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Integrated management tactics for predicting and alleviating pocket gopher (*Thomomys* spp.) damage to conifer reforestation plantings

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Abstract

Pocket gophers cause extensive damage to reforestation plantings in the western United States, and pose acute and chronic problems for forest managers. We examine the components of an integrated pest management strategy for reducing pocket gopher damage to conifers: the predictive factors for assessing the risk for damage, techniques for monitoring gopher populations and assessing efficacy of control methods, and damage control strategies and methods. The information in each component is reviewed and presented so that an optimal damage reduction plan can be developed in a logical, cost-effective, environmentally responsible fashion.

Introduction

Pocket gophers (*Thomomys* spp.) are fossorial rodents that probably account for more damage to natural regeneration or artificially planted conifers in western forests than all other animals combined (Crouch 1986; Borrecco & Black 1990). Pocket gophers generally are not found in densely forested areas (Barnes 1973; Bonar 1995; Crouch 1982), but rather in grasslands, natural meadows, and areas of early successional vegetation caused by wildfire, logging or other disturbance. Forest harvest also results in early successional vegetation, particularly succulent perennial herbaceous plants that provide substantial gopher habitat (e.g., Burton & Black 1978; Ward & Keith 1962). Reforestation problems result from gopher populations responding to these favorable changes in their habitat (Barnes 1973). Densities for *Thomomys* of 40–50 ha are routine, and can exceed 150 ha (Case & Jasch 1994). Seedlings usually are planted within a year of forest harvest, resulting in several years of vulnerability while the habitat is improving for gophers and their densities are increasing.

Pocket gophers forage both above and below ground, and severed or girdled stems and roots are the usual forms of damage (e.g., Barnes 1973). Damage as extensive as complete debarking of larger seedlings (e.g., Hoooven 1971), and complete removal of seedlings into burrows from underground also occurs (Black 1994). Reduced growth can result from lesser amounts of damage, whereas greater damage levels produce seedling or sapling mortality (Marsh & Steele 1992).

Conifer seedlings often do not survive long enough to receive the benefit from the tree and brush establishment that would suppress herbaceous vegetation cover, and consequently, pocket gopher density (Barnes 1974). If enough trees survive to near complete canopy closure, pocket gopher densities decline dramatically and are no longer a serious threat to regenerating forest stands. Unfortunately, repeated complete failures at reforestation are not uncommon, sometimes lasting decades (e.g., Crouch 1971; Barnes 1978). Several hundred dollars per acre in additional reforestation costs are often incurred in attempts to reduce pocket gopher damage.

Damage reduction usually has involved lethal control of pocket gopher populations, but the habitat remains favorable for pocket gopher occupancy and populations can recover rapidly (Witmer *et al.* 1996; Engeman & Campbell 1999). Control of gopher damage in reforestation plantings is an acute and chronic challenge, but a variety of control methods exist to address both the acute and chronic nature of the damage.

We review risk factors and current and potential damage reduction methods. Concomitant with, and in advance of, the need to devise a control strategy are the needs to assess the risk for damage, population levels, and the efficacy of control methods. The use of multiple methods (cultural, physical, chemical) to reduce damage potential can provide an effective, integrated pest management program to reduce pocket gopher damage to reforestation.

Factors affecting the risk for damage

Many factors affect the extent to which a reforestation unit is susceptible to damage from pocket gophers. Some factors are inherent to the local geography, geology, and climate, while others relate to forest management approaches (see Emmingham *et al.* 1992; Owsten *et al.* 1992 for discussions on the relation of silvicultural practices to animal damage in general). Each factor relates to the ecology of pocket gophers and some also can be used to predict damage and be manipulated as part of a damage prevention strategy.

Risk factors associated with forest management

Recency of harvest. If the site has been cleared of timber, then the successional processes that promote optimal gopher habitat have been set in motion. If the site has not been cleared, then more latitude exists for planning the harvest to minimize the potential for pocket gopher occupancy. The time elapsed after forest harvest or burn usually relates to the extent of plant successional development. Early successional stages, supportive of high pocket gopher densities, usually establish within 5 years post-clearing, and can prevail for many years (≥ 15 yr) before being curtailed by overstory growth (Pase & Hurd 1957).

Forest harvest method/size. The degree to which an area is cleared (or burned in a forest fire) affects the degree

and length of time plant communities are returned to an earlier seral stage (e.g., Franklin & Dyrness 1973). Clearcuts hold more potential for establishment of high gopher populations than partial cuts or shelterwood cuts that leave $> 40\%$ overstory canopy cover (Jameson 1967; Krueger 1981), although Pipas and Witmer (1999) found little difference in gopher populations and seedling damage between clearcuts and shelterwood cuts when the shelterwood cuts resulted in a small fraction ($< 30\%$) of the original overstory. Consequently, some forest harvest methods (clearcut, shelterwood cuts) provide better conditions for pocket gophers than other types of cuts such as partial, single-tree, salvage, or commercial thinning (Marsh & Steele 1992).

