THERMAL INDEX AND THERMAL CONDUCTIVITY OF SNOW AND THEIR RELATIONSHIP TO WINTER SURVIVAL OF THE MEADOW VOLE, MICROTUS PENNSYLVANICUS

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ABSTRACT

Air, snow, subnivean and meadow vole, *Microtus pennsylvanicus*, nest temperatures were measured during the winters of 1982-83 and 1983-84. The theoretical basis of a thermal index that describes the insulating properties of a snowpack, developed by Marchand (1982), was examined by assessing thermal conductivity and density of distinct layers within the snowpack. No direct relationship was found between conductivity and density but a high correlation ($r^2 = 0.98$, $p < 0.001$) was established between the thermal index and the reciprocal of the summed conductivities of the various layers of the snowpack. Thermal index was determined to have biological relevence and to be a useful tool for studies in winter ecology because it was simple, rapid, and founded on a sound physical base. Meadow vole survival in winter was found to be strongly influenced by the thickness and characteristics of the snowpack beneath which they are active.

INTRODUCTION

Some small mammals with a high surface to mass ratio endure cold winter temperatures by taking refuge in the subnivean environment (Pruitt 1970). Under ideal conditions, small mammals are known even to reproduce beneath the snow (Frank 1957, Beer and Macleod 1961). Many species of insects also use the protection afforded by snow to over-winter successfully (Danks 1981).

The use and importance of the subnivean environment has been well documented in the literature (Formosov 1946, Frank 1957, and Pruitt 1957) but little is known either about the way small mammals modify this environment or about nest temperatures within the subnivean environment. Pruitt (1957), however, states that to provide adequate protection to small mammals the snow must reach some minimum thickness; a level that he terms the *hiemal threshold*.

The physical properties of snow dictate the insulative capacity of any given snowpack. Pruitt (1970) and Marchand (1982) have derived snow indices that seek to quantify the insulative capacity of the snowpack in a way that is ecologically significant. Both indices are based on snow density but Pruitt's formula, that implies a direct relationship with density and thickness, is of little use for estimating the temperature stability of the subnivean environment (Marchand 1982). Marchand's (1982) thermal index, on the other hand, is related directly to thickness and indirectly to density, and is predicated upon the principle that the thermal insulation of snow will increase as snow thickness increases and density decreases. This is indeed the case because thermal conductivity, the ability of the snow to transmit heat, is related directly to density (Langham 1981).

Both indices have a logical rather than a physical base and, as a result, the units in which the indices are expressed are not pure in a physical sense. Marchand's thermal index, however, must be shown to be based on physical properties and must have distinct

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advantages with respect to field use by the ecologist if it is to take the place of a purely physical measure such as conductivity.

This paper has two purposes: 1) to examine Marchand's thermal index in relation to thermal conductivity of the snow so as to justify its validity as a tool in the winter ecology of subnivean organisms, and 2) to relate meadow vole response to the thermal snow index to show that the index has ecological meaning in terms of organisms that exist beneath the snow.

METHODS AND MATERIALS

Measurements of temperature and meadow vole activity were made at a site of known meadow vole activity in the Botanical Garden of Laurentian University, Sudbury, Ontario (46°28'N,80°58'W). An enclosure 3.5 m long, 2.5 m wide, and 1.5 m high was constructed from aluminum siding that extended into the soil to a depth of 15 cm. Following a threat of predation by foxes the enclosure was covered by heavy, large mesh (10 cm x 10 cm) wire netting that allowed snow to pass through unimpeded.

A 1 m high mast that supported a series of paired thermisters and thermocouples was placed in the enclosure. The sensors were positioned at 100, 50, 25, 10, 5 and 2 cm above the soil surface, at the soil surface, and at 5 cm below the soil surface. A similar mast was placed in a control site adjacent to the enclosure. Snow stakes marked off at 10 cm intervals were placed in both the enclosure and the control area to provide a measure of snow depth.

A multipoint chart recorded (Grant Instruments Model 2020B) was used to record the temperature sensed by the thermisters every hour. A portable millivolt potentiometer (Wescor, Inc. Model MJ-55) was used to take spot readings of thermocouple output via a 20-position rotary switch. The Grant recorded was housed in a styrofoam cooler that was sunk into the ground beside the enclosure in an attempt to prevent the instrument from being subjected to temperatures much below 0°C. Heated gel 'hot-paks' were used during very cold weather to heat the cooler. Snow was piled on top of the cooler lid to provide further insulation.

Thermal index was calculated according to Marchand's (1982) equation:

$$I_T = \sum_{i=1}^{n} (z/G) \quad i$$

where I_T = thermal index ($\mathrm{cm.cm^3\ g^{-1}}$), z = thickness (cm), G = snow density ($\mathrm{g\ cm^{-3}}$) and i = any given snow layer for which z and G have been measured. The use of symbols is in accord with the snow literature (Langham 1981) and current scientific nomenclature.

