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Frost Distribution and Occurrence on a Rangeland Watershed in Southwest Idaho*

Abstract

In the Pacific Northwest, one of the primary causes of severe flooding and soil erosion is rain and/or snowmelt on frozen soil. This study gives a descriptive view of how location on a watershed and the associated antecedent soil water (fall precipitation), air temperature, and snow cover affect depth and occurrence of soil frost. Hydrologic and climatic data from three sites on the Reynolds Creek Experimental Watershed in southwestern Idaho for the 1976 through 1984 winter seasons were used in the study. Maximum seasonal frost depths averaged 42 cm at the lowest elevation site where fall precipitation was the least and snow cover at the time of maximum frost depth averaged only 1 cm. At the mid and highest elevation sites, the maximum seasonal frost depths averaged 26 and 24 cm, respectively. Snow cover averaged 9 and 44 cm at the time of maximum frost depth at the upper two sites. Air temperatures at the higher elevations were colder and remained colder longer than at the lower elevation sites; however, frost penetration at the high elevations was less because of deeper snow cover and more fall precipitation. When soil frost occurred at the high elevation site, it stayed longer than at the low elevation site where there was more than one freeze-thaw cycle during several seasons. In general, the low elevation site had the deepest maximum soil frost depth because of dry soil conditions, lack of snow cover, and cold night temperatures. Because of snow cover and warmer night time temperatures at the mid elevation site, average maximum soil frost depth at the mid and high elevation sites was about the same which was a little more than one-half of the average maximum frost depth at the low elevation site.

Introduction

Flooding and soil erosion from runoff often result when rain and/or snowmelt occurs on frozen soil. Loss of soil and associated reduced productivity are two reasons for studying soil frost. These losses can have considerable impact on the management practices in frost-prone areas.

The occurrence of soil frost depends upon a complex mix of site characteristics and climatic factors. Magnitude and duration of subfreezing air temperatures, soil water, snow depth, soil type, and vegetation cover, as well as slope and aspect, have a significant influence on the rate of frost penetration, frost depth and areal extent, and type of soil frost.

Several investigators have reported that dry soils freeze deeper and faster than wet soils (Willis *et al.* 1961; Steppuhn 1981). They also reported that dry soils thawed faster than wet soils.

Benoit (1973) pointed out that in soils with a high moisture content, soil hydraulic conductivity may decrease due to freezing and thawing regardless of soil aggregate size or freezing temperature, but soil with a low water content will do just the opposite. However, Hinman and Bisal (1973) showed that freezing and thawing tend to increase the hydraulic conductivity of high water content clays and reduce the conductivity in loam soils. Alternating freezing and thawing tended to reduce the conductivity less in loam soils than a continuous freeze.

Previous studies indicate that next to air temperature, snow cover probably has the greatest effect on frost penetration. Bullard (1954) summarized observations made by others in previous studies. He reported that snow depth was controlled by plant cover, aspect, and local topography, and that density of snow affects its insulating ability. One study showed that with a snow depth of at least 90 cm, there was sufficient insulation to prevent soil freezing. Soil that is initially frozen began to thaw with a snow cover of at least 25 cm. It was reported that for each 10 cm of snow, frost depth was reduced by 80

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percent. Steppuhn (1981) reported, that in Europe, a rule-of-thumb is that for every centimeter of snow cover, soil temperature in the root zone increases by at least 0.1°C. Hale (1950; 1951) reported that up to 19 cm of impermeable frost occurred in sagebrush and grass ranges in eastern Oregon and Washington during winter and spring snowmelt. Over 13 cm of concrete frost thawed under about 25 cm of snow cover, and with a snow depth of 76 cm on east slopes frost disappeared.

