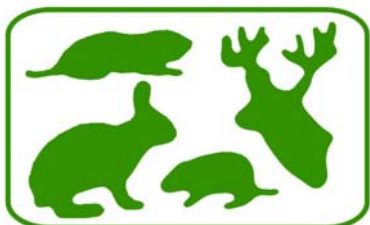


VOLE POPULATIONS, TREE FRUIT ORCHARDS, and LIVING MULCHES

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1.0 SUMMARY

The problem of feeding damage to forest and agricultural crops by herbivorous small mammals has a long history in temperate ecosystems of North America. In agriculture, voles of the genus *Microtus* are considered the major mammalian species affecting tree fruit crops and cultivated field crops. Populations of some species of voles tend to have cyclic fluctuations in abundance in northern latitudes with a peak every 3 to 5 years, although these periods may be interspersed with annual fluctuations in abundance. Three species of *Microtus*: the montane vole (*M. montanus*), the meadow vole (*M. pennsylvanicus*), and secondarily, the long-tailed vole (*M. longicaudus*), are implicated as major pests of fruit trees in Washington state and British Columbia. The northern pocket gopher (*Thomomys talpoides*) is a fourth small rodent species that may feed on the stems and roots of fruit trees.

It is primarily during overwinter periods when high populations of these microtines (and the northern pocket gopher) feed on fruit trees. Signs of voles include well worn runways, open holes in the orchard floor, and clippings of vegetation. Signs of gophers include soil mounds from excavations of burrows and in the spring, cylindrical casts of soil left from burrows dug in the snow during winter. Voles feed on bark, vascular tissues (phloem and cambium), and sometimes roots of trees. Direct mortality may result from girdling of apple tree stems, and even older trees may be completely girdled. In addition, sub-lethal feeding damage may lead to reduced growth and yield.

Current control methods rely on various rodenticides to reduce vole and gopher populations. However, the problem of resiliency (population recovery) in these rodent populations has indicated that only short-term (if any) substantial control has been achieved with toxicants or other methods of depopulation. Despite the variability in efficacy, rodenticides continue to be the major method used to reduce vole populations in orchards. An alternative approach to rodent control in orchards involves habitat manipulation by means of mechanical, chemical, or changes in plant species composition. Changes in habitat structure (particularly food and cover) may have profound effects on these rodent populations. The influence of cultural practices in reducing vole populations has been reported by several authors.

Cover crops and living mulches have the potential to alleviate many of the problems inherent in managed crop systems. Appropriate cover crops could provide and conserve nitrogen, decrease potential soil erosion, increase soil organic matter, and decrease weed competition. However, a major problem has been voles occupying these living mulch habitats and their consequent feeding damage to crops. In a review of the literature concerning living mulches in agricultural settings, 24 papers discussed potential living mulches at the species-specific level. These papers investigated 30 different forbs plus three studies on grasses. A literature review of vole food preferences was also done, with 30 publications representing 70 plant species or groups in relation to vole food preference.

Of the 11 genera of plants in common between the two sets of literature, seven genera were consistently preferred food of voles. The three genera which were not a preferred food of voles were: crownvetch (*Coronilla varia*), wheat (*Triticum aestivum*), and a vetch (*Vicia cracca*). *Vicia* spp. holds the most promise as living mulches that voles are likely to avoid. Future research should investigate this genus as a potential living mulch in orchard environments.

2.0 NATURAL HISTORY and MANAGEMENT

2.1 Vole populations and habitats

The problem of feeding damage to forest and agricultural crops by herbivorous small mammals has a long history in temperate and boreal ecosystems of North America and Eurasia (Moore 1940; Myllymäki 1977; Byers 1984; Getz 1985; Conover 2002). In agriculture, voles of the genus *Microtus* are considered the major mammalian species affecting tree fruit crops and cultivated field crops in North America (Byers 1984; Godfrey 1986; Sullivan and Hogue 1987; Askham 1988). Populations of some species of voles tend to have cyclic fluctuations in abundance in northern latitudes with a peak every 3 to 5 years, although these periods may be interspersed with annual fluctuations in abundance (Krebs and Myers 1974; Taitt and Krebs 1985; Körpimäki and Krebs 1996; Boonstra et al. 1998). There is a tremendous capacity for increase in abundance of these small mammals, ranging from 8- to 22-fold in the microtines during the increase phase of the population cycle (Krebs and Myers 1974). Explanations for what regulates these population cycles include food, predation, disease, stress, and behavioural changes arising from limitations of these various factors.

Microtus spp. prefers perennial grassland habitats that provide both cover and food sources such as grasses, sedges, forbs, and shrubs (Reich 1981; Batzli 1985; Ostfeld 1985; Getz 1985). Multi-annual population fluctuations appear to require a minimum level of vegetative cover to generate increases in abundance of voles (Birney et al. 1976). Three species of *Microtus*: the montane vole (*M. montanus*), the meadow vole (*M. pennsylvanicus*), and secondarily, the long-tailed vole (*M. longicaudus*), are implicated as major pests of fruit trees in Washington state and British Columbia (Figs. 1a, 1b, 2a).

The montane vole has a grizzled greyish dorsal pelage and grey to white undersides (Nagorsen 2005). The dorsal surface of the feet has silver-grey fur. The tail is bicoloured with grey to greyish-brown above and white below, and the tail is less than 30% of the animal's total length. The meadow vole has variable dorsal pelage that ranges from grey to rich brown and the undersides are silver-grey (Nagorsen 2005). The hind feet have grey to blackish fur on their dorsal surface. The range of tail lengths is similar to that of the montane vole but is brown on the dorsal surface and whitish-grey on the underside. Since the range of these two voles overlap, it can sometimes be difficult to distinguish between them in mixed populations. The long-tailed vole, as its name suggests, has a relatively long tail that is 30 to 44% of its total length (and is

sometimes more than one-half the body length). The dorsal pelage of this species ranges from greyish-brown to reddish-brown and the ventral fur is grey (Nagorsen 2005). The tail has relatively less fur than the other species and is dark on top and slightly paler on the underside. The hind feet have grey or light brown fur on their dorsal surface.

The montane vole is distributed throughout the central cordilleran region of western North America (Banfield 1974) (Fig. 3). This species prefers arid short grassland in high elevation alpine meadows in the southern part of its range, but it occurs at lower elevations and in valley bottoms towards the northern extent of its range (Banfield 1974). This vole is similar to the meadow vole in many of its habits with some limited evidence reported for both multi-annual and annual cycles of abundance. The meadow vole has the largest distribution of any species of *Microtus* in North America, occurring throughout Canada, the northern and eastern regions of the United States, and into Mexico (Reich 1981) (Fig. 4). The long-tailed vole occupies the western cordillera from Alaska, the Yukon, and western Northwest Territories to the southwestern U.S. (Smolen and Keller 1987) (Fig. 5).

In dry grasslands, the meadow vole usually occurs in moist riparian habitats, whereas the montane vole is found in the more arid grasslands (Banfield 1974). Either species may occur in tree fruit orchards and vineyards, depending on the relative moisture regime and degree of vegetation cover (Sullivan and Hogue 1987). There are few population studies of these species in orchards, but abundance of montane voles in apple orchards in the Okanagan Valley of B.C. reached peaks of 35 to 40 animals per ha (Sullivan et al. 2003). A more recent study reported very low (< 1 vole/ha) numbers of montane voles in apple orchards compared with old fields (mean of 17/ha) in the Okanagan Valley (Sullivan and Sullivan 2006). Abundance of meadow voles in apple orchards in the Okanagan Valley ranged from 22 to 60 animals per ha (Sullivan and Hogue 1987). Numbers of these voles may reach well into the 100's per ha in other grass-dominated habitats (Reich 1981; Sullivan et al. 2001a; Nagorsen 2005; Sullivan et al. 2003; Sullivan and Sullivan 2004).