Site preparation. Many types of site preparation and associated soil disturbances affect the early seral plant community and, hence, the potential for establishment of gopher populations. The logging practices used to achieve different intensities of forest harvest (clearcut, shelterwood, single tree selection, salvage, commercial thinning) also contribute to site disturbance. Differences in pocket gopher populations between clearcut and shelterwood sites are partially due to the soil conditions after harvest, in addition to the amount of overstory remaining (Barnes 1974). Soil scarification and slash piling usually produce a substantial supply of loose soil in which pocket gophers can readily establish new burrow systems, and also return plant communities to earlier stages (Barnes 1974). Many site preparation activities reduce the woody plant material in the understory and shrub layers that would minimize the carrying capacity for pocket gophers. In contrast, leaving a substantial litter blanket (dead plant material) after clearing can delay establishment of early seral plants and has been successful in other contexts to reduce rodent invasion rates (e.g., Whisson 1996). Herbicide usage to reduce vegetative competition with newly planted seedlings also may delay the development of the plant communities attractive pocket gophers.

Risk factors inherent to the site

Gopher presence. The presence of pocket gophers at a site, or at nearby sites, substantially increases the probability for future damage. The distance to an established pocket gopher population may influence site invasion (Barnes 1974), because young gophers have

good dispersal capabilities. Sites adjacent to meadows, or other forest openings which support pocket gopher populations (Barnes 1973), are more susceptible to invasion.

Soil type. Knowledge of soil types can be used to anticipate gopher damage before forest harvest, as gopher populations are greatly influenced by soil type (Horton 1987). Deep, well-drained and light-textured soils offer optimal conditions for burrowing and optimal gas exchange with the atmosphere. Soils such as clay loams, granitics and pumices promote the establishment of pocket gopher populations, but soils such as heavy clays, excessively sandy or rocky soils and poorly drained soils tend to have marginal pocket gopher populations.

Plant association. After a site is harvested, the plants expected to follow in succession and their importance for supporting pocket gophers can be used to predict the establishment and buildup of gopher populations (Franklin & Dyrness 1973; Marsh & Steele 1992). Species combination and vegetation palatability are indicative of which plant association will promote or inhibit pocket gopher populations (Black 1994). In some areas, the seral stages and plant communities that favor gophers after tree removal have been identified and categorized according to risk of gopher damage (e.g., Volland 1974; Steele & Geier-Hayes 1987, 1989).

Snow accumulation. Pocket gophers are active year-round and much of the gopher damage to seedlings occurs from late fall to spring when succulent green plants are not available and snow often covers the ground (e.g., Crouch 1971, 1982; Barnes 1973, 1978; Burton & Black 1978). Above-ground portions of trees are exposed to damage by gophers as they burrow through the snow, with the risk for damage increasing with snow accumulation and snowpack duration (Barnes 1978). Less than 0.3 m of snow provides minimal risk whereas a snowpack lasting until May results in a maximal risk for damage (Horton 1987).

Slope. Damage tends to be inversely related to the slope of a site. Slopes greater than 35% usually can be expected to support only low gopher populations (Horton 1987; Marsh & Steele 1992), whereas slopes less than 10% are optimal for gopher populations (Horton 1987).

Assessing gopher abundance/activity

Pocket gopher populations should be monitored to predict if and when control measures are needed. Monitoring adjacent sites allows the manager to evaluate the potential for invasion. Furthermore, monitoring gopher activity permits the manager to assess the efficacy and longevity of preventative or control measures applied to damage to seedlings.

Because fossorial animals are difficult to observe directly, they are observed indirectly, using animal sign to reflect abundance, distribution, and level of activity. Pocket gopher mound density has been used as an index of population density and many sampling methods are available for estimating mound density. One sampling approach for monitoring distribution of gopher populations is to establish a transect with a series of plots throughout the site. Marsh & Steele (1992) recommended using 1/100 ac plots to sample 1–5% of the site. Judgements on the need for control are made on the bases of stand age and the percent of the plots showing activity. Greater percentages of activity indicate greater potential for damage. For example, the U.S. Forest Service suggests gopher population reduction if over 25% of plots are active on 0–2 year-old plantations, or over 40% on 3–5 year-old plantations (Black 1994).

Temporal changes in forest pocket gopher activity usually are assessed by examining sample plots for new mounds (Anthony & Barnes 1984; Smallwood & Erickson 1995) or monitoring opened burrows for closure (Richens 1967). Typically, existing mounds are flattened, and then the area is checked a few days later for new gopher sign. However, mound building activity fluctuates seasonally and is especially high in the spring and fall when favorable soil moisture levels prevail. Pocket gopher burrow systems have a single occupant, except during mating and while young are with the mother. Thus, open-hole assessments are most valuable (Engeman *et al.* 1993) when assessing the effectiveness of direct population control measures. Generally, 2 or 3 holes are opened in each burrow system and then rechecked after 24–48 h for closure. If even one hole is closed, the burrow system is considered occupied. Parameters for the application of the open hole method that optimize the sensitivity of the results relative to the labor required in the field (number of holes opened, size of activity plots) also have been investigated (Engeman *et al.* 1993, 1999b).