Bay *et al.* (1952) showed that 46 cm of snow insulated the soil sufficiently to prevent frost penetration past a depth of 30 cm when the average daily minimum temperature was as low as —25°C. The 46 cm of snow did not prevent frost penetration past the same depth when the average daily minimum temperature was —29°C; however, frost penetration was stopped when the snow depth was increased to 61 cm. Winters with little snow permitted frost penetration to as much as 91 cm under usual farming practices.

The purpose of this paper is to give hydrologists and others interested in mountainous environments a descriptive view of the temporal and spatial distribution of soil frost in watersheds that are located within mountain ranges. To accomplish this goal, hydrologic and climatic data from three weather station sites on the Reynolds Creek Experimental Watershed in southwestern Idaho were used to illustrate how location on the watershed and associated antecedent soil water (fall precipitation), air temperature, and snow cover affect depth and occurrence of soil frost.

Methods

Watershed Description

The Reynolds Creek Experimental Watershed (Figure 1) has been operated by the U.S. Department of Agriculture, Agricultural Research Service (ARS), Boise, Idaho since 1960 for the purpose of studying water yield, flood flow, sedimentation, and range resources (Robins *et al.* 1965). The stream is a foothill tributary of the Snake River and is located approximately 64 km southwest of Boise, Idaho.

The 234 km^2 watershed is approximately 29 km long and from 4.8 to 11.3 km wide. The valley is the deepest declivity in the rolling plateau country between the Snake River and the Idaho-Oregon border. The valley floor has an elevation of about 1,160 m a.s.l., while the surrounding rim averages about 1,830 m elevation. The highest peak in the watershed is about 2,100 m elevation with isolated peaks to the south and west of the valley rising to 2,400 m (Cooper 1967). The north and northwest trending ridges with gently inclined windward slopes and steep north and east facing slopes are vegetated with sagebrush (*Artemisia* spp.) and other rangeland grasses. Intermittent stands of Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), western juniper (*Juniperus occidentalis* Hook.), aspen (*Populus tremuloides* Michx.), and scattered meadows occur in the higher elevations. These areas comprise only about 2 percent of the total watershed and are found mainly in protected or snow drift areas in the higher elevations. About 610 ha of irrigated hay are grown in the valley along the lower reaches of the main channel and its tributaries (Hamon and Johnson 1965). While the vegetation in the watershed is principally sagebrush and related woody species, there is an understory of annual or perennial grasses.

Winter precipitation varies with elevation as well as with location on the watershed with the leeward sites receiving more precipitation than windward sites at equal elevations (Hanson *et al.* 1980, Hanson 1982). The location of maximum annual precipitation on the watershed is just leeward of the western watershed boundary. Annual precipitation varies from about 250 mm at the lower elevations to 1,150 mm at the higher elevations. About 80 percent of the annual precipitation occurs from October through April and is mainly in the form of snow at the high elevations. At the lower elevations, about 67 percent falls during the same period and is about 25 percent snow. This precipitation is a result of general frontal-type storms moving in from the west-southwest (Molnau *et al.* 1980; Hanson *et al.* 1980). Snowfall on the watershed is strongly influenced by a predominantly southwest wind interacting with vegetation and local topography so that snow is deposited in irregular spatial patterns. Under some circumstances, a considerable amount of the snowfall is concentrated by wind within a small area of the watershed (Rawls and Jackson 1979).

Watershed soils are predominantly residual, having been developed from volcanic rock, granite, and lake sediment parent material (Stephenson 1977) (Table 1).