Montane voles in apple orchards appeared to have an annual cycle of abundance with low spring densities and relatively higher numbers in autumn (Sullivan et al. 2003). Old field populations had a multi-annual population fluctuation overlying annual changes in abundance. This dichotomy of population dynamics fits the patterns described for voles for which the amplitude of numerical change is < 5 -fold for annual fluctuations and usually > 10 -fold for multi-annual cycles (Taitt and Krebs 1985).

There appear to be no reports on numbers of long-tailed voles in orchards. Abundance of *M. longicaudus* ranges from 40-120 animals per ha in prime habitats dominated by herbs and shrubs (Van Horne 1982; Smolen and Keller 1987; Sullivan and Sullivan 2001). The long-tailed vole lives in a wide range of habitats including grassy meadows, shrub-dominated riparian areas, and several early successional (herb and shrub) post-harvest forested sites (Sullivan et al. 1999; Nagorsen 2005). In dry

grasslands, the long-tailed vole is found in shrub habitats such as common snowberry and rose (Nagorsen 2005).

2.2 Northern pocket gopher populations and habitats

The northern pocket gopher (*Thomomys talpoides*) is a fourth small rodent species (Fig. 2b) that may feed on the stems and roots of fruit trees. This slightly larger (60-120 g) rodent generally has brown dorsal pelage with some geographic variations. Small eyes and ears, short, nearly hairless tail, and long claws on their front feet epitomize their fossorial nature (Banfield 1974; Nagorsen 2005). The pockets referred to in their name are fur-lined cheek pouches which reach from their face to their shoulder area. These gophers live in dry grasslands, open subalpine forest, and subalpine or alpine meadows but also reside in disturbed areas such as hay or alfalfa fields, orchards, and gardens (Nagorsen 2005). They prefer deep and loamy or light and crumbly soil. Populations in old field habitats have been reported to be 15-31 per ha while in orchards their numbers are 5-18 per ha (Sullivan et al. 2001b). Populations generally fluctuate on an annual cycle, being lowest in spring and highest in autumn. The northern pocket gopher distribution includes the central plains and western mountain regions of North America (Figure 6) (Banfield 1974).

2.3 Feeding damage

It is primarily during overwinter periods when high populations of these microtines (and the northern pocket gopher) feed on fruit trees. Signs of voles include well worn runways, open holes in the orchard floor, and clippings of vegetation. Signs of gophers include soil mounds from excavations of burrows and in the spring, cylindrical casts of soil left from burrows dug in the snow during winter. Voles feed on bark, vascular tissues (phloem and cambium), and sometimes roots of trees. Direct mortality may result from girdling of 1-year-old apple tree stems (Figs. 7 and 8). However, even older trees may be completely girdled (Figs. 9 and 10). In addition, sub-lethal feeding damage may lead to reduced growth and yield (Pearson and Forshey 1978; Askham 1988). Estimates of economic loss due to voles in years of heavy infestations (30% of orchards) range from \$1,100 to \$7,500/ha in Washington state (Askham 1988). It is important to note that these are estimates only and they cover a wide range of values. Habitat conditions that favor high populations of voles (e.g., poor vegetation management on the orchard floor) were likely responsible for these estimated levels of economic loss.

2.4 Conventional control techniques

Current control methods rely on various rodenticides to reduce vole and gopher populations. However, the problem of resiliency (population recovery) in these rodent populations has indicated that only short-term (if any) substantial control has been achieved with toxicants or other methods of depopulation (Sullivan 1986). Orchard population changes of montane voles reported by Sullivan et al. (2003) may have been influenced more by natural factors than by rodenticides. Merwin et al. (1999) reported

that anticoagulant rodenticides did not adequately control meadow voles in apple orchards in New York. Despite the variability in efficacy, rodenticides continue to be the major method used to reduce vole populations in orchards (Byers 1985; Merwin et al. 1999).

An alternative approach to rodent control in orchards involves habitat manipulation by means of mechanical, chemical, or changes in plant species composition. Changes in habitat structure (particularly food and cover) may have profound effects on these rodent populations. The influence of these cultural practices in reducing vole populations has been reported by Byers and Young (1978), Godfrey (1986), Sullivan and Hogue (1987), and Merwin et al. (1999). Orchard habitats appear to provide a predictable environment for montane voles, and thus may explain the relatively consistent, albeit low, abundance patterns over the four years reported by Sullivan et al. (2003).

The relationship between vole populations in old field or source area habitats and orchards is likely a source-sink whereby lands adjoining an orchard may contribute to population recovery and maintenance through immigrating animals (Horsfall 1964). Clearly, there were substantial populations in our old field sites and during increase periods (e.g., autumn 1983 and 1984), dispersal of voles was high, as documented experimentally by Myers and Krebs (1971) and Krebs et al. (1976). During these periods of high dispersal in autumn and early winter, attempts at population reduction are essentially futile owing to the surplus of animals available to colonize depopulated areas (Sullivan 1986). This surplus of animals was particularly dramatic in the outbreaks of montane voles in the western U.S. in 1906-1908 and in 1957-1958 when this microtine caused widespread damage to agricultural crops (Getz 1985).

In general, removal of vegetative cover by grazing, mowing, or herbicides has reduced considerably the number of voles (Eadie 1953; LoBue and Darnell 1959; Hansson 1968; Black and Hooven 1974; Kirkland 1978). Birney et al. (1976) have noted that a minimal level of vegetative cover is necessary to permit *Microtus* spp. to increase in numbers during multi-annual population fluctuations. Insufficient cover exposes diurnal *Microtus* to increased predation from vision-oriented diurnal predators. In addition, the use of herbicide on rangelands has caused pronounced reductions in the populations of northern pocket gophers (Keith et al 1959; Tietjen et al. 1967). These changes were due to a decline in herbs and an increase in grasses in the vegetation, since gophers were very dependent on certain herb species for food.

Orchard populations of montane voles appear to be linked to source area dynamics of populations in old field habitats. Mean abundance of voles/ha ranged from 26.0-125.7 in old field sites and from 0.3-41.4 in orchard sites. Mean recruits/ha also followed this pattern. Length of breeding seasons and proportion of reproductive voles were generally similar in old field and orchard sites, but overall survival and mean body mass were consistently higher in old field than orchard sites. Traditional methods of vole control (rodenticides) have little effect on vole numbers during peak years as voles from adjacent habitats readily move into orchards. Sullivan et al. (2003) suggest that

other methods of vole control (habitat alteration) may be more effective at limiting vole-caused damage.