Measurements of thermal index were taken by exposing a snowface, measuring the thickness of each layer and determining the density of each layer. Density was obtained by weighing a 500 $\mathrm{cm^3}$ volume of snow that was collected in an aluminum dish (12.5 x 8.0 x 5.0 cm) inserted horizontally into the snowpack. Care was taken not to compact the snow.

The effective thermal conductivity (Langham 1981) was measured with six conductivity units constructed in the laboratory. These consisted of a Thornthwaite soil flux plate and two 20-gauge copper-constantan thermocouples that were placed on each side of the flux plate and 1 cm away from it. The conductivity units were inserted into a freshly cut snowface with the flux plate horizontal. The hole in the snow was gently refilled to avoid disturbing the conductivity units. One conductivity unit was placed permanently as close to the soil surface as possible whereas the remainder were placed in each distinct layer of the snowpack as required and allowed to equilibrate for 24 h prior to measurement with the portable millivolt potentiometer. Effective conductivity (k_e) was calculated from the Fourier equation (Langham 1981):

$$q = -k_e \, (dT/dz)$$

where q = heat flux, and dT/dz = temperature gradient.

Naturally formed nests of meadow voles could not be found and attempts to do so were very destructive to the habitat. Meadow voles, therefore, were placed in cages to force them to form nests that could be located and into which thermocouples and thermisters could be placed. The cages used were 30 x 13 x 8 cm plastic animal cages with a V-shaped wire screen lid. A 5 cm thick sod block, including vegetation, was removed from the enclosure and placed in each cage. The cage was then sunk into the space left by removal of the sod.

RESULTS AND DISCUSSION

Temperature profile data from the enclosure and from the control site were examined to determine whether or not the enclosure modified the thermal regime of the snowpack. There was no significant difference (Table 1) between temperatures taken at specific heights within the enclosure and at the control site ($p = < 0.001$). However, surface temperatures at the control site were significantly higher ($0.05 < p < 0.01$) than those in the enclosure. This difference is attributed to possible meadow vole activity in the vicinity of the surface sensor.

Table 1. Comparison of mean weekly temperatures (°C) over a nine week period at different heights in the enclosure and at the control site. NS = not significant; * = $.05 < p < .01$.

Height (cm)	Enclosure	Control	Significance
100	-7.7	-7.3	NS
50	-7.1	-6.1	NS
25	-3.4	-2.9	NS
5	-0.8	0.0	NS
0	0.0	1.0	*

The precipitation regime of winter 1982-83 was very different from that of winter 1983-84 (Fig. 1). In winter 1982-83, an abnormal amount of rain fell in December and January. As a result, snow depth did not reach its maximum (20 cm) until February. In winter 1983-84 there was little rain in December and January and the maximum snow depth of 70 cm was recorded in January. This was followed by an almost complete loss of the snowpack in February owing to warm temperatures accompanied by rain. Although the *hiemal threshold* was attained by January, it was lost again in February. Meadow voles, therefore were exposed to extremely cold temperatures with little insulation.

A temperature profile from 1 m above the soil, through a snow-pack, to 5 cm below the soil surface represents thermal conditions over a nine week period in winter 1983-84 (Fig. 2). The horizontal bars at the level of each sensor indicate the amplitude of weekly means during the measurement period whereas the vertical bar indicates the variation in snow depth. From an air temperature of -7°C there was a progressive increase through the snowpack to 0°C at the soil-snow interface. Air temperatures at 1 m showed the greatest fluctuations (24 Celsius degrees) followed by temperatures in the vicinity of the snow surface (17 Celsius degrees). Within the snowpack the fluctuation rapidly decreased to a maximum of 3 Celsius degrees. This attenuation demonstrates very clearly both the insulative properties of the snow and the great temperature stability that exists with time at the soil-snow interface.