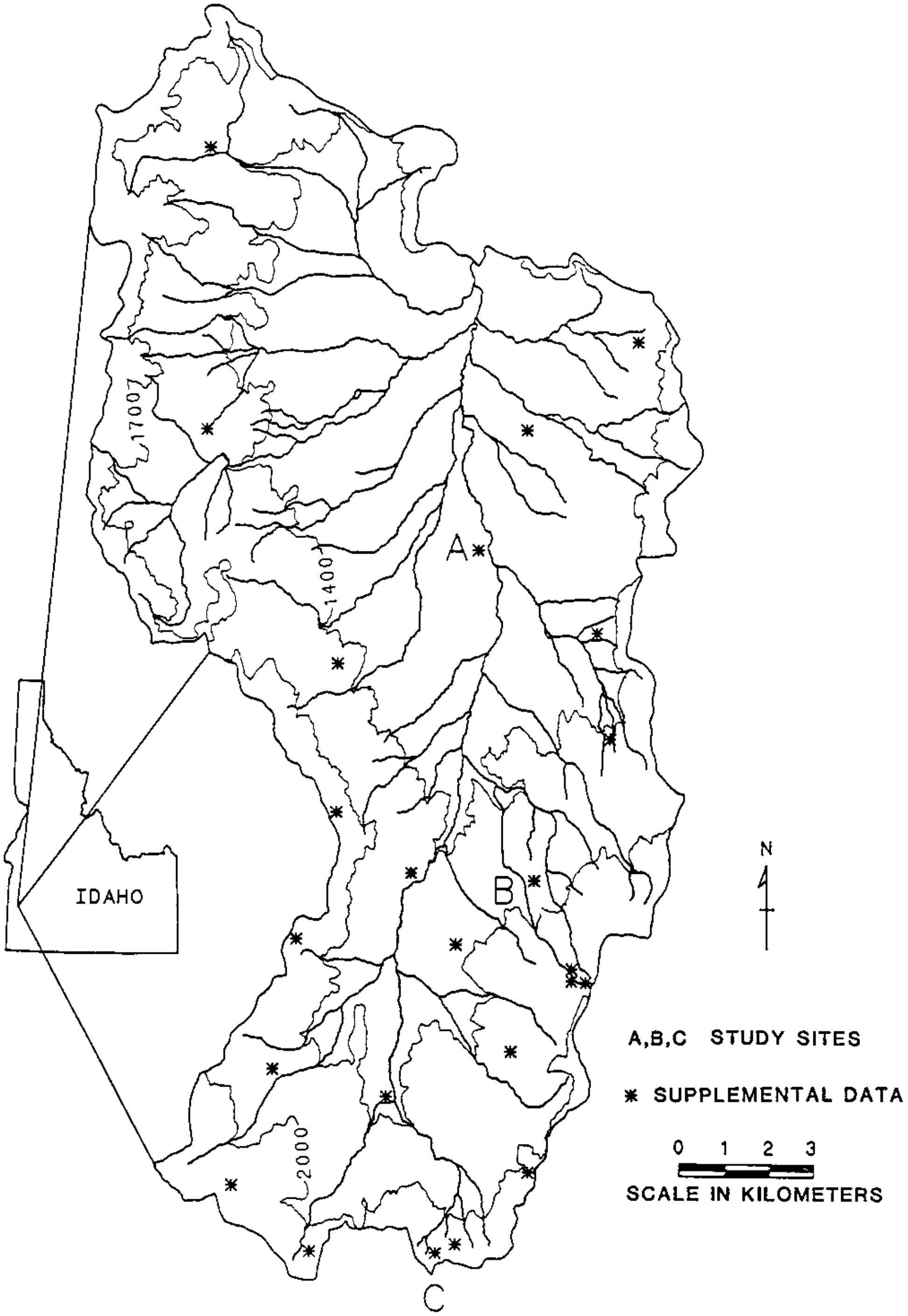

Figure 1. Vicinity map, topography and frost sites of the Reynolds Creek Experimental Watershed, Idaho. Depth of frozen soil was measured by soil water resistance blocks and frost tubes at sites A, B and C and only by soil water resistance blocks at the other sites.

TABLE 1. Description of soils at frost study sites on Reynolds Creek Experimental Watershed, Idaho.