Damage control methods

Many methods have been tested with varying degrees of success for reducing damage by pocket gophers. Traditionally, lethal methods have been used to directly reduce populations (Case & Jasch 1994), but this approach often offers only short-term control and usually requires repeated applications. Besides the issue of cost-effectiveness, the public increasingly prefers non-lethal means of damage reduction (e.g., Acord 1992). Various nonlethal strategies have been investigated or tried, including vegetation management to minimize gopher food supplies, silvicultural practices that prevent production of optimal gopher forage and soil conditions, or prevention of gopher access to seedlings through the use of barriers or repellents. Although pesticides and herbicides may have major roles toward reducing pocket gopher damage for the foreseeable future, they are becoming more limited in their usage, thereby increasing the need for preventive management practices. A single control strategy does not exist for all damage situations. The acute and chronic natures of gopher damage require a customized damage prevention strategy using a combination of tools and approaches appropriate for the specific situation. Hence, a thorough knowledge of the methods, including the benefits and limitations of each, is needed.

Direct population reductions

Hansen (1960) reported an annual natural mortality rate of 75% in pocket gopher populations. Thus, an effective lethal control program would need to provide significant additional mortality, probably to a total annual rate of at least 90% (Teipner *et al.* 1983). Marsh and Steele (1992) noted that the percent reduction is not as important as the density of the remaining gophers and acceptable long-term control is achieved when densities are less than 5 gophers/ha. Caughley and Sinclair (1994) emphasized that the individuals remaining after lethal control have relatively greater resources available to them, which in turn may stimulate reproduction. Due to the high reproductive potential of pocket gophers and their ability to rapidly invade an area of high quality habitat, repeated lethal treatments are often needed to adequately suppress the population until the seedlings have grown beyond their vulnerability (Bonar 1995; Sullivan 1986).

The timing of direct control is an important consideration for rodents with high reproductive potential, such as pocket gophers. Cantrill and Ramsey (1991) used

a simple simulation to demonstrate that when conditions are conducive for rapid population growth, the effectiveness and duration of damage control efforts increase the earlier they are applied. Similar observations about growth of rodent populations have been noted by Redhead (1987); Redhead *et al.* (1985). Bonar (1995) provided examples that also demonstrate that reducing a population at low densities can prevent a more serious build-up in the future.

Oral toxicants. Poisons are usually applied as a coating to grain baits or as an ingredient of manufactured pelleted baits. Baits can be applied by hand or mechanically by use of a baiting probe or a burrow builder (e.g., Black 1994; Case & Jasch 1994). For hand baiting, pocket gopher burrows are usually located with a metal probe in the vicinity of fresh sign. The burrow is opened and bait placed in the runway. The hole must be recovered or the gopher will plug the burrow with soil to maintain a closed system, and hence, will not encounter the bait. Also, a mechanical probe is available that allows the applicator to probe the burrow and dispense bait in the same motion (Barnes 1973). Typically, several bait applications are made in each burrow system. Hand baiting cannot be conducted effectively until mounding becomes extensive enough in the spring to identify the locations of burrow systems. Otherwise, too many occupied burrows would be missed and control would not be effective. Burrow building activity, and hence mound production, is often highest in the spring and fall during mild temperatures and moist soil combinations. As an alternative to hand baiting larger areas, the burrow builder, a tractor-drawn implement, creates parallel artificial burrows into which bait is automatically dispensed at regular intervals (e.g., Barnes 1973; Evans *et al.* 1990). Burrow builders require favorable soil conditions and a lack of impediments such as large rocks, stumps, and shallow bedrock. While toxic baits placed within a sealed burrow system pose a low primary or secondary hazard to nontarget species (e.g., Hegdal & Gatz 1976; Record & Marsh 1988), spills must be carefully cleaned up to reduce a potential hazard. Further reducing secondary hazards in the unlikely event that gophers die on the surface, small mammal carcasses deteriorate rapidly (Witmer *et al.* 1995b).

Bait formulation and quality are important considerations because of the keen sense of smell of pocket gophers (Bonar 1995). Moldy, rancid or damp baits are rarely accepted. If one bait is not effective, a different formulation or toxicant should be tried. Because

pelleted and grain baits may degrade over time, especially in moist burrow conditions, longer-lasting baits have been developed, usually by mixing the baits with paraffin. Such baits are frequently moved to nest chambers (Campbell *et al.* 1992; Vossen & Gadd 1990), but may be less palatable to gophers. In theory, after the death of the resident animal, the bait block still may be available to subsequent invading gophers. Some experimentation may be necessary to identify the most acceptable commercial bait and the most effective time of year for baiting (Proulx 1998).

Acute toxicants, designed to be lethal with a single feeding, are a relatively inexpensive means to rapidly reduce populations, although sublethal doses can produce a learned bait aversion that leaves enough survivors to quickly rebuild the population (e.g., Nolte & Otto 1996). Strychnine alkaloid and zinc phosphide are the most commonly used acute toxicants for pocket gopher control in the U.S., with zinc phosphide less effective than strychnine (Barnes *et al.* 1982; Bonar 1995), probably due to taste aversions. Acute toxicants must be handled carefully, as they can pose hazards to nontarget species, including humans. There are no known antidotes for these two toxicants.