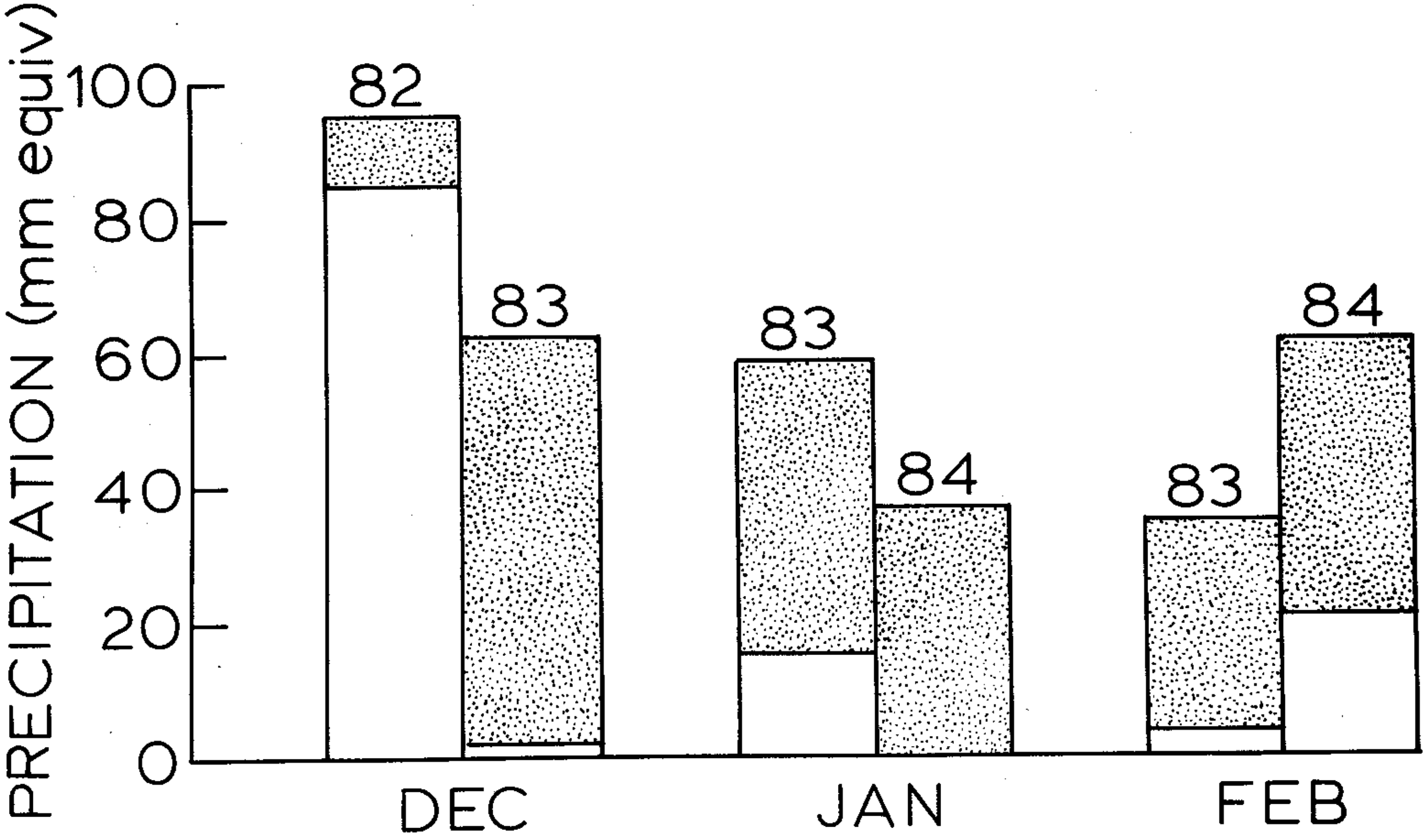

Fig. 1 Rain, and snow as liquid equivalent precipitation (stippled), from December to February for winter 1982-83 and 1983-84.