Site	Elevation (m a.s.l.)	Aspect	Geologic Material	Soils					Vegetation
				Subgroup	Family	Series	Field Capacity (g/g)	Wilting Point (g/g)	
A	1193	Flat	Sedimentary	*Xerollic Haplargids*	Fine loamy, mixed, mesic	Larimer stony loam	27	14	Big sagebrush-grass
B	1649	N	Basalt	*Calcic Argixerolls*	Loamy skeletal, mixed, frigid	Searla gravelly loam	29	14	Low sagebrush-grass
C	2097	NW	Rhyolite	*Pachic Cryoborolls*	Fine loamy, mixed	Bullrey gravelly loam	25	9	Big sagebrush-grass

Soil Frost Measurements

Frost penetration data for 1976 through 1984 for three sites (A, B, and C) (Figure 1) were used in this study. These data were measured using soil water resistance blocks (Burgess and Hanson 1979) and frost tubes. Two sets of resistance blocks were installed at a level site at each location. The blocks were positioned at 5, 10, 15, 20, and 30 cm depths. In addition, one stack of blocks at site A was positioned at 5, 10, 15, 20, 30, 40, 50, and 60 cm depths. Frost depth was measured on a weekly basis during the cold period at sites B and C, and more often at site A. Frost penetration was known to be somewhere between two adjacent depths, e.g., frozen at 5 cm but not at 10 cm. When soil frost was measured at 30 cm, the depth was noted as 30 cm or greater.

Several investigators (Garstka 1944; Harrold and Roberts 1960; Sartz 1967) have shown soil water blocks to be reliable and easy to use. Burgess and Hanson (1979) reported that frozen soil conditions could be accurately determined using soil-water blocks. The changes in electrical resistivity of the material in the blocks caused by freezing and thawing were measured. A sharp rise in resistance indicated soil freezing while a drop in resistance indicated soil thawing.

Frost tubes filled with sand and dye solution were used along with the frost blocks. These frost tube type gages are similar to those described by Harris (1970). The tubes were installed to a depth of 100 cm in the soil and protruded above the ground surface. When the soil temperature was below freezing, the dye solution within the tubes changed color, indicating the presence of a below freezing temperature, and presumably frost. Harris (1970) reported that the tube-type gage is economical and is a reliable indicator of frost depth to within plus or minus 5 cm of the indicated true frost depth, 95 percent of the time.

Where frost data were missing, depth of frost and snow was interpreted by comparing frost and snow depth at other sites with a similar local environment. Frost depth was the maximum indicated by either method previously described; however, most frost data reported herein were from frost tubes. This study was concerned with frost depth only; any surface thaw that may have occurred while a portion of the soil profile was frozen was not included.

Daily maximum and minimum air temperatures were measured by hygro-thermographs at the three sites. Snow depth was measured at the time of frost readings and it represented average depth at the site of frost measurement. Precipitation was measured by a dual-gage system located at each frost site (Hamon 1973; Hanson *et al.* 1980). The dual-gage system consisted of an unshielded and a shielded gage and the amount of precipitation was computed from a logarithmic relationship which used the catch in both gages. This system has proven to provide reliable measurements of both rainfall and snowfall (Hamon 1973; Hanson *et al.* 1980).

Results and Discussion

The years chosen to illustrate the effect of site location on frost depths were 1977-78, 1978-79, and 1983-84 because each of these years was quite different from the other. Soil frost depths for 1976-77 through 1983-84 frost season, long-term mean monthly temperatures, and the mean monthly temperatures for the selected years are listed in Tables 2 and 3. Precipitation during the fall of 1977-78 was about average with a shallow snow cover (Table 2), and the midwinter temperatures were about 2°C above average (Table 3). During the fall of 1978-79, precipitation was between 13 and 60 mm below average with moderate snow cover and winter temperatures that were about 4°C below average (Table 3). Precipitation during the fall of 1983-84 varied between 14 and 25 mm below average (Table 2) with deep snow cover and winter temperatures that were about 2°C below average (Table 3).

