to in these runways and flush with the ground.

Rodenticides

When voles are numerous or when damage occurs over large areas, it may be necessary to use a rodent toxicant to reduce the population and therefore, the damage levels. When using toxic baits, it is essential to assure the safety of children, pets, and non-target animals. This is mainly done by carefully following the EPA label instructions. The options for rodenticide use on agricultural lands are somewhat limited, especially during crop production cycles. This is to reduce the likelihood of pesticide residues in foods. Rodenticide use is less restricted for rangelands, orchards, along fencerows, on right-of-ways, and in and around buildings. A variety of rodenticides are available (EPA-registered for use in the U.S.) for vole population control:

- Acute rodenticides
    - Zinc Phosphide (2% a.i.)

- Anticoagulant rodenticides (1st Generation only)
    - o Diphacinone (0. 005% a.i.)
    - o Chlorophacinone (0. 005% a.i.)
    - o Warfarin (0. 025% a.i.)
- Fumigants
    - o Aluminum Phosphide (56% a.i.)

Detailed information on rodenticides and their use in the USA was provided by Jacobs (1994), Timm (1994), and Witmer and Eisemann (2007). Zinc phosphide is an acute toxicant, meaning that the animal generally consumes a lethal dose in one feeding and dies relatively soon thereafter. On the other hand, the anticoagulants are often called multiple-feeding or slow-acting toxicants because the animal feeds on the bait for several days, eventually accumulating a lethal dose and dying from internal hemorrhaging as its blood clotting ability declines. The anticoagulants are subdivided into two groups: the first-generation compounds (e.g., warfarin, chlorophacinone, diphacinone) are less toxic and have less persistent residues in tissues than the more recently developed second-generation compounds (e.g., brodifacoum, bromadiolone, difethialone). The second-generation anticoagulants were developed because of the increased incidence of genetic resistance to the first-generation compounds (Buckle et al. 1994). Of the anticoagulants, only first-generation compounds are EPA-registered for use to control vole populations in the U.S. Salmon and Lawrence (2006a) recently reported resistance to first-generation anticoagulants in voles in California artichoke fields. Hence, it may be important to investigate alternative rodenticides for vole control in this crop type (Salmon and Lawrence 2006b). Other rodenticides such as cholecalciferol (Moran 2003) and brodifacoum (Kaukeinen 1984) could be investigated for registration for vole control.

Zinc phosphide can be applied in a variety of formulations: coated grain and pelleted products are available. In recent years, zinc phosphide pellets, when applied at 4.5–6.75 kg per ha, have proven effective in reducing rodent populations in no-till corn when applied in-furrow before planting or at planting time. Some EPA registrations for zinc phosphide use in corn, milo, and soybeans have been obtained (Hygnstrom et al. 2000). It should be noted, however, that zinc phosphide is known to sometimes cause “bait-shyness” in rodents. Consequently, bait efficacy can be improved by pre-baiting with a formulation that is very similar to the toxic bait, but does not contain the toxicant (Sterner 1999). Alternatively, one can switch to a different toxicant if efficacy is too low or decreases over time.

The anticoagulants occur as pellets or blocks. The blocks are generally intended to be used in bait stations. Rodenticides intended for voles can be applied in a variety of ways: broadcast by hand or seed spreader, placed by hand in runways and burrow openings, or placed in bait stations. As a side note, some researchers have shown ground sprays of anticoagulant solutions to be effective in controlling vole populations (Byers 1975). Generally, baits can be applied at various times of the year, but it is good to monitor populations and apply the baits before the population becomes sizable and significant damage begins to occur. Often, baits are applied in the late winter or early spring when the vole population is at its lowest level, natural foods are scarce, and high levels of reproduction have not yet begun. Ecologically-based baiting strategies have been developed and are thoroughly discussed by Ramsey and Wilson (2000), who have studied Australian rodent irruptions which have become a serious problem in grain and other crops.

While broadcast-baiting can effectively and quickly reduce rodent numbers (Witmer and Fantinato 2003), the effect does not last very long and rodent populations can recover within a year or two. Johnson (1987) noted that zinc phosphide treatment resulted in only a brief population decline in voles in the Pacific Northwest. In studies in the midwestern U.S., Hygnstrom et al. (2000) noted that in-furrow drilling of zinc phosphide pellets reduced vole damage by 7–34%.

It is also important to treat the fallow lands (i.e., refugia) around croplands because many of these areas have dense vegetation and support vole and other rodent populations. Croplands do not support abundant rodent populations during portions of the year (after harvest or during winter), but the rodent populations subsist in the bordering habitats and “invade” the cropland each year when the crops begin to grow, providing food and protective cover. Dispersing young animals are especially likely to invade, hence, strategies to keep rodent densities low in refugia can help reduce crop damage.

Fumigants can be used for control of rodent populations in situations where well-developed burrow systems occur. With many vole species, unfortunately, the burrows are complex, shallow, and often have numerous openings. This situation allows the fumigant gas to escape and results in poor effectiveness; therefore, fumigants are generally not recommended for vole control.

There are two types of hazards to non-target animals from the use of rodenticides: primary hazards result from the direct consumption of the rodenticide bait, while secondary hazards result from consuming rodents that have previously consumed the rodenticide bait (Witmer and Eisemann 2007). Zinc phosphide baits convert to phosphine gas inside the rodent and the gas diffuses into the air, hence, there are few secondary hazards from these formulations (Johnson and Fagerstone 1994). However, zinc phosphide is very toxic to most birds and mammals, so it can present a primary hazard to some nontarget animals. This is why it must be used very carefully and why accidental spills of bait must be cleaned up quickly. There have been recent die-offs of geese in the Pacific Northwest that have been attributed to the use of zinc phosphide-treated grain for vole control on hay and grass seed production fields (Rose Kachadoorian, Oregon Department of Agriculture, personal communication). A researcher at the National Wildlife Research Center is investigating the potential addition of a bird repellent (anthraquinone) to zinc phosphide-treated grain to reduce the hazard to birds (Scott Werner, USDA, APHIS, Wildlife Services, personal communication). With the first-generation anticoagulants registered for vole control, there has been concern raised recently about possible losses of predatory animals (both avian and mammalian) to the secondary hazard of consumption of rodents that have consumed rodent baits (Peter Gober, U.S. Fish and Wildlife Service, personal communication). While the toxicity levels and persistency durations of first-generation anticoagulants make them less of a hazard than the second-generation compounds, nonetheless, they can pose a secondary hazard (Mendenhall and Pank 1980, Brakes and Smith 2005). As a result, the residue levels and persistency durations in the tissues of rodents are being investigated.

RESEARCH NEEDS

Despite many decades of research on voles and thousands of publications, Pugh et al. (2003) noted that there is still much to learn about voles. Researchers should continue to seek ways to reduce rodent populations and damage to agriculture (Witmer et al. 1995).

Some promising areas of research include the use of endophytic (alkaloid-producing) grasses in non-production areas (Fortier et al. 2000) and fertility control (Miller et al. 1998). Other areas of research could include:

- Predicting vole outbreaks/irruptions (as per house mice in Australia; Krebs et al. 2004).
- Protecting root systems from damage by tunneling voles.
- Effective rodenticides and methods to further reduce nontarget animal hazards.
- Effective and durable repellents.
- Species interactions with other native and non-native rodent species.
- Food safety issues in agricultural areas.

Clearly, managing vole populations and the damage they cause will continue to challenge researchers and land managers for a long time to come.

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