3.0 LIVING MULCHES

3.1 Cover crops and living mulches

Cover crops and living mulches have the potential to alleviate many of the problems inherent in managed crop systems. Appropriate cover crops could provide and conserve nitrogen, decrease potential soil erosion, increase soil organic matter, and decrease weed competition (Hartwig and Hoffman 1975). Increased organic matter in the soil enhances earthworm populations (Schmidt et al. 2003) and infiltration rates, as well as water holding capacity of the soil (Brady and Weils 2002). Cover crop studies indicate that structure and water retaining attributes of soil are improved and soil surface temperature is decreased (Frye et al. 1988; Donaldson et al. 1993). They could function as a weed management tool via competition for resources, light and inhibition of weed germination via allelochemicals (Brady and Weil 2002). Environments which include cover crops would have enhanced biodiversity and consequent insect diversity with its own means of pest/predator controls (Schellhorn and Sork 1997; Hooks and Johnson, 2004; Peet 2005).

These latter two sets of attributes give this cover crop technique a means to limit herbicide and overall pesticide use. Living mulches may be considered a specific form of cover crop that may eliminate the need to re-seed each year. Cover crops are living ground covers that are part of, or planted after, the main crop, but are killed before the next crop is planted. Living mulches, on the other hand, are planted before, or with the main crop, and are maintained through the growing season and, if perennial, persist from year to year (Hartwig 1983, 1987). The living mulch is usually suppressed by some means, such as tillage or herbicide, before the main crop is planted the next season (Teasdale 1996).

3.2 Literature review

In a review of the literature concerning living mulches in agricultural settings, 24 papers discussed potential living mulches at the species-specific level. These papers investigated 30 different forbs plus three studies on grasses and/or sod. Clover species accounted for 20% of these 30 species and represented 37% of the species-specific citings in the papers. Vetches were the next most commonly mentioned and represented 10% of the species and 22% of the citings. Three species of rye (10% of the species) were cited 1% of the time. This information alone indicates the relative interest of the various species for use as living mulches.

The majority of studies on living mulches involved vegetable crops such as corn, broccoli, beets, cabbage, potatoes and other assorted low-height crops (Table 1). In these situations weed suppression, especially by the second year (White and Scott

1991), was generally good, however, yields tended to be reduced due to competition with the living mulch (Nicholson and Wien 1982, 1983; Brandsaeter et al. 1998; Miura and Watanabe 2002; Liedgens et al. 2004) and was most pronounced by the second year (White and Scott 1991). Duiker and Hartwig (2004) found that sweet corn (*Zea mays*) yields could be maintained with maximum nitrogen applications. White and Scott (1991) suggested that yields of winter-wheat and rye could be maintained if top-dressed with nitrogen. Miura and Watanabe (2002), in their studies with sweet corn, suggested that there should be little competition for nitrogen due to the fact that nitrogen requirements of living mulches decreased as those for corn increased with time.

Moisture and light competition is not an issue when living mulches are used in vineyards or orchards especially where annual rainfall is over 1,100 mm or the mulch is suppressed 80-90% early in the growing year (Hartwig and Ammon 2002). Table 2 lists studies on species of living mulches used in tree fruit and forest environments. In the study by Alley et al. (1999), all seedlings grew better with no competition but red clover (*Trifolium pratense* L.) showed the most promise for weed suppression and tall fescue (*Festuca arundinacea* Schrebe.) resulted in reduced growth in hardwood seedlings. Merwin and Stiles (1994) carried out an extensive study of groundcover management in an apple orchard environment. These authors measured apple tree trunk cross-sectional area and fruit yield and determined that crownvetch, as a living mulch, was comparable to chemical growth-regulated and close-mowed sodgrass after five years. However, all three of these treatments resulted in lower trunk cross-sectional area and fruit yield than hay-straw mulch, glyphosate or pre-emergent herbicides. Merwin and Stiles (1994) found phytophthora root rot and meadow voles to be serious problems in the hay-straw and living crownvetch mulch systems.

3.3 Living mulches and voles

Valid concerns exist that cover would be advantageous to soils and crops while functioning as a vegetation management tool, but may encourage unwanted small mammal populations (deCalestra 1982; Teivainen et al. 1986; Pusenius et al. 2000; Turchin and Batzli 2001; Pusenius and Schmidt 2002). These small mammals, voles (*Microtus* spp.) in particular, are known to damage crops. Regardless of farming practice (mulching, mowing, harvesting wheat or ploughing) home-range size of common voles (*Microtus arvalis*) has been shown to be positively related to vegetation height but not vegetation cover (Jacob and Hempel 2003). However, none of these farming techniques affected population density or breeding of voles so it was concluded that only ploughing would result in vole pest management (Jacob 2003). The presence of other preferred habitat characteristics, such as woodchuck burrows, has been shown to affect populations of small mammals (Swihart 1995) and should be considered when attempting to manage populations.

Many papers have been written regarding the food preferences of voles. These studies were often aimed at understanding the driving forces behind vole multi-annual cycles in population densities. From these studies it has been determined that vole

food preferences are not random but rather inherent in the animal, partially determined by their present or past environment, but not determined by abundance of the food source. Voles do not arbitrarily select their food items (Gill 1977), but plant palatability can be quite variable within a morphological group (Hjalten et al. 1996). Grasses are generally preferred over forbs (Gill 1977; Hjalten et al. 1996), particularly seed heads of grasses (Gill 1977). Hjalten et al. (1996) determined that two vole species (*Clethrionomys glareolus* and *Microtus agrestis*) prefer small umbrella herbs versus rosette herbs, dwarf shrubs, tall umbrella herbs, or evergreens. Although grass leaves are the main vole food, preference varies with season with more broad-leaved plants eaten in the summer and seeds in the summer and autumn (Larsson and Hansson 1977). Bark consumption occurs in the autumn, winter and spring (Larsson and Hansson 1977).

While small mammal feeding damage does not seem to be an issue in vegetable crops, they may become a factor in living mulch orchard environments. A literature review of vole food preferences is presented in Table 3. Of the 30 publications reviewed, 70 plant species or groups were studied in relation to vole food preference. Of these, 60% registered preferences, 33% non-preferred and 7% consumed but not preferred. *Microtus* spp. were cited 78 times in this literature and were represented by the following species: *M. pennsylvanicus* 47% (37/78), *M. ochrogaster* 24% (19/78), *M. agrestis* 12% (9/78), *M. californicus* 9% (7/78), *M. arvalis* 6% (5/78), *M. pinetorum* 1% (1/78). *Clethrionomys glareolus* and *C. rufocanus* were cited five times, and one time, respectively.

Of the 11 genera of plants in common between the two sets of literature, seven genera were consistently preferred food of voles (Table 4). The three genera which were not a preferred food of voles were: crownvetch (*Coronilla varia*), wheat (*Triticum aestivum*), and a vetch (*Vicia cracca*). *Coronilla varia* is reported to have negative effects on crop yield (Merwin and Stiles 1994), requiring full nitrogen applications to maximize crop yields (Duiker and Hartwig 2004). White and Scott (1991) found little yield reduction in winter wheat and rye production in the first year with *C. varia*, but by the second year yield was reduced and weed suppression was poor.

Triticum aestivum consumption by voles was inconsistent, depending upon site and month (Fleharty and Olson 1969). It was suggested that the increase in *T. aestivum* consumption may have resulted from increased rain in the area softening the wheat seeds, which are usually too hard for vole consumption (Dice 1922; Fleharty and Olson 1969). *T. aestivum* is reported to provide good coverage and weed suppression (Nelson et al. 1991).