Frost and snow depths at the three sites are shown in Figures 2-4 and monthly temperatures are shown in Table 3. Frost penetration at site A was as great or greater than at sites B or C for all but site C during 1977-78. This manifestation of persistent frost depth is also shown in the summary in Table 2. The maximum frost depths noted at site A for the years 1977-78, 1978-79, and 1983-84 were 14, 80, and 39 cm, respectively (Table 2). For the same periods, the frost depths were 13, 80, and 18 cm for site B and 22, 46, and 0 cm for site C. Occasionally, initial frost at site C occurred at the same time of year or preceded the initial frost at site A. For example, during 1978-79 initial frost occurred at both sites on 13 November 1978.

Site A also experienced considerably shorter frost durations relative to other sites at higher

TABLE 2. Occurrence of soil frost at sites A, B and C on Reynolds Creek Experimental Watershed, Idaho, 1976-1984.

Site	Year	Fall Precipitation Sept-Nov (mm)	Maximum Frost Depth			Occurrence of Frost	
			Depth (cm)	Date	Snow Cover (cm)	First (date)	Last (date)
A	1976-77	43	58	01 14 77	5	11 29 76	02 14 77
	1977-78	68	14	11 21 77	2	11 18 77	01 06 78
	1978-79	44	80	02 07 79	0	11 13 78	02 16 79
	1979-80	42	42	02 04 80	0	11 20 79	02 19 80
	1980-81	96	45	12 22 80	0	11 17 80	02 17 81
	1981-82	73	45	02 17 82	0	01 11 82	02 18 82
	1982-83	71	15	11 26 82	2	11 26 82	02 15 83
	1983-84	78	39	01 25 84	0	12 16 83	03 05 84
	Average	64	42		1	11 30	02 13
B	1976-77	48	32	01 31 77	0	12 28 76	02 09 77
	1977-78	62	13	11 22 77	18	11 22 77	03 21 78
	1978-79	63	80	02 06 79	8	11 14 78	03 13 79
	1979-80	55	25	02 05 80	0	11 13 79	03 03 80
	1980-81	85	17	01 19 81	0	12 02 80	02 19 81
	1981-82	86	9	02 10 82	38	01 06 82	02 17 82
	1982-83	107	17	12 14 82	8	12 07 82	02 23 83
	1983-84	101	18	02 07 84	0	12 27 83	03 13 84
	Average	76	26		9	12 07	03 01
C	1976-77	84	55	02 14 77	15	12 06 76	04 06 77
	1977-78	208	22	12 28 77	23	11 10 77	03 13 78
	1978-79	117	46	01 09 79	76	11 13 78	03 26 79
	1979-80	159	24	01 15 80	46	11 27 79	04 22 80
	1980-81	163	21	01 20 81	0	11 24 80	03 17 81
	1981-82	218	22	02 16 82	61	01 13 82	04 27 82
	1982-83	261	6	01 04 83	91	11 22 82	02 15 83
	1983-84	197	0	02 23 84	122[1]	—	—
	Average	176	24		54	11 29	03 27

[1] Depth given to indicate snow cover only.

TABLE 3. Average and seasonal air temperatures at sites A, B and C on Reynolds Creek Experimental Watershed, Idaho.