Chronic toxicants normally require multiple ingestions to be lethal and include anticoagulants such as warfarin, chlorophacinone and diphacinone. Cholecalciferol (vitamin D₃) also usually requires multiple doses to produce mortality (Nolte & Otto 1996). Vitamin K can be given as an anticoagulant antidote to humans or pets. A single chronic toxicant ingestion is not likely to be lethal to nontarget species, but scavenging animals can be exposed to secondary hazards from anticoagulants. Chronic toxicants are not likely to produce taste aversions because the delayed onset of symptoms does not permit association of symptoms with feeding. The need for multiple ingestions also means that chronic toxicants may not reduce populations as rapidly as acute toxicants and mortality rates may suffer if baits deteriorate or run out.

Fumigants. Toxic gases may be introduced into burrow systems to kill gophers. Smoke cartridges (e.g., Savarie *et al.* 1980; Matschke *et al.* 1996) can be used to produce carbon monoxide and carbon dioxide gases, while aluminum phosphide pellets placed in burrows react with ambient moisture to produce phosphine gas. Fumigants tend to be more expensive to apply than toxic baits and they are often of low efficacy due to gas leakage, especially in dry, porous soil, and because pocket gophers may rapidly seal off affected burrows

(Marsh 1992; Stewart & Baumgartner 1973). Sullins and Sullivan (1993) tested a mixture of propane and oxygen, which when ignited after injecting it in a burrow system, was supposed to kill gophers through the concussion of the explosion, but efficacy was low (12%). Fumigants also pose greater hazards than poison baits to nontarget animals in the burrow system, and pose a potential hazard to the applicator (Nolte & Otto 1996).

Trapping. Trapping is a labor-intensive method that is rarely well-suited for large areas or dense gopher populations (Barnes 1973; Crouch & Frank 1979; Nolte & Otto 1996; Teipner *et al.* 1983), but it merits consideration to remove remaining animals after toxic baiting, or to remove small gopher populations from a site before harvest, or in situations where toxicants cannot be used (e.g., endangered species, water quality).

The procedures for trapping pocket gophers are well-described (Marsh 1997; Marsh 1998; Witmer *et al.* 1999). Most gopher traps are pincher traps, which crush the animal with two spring-loaded jaws, or box chokers, which pin an animal to the floor of the box with a spring-loaded wire jaw similar to a snap trap (Marsh 1998). The Macabee trap is a pincher design that is probably the most commonly used gopher trap (Marsh 1992) because of its efficacy and ease of setting with minimal digging (Storer 1953). Proulx (1997a) evaluated several types of traps and found box traps to be more effective in catching pocket gophers. Although some nontarget animals may be caught in each type of trap, the rate of capture of nontargets is usually very low (Witmer *et al.* 1999).

Enhancing predation. Many animals prey on pocket gophers, but prey density typically controls predator density for co-evolved species, rather than the other way around. However, enhancing natural predation through low-cost means, such as using artificial raptor perches to deter above-ground dispersal (Howard *et al.* 1985; Reid 1973), can complement other management strategies.

Indirect population reductions through habitat manipulation

Habitat manipulation has been described as the most elegant population control mechanism (Caughley & Sinclair 1994), as it serves to reduce the resources available per individual, thus promoting a negative feedback response whereby reproduction also is likely to

diminish in the face of limited resources. Manipulation of habitat characteristics relating to food and cover can have a substantial effect on rodent populations (e.g., Hansson 1975; Marsh & Steele 1992). These methods involve reducing the availability of the essential or preferred gopher foods, or avoiding harvest or site preparation methods that improve gopher burrowing capabilities.

Vegetation management through herbicides. Vegetation management through the use of herbicides on rangelands (Keith *et al.* 1959; Hull 1971; Tietjen *et al.* 1967) and in orchards (Sullivan & Hogue 1987) has resulted in reductions in pocket gopher populations. Others have described improved seedling establishment environments and increased seedling stocking rates following the use of herbicides (Cristensen *et al.* 1974; Crouch 1979; Crouch & Hafenstein 1977). Black & Hooven (1977) demonstrated improved seedling survival for five species of conifers from the use of combinations of herbicides including atrazine, simazine and 2,4-D. Longer-term studies that monitored individual seedlings for damage and survival showed substantially improved survival of pine seedlings and long-term reductions in gopher populations following atrazine treatments (Engeman *et al.* 1995a), and 2,4-D treatments (Engeman *et al.* 1997b).