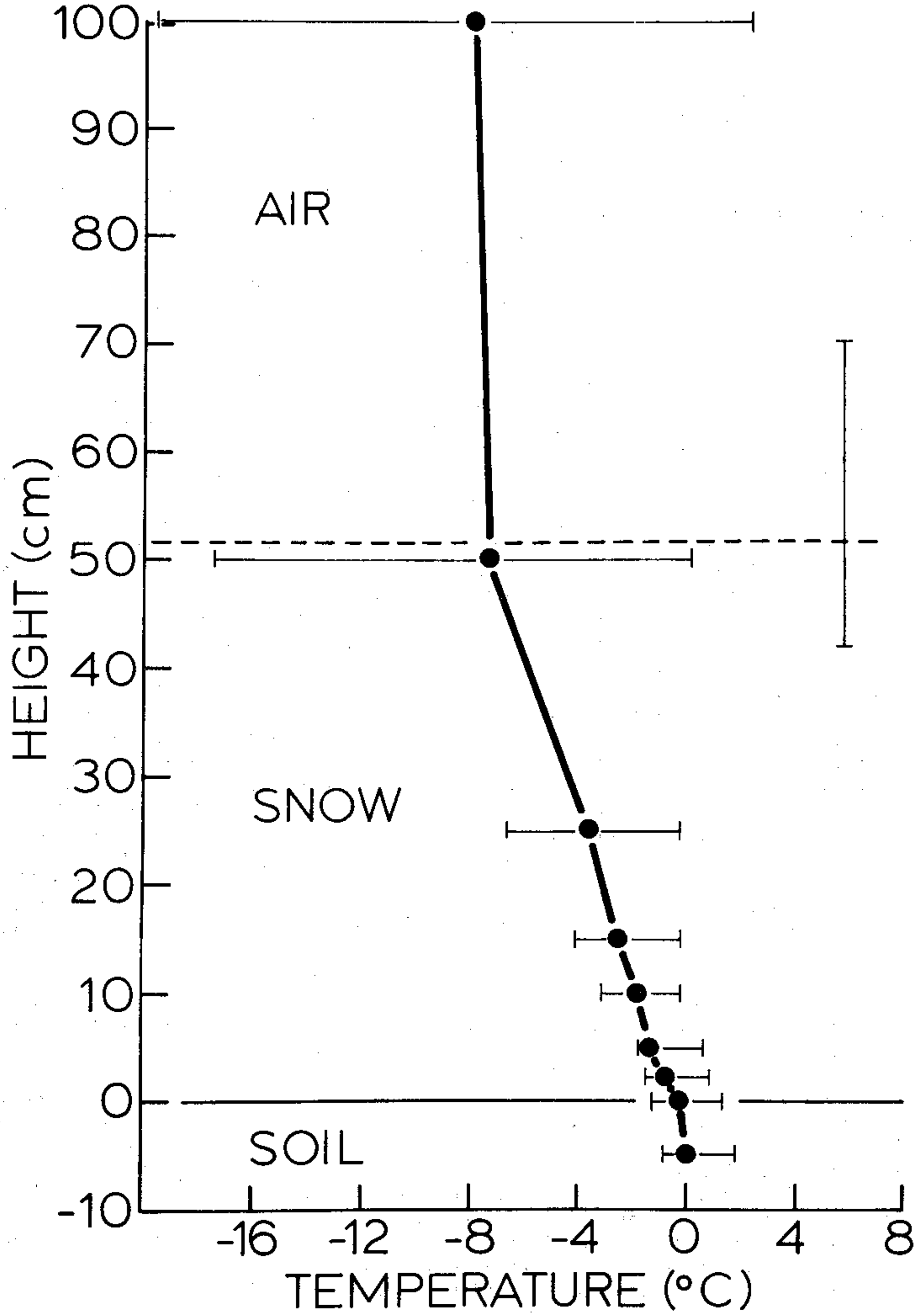

Fig. 2 Profile of mean weekly temperatures over a nine week period, from 100 cm above the soil surface (air), through a snowpack, to a depth of 5 cm below the soil surface. the maximum and minimum amplitude at any given height (horizontal bars) and amplitude of snow depth (vertical bar) is also shown.

Quantitative evidence of the capacity of snow to insulate may be obtained by plotting the ratio of diurnal amplitude of temperatures beneath the snow to that above the snow ($\Delta T_s/\Delta T_a$) against the thermal index, I_T, (Marchand 1982). The curve that is shown in Fig. 3 is taken from Marchand (1982) and is seen to asymptote at a thermal index value of 200 $cm.cm^3\ g^{-1}$. This point corresponds to the *hiemal threshold* (Pruitt 1970) and is the value at which snow depth is sufficient to prevent any significant fluctuation in subnivean temperature with time and which, according to Pruitt (1970), signifies the beginning of the true winter season for organisms that are active beneath the snow. Data from the present study show that in winter 1982-83 (closed circles) the *hiemal threshold* was never established and that the data points departed widely from the curve. In winter 1983-84 early, heavy snow and very little rain (Fig. 1) resulted in the very rapid establishment of a snowpack at a time when it was not possible to make field measurements. As a result no temperature data were obtained when snow cover was thin and thermal index values consequently were low. All thermal index values for the snowpack exceeded 200 $cm.cm^3\ g^{-1}$ with very low, concurrent values of $\Delta T_s/\Delta T_a$. The data points (open circles, Fig. 3) corresponds very well with Marchand's curve and indicate that the *hiemal threshold* was reached.

Although the thermal index gives a good, quantitative measure of the ability of snow to insulate, and is based upon a physical measure (density); nevertheless, the units of thermal index ($cm.cm^3\ g^{-1}$) that result from the way in which the index is derived are difficult to visualize in the context of heat transfer through the snowpack. Many authors cite a direct relationship between density and conductivity (Mellor 1977 in Langham 1981) whereas others cite a relationship between the square of density and conductivity (Williams and Gold 1958, Geiger 1965). In the present study neither relationship was found to hold for individual layers of different density throughout the snowpack although conductivity increased as density increased. Whereas exact methodology is not clearly stated it appears that in most studies determinations of conductivity have been made on the entire snowpack rather than on the individual layers that comprise the snowpack. The complexity that can exist may be seen from the schematic representation (Fig. 4) of the snowpack, consisting of seven distinct layers, that was sampled on 1 February 1984 at the study site. The corresponding values of density (G) and effective conductivity (k_e) of each layer are also given. Density generally increased with age from the top to the bottom of the snowpack. The most recent snowfall had the lowest density (.03 $g\ cm^{-3}$) and the two oldest, bottom layers were the most dense (.28 $g\ cm^{-3}$). It should be noted that whereas conductivity also tended to increase with age of the snow layer there was a marked difference in the conductivity of the two lowest layers, .12 and .37 $W\ m^{-1}\ K^{-1}$. Even though the density was the same, the microstructure and probably also the moisture content of the snow layers was different and hence the conductivities were different. Although the values of conductivity of snow of different ages fell within the range of values given in the literature (Table 2); nevertheless, no significant correlation was found when conductivity was regressed as a function of density owing to the great variation that existed from layer to layer within any given snowpack.