Site	Oct	Nov	Dec	Jan	Feb	Mar	Apr
	Average Daily (°C)						
A (1964-84)	8	3	−1	−2	2	3	6
1977-78	9	4	3	2	3	7	7
1978-79	10	2	−4	−7	1	3	6
1983-84	10	4	−4	−4	−1	4	6
B (1967-84)	8	2	−2	−3	0	2	4
1977-78	10	1	0	0	0	6	5
1978-79	11	1	−5	−8	−1	2	4
1983-84	10	2	−5	−4	−2	2	3
C (1967-84)	5	−1	−5	−5	−3	−3	0
1977-78	7	−1	−3	−2	−2	3	1
1978-79	9	−2	−9	−9	−5	−2	−1
1983-84	7	−2	−7	−3	−3	−1	0
	Average Daily Maximum (°C)						
A	16	8	3	3	7	9	13
1977-78	17	9	7	6	7	14	12
1978-79	19	8	1	−2	5	10	13
1983-84	17	8	0	1	3	10	12
B	12	5	1	0	4	5	9
1977-78	14	5	3	2	2	9	9
1978-79	16	4	−2	−5	1	6	9
1983-84	14	5	−2	0	2	5	8
C	9	2	−2	−2	0	1	4
1977-78	11	2	−1	0	1	6	4
1978-79	13	1	−5	−7	−3	1	3
1983-84	12	1	−4	2	2	4	5
	Average Daily Minimum (°C)						
A	1	−3	−6	−6	−3	−3	−1
1977-78	1	−2	−2	−2	−1	0	1
1978-79	1	−4	−9	−13	−3	−3	−1
1983-84	2	0	−8	−8	−4	−1	0
B	4	−2	−5	−6	−3	−2	0
1977-78	5	−2	−3	−2	−2	2	1
1978-79	6	−2	−8	−11	−3	−2	0
1983-84	6	−1	−8	−7	−5	−1	−1
C	1	−4	−7	−8	−6	−6	−4
1977-78	3	−4	−5	−4	−5	−1	−2
1978-79	4	−5	−12	−12	−7	−5	−4
1983-84	3	−4	−9	−7	−7	−5	−4

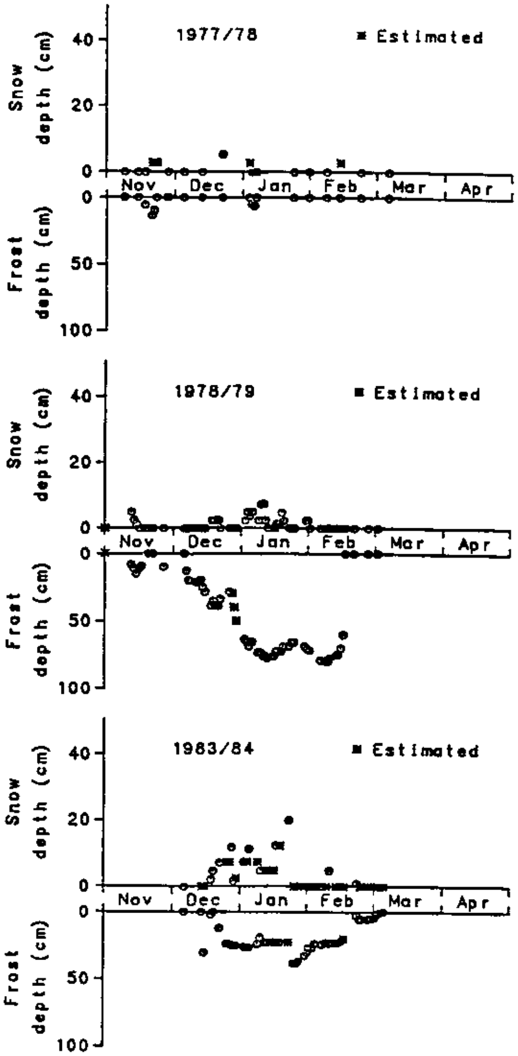

Figure 2. Frost and snow depth for three seasons at site A.

