Management of Winter Soil Temperatures to Control Streambank Erosion

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Abstract.—Winter soil temperatures were measured in streambanks under different vegetation cover conditions in northeastern Nevada. Grass provided significant streambank insulation at two different elevations and aspects when compared to bare soils. Grass cover moderated average maximum and minimum soil temperatures, reduced average daily soil temperature fluctuations, and decreased the number of days that the soil temperature fell below 0° C. Previous research on horizontal soil surfaces has shown that frost-heaving and freeze-thaw cycles alter soil strength. Therefore, it is postulated that the formation of soil ice weakens the internal structure of streambanks. Weakened banks are less able to resist disturbance from high velocity run-off flows and ice floes and overburden pressure exerted on the weight-bearing strata. The temperature modifications resulting from vegetative cover appear to be sufficient to reduce the number of freeze-thaw cycles along the streambank face. Riparian management should be designed to provide sufficient vegetative cover over the winter to insulate streambanks and maintain soil strength.

Streambank stability is determined internally by the soil's ability to resist displacement and externally by vegetative cover and streamflow characteristics. Some of the external forces which work to displace streambank soils are tractive force from high velocity flows and ice floes, gravity, and trampling. A streambank's ability to resist these forces (i.e., soil strength) can be internally weakened by ice formation in the soil and frost-heaving. By understanding the processes which weaken streambanks, land managers can develop streamside management strategies which reduce streambank vulnerability and favor functional stability.

As soil water freezes and expands, it increases soil volume by pushing soil particles above the level of the original soil surface. This effect is commonly observed in the formation of needle ice which pedestals soil particles. Severe frost formation can lift large amounts of soil and objects as large as fenceposts. When soil displacement occurs on a nearly vertical surface, such as the face of a streambank, gravity transports the particles locally and streamflow can carry them off-site. Susceptibility to frost formation and magnitude of soil weakening from freezing and thawing may vary with soil texture, bank height, and arrangement of soil layers. The frequency and depth of freezing, however, reflect the extent to which the soil is exposed directly to air temperatures. Insulation appears to be one mechanism by which streambank vegetation helps stabilize and form bank shape. This paper presents data that support the hypothesis that streambank vegetation has powerful insulation potential. The paper also reviews literature that suggests insulation of streambank soils may be important to overall bank stability, and addresses the implications and direction for management which derive from this information.

Literature Review

Ice formation in the horizontal soil surface and the resultant heaving and erosion have long been recognized by agriculturists, silviculturists, and engineers as important mechanisms of soil aggregate destruction. For ice to form in soil, subfreezing temperatures, water, and, usually, small soil pore spaces must be present. The magnitude of soil ice formation varies with soil type, moisture content, and temperature gradient (Hinman and Bisal 1968; Penner 1968; Chamberlain 1981; Meentemeyer and Zippin 1981). Frost-heaving may be more prevalent in soils with higher bulk densities, probably because smaller soil pores facilitate the capillary flow of water to the freezing zone and are quickly filled by the expanding ice crystals (Heidmann and Thorud 1975; Chamberlain and Gow 1979). However, leaf litter and snow insulation appear to be more important factors in determining frost susceptibility than soil type (Thorud and Anderson 1969).

Ice formation apparently creates a suction (from a moisture gradient, or negative matric potential) in the immediate soils which draws water from underlying layers (Domby and Kohnke 1955; Broms and Yao 1964; Soons and Greenland 1970; Pikul and Allmaras 1985). Soil structure is increasingly altered as moisture content increases in well-aggregated soils (Logsdail and Webber 1959; Benoit 1973; Bullock et al. 1988). Saturated soil conditions during thawing lower the soil's internal angle of friction, particularly in soils that were frozen slowly (1.27 cm/d) or subjected repeatedly to freeze-thaw cycles (Broms and Yao 1964). The net result is decreased slope stability. Slope destabilization also results from a decrease in shearing strength and bearing capacity when soil density decreases from frost-heaving (Broms and Yao 1964; Formanek 1983). Ice expansion that compress rather than heavees soils can also leave cracks (Chamberlain and Gow 1979). Increased moisture, decreased density, and cracks weaken soil strength.