The apparent lack of correlation between conductivity and density has been reconciled, at least from the standpoint of ecological studies, by plotting thermal index against the reciprocal of total effective conductivity. For a snowpack on any given day, the total conductivity was obtained by summing the conductivity of each individual layer because the layers act in series. The straight line curve that results (Fig. 5) has a high regression coefficient ($r^2 = 0.98$) and is highly significant ($p =< 0.001$). The curve does not pass through the origin, but rather it intercepts the x-axis at a thermal index value that corresponds closely to the *hiemal threshold* value of 200 $cm.cm^3\ g^{-1}$ described from Fig. 3. The authors believe that as thermal index values fall below 200 $cm.cm^3\ g^{-1}$ linearity is lost and the curve approaches the x-axis but never reaches it. The reason is that as thermal index approaches zero, conductivity increases to such a degree that the value of the reciprocal of conductivity becomes exceedingly small. Further research is required to confirm the relationship predicted at low values of the thermal index.

The ecological significance of the thermal index may be seen in Fig. 6 where thermal index has been plotted against time during a winter with an inadequate snow cover (1982-83). The depth of the snowpack also is shown. Snow depth data were taken at the study site from January 1 to February 14. After February 14 the values of snow depth used were those gathered at the Sudbury Airport weather station which is situated 23 km northeast of the

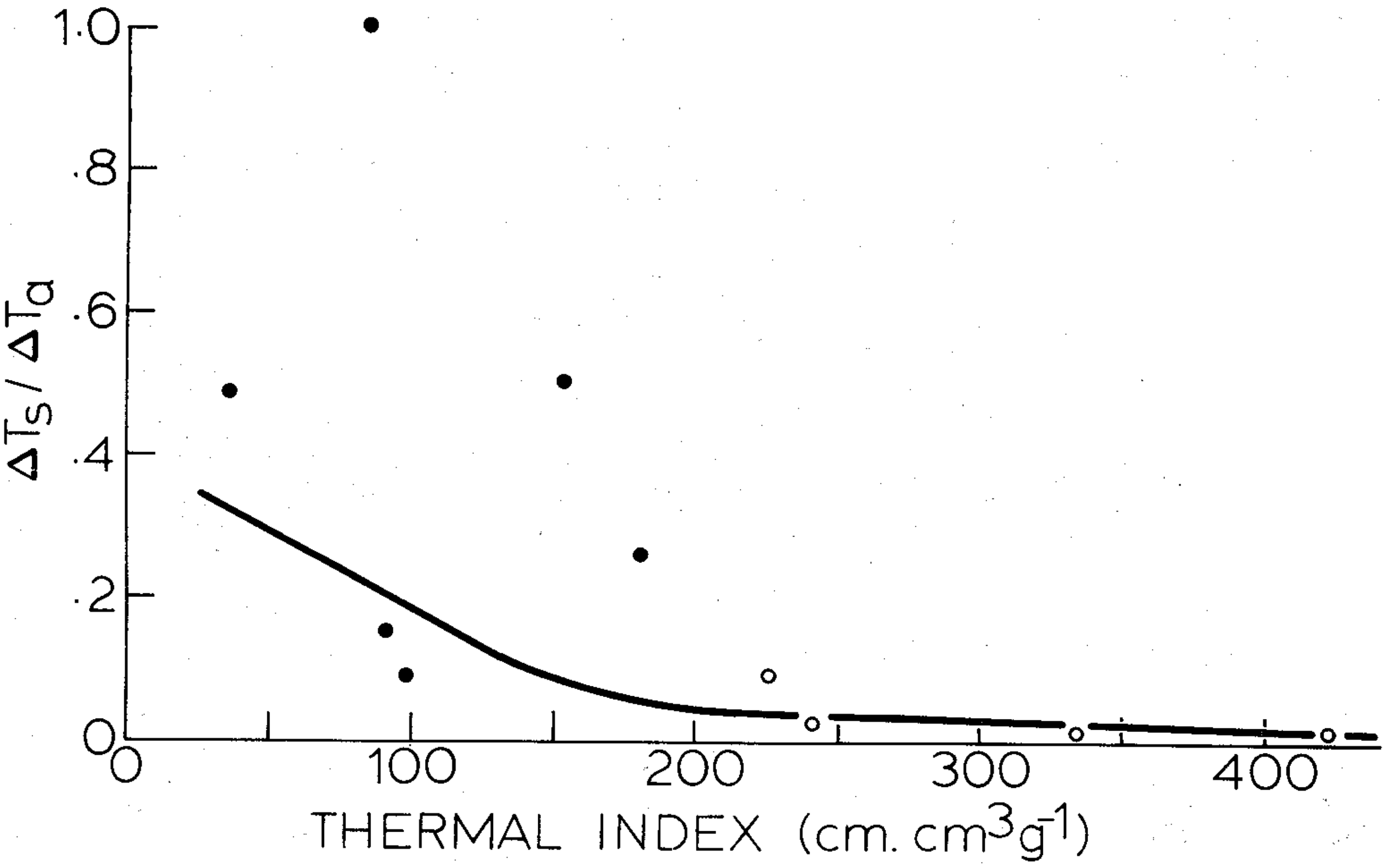

Fig. 3 Temperature stability of the subnivean environment ($\Delta T_s/\Delta T_a$) in relation to snowpack thermal index values (curve) after Marchand (1982). Values for winter 1982-83 (closed circles) and 1983-84 (open circles) are from the present study.