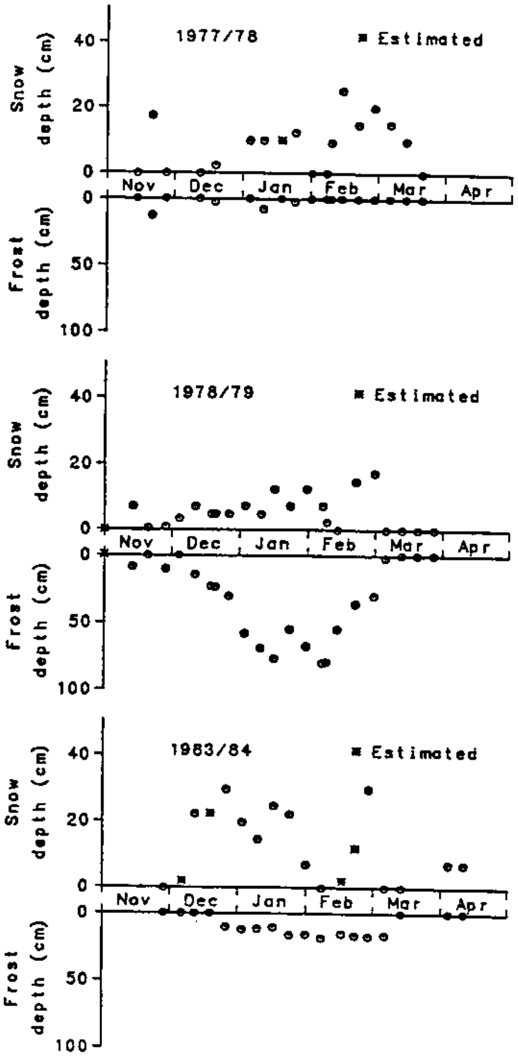

Figure 3. Frost and snow depth for three seasons at site B.

elevations. For example, during 1978-79 at site A (Figure 2), the depth of soil frost fluctuated during the season and the season was shorter than at site C (Figure 4) where the depth of frost was less and the depth did not vary much during the period of snow cover. In addition, site A typically experienced an earlier occurrence of initial frost and quicker thaw than the sites at higher elevations.

Lower elevations experienced deeper frost depths than higher elevations because there was less snow cover at the lowest elevation site and the minimum air temperatures were lower than mid elevation temperatures (Table 3). This phenomena was a result of cold air drainage.

The average monthly air temperatures at the three sites are listed in Table 3. Site A had the coldest extreme minimum temperature and about the same average monthly minimum temperature as the other sites which, along with the minimum snow cover and driest soils, resulted in the deepest frost penetration. Site A also had the overall shortest frost season because of the warmer maximum temperatures and little or no snow cover.

Site B had the overall warmest minimum temperatures and, on average, the shallowest

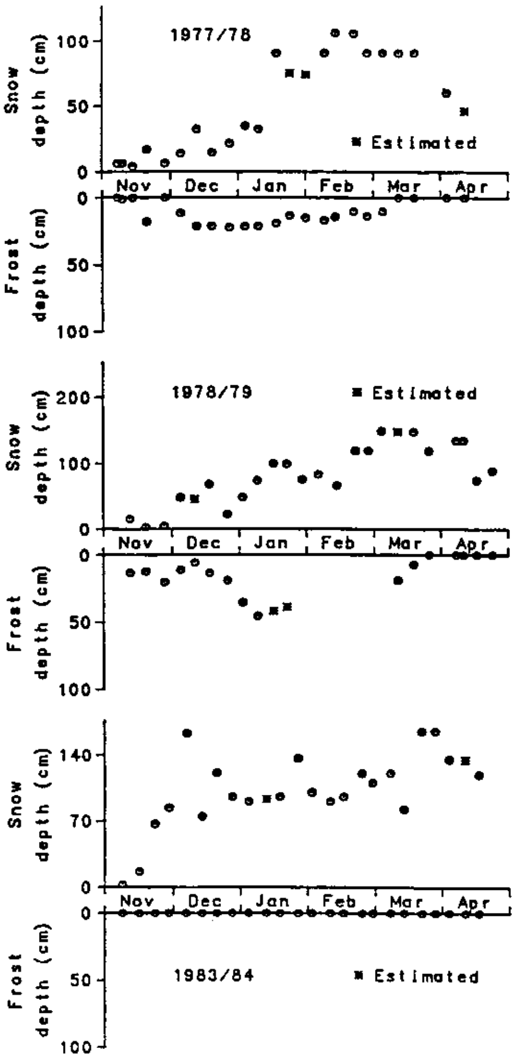

Figure 4. Frost and snow depth for three seasons at site C.

frost depth. For example, in 1976-77 the mean minimum temperature for January was —5°C with a maximum frost of 32 cm (Table 2). Sites A and C for the same period had mean minimum temperatures and maximum frost depths of —11°C and 58 cm, and —7°C and 55 cm, respectively.