The one study discussing *V. cracca* and vole food preference suggested it was a bit of an anomaly as it ranks high in protein content yet is not a preferred food of *Microtus pennsylvanicus* in meadows. The *Vicia* used in living mulch studies was *Vicia villosa* and was generally found to have no effect on crop yield (Infante and Morse 1996; Boyd et al. 2001; Brainard et al. 2004), though Duiker and Hartwig (2004) found that full nitrogen rates were required to optimize yield. Weed suppression by *V. villosa* was

rated as good (Hartwig and Ammon 2002; Infante and Morse 1996), equivalent to cultivation (Brainard et al. 2004), next best to grasses (Infante and Morse 1996), but poorer than a vetch-rye mix (Vanek et al. 2005). An advantage of *T. aestivum* and *V. villosa* is their sensitivity to herbicides for seasonal suppression (Vanek et al. 2005; Alley et al. 1999).

Taking these reviews into account, it would appear that, of these three genera, *Vicia* spp. holds the most promise as living mulches that voles are likely to avoid.

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Table 1. Living mulch summary for vegetable crops. Mulch species are organized alphabetically.

Reference	Crop	Mulch species	Weed suppression	Crop yield	Sensitivity to herbicide
Brainard et al. 2004	cabbage	<i>Avena sativa</i>	no effect	poor	
Biazzo & Masiunas 2000	hot pepper & okra	<i>Brassica napus</i>	moderate	poorer than tillage	
Peterson & Rover 2005	sugar beet	<i>Brassica napus</i>	moderate	poor crop emergence	
Duiker & Hartwig 2004	corn	<i>Coronilla varia</i>		full N required	good
White & Scott 1991	winter wheat & rye	<i>Coronilla varia</i>	poor	little effect 1st yr	
Nelson et al. 1991	vegetables	<i>Festuca elatior</i>	inadequate		
Nelson et al. 1991	vegetables	<i>Festuca rubra</i>	inadequate		
Duiker & Hartwig 2004	corn	<i>Galega officinalis</i>		full N required	
Nelson et al. 1991	vegetables	<i>Hordeum vulgare</i>	good		killed
Duiker & Hartwig 2004	corn	<i>Lathyrus sylvestris</i>		full N required	very sensitive
Nelson et al. 1991	vegetables	<i>Lolium multiflorum</i>	good		good
Biazzo & Masiunas 2000	hot pepper & okra	<i>Lolium pratense</i>	best		
Liedgens et al. 2004	maize	<i>Lolium pratense</i>		decreased	
Duiker & Hartwig 2004	corn	<i>Lotus corniculatus</i>		not affected with N	fairly sensitive
White & Scott 1991	winter wheat & rye	<i>Lotus corniculatus</i>	good -2nd yr	reduced 2nd yr	
Miura & Watanabe 2002	maize, sweet	<i>Medicago sativa</i>	good	reduced	
White & Scott 1991	winter wheat & rye	<i>Medicago sativa</i>	good -2nd yr	reduced 2nd yr	
Hooks & Johnson 2004	broccoli	<i>Melilotus officinalis</i>	good	reduced	
Boyd et al. 2001	potato	<i>Poa pranses</i>		no effect except sod	
Nelson et al. 1991	vegetables	<i>Poa pranses</i>	inadequate		
Peterson & Rover 2005	sugar beet	<i>Raphanus sativus</i>	moderate	emergence good	
Hartwig & Ammon 2002	review paper	<i>Secale cereale</i>			
Peterson & Rover 2005	sugar beet	<i>Secale cereale</i>		poor emergence	
Nelson et al. 1991	vegetables	<i>Secale cereale</i>	good		good
Peterson & Rover 2005	sugar beet	<i>Sinapis alba</i>	moderate	emergence good	
Hooks & Johnson 2004	broccoli	<i>Trifolium fragiferum</i>	not as good		
Nelson et al. 1991	vegetables	<i>Trifolium incarnatum</i>	good, grass better		
Infante & Morse 1996	broccoli	<i>Trifolium pratense</i>	good	no effect	
Alley et al. 1999	hard wood & pine seedlings	<i>Trifolium pratense</i>	most promise		
Biazzo & Masiunas 2000	hot pepper and okra	<i>Trifolium pratense</i>	< T. repens	better with mowing	
Miura & Watanabe 2002	maize, sweet	<i>Trifolium pratense</i>	good	suppressed	
Boyd et al. 2001	potato	<i>Trifolium pratense</i>		no effect except sod	

Table 1. Continued

Reference	Crop	Mulch species	Weed suppression	Crop yield	Sensitivity to herbicide
White & Scott 1991	winter wheat & rye	<i>Trifolium pratense</i>	good 2nd yr	OK for rye; bad for wheat	
Hooks & Johnson 2004	broccoli	<i>Trifolium repens</i>	mulch better		
Infante & Morse 1996	broccoli	<i>Trifolium repens</i>	good	no affect	
Brandsaeter et al. 1998	cabbage	<i>Trifolium repens</i>	least negative		
Biazzo & Masiunas 2000	hot pepper and okra	<i>Trifolium repens</i>	best		
Martin et al. 1999	maize	<i>Trifolium repens</i>		reduced	
Miura & Watanabe 2002	maize, sweet	<i>Trifolium repens</i>	good	unaffected	
Neuweiler et al. 2003	strawberries	<i>Trifolium repens</i>		poor	
Hiltbrunner et al. 2004	winter wheat	<i>Trifolium repens</i>	good		
White & Scott 1991	winter wheat & rye	<i>Trifolium repens</i>	good 2nd yr	little affect 1st yr	
White & Scott 1991	winter wheat & rye	<i>Trifolium repens</i>	2nd yr		
Brandsaeter et al. 1998	cabbage	<i>Trifolium subterraneum</i>	good	lowest	
Nelson et al. 1991	vegetables	<i>Triticum aestivum</i>	good		good
Infante & Morse 1996	broccoli	<i>Vicia villosa</i>	good	no effect	
Brainard et al. 1004	cabbage	<i>Vicia villosa</i>	same as cultivation	no effect	
Brainard et al. 1004	cabbage	<i>Vicia villosa</i>	same as cultivation		
Duiker & Hartwig 2004	corn	<i>Vicia villosa</i>		full N required	
Boyd et al. 2001	potato	<i>Vicia villosa</i>		no effect except sod	
Vanek et al. 2005	pumpkins	<i>Vicia villosa</i>	poorer than vetch-rye		
Hartwig & Ammon 2002	review paper	<i>Vicia villosa</i>	good		
Nelson et al. 1991	vegetables	<i>Vicia villosa</i>	best next to grasses		not killed
Vanek et al. 2005	pumpkins	<i>Vicia villosa</i> / <i>Secale cereale</i>	better than vetch		
Briner et al. 2005	fields	wildflower strips			
Martin et al. 1999	maize	grasses mixed		poor	
Boyd et al. 2001	potato	native sod		no effect except sod	

Table 2. Living mulch summary for non-vegetable plants.