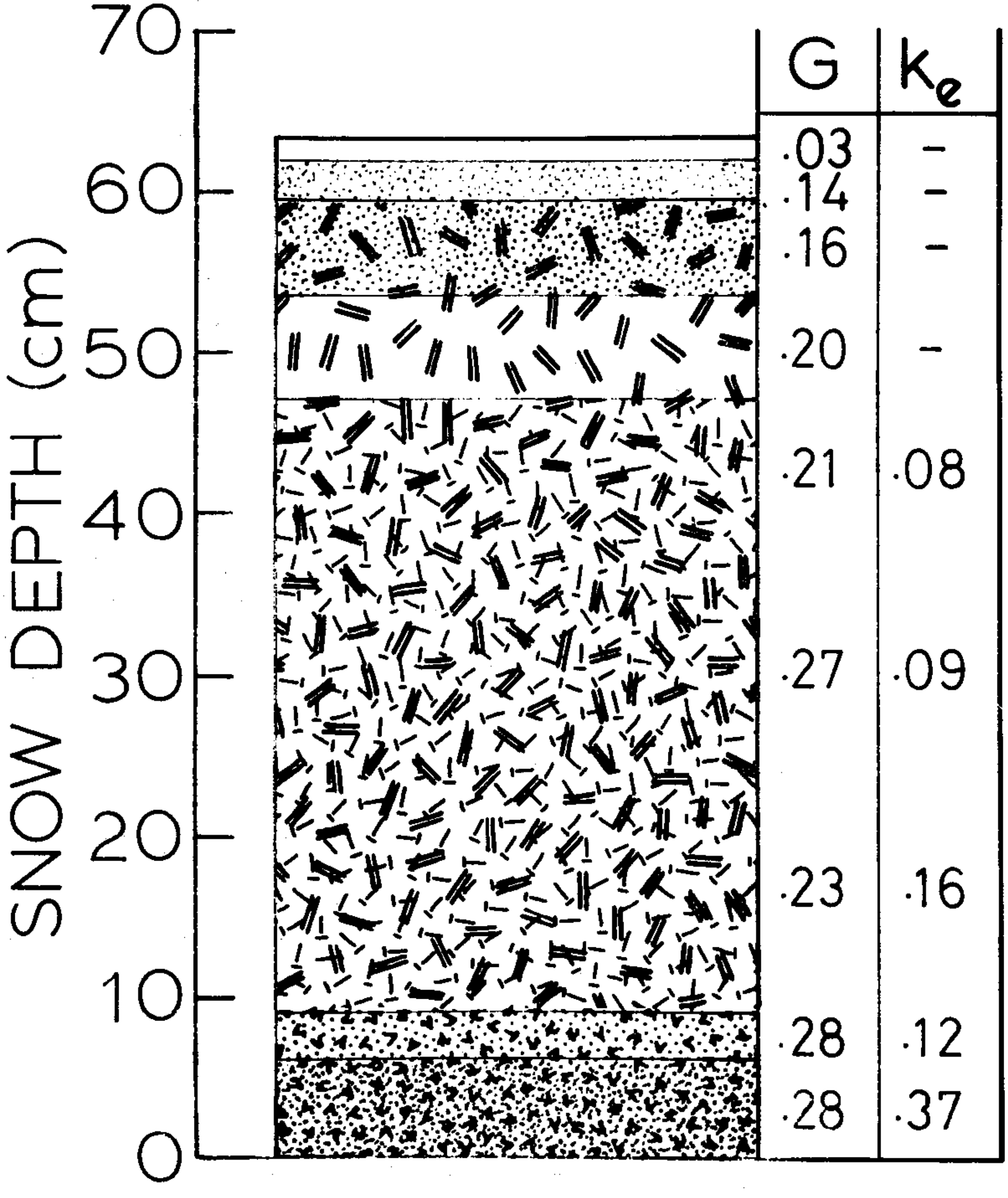

Fig. 4 Schematic representation of a snowpack consisting of seven distinct layers, and corresponding density, G (g cm^{-3}), and effective thermal conductivity, k_e (W m^{-1} K^{-1}).