Nonchemical vegetation management. Grazing by sheep or cattle has been examined as another means to reduce the amount of preferred pocket gopher forage on a site. Lower pocket gopher densities have been reported on heavily grazed (mainly cattle) versus ungrazed sites (Hansen 1965; Hunter 1991; Turner 1969). Phillips (1936) found that moderately overgrazed ranges supported greater numbers of pocket gophers than ungrazed sites, but heavily overgrazed areas had lower gopher densities than ungrazed sites. Cattle grazing was found by Kingery and Graham (1987) and Kingery *et al.* (1987) to be inversely proportional to above-ground gopher damage. Owsiak (1996) found intensive sheep grazing to substantially reduce pocket gopher densities, more so than free-range cattle grazing. Cattle and sheep grazing induced elevated grass consumption by pocket gophers, but root biomass in free-range cattle-grazed units was 50% higher than on intensive sheep-grazed and ungrazed units. On the other hand, grazing may present detrimental environmental consequences, such as erosion or degradation in water quality, and grazing must be carefully monitored

to avoid livestock trampling, feeding and rubbing damage to seedlings or saplings.

Another nonchemical method to reduce gopher forage without applying chemicals is to leave logging debris, organic litter, or residual shrub cover on the site after forest harvest. This can delay growth of herbaceous vegetation, the preferred pocket gopher food, and has been used in other rodent control contexts to slow population buildups in crops (e.g., Whisson 1996). Burning and mowing have been used to manage vegetation and to reduce the habitat quality for some rodent species (e.g., Gates & Tanner 1988), generally in orchard settings. Burning is decreasing in reforestation units because of air quality concerns and the risk of fires escaping containment.

Planting unpalatable vegetation. Planting vegetation unpalatable to gophers may deter the growth of preferred gopher forage. Fine-rooted grasses have been used on clearcuts to deter a buildup of bull thistle density (Marsh & Steele 1992), an important gopher food source. Engeman *et al.* (1998b) used grass seeding in addition to herbicide treatment to reduce production of preferred gopher forage, but did not demonstrate conclusive beneficial results. Dense shrub cover may also limit the growth of gopher forage, but it could be detrimental to growth of some conifers (Barnes 1974), but for some species of conifers, such as Douglas fir (*Pseudotsuga menziesii*), this approach may be beneficial under some circumstances (Marsh & Steele 1992; Steele & Geier-Hayes 1989).

Extent of overstory removal. In addition to providing some opportunity for natural regeneration of tree stocks, retaining a relatively high level of forest overstory may limit sunlight to inhibit the growth of herbaceous ground vegetation. The existing understory vegetation receives less damage and is more able to compete with early seral plants that could become established. Thus, certain harvest methods can be used to reduce gopher population increases. Cuts that remove a substantial portion of overstory canopy, especially clearcuts, create the most favorable conditions for gophers.

Soil disturbance. The means by which logs are removed and the site prepared for replanting can greatly affect gopher burrowing capabilities. In general, greater overstory removal creates greater soil disturbance, which results in better quality habitat for pocket gophers

by facilitating burrowing and promoting a flush of herbaceous plant growth favored by pocket gophers (Black 1994).

Reducing gopher access to seedlings

Another damage reduction strategy is to deter gopher access to individual seedlings or larger areas with barriers, which can be physical obstructions, or sensory obstructions using aversive tastes, smells, or frightening devices. Physical and chemical devices have been used with varying levels of success to control damage by pocket gophers.

Mechanical barriers. Mechanical barriers are an alternative to managing gopher populations to reduce damage (e.g., Marsh *et al.* 1990). Wire mesh fencing installed from below ground to above the height of snow accumulation can exclude gophers from an area, but is rarely an affordable solution. Occasionally it is used to protect seed nurseries, high-valued truck vegetable crops, or research plots. The buried wire mesh should extend at least 1 m deep. Some individuals occasionally may breach the barrier, prompting the use of trapping or other control measure inside the barrier.

Wire cages around individual seedlings deter animal damage (Black *et al.* 1969), but caging was not practical for extensive use until plastic mesh tubes were developed as seedling protectors (Campbell & Evans 1975). Seedling protectors originally were developed for reducing feeding injuries to Douglas-fir by lagomorphs and ungulates, but since have been used in areas with pocket gopher damage. Unlike previously used materials, plastic mesh tubes can be used to surround the seedling's roots as well as the above-ground parts. Studies have demonstrated the effectiveness of plastic mesh tubes for reducing gopher damage, including a long-term geographically extensive evaluation that individually monitored large numbers of protected and unprotected seedlings in areas of historically high gopher damage (Engeman *et al.* 1999a). Even so, when tubes are used in areas with high gopher densities, seedlings can still receive high damage levels (Pipas & Witmer, 1999). Some foresters have expressed concern that roots may be damaged by plastic tubes, but Engeman *et al.* (1997a) did not find that to be the case. The use of plastic tubes may also result in increased growth rates of some conifer species, probably as a result of improved microclimates within the tubes (Engeman *et al.* 1999a; Neel & Harris 1971). Use of seedling

protectors increases planting costs, but they also may reduce other wildlife damage, as they have been effective barriers to other rodents, ungulates, and lagomorphs (Borrecco & Anderson 1980; Baer 1980; Black 1992; Campbell & Evans 1975).

Repellents. Repellents are intended to ward off gophers from individual seedlings on contact, or repel gophers from the general area planted with seedlings. In either case, effective chemical repellency has not been demonstrated. Similarly, mechanical frightening devices have not effectively driven rodents from areas (Marsh *et al.* 1990).