Study Site

Gance Creek is primarily a snowmelt-fed stream in the North Fork of the Humboldt River basin in northeastern Nevada. The stream originates in the Independence Mountains, about 64 km north of Elko, Nevada, where streamflow is perennial and supplemented by numerous small springs. Precipitation in this area averages about 63.5 cm annually, falling primarily as snow (unpublished data, Saval Research Project, U. S. Bureau of Land Management). However, the 1986-1987 winter was particularly dry and the study site experienced substantially less snowpack than normal. After leaving the mountains, Gance Creek flows across a typical northern Great Basin big sagebrush *Artemisia tridentata wyomingensis,* rabbit brush *Chrysothamnus viscidiflorus*, and bluebunch wheatgrass *Agropyron spicatum* valley. Irrigation water withdrawal occurs in some years and the lower reaches often dry up for part of the summer. Precipitation in this area is about 33 cm annually, falling primarily as snow. The snowpack was

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also low in 1986-1987, but it did blanket the area. Although vegetation and soils can have very patchy arrangements in riparian areas, the specific location of the temperature measurements were in sandy loam soils with Kentucky bluegrass *Poa pratensis* and willow *Salix* spp. cover in the upper reaches and also in the valley.

Methods

Stainless steel-fiberglass wafer temperature sensors were buried about 3 cm into the face of streambanks in pairs of exposed and grass-covered (with Kentucky bluegrass) soils. Because the calibration of stainless steel wafer sensors can vary among wafers, several sensors were tested in the laboratory and those with similar responses were selected for field use. Data recorders logged average temperature every 3 h from January through May 1987. Two pairs of sensors were buried at the upper elevation site and two pairs at the lower elevation for a total of four sets of paired sensors. The upper elevation site was at 2,048 m, where the snow free period extended from 2 April to 13 May 1987. One sensor of each pair was under a 1- to 2-cm deep cover of grass and litter. The other sensor of each pair was in exposed streambank soil. One pair faced west and the other faced east. The lower elevation site, at 1,786 m, was snowfree from 6 March to 6 May 1987. Although the ground cover was the same as the upper elevation site (1-2 cm of litter and Kentucky bluegrass), there was also a sparse overstory of willow over the west-facing pair. The lower site had one west-facing pair and one east-facing pair.

The temperature data were divided into periods of snow cover and no snow cover (< 3 cm depth); only data from the no-snow period were used to avoid confounding the results with insulation effects from snow. Average daily soil maximum temperature, minimum temperature, and temperature change (maximum minus minimum) were determined for each sensor point. Paired *t*-test analysis compared the effects of grass cover and bare soil on the three temperature variables only in streambanks with no snow cover.

Results

Because snow is an effective insulator, the analysis of grass cover versus bare soil was performed on soil temperatures without snow cover. The daily temperatures crossed 0° C almost twice as often in bare soils than in grass-covered soils (Table 1). This is used as an indication of the relative number of freeze-thaw cycles. Further analysis showed that grass-covered soils had significantly lower average maximum temperatures and significantly higher minimum temperatures, resulting in smaller average daily temperature fluctuations than in uncovered soil (Table 2). Each site was examined and photographed every week or 2 weeks throughout the data collection period; concrete ice and needle ice formation in the exposed banks were observed. Loose soil on snow covering the toe of the stream bank was also noted beneath exposed banks.

Table 1.—Percent of days with streambank soil temperature change crossing the freezing point along Gance Creek, spring 1987. Soils were snow-free.

Station	Grass cover	Bare soil
Pair 1, lower	48%	90%
Pair 2, lower	47%	88%
Pair 3, upper	39%	65%
Pair 4, upper	52%	71%

Table 2.—Paired *t*-test comparing streambank soil temperatures at stations on Gance Creek with grass cover or bare soil in spring 1987. Soils were snow-free. Asterisks denote significantly higher mean temperature ($P < 0.05$* or $P < 0.01$**). Degrees of freedom=3.