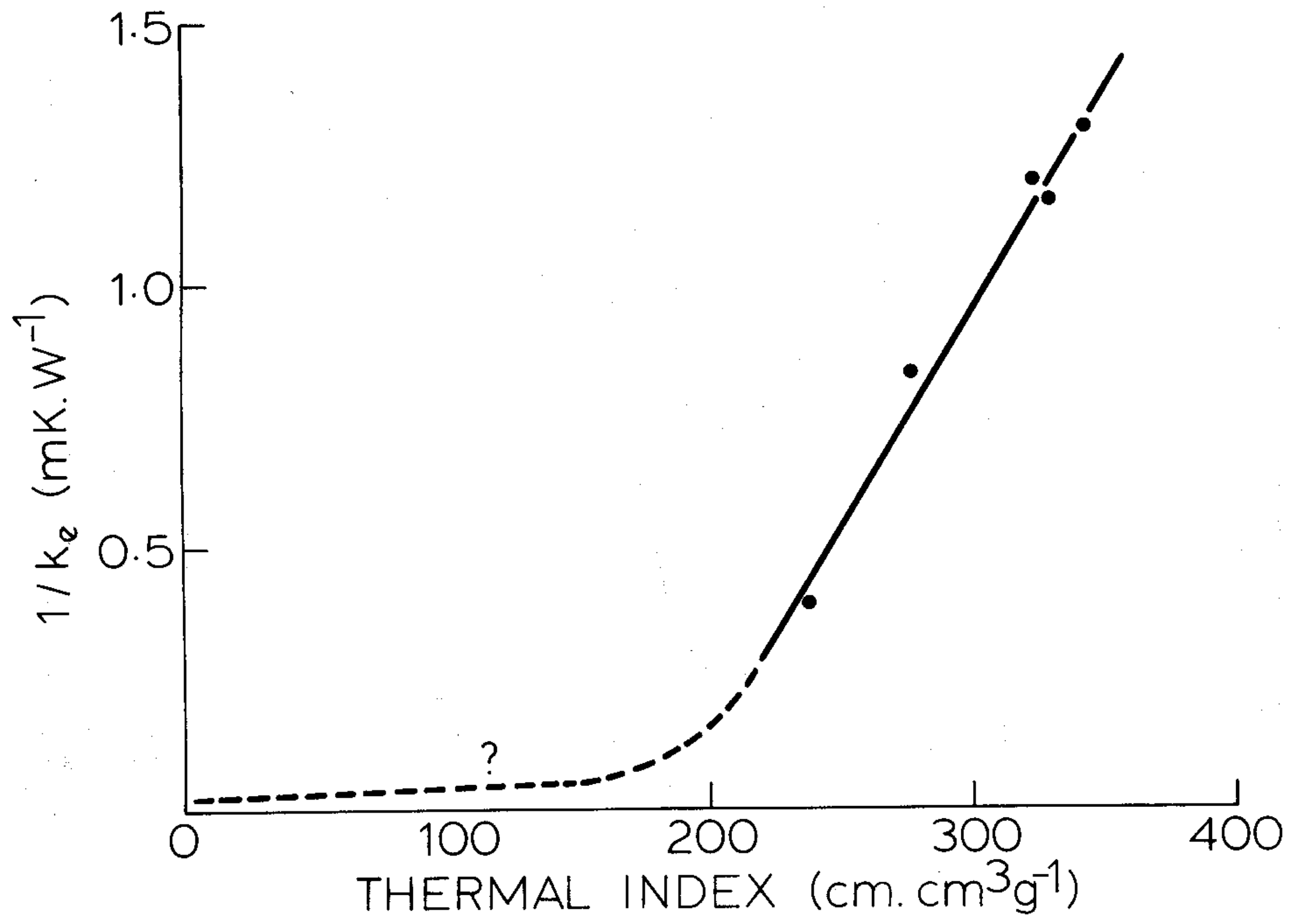

Fig. 5 The relationship between the reciprocal of the summed effective thermal conductivities (m.K W^{-1}) and the thermal index (cm.cm^3 g^{-1}) for the snowpack from January through February 1984. $r^2 = 0.98$; $p = < 0.001$.