Reference	Crop	Mulch common name	Mulch species name	Effect on crop
Merwin & Stiles 1994	orchard - apple		grasses – mowed sod	trunk cross-sectional area & fruit yield lower after 5 years versus dead mulch, chemical or tilled treatments
Sanchez et al. 2003	cherry orchards		mixes of legumes, grasses, and other forbs	yield unaffected
Sanchez et al. 2003	cherry orchards		natural weeds	yield unaffected
Sanchez et al. 2003	cherry orchards	early in the study when grasses did not dominate	mixes of legumes, grasses, and other forbs	yields not reduced
Sanchez et al. 2003	cherry orchards	later in the study when grasses did dominate	mixes of legumes, grasses, and other forbs	yields reduced
Merwin & Stiles 1994	orchard-apple	vetch crownvetch	Coronilla varia	trunk cross-sectional area & fruit yield lower after 5 yrs versus dead mulch, chemical or tilled treatments
Alley et al. 1999	hard wood & pine seedlings	fescue tall	Festuca arundinacea	greatly reduced growth of hardwood seedlings
Alley et al. 1999	hardwood & pine seedlings	birdsfoot trefoil	Lotus corniculatus	all seedlings grew better without competition
Alley et al. 1999	hardwood & pine seedlings	clover kura	Trifolium ambiguum	all seedlings grew better without competition
Alley et al. 1999	hardwood & pine seedlings	clover strawberry	Trifolium fragiferum	all seedlings grew better without competition
Alley et al. 1999	hardwood & pine seedlings	clover red	Trifolium pratense	greatest promise as living mulch for hardwood seedlings
Alley et al. 1999	hardwood & pine seedlings	clover small & lg white	Trifolium repens	greatest promise as living mulch for pine seedlings
Alley et al. 1999	hard wood & pine seedlings	vetch hairy and 'AU Early' hairy vetch	Vicia villosa	all seedlings grew better without competition

Table 3. Summary of literature concerning vole food preference.

Reference	Year	Species	Plant food	preferred	neutral	not preferred
Bucyanayandi et al.	1992	<i>M. pennsylvanicus</i>	<i>Agropyron repens</i>	1		
Batzli & Pitelka	1971	<i>M. californicus</i>	<i>Avena fatua</i>	1		
Fleharty & Olson	1969	<i>M. ochrogaster</i>	<i>Bouteloua gracilis</i>	1		
Fleharty & Olson	1969	<i>M. ochrogaster</i>	<i>Bromus japonicus</i>	1		
Gill	1977	<i>M. californicus</i>	<i>Bromus racemosa</i>	1		
Batzli & Pitelka	1971	<i>M. californicus</i>	<i>Bromus rigidus</i>	1		
Wheeler	2005	<i>M. agrestis</i>	<i>Deschampsia flexuosa</i>	1		
Fleharty & Olson	1969	<i>M. ochrogaster</i>	<i>Digitaria sanguinalis</i>	1		
Thompson	1965	<i>M. pennsylvanicus</i>	<i>Equisetum arvense</i>	1		
Bucyanayandi et al.	1992	<i>M. pennsylvanicus</i>	<i>Festuca elatior&rubra</i>	1		
Bergeron & Jodoin	1987	<i>M. pennsylvanicus</i>	<i>Festuca rubra</i>	1		
Bélanger & Bergeron	1987	<i>M. pennsylvanicus</i>	<i>Fragaria virginiana</i>	1		
Tattersall et al	2000	<i>M. agrestis</i>	grass seed mix of tall & tussocky	1		
Thompson	1965	<i>M. pennsylvanicus</i>	grasses adventive(non-native)	1		
Gill	1977	<i>M. californicus</i>	<i>Hordeum stebbinsii</i>	1		
Fleharty & Olson	1969	<i>M. ochrogaster</i>	<i>Kochia scoparia</i>	1		
Skorupska	1999	<i>M. arvalis</i>	<i>Ornithopus sativus</i>	1		
Bélanger & Bergeron	1987	<i>M. pennsylvanicus</i>	<i>Leontodon autumnalis</i>	1		
Lindroth & Batzli,	1984	<i>M. pennsylvanicus</i> - prairie	<i>Lespedeza</i>	1		
Batzli & Pitelka	1971	<i>M. californicus</i>	<i>Lolium multiflorum</i>	1		
Gill	1977	<i>M. californicus</i>	<i>Lolium perenne</i>	1		
Bélanger & Bergeron	1987	<i>M. pennsylvanicus</i>	dicots vs monocots, many plants tested	1		
Thompson	1965	<i>M. pennsylvanicus</i>	<i>Medicago sativa</i>	1		
Kendall & Leath	1976	<i>M. pennsylvanicus</i>	<i>Medicago sativa</i> L.-low-saponin	1		

Table 3. Continued

Reference	Year	Species	Plant food	preferred	neutral	not preferred
Lindroth & Batzli	1984	<i>M. pennsylvanicus</i> - prairie	<i>Penstemon</i>	1		
Zimmerman	1965	<i>M. pennsylvanicus</i>	<i>Poa compressa</i>	1		
Bucyanayandi et al.	1992	<i>M. pennsylvanicus</i>	<i>Poa pratensis</i>	1		
Lindroth & Batzli,	1984	<i>M. pennsylvanicus</i> – from blue grass habitat	<i>Poa pratensis</i>	1		
Zimmerman	1965	<i>M. pennsylvanicus</i>	<i>Poa pratensis</i>	1		
Hjalten et al.	2004	<i>Clethrionomys glareolus</i>	<i>Populus tremula</i>	1		
Fleharty & Olson	1969	<i>M. ochrogaster</i>	<i>Rumex crispus</i>	1		
Skorupska	1999	<i>M. arvalis</i>	seeds, vegies, oilseed rape leaves	1		
Lindroth & Batzli	1984	<i>M. pennsylvanicus</i> – from prairie habitat	<i>Solidago</i>	1		
Hjalten et al.	2004	<i>Clethrionomys glareolus</i>	<i>Sorbus aucuparia</i>	1		
Fleharty & Olson	1969	<i>M. ochrogaster</i>	<i>Sporobolus asper</i>	1		
Lindroth & Batzli	1984	<i>M. pennsylvanicus</i> – from blue grass habitat	<i>Taraxacum</i>	1		
Thompson	1965	<i>M. pennsylvanicus</i>	<i>Taraxacum officinale</i>	1		
Curtis et al	2002	<i>M. ochrogaster</i>	<i>Taraxicum officinalis</i>	1		
Lindroth & Batzli	1984	<i>M. pennsylvanicus</i> – from blue grass habitat	<i>Trifolium</i>	1		
Thompson	1965	<i>M. pennsylvanicus</i>	<i>Trifolium pratense</i>	1		
Zimmerman	1965	<i>M. pennsylvanicus</i>	<i>Trifolium pratense</i>	1		
Curtis et al.	2002	<i>M. ochrogaster</i>	<i>Trifolium repens</i>	1		
Thompson	1965	<i>M. pennsylvanicus</i>	<i>Trifolium repens</i>	1		
Hjalten et al.	2004	<i>Clethrionomys glareolus</i>	<i>Vaccinium myrtillus</i>	1		
Hambäck et al.	2002	<i>Clethrionomys rufocanus</i>	<i>Vaccinium myrtillus</i>	1		
Bergeron & Jodoin	1987	<i>M. pennsylvanicus</i>	<i>Vicia cracca</i>	1		
Gill	1977	<i>M. californicus</i>	<i>Bassica nigra</i>	1		