Repelling gophers from seedlings has been attempted systemically with a bitter compound, denatonium benzoate, but was not effective, partly due to variable uptake and redistribution of the compound by conifers (Engeman *et al.* 1995b; Witmer *et al.* 1998). Compounds tasting bitter to omnivorous animals (bears, humans) probably are not as aversive to strict herbivores, including deer, gophers, and rabbits (Jacobs *et al.* 1978; Nolte *et al.* 1994). Witmer *et al.* (1997) tested a variety of commercially available compounds and found few that would deter captive gophers from feeding on treated apple chunks, although application of predator odors showed some promise.

In contrast to repelling gophers from individual seedlings, repelling gophers from a planted area has also been tested. Predator-derived odors (urines, feces, and anal gland compounds) are generally aversive to prey (e.g., Epple *et al.* 1993) and may deter herbivores from entering an area. Sullivan *et al.* (1988) altered the distribution of gophers within treatment grids by applying synthetic mustelid anal gland chemicals. Sullivan *et al.* (1990) reported reduced over-winter re-invasion rates using the same anal gland compounds. Witmer *et al.* (1997) showed reduced gopher feeding using predator urines in pen trials, but the compounds did not reduce rapid re-invasion during a field trial. A commercial repellent product currently is not available in the United States that effectively (and economically) repels gophers on an operational scale. Most predator odors are volatile compounds, making long-term delivery for field conditions problematic. Also, without reinforcement stimuli (i.e., actual presence of predators and acts of predation), herbivores may learn to ignore the odors (Garcia *et al.* 1972).

Seedling size and vigor. Larger seedlings at planting more quickly reach a size where they are less

vulnerable to gopher damage (Capp 1976). Seedlings less than 1.3 cm in diameter are commonly clipped by gophers, whereas larger seedlings may be chewed, but often escape clipping or complete girdling. Marsh & Steele (1992) suggested the use of seedlings grown in a nursery for 2 years (2-0 seedlings) that show a good root-to-shoot ratio.) Similarly, seedlings with high vigor not only grow more rapidly to less vulnerable sizes, they also tolerate more damage than weaker seedlings (Marsh & Steele 1992). The seedlings should also be planted before pocket gopher populations have a chance to occupy the site at substantial densities. However, there is anecdotal evidence that nursery-grown seedlings may be more attractive to gophers because of their higher nutrient (especially nitrogen) content.

Resistant seedlings. Case (1983) suggested planting seedlings that demonstrate resistance to gopher feeding, because of reduced palatability. This is a difficult task to accomplish. Cummins (1975) found that pocket gophers did not show a preference among six varieties of ponderosa pine seedlings, but there were differences in the amounts consumed. Similarly, Crouch (1971) found no differences in susceptibility among three species of pine. Conifers can differ among species, strains, and individuals in chemical composition (Radwan *et al.* 1982; Kimball *et al.* 1998). Eventually, it may be possible to genetically select, or alter, seedlings to create chemical compositions that gophers least prefer. Currently, foresters use genetic selection of tree varieties for hardiness and disease resistance, but not for resistance to vertebrate foraging. Some tree species appear less susceptible to gopher foraging (e.g., Bonar 1995), but foresters are under many constraints as to which species and in what proportions they can use. Another approach might be to plant less valuable species with high survival probability, rather than more valuable species that are highly palatable to gophers (Emmingham *et al.* 1992; Owsten *et al.* 1992).

Rapid restocking. Early restocking is another damage prevention method. Seedlings that are in the ground before herbaceous growth has had an opportunity to proliferate, and before gophers densely populate the site, have a greater chance to grow to a less vulnerable size. Prompt restocking (within 8 months of harvest) may be the most important silvicultural practice for the prevention of future pocket gopher damage (Marsh & Steele 1992).

Buffer zones. Retaining buffer zones of mature forest around the periphery of harvested units has slowed invasion by pocket gophers. Barnes (1974) reported that 183–213 m buffer strips of mature lodgepole pine forest were rarely crossed by pocket gophers after 4 years. He also found buffer strips at another site to deter invasion for about 2.5 years. Marsh & Steele (1992) suggest that a buffer as narrow as 60 m would be helpful but the minimum should probably be 120–180 m. Buffer zones could comprise any habitat that does not support significant gopher populations, such as forested areas, lightly harvested areas, brush fields, or non-gopher infested grasslands. Buffer zones increase the distance gophers must travel to disperse into a harvested area, and coupled with other measures, may further inhibit invasion. For example, a buffer zone could be periodically trapped or baited for invading gophers after the gophers have been removed from the harvest unit (e.g., Proulx 1997b).

Supplemental feeding

Supplemental feeding has successfully been used to manage damage by some wildlife species to regenerating trees (e.g., Campbell & Evans 1978; Sullivan 1998; Ziegler 1994), but the results have been mixed for overcoming gopher damage. Strategies include providing gophers with a preferred, alternate forage to seedlings, or saturating an area with seedlings so that sufficient numbers survive to outgrow their vulnerability.