	Average maximum temperature (°C)	Average minimum temperature (°C)	Average daily temperature change (°C)
Air	12.5	-3.4	15.90
Grass soils	12.1	0.45	11.65
Bare soils	18.5	-2.98	21.49
t value comparing grass and bare soils	3.568 *	10.46 **	4.742 *

Discussion

Temperature Effects on Soils

In bare soils without snow cover, wide daily temperature fluctuations occurred. Grass cover significantly moderated the daily fluctuations in soil temperatures and greatly reduced the number of days that the soil temperatures crossed zero, suggesting fewer freeze-thaw cycles and less opportunity for frost-heaving in grass-covered soil. Repeated freeze-thaw cycles can magnify the effects of a single cycle. Formanek (1983) reported that the rate of water migration to the freezing front in saturated soils increased with each freeze, up to three freezes. Broms and Yao (1964) found that one cycle of rapid freezing (7.6 cm/day) reduced the strength to 50-70% of that found in control soils, and repeated freeze-thaw cycling further reduced the strength to 10-20% of the controls.

Colder temperatures also increase the effects of freezing. Changjian and Zongyan (1981) investigated horizontal frost heave thrust acting on buttress construction and reported that the thrust of the soil increases as the temperature falls, until it reaches a maximum value of about -7° C. Thus, colder temperatures increase the likelihood of soil displacement and streambank damage. Weakening the internal structure of a streambank with repeated freeze-thaw cycles leaves the bank vulnerable to accelerated failure due to gravity, streamflow, ice floes, and animal trampling.

Vegetation Effects on Temperature

The grass cover on the streambanks moderated soil temperatures in much the same way plant cover and mulches do on horizontal soil surfaces. It is notable that significant temperature differences were found with so little vegetative cover; more cover could dramatically alter the temperature fluctuations. Vegetation lowers both surface wind velocity and the turbulent exchange of heat between the soil surface and the atmosphere, thus buffering temperatures at the soil surface. Furthermore, organic matter forms air pockets and roots loosen the soil, creating more air spaces which lower heat conductivity into and through the soil (Tyrtikov 1969). Atkinson and Bay (1940) reported that depth of frost in agricultural fields decreased as the depth of vegetal cover or snow cover increased. Straw mulch on plowed and disked fields produced average daily soil temperatures similar to soils in mulched and bare silt-loam fields (Kohnke and Werkhoven 1963); however, daily soil temperature fluctuations in the bare fields were two times greater than in the mulched fields, and the frequency of freeze-thaw cycles was 3.6 times greater in the bare fields. Although frost did not form in soil under a standing stubble surface cover, the maximum soil frost penetration in bare surface plots was 1.3 cm (Pikul and Allmaras 1985). Thorud and Anderson (1969) found that layers of leaf litter or snow increased the freezing time to selected depths, decreased the overall depth of the freeze, and pine needles insulated better than oak leaves. Wet litter was not as effective as air-dry litter, but a layering of litter and snow seemed to have an additive effect. Tyrtikov (1969) also reported more moderate maximum and minimum temperatures and less severe freezing in soil under coarse pasture (need grass *Calamagrostis langsdorffi* and thistle *Cirsium heterophyllum*) than from bare ground, even when both the pasture and bare soil had a snow cover. Decker and Ronningen (1957) found considerably more frost-heaving in bare plots than under smooth bromegrass *Bromus inermis*, Ladino clover *Trifolium repens*, orchardgrass *Dactylis glomerata*, alfalfa *Medicago sativa* or Kentucky bluegrass sod. The least disturbance occurred under Kentucky bluegrass, while the Ladino clover, with its small shallow root system and sparse vegetative cover, was the most susceptible to soil frost disturbance. In orchardgrass, heaving occurred between the grass clumps but seldom next to or within clumps.