Table 3. Continued

reference	Year	Species	Plant food	preferred	neutral	not preferred
Lindroth & Batzli	1984	<i>M. pennsylvanicus</i> – from prairie habitat	<i>Andropogon</i>			1
Curtis et al.	2002	<i>M. ochrogaster</i>	<i>Buxus sempervirens</i>			1
Curtis et al.	2002	<i>M. ochrogaster</i>	<i>Coronilla varia</i> L.			1
Wheeler	2005	<i>M. agrestis</i>	<i>Eriophorum vaginatum</i>			1
Zimmerman	1965	<i>M. pennsylvanicus</i>	<i>Ispedeza</i>			1
Kendall & Leath	1976	<i>M. pennsylvanicus</i>	<i>Medicago sativa</i> L.-high-saponin			1
Bélanger & Bergeron	1987	<i>M. pennsylvanicus</i>	monocots versus dicots, many plants tested			1
Zimmerman	1965	<i>M. ochrogaster</i>	<i>Muhlenbergia sobolifera</i>			1
Curtis et al.	2002	<i>M. ochrogaster</i>	<i>Narcissus pseudonarcissus</i>			1
Thompson	1965	<i>M. pennsylvanicus</i>	native boreal & bog plants			1
Schlegl-Bechtold	1980	<i>M. agrestis</i>	Norway spruce			1
Curtis et al.	2003	<i>M. ochrogaster</i>	<i>Pachysandra terminalis</i>			1
Curtis et al.	2002	<i>M. ochrogaster</i>	<i>Pachysandra terminalis</i>			1
Zimmerman	1965	<i>M. pennsylvanicus</i>	<i>Panicum capillare</i>			1
Zimmerman	1965	<i>M. ochrogaster</i>	<i>Panicum capillare</i>			1
Zimmerman	1965	<i>M. pennsylvanicus</i>	<i>Plantago lanceolata</i>			1
Zimmerman	1965	<i>M. ochrogaster</i>	<i>Plantago lanceolata</i>			1
Zimmerman	1965	<i>M. pennsylvanicus</i>	<i>Poa</i>			1
Lindroth & Batzli	1984	<i>M. pennsylvanicus</i> – from blue grass habitat	<i>Poa</i>			1
Fleharty & Olson	1969	<i>M. ochrogaster</i>	<i>Triticum aestivum</i>			1
Bélanger & Bergeron	1987	<i>M. pennsylvanicus</i>	<i>Vicia cracca</i>			1
Fleharty & Olson	1969	<i>M. ochrogaster</i>	<i>Xanthium commune</i>			1
Servello et al.	1984	<i>M. pinctorum</i>				1

Table 3. Continued

Reference	Year	Species	Plant food	preferred	neutral	not preferred
Wheeler	2005	<i>M. agrestis</i>	<i>Molinia caerulea</i>		1	
Wheeler	2005	<i>M. agrestis</i>	<i>Nardus stricta</i>		1	
Thompson	1965	<i>M. pennsylvanicus</i>	native monocots		1	
Bucyanayandi et al.	1992	<i>M. pennsylvanicus</i>	<i>Phleum pratense</i>		1	
Zimmerman	1965	<i>M. ochrogaster</i>	<i>Poa compressa</i>		1	

Table 4. Comparison of citings in common between vole food preference studies and living mulch studies. Preferred foods indicated by + and non-preferred vole food by -.

Vole citings	Food preference	Mulch citings	Weed suppression	Yield of crop
<i>Avena fatua</i>	+	<i>Avena sativa</i>	no affect	poor
<i>Brassica nigra</i>		- <i>Brassica napus</i>	moderate	poorer than tillage
		<i>Brassica napus</i>	moderate	poor field emergence
<i>Coronilla varia</i> L.		- <i>Coronilla varia</i>		full N required
		<i>Coronilla varia</i>		poor
		<i>Coronilla varia</i>	poor	little effect 1 st year
<i>Festuca elatior</i> & <i>F. rubra</i>	+	<i>Festuca arundinacea</i>		reduced
<i>Festuca rubra</i>	+	<i>Festuca elatior</i>	inadequate	
		<i>Festuca rubra</i>	inadequate	
<i>Hordeum stebbinsii</i>	+	<i>Hordeum vulgare</i>	good	
<i>Lolium multiflorum</i>	+	<i>Lolium multiflorum</i>	good	
<i>Lolium perenne</i>	+	<i>Lolium pratense</i>		decreased
		<i>Lolium pratense</i>	best	
<i>Medicago sativa</i>	+	<i>Medicago sativa</i>	good	reduced
<i>Medicago sativa</i> L.-low-saponin	+	<i>Medicago sativa</i>	good -2 nd year	reduced 2 nd year
<i>Poa</i>	+	<i>Poa pratensis</i>		no effect except sod
<i>Poa</i>	+	<i>Poa pratensis</i>	inadequate	
<i>Poa</i>	+			
<i>Poa compressa</i>	+			
<i>Poa pratensis</i>	+			
<i>Trifolium</i>	+	<i>Trifolium fragiferum</i>	not as good	
		<i>Trifolium fragiferum</i>		
		<i>Trifolium incarnatum</i>	good	
<i>Trifolium pratense</i>	+	<i>Trifolium pratense</i>		better with mowing
<i>Trifolium pratense</i>	+	<i>Trifolium pratense</i>	most promise	
<i>Trifolium pratense</i>		- <i>Trifolium pratense</i>	good	suppressed
		<i>Trifolium pratense</i>	good 2 nd year	OK for rye;bad for wheat
		<i>Trifolium pratense</i>		no effect except sod
		<i>Trifolium pratense</i>	least negative	
		<i>Trifolium pratense</i>	best	
		<i>Trifolium pratense</i>	mulch better	
		<i>Trifolium pratense</i>	good	unaffected
		<i>Trifolium pratense</i>		poor
		<i>Trifolium pratense</i>	good	
		<i>Trifolium pratense</i>	good 2 nd year	little effect 1 st year
<i>Trifolium repens</i>	+	<i>Trifolium repens</i>	2 nd year	
<i>Trifolium repens</i>	+			
<i>Triticum aestivum</i>		- <i>Trifolium subterraneum</i>	good	lowest
		has allelopathy-Hartwig		
		<i>Triticum aestivum</i>	good	
<i>Vicia cracca</i>	+	<i>Vicia villosa</i>	same as cultivation	
<i>Vicia cracca</i>		- <i>Vicia villosa</i>	poorer than vetch-rye	

Table 4. Continued

Vole citings	Food preference	Mulch citings	Weed suppression	Yield of crop
		Vicia villosa	same as cultivation	no effect
		Vicia villosa	good	
		Vicia villosa		no effect except sod
		Vicia villosa	good	no effect
		Vicia villosa		full N required
		Vicia villosa	best next to grasses	
		Vicia villosa / Secale cereale	better than vetch	

Figure 1. (a) Montane vole; (b) Meadow vole.

(a)



(b)



Figure 2. (a) Long-tailed vole; (b) Northern pocket gopher.

(a)



(b)



Figure 3. Distribution of the montane vole (*Microtus montanus*) in North America.