Alternate forage. Borrecco (1976) reviewed the use of supplemental foods to reduce damage to seedlings, although Bonar (1995) contended that supplemental feeding would improve the carrying capacity for gophers to create a cycle of increasing need for alternate forage to keep up with increasing gopher population density. Furthermore, much seedling damage occurs during the winter when alternative, preferred forages (herbaceous plants) are not available. If damage occurred during a short, intense period, then supplemental feeding (if suitable food were available) could divert damage as in other species (e.g., Sullivan 1998).

Increase seedling stocking rate. A 5-year study found that the number of seedlings surviving on double-stocked plots was approximately double that for the baseline subplots (Engeman *et al.* 1998a). Doubling the stocking level did not saturate the areas with enough

seedlings to overwhelm the damage rate by pocket gophers, but also did not fall short of producing twice the number of survivors. Thus, for some situations, increasing the stocking rate may be an effective and less costly alternative to other more expensive or legally restricted damage control methods.

Devising a damage reduction strategy

Strategies for reducing animal damage have evolved considerably from essentially reactive lethal control programs to organized integrated pest management approaches using a combination of tactics (e.g., Fall & Jackson 1998). A battery of preventative and reactive measures blending lethal and nonlethal control techniques is available for the forest manager to select the most cost-effective route for minimizing damage, while also minimizing adverse environmental effects (e.g., Fiedler & Fall 1994; Witmer *et al.* 1995a). Reforestation sites can be characterized by a set of damage risk factors, some of which can be controlled or manipulated by the forest manager before, during, or after forest harvest. Similarly, each site can be characterized by feasible damage control methods, restrictions on methods, and reforestation options and objectives.

The specific steps to minimize the impact of pocket gophers to reforestation efforts should be considered sequentially. First, the potential for future damage on a currently forested site should be evaluated by examining the site's risk factors before harvest (Table 1). This assessment should be completed before deciding on a damage control strategy, because the potential for damage is related to, or can be altered by, many factors. If a site already has been cleared of trees and replanted, risk assessment also would involve evaluating current damage levels (Engeman, *in press*) and projecting the damage likely to accumulate before seedlings outgrow their vulnerability. The options available for reducing the damage potential decreases as work on the site progresses from before harvest, to harvest and site preparation, to post-planting of seedlings, and finally, to reforestation objectives. If damage or the risk for damage is excessive, then an integrated damage reduction strategy should be developed and implemented.

Second, the feasibility, costs, effectiveness, durability and legality of all possible damage reduction materials, methods, and strategies (Table 2) should be evaluated. If the potential for damage appears less than the probable costs of damage control, then the forest manager would continue to monitor the situation.

Again, the further this assessment of a serious damage situation is accomplished in advance, the more flexibility the manager will have, to prevent damage or respond to damage as it occurs. Each subsequent stage of the forest management cycle at which the manager implements damage reduction measures will further restrict options, and possibly, increase costs while sustaining more damage than necessary. The advantages and disadvantages of each potential action or method should be carefully considered, and the compatibility of methods should be assessed for each situation. Some methods have greater restrictions on their use, especially the application of chemicals (toxicants and herbicides) in the environment, while the use of any lethal control method may be of concern in areas where endangered species are present. The economics of a control method not only encompass the immediate costs, but also such issues as the number of reapplications that may be required, the durability of the method, maintenance requirements and liability issues.

Numerous criteria in addition to economics and legality need to be considered in the selection of damage reduction methods and strategies. These include potential environmental impacts, socio-political acceptability of the methods (especially concerning lethal controls), the effect on other damaging wildlife, the effects on nontarget species, potential negative effects on seedling survival, and safety (Table 3).

Once the risk for damage has been assessed and the damage reduction methods thoroughly evaluated, a comprehensive strategy can be developed and implemented to reduce damage. No one strategy will suit all situations, because of the large number of combinations of site variables and management objectives and constraints. More than likely, a combination of damage reduction methods will be employed to help assure successful reforestation, and the implemented strategy should have been customized to suit the particular site and management objectives and constraints.

Once a damage reduction strategy has been designed and implemented, its use should not be considered inalterable. The efficacy of the methods used, such as population reductions or forb removal, should be monitored and evaluated. If the efficacy appears insufficient, alternatives or modification of the strategy should be examined. Likewise, if secondary or unanticipated problems arise, the strategy should be re-evaluated and modified as necessary. Any application of methods should be based on a rationale derived from an examination of the risk factors and an evaluation of potential methods relative to the criteria and management objectives.

Table 1. Summary of risk factors and relative risk levels that predispose a site to seedling damage by pocket gophers and allow the formulation of a damage reduction strategy^a.