Management Implications

Management promoting good streambank insulation can help control the frost-heaving and internal soil weakening and perhaps reduce bank failures. For example, along stream reaches where grass is the predominant streambank cover, early light grazing and then rest to allow plant regrowth before winter, leaves an insulating layer of vegetation. In shrub communities, where snow canopy on the branches and litter provides insulation, management can be designed to encourage dense woody growth. Some areas may have to be grazed early when an abundance of other palatable vegetation can reduce the pressure on the less palatable willow (W. Platts, U. S. Forest Service, personal communication). Although not tested in this study, some types of vegetation may insulate better than others, such as occurs with crops on agricultural fields. Vegetative insulation on top of the bank may also be important in preventing frost in the soil surface which may lead to stress cracks and slab failures. Managing vegetation to provide natural insulation is one way to influence channel stability in some climates.

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References

Atkinson, H. B., and C. E. Bay. 1940. Some factors affecting frost-penetration. Transactions, American Geophysical Union, Reports and Papers, Snow-Conference, Seattle.

Benoit, G. 1973. Effect of freeze-thaw cycles on aggregate stability and hydraulic conductivity of three soil aggregate sizes. Soil Science Society of America Proceedings 37:3-5.

Broms, B., and L. Yao. 1964. Shear strength of a soil after freezing and thawing. American Society of Civil Engineers Proceedings, Soil Mechanics and Foundations Division 90(SM4):1-26.

Bullock, M. S., W. D. Kemper, and S. D. Nelson. 1988. Soil cohesion as affected by freezing, water content, time and tillage. Soil Science Society of America Journal 52:770-776.

Chamberlain, E. 1981. Frost susceptibility of soil. U. S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, CRREL Monograph 81-2, Hanover, New Hampshire.

Chamberlain, E., and A. Gow. 1979. Effect of freezing and thawing on the permeability and structure of soils. Engineering Geology (Amsterdam) 13:73-92.

Changjian, T., and S. Zongyan. 1981. Horizontal frost heave thrust acting on buttress construction. Engineering Geology (Amsterdam) 18:259-268.

Decker, A. M. Jr., and T. S. Ronningen. 1957. Heaving in forage stands and in bare ground. Agronomy Journal 49:412-415.

Domby, C. W., and H. Kohnke. 1955. The effect of freezing and thawing on structure of the soil surface. Agronomy Journal 47:175-177.

Formanek. G. 1983. Shear strength of a thawing silt loam: an approach to erodibility. Master's thesis. Washington State University, Pullman.

Heidmann, L. J., and D. Thorud. 1975. Effect of bulk density on frost heaving of six soils in Arizona. U. S. Forest Service Research Note RM-293.

Hinman, W. C., and F. Bisal. 1968. Alterations of soil structure upon freezing and thawing and subsequent drying. Canadian Journal of Soil Science 48:193-197.

Kohnke, H., and C. H. Werkhoven. 1963. Soil temperature and soil freezing as affected by an organic mulch. Soil Science Society of America Proceedings 27:13-17.

Logsdail, D. E., and L. R. Webber. 1959. Effect of frost action on structure of Haldimand clay. Canadian Journal of Soil Science 39:103-106.

Meentemeyer, V., and J. Zippin. 1981. Soil moisture and texture controls of selected parameters of needle ice growth. Earth Surface Processes and Landforms 6:113-125.

Penner, E. 1968. Particle size as a basis for predicting frost action in soils. Soils and Foundations 8(4):21-29.

Pikul, J. L., and R. R. Allmaras. 1985. Hydraulic potential in unfrozen soil response to diurnal freezing and thawing of the soil surface. Transactions of the American Society of Agricultural Engineers 28(1):164-168.

Soons, J., and D. Greenland. 1970. Observations on the growth of needle ice. Water Resources Research 6:579-593.

Thorud, D., and D. Anderson. 1969. Freezing in forest soil as influenced by soil properties, litter, and snow. University of Minnesota, Water Resources Research Center, Bulletin 10, Minneapolis.

Tyrtikov, A. P. 1969. Effects of vegetation on the freezing and thawing of soils. Moscow University Press. Translated and published for U. S. Forest Service in 1976, Amerind Publishing, New Delhi, India.