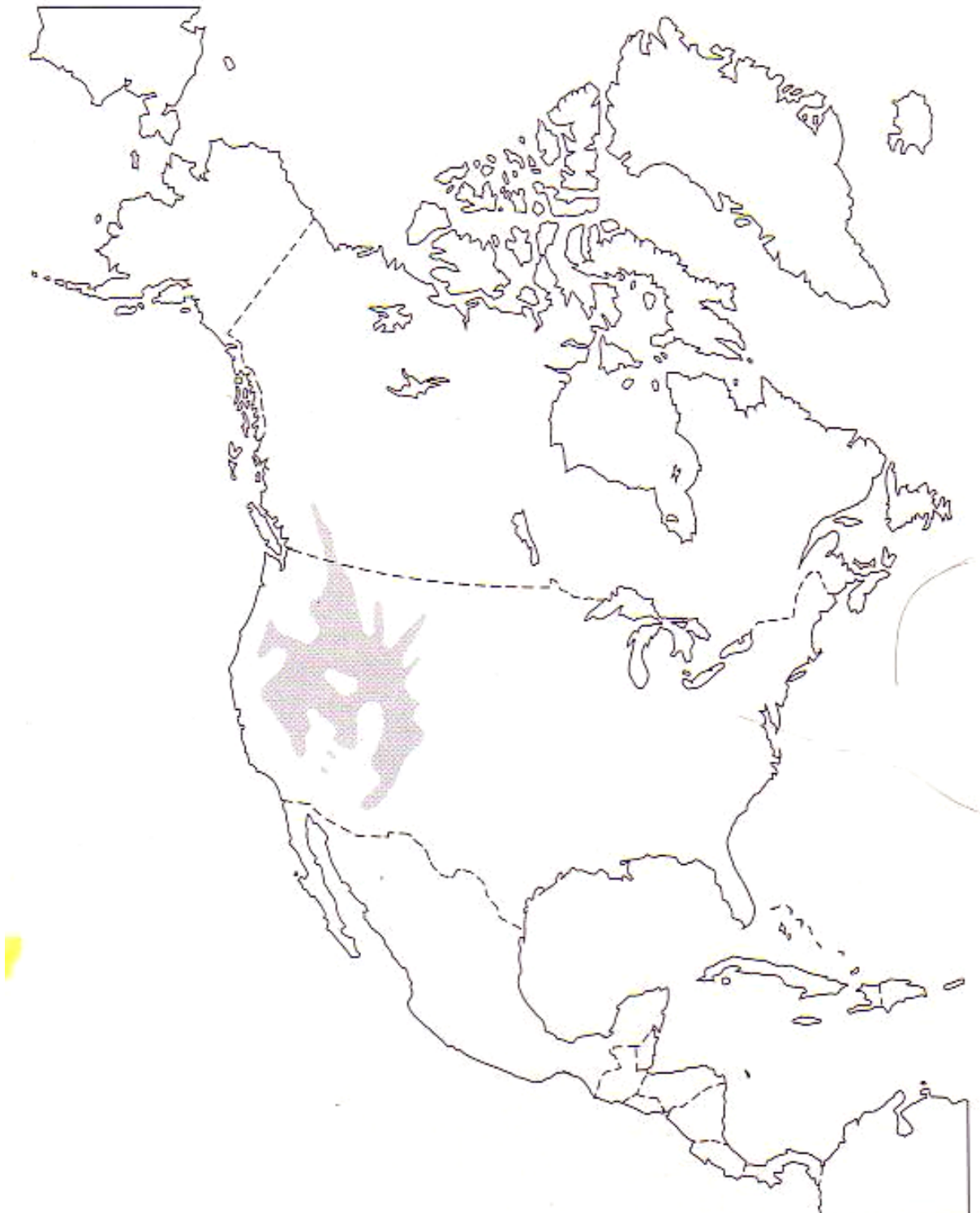


Figure 4. Distribution of the meadow vole (*Microtus pennsylvanicus*) in North America.

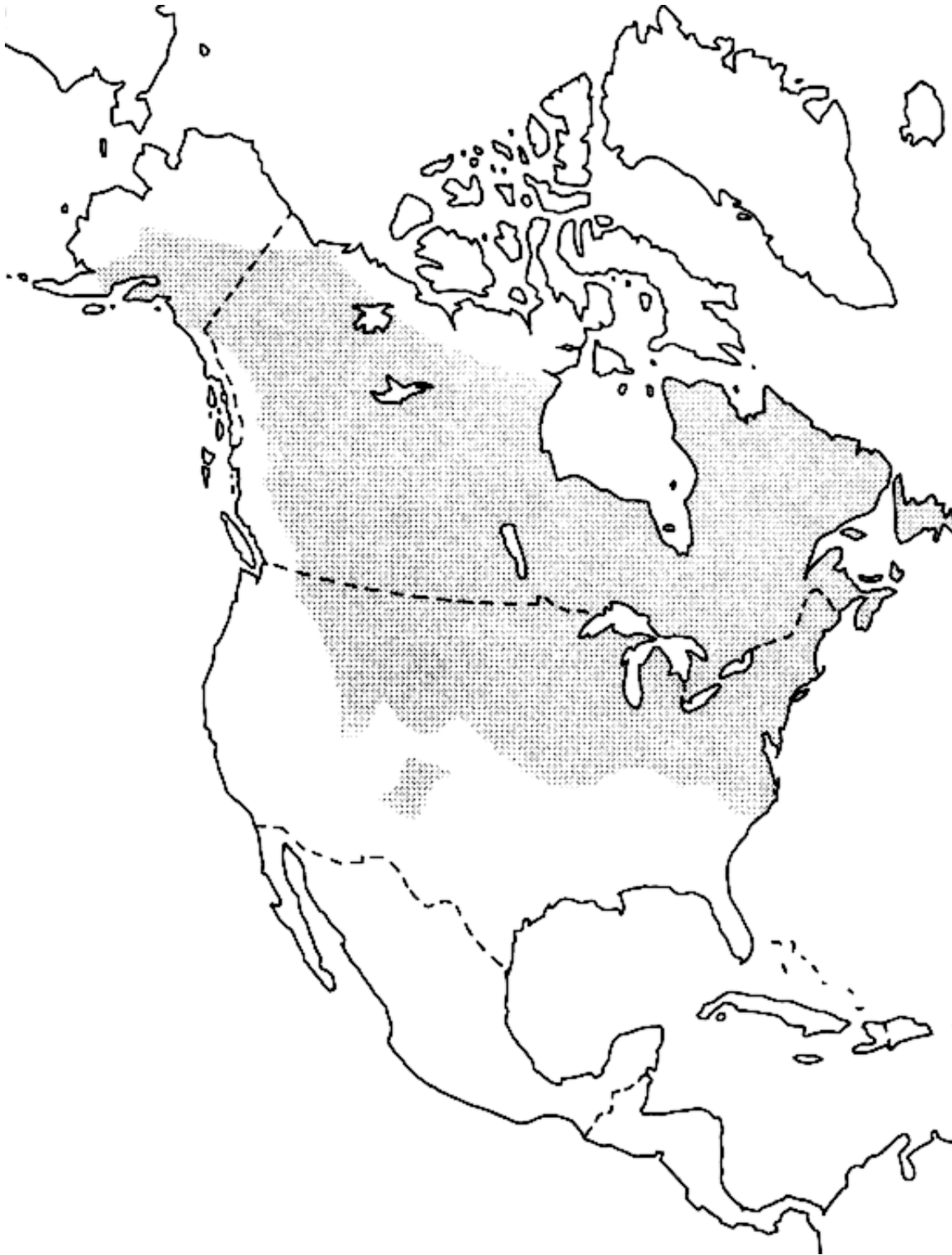


Figure 5. Distribution of the long-tailed vole (*Microtus longicaudus*) in North America.