Risk factors (predictors)	Relative risk levels	Risk points
<i>A. Factors associated with management practices</i>		
1. Site cleared		
Yes	Moderate-high	2-3
No	Low-moderate	1-2
2. Time since clearing		
Immediate	Low-moderate	1
1 year	Moderate	1-2
2-5 years	Moderate-high	2-3
> 5 years	High	3
3. Forest harvest method/size		
Clearcut	High	3
Shelterwood	Moderate-high	2-3
Selective tree	Low	1
4. Site preparation		
Scarification	High	3
Slash piling	High	3
Substantial Litter layer	Low-moderate	1-2
Herbicides	Low-moderate	1-2
<i>B. Factors inherent to the site</i>		
5. Gopher history at site		
Gopher history on site	High	3
Adjacent gopher site	High	3
Adjacent gopher habitat	Moderate-high	2-3
No gopher history	Low	1
6. Soil type		
Well-drained	High	3
Poorly drained	Low	1
Easy burrowing	High	3
Difficult burrowing	Low	1
7. Successional plants		
Abundant forbs	High	3
Fewer forbs, more grasses or shrubs	Low-moderate	1-2
8. Snow accumulation		
Snowpack until May	High	3
> 30 cm	High-moderate	2-3
< 30 cm	Low-moderate	1-2
9. Slope		
< 10%	High	3
> 10% and < 35%	Moderate-high	2-3
> 35%	Low	1-2
<i>C. Damage risk evaluation</i>		
<i>Total points</i>	<i>Damage potential</i>	
≤ 14	Low potential for gopher damage; losses should be insignificant compared to potential control costs; population monitoring may be warranted	
15-21	Moderate potential for gopher damage; population monitoring needed; localized damage could occur; consider remedial action if necessary	
≥ 22	High potential for gopher damage; severe losses can be expected; population monitoring essential; develop a damage management strategy; implement before tree harvest, if possible	

^aBased, in part on Horton (1987) and other unpublished USDA Forest Service guidelines, but without weighting factors.

Table 2. Summary of methods for the reduction of damage to conifers by pocket gophers and qualitative assessment of the relative attributes for each method.

Method	Cost per application	Applications/ year	# years of application	Efficacy	Duration
<i>A Direct population reductions</i>					
[1] Rodenticide baits	Moderate	1–2	1–5	High	Short
[2] Fumigants	High	1–2	1–5	Low	Short
[3] Trapping	Moderate	1–2	1–5	High	Short
[4] Enhance predation	Low	1	1	Low	Long
<i>B Indirect population control through habitat manipulation</i>					
[1] Herbicide removal of forage	Low–moderate	1–2	1–2	Moderate	Intermediate
[2] Nonchemical forage removal					
a. Cattle, sheep grazing	Low–moderate	1–3	1–3	Moderate	Intermediate
b. Litter layer	Low	1	1	Moderate	Long
[3] Unpalatable vegetation	Low	1	1	Moderate	Long
[4] Limited overstory removal	Moderate	1	1 +	Moderate–high	Long
[5] Minimizing soil disturbance	Moderate–high	1	1	Moderate	Long
<i>C Reducing access to seedlings</i>					
[1] Mechanical barriers (costs are substantially less if they prevent damage from other species)					
a. Fencing off area	High	1	1	High	Long
b. Seedling tubes	Moderate	1	1	Moderate–high	Long
[2] Repellents	Moderate–high	1–3	2–5	Low	Short
[3] Buffer zones	Low–moderate	1	2 +	Moderate	Intermediate
[4] Increase seedling size/vigor	Moderate–high	1	1	Moderate	Long
[5] Rapid restocking	Low	1	1	Moderate–High	Long
<i>D Supplemental feeding</i>					
[1] Alternate forage	Low	1	1–3	Low–moderate	Intermediate
[2] Increase stocking rate	Moderate–high	1	1	Moderate–high	Long

Table 3. Summary of criteria for evaluating applicability of control methods for reducing pocket gopher damage to conifers.

Evaluation criteria	Sample issue or question
[1] Feasibility	Is the problem considered significant? Can the strategy be implemented? Is there adequate support?
[2] Economics	Is damage significant? Will benefits outweigh costs?
[3] Legality	Are proposed methods legal? Will there be legal challenges to proposed actions?
[4] Environmental impacts	Are there water quality considerations? Are there soil erosion concerns?
[5] Social perceptions	Are the land-use practices acceptable? Are there aesthetics considerations?
[6] Duration	Is a method a short- or long-term solution? Will costly applications need to be repeated?
[7] Applicable to other wildlife damage	Will a method also resolve damage by other wildlife? Will a method lead to other wildlife damage problems?
[8] Nontarget species impacts	What sensitive or protected species are in the vicinity of the site? Would they be put at risk by pocket gopher damage reduction methods?
[9] Effects on seedlings	Can seedlings be adversely affected by the methods used? Will seedlings significantly benefit from gopher damage control?
[10] Safety	Are the methods safe for the applicators and the public? Can safety risks be reduced or minimized?

The strategy selected and implemented should be well-documented to assist future actions, new personnel, and for use in any controversy or legal action that might ensue.

The potential for gopher damage to reforestation can be assessed using Table 1. If pocket gopher damage can be anticipated, Table 2 can be used to identify damage reduction methods that appear appropriate for the situation, either singly or in combination. The further formulation and customization of a damage reduction strategy can be facilitated by considering the method selection criteria in Table 3. Implementation of a successful pocket gopher damage reduction strategy will help assure abundant wood fiber resources for the future.

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