Site C had the most snow cover and, generally, frost depth was less than at site A. The maximum frost depth and the amount of snow cover at time of maximum frost depth are shown in Table 2. During the years of deeper snow depths, snow provided sufficient protection to prevent soil frost which agrees with studies summarized by Bullard (1954). This insulative effect was observed at site C during the 1983-84 winter period (Figure 4). When frost with a snow cover did occur at this site, the duration of frost tended to be longer than at site A as seen in Figures 2 and 4 for 1977-78.

During the winter of 1983-84, snow began to accumulate at site C about the second week of November. As temperatures dropped with the onset of winter, the upper elevation of the watershed was protected by a snow cover before subfreezing air temperatures arrived. Snow continued to accumulate and provided insulative cover to the soil which remained unfrozen throughout the winter. The snow remained well beyond April and soil was not exposed until warmer temperatures were predominant. At the same site in 1977-78 there was little, if any, snow cover on the ground at the time when freezing began during the last week of November and first week of December. A frost depth of about 22 cm persisted into the fourth week of January when a heavy snowfall occurred. Frost remained in the soil until March 13, 1978 under a snow depth of about 1 m. At lower elevations in the watershed, the snow started to accumulate late in the fall and did not develop as deep and melted earlier in the spring than at higher elevations. Frost was generally confined to the soil where the snow was shallow. The lower elevations of the watershed were free of snow by the middle of February.

Maximum frost depth, snow depth at time of maximum frost, and the occurrence of soil frost for the three study sites are shown in Table 2. It can be seen that there is a wide variation in maximum frost depth between the three sites, again, with greater depths of frost and lesser snow cover being more noticeable at lower elevations. For example, at site A for 1978-79, the maximum frost depth was 80 cm with no snow cover. At site C the maximum frost depth was 46 cm with 76 cm of snow.

The maximum soil frost depth during 1978-79 was not only caused by a shallow snow cover and cold air temperatures, but also by dry fall soil conditions (Table 2). In general, soil frost did not penetrate as deep during winters that followed a wet fall.

Conclusions

On the Reynolds Creek Experimental Watershed, depth of maximum frost penetration and the time of maximum depth varied between seasons at each of the study sites. At the lowest elevation site (site A), the maximum seasonal frost depth varied between 14 cm on November 11, 1977 to 80 cm on February 7, 1979, with an average of 42 cm for the winter seasons of 1976-77 through 1983-84. The average seasonal maximum frost depth was greatest at site A because of the shallow snow cover which averaged only 1 cm at the time of maximum frost depth, and because the site received the least fall and winter precipitation.

The maximum seasonal frost depth at the mid elevation site (site B) varied between 9 cm on October 2, 1982 to 80 cm on February 6, 1979, with a mean maximum depth of 26 cm. In general, the maximum frost depth was less at site B than A because of deeper snow cover, more fall and winter precipitation, and warmer minimum temperatures.

The highest elevation site (site C), where there was the deepest average snow cover (54 cm) and the most fall and winter precipitation, had a 24 cm average maximum soil frost depth, which was the least of the three sites. The seasonal frost depth varied between 0 in 1983-84 to 55 cm maximum on February 14, 1977. An observed snow depth of about 1 m prevented soil frost at this site.

A combination of minimum air temperature, depth and timing of snow cover, and the amount of soil water were factors that determined the depth of soil frost at the three study sites. Soil frost depth was not uniformly distributed throughout the watershed.

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