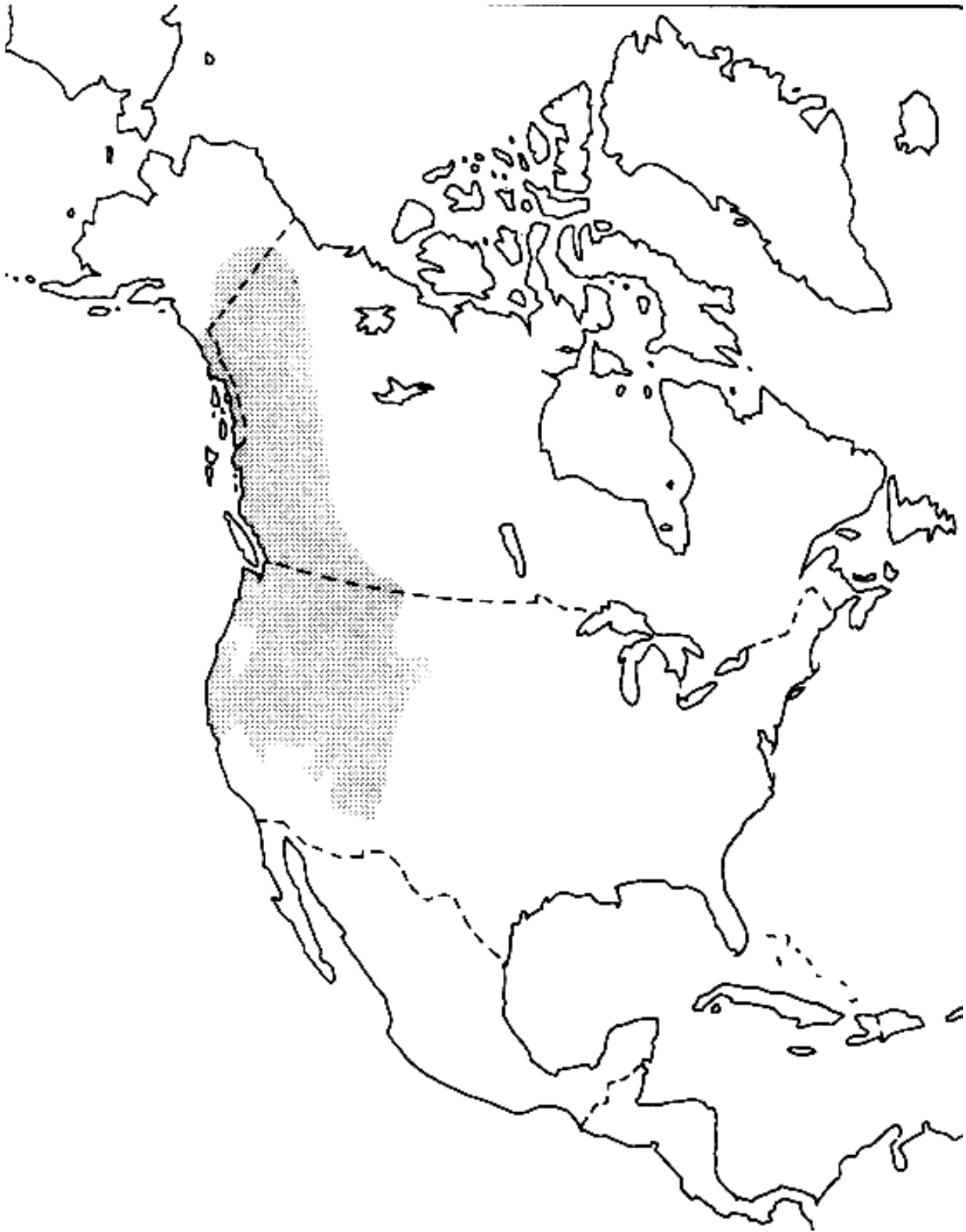


Figure 6. Distribution of the pocket gopher (*Thomomys talpoides*) in North America.

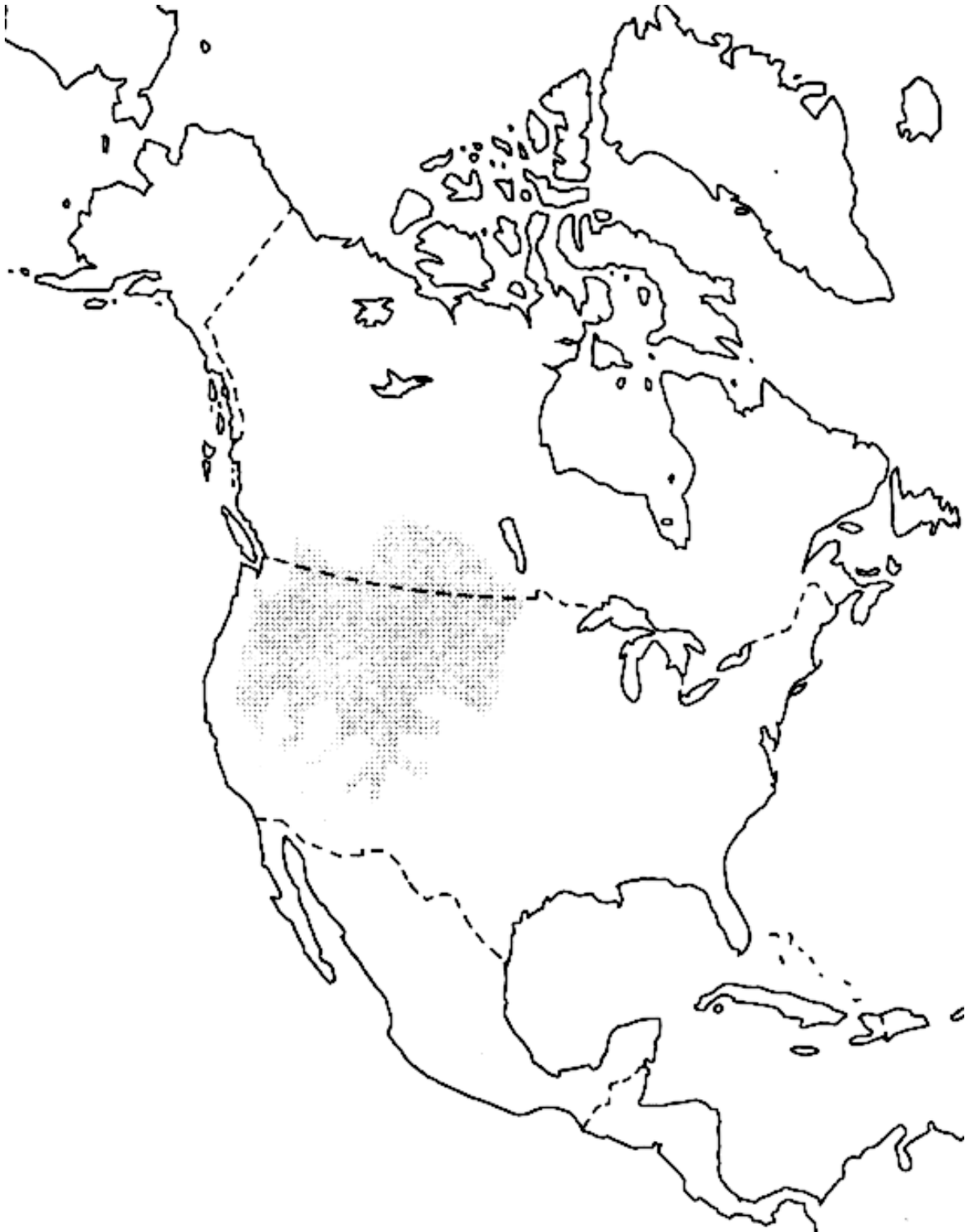


Figure 7.



Figure 8.



Figure 9.



Figure 10.