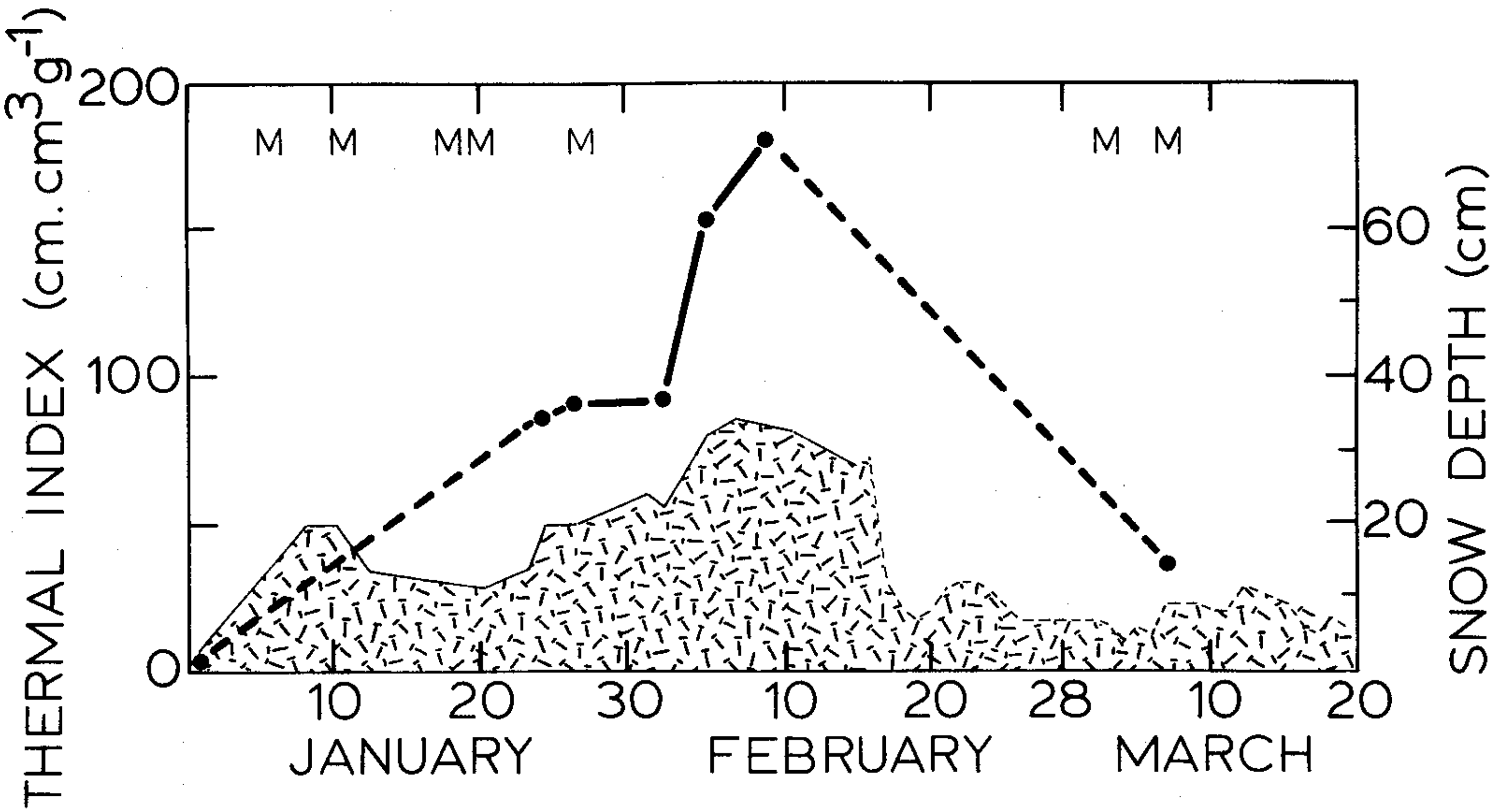

Fig. 6 The relationship of thermal index (cm.cm3 g^{-1}) and snow depth (cm) to meadow vole mortality (M) during winter 1982-83.

study site.

Table 2. Comparison of thermal conductivity values (W m^{-1} K^{-1}) of snow from a snowpack on 1 February 1984 with values taken from the literature

Snow Characteristics	Conductivity (W m^{-1} K^{-1})	Source
New snow (0.2 g cm^{-3})	.084-.126	Geiger (1965)
New snow	0.08	Oke (1978)
Fresh light snow	0.046	Steppuhn (1981)
New snow (sub-surface)	0.09	This study
Old snow	0.42	Oke (1978)
Old dense snow	0.326	Steppuhn (1981)
Crust within snowpack	0.12	This study
Metamorphosed mid-layer	0.16	
Old metamorphosed snow	0.37	

The thermal index was low but relatively stable from January 31 to February 9. No data were obtained prior to January 2 because periods of alternating rain and extreme cold left the ground covered with a thin, icy crust for which it was virtually impossible to measure an accurate thermal index. After February 14, a thaw rapidly reduced snow depth and the snowpack became saturated. Mortality of meadow voles (M) also is given (Fig. 6) and mortality occurred at times when thermal index was less than 100 cm.cm^3 g^{-1}. Under these conditions the meadow voles were exposed to extended periods of extreme cold. In the latter part of the winter there was the additional danger of the animals becoming wet and thus increasingly vulnerable to heat loss.

CONCLUSIONS

The amount and type of winter precipitation that falls in any given year dictates the depth and type of snowcover that results. When the snow is deep and uncompacted the temperature beneath the snow is stable and *ca* 0°C. This permits the meadow voles to maintain homeothermy and to forage as necessary to obtain food. Conditions of wet snow and rain that alternate with extreme cold lead to high meadow vole mortality.

The stable subnivean environment that results from an adequate depth of snow has been documented by means of a snow index (Marchand 1982) that is based upon the density of distinct layers within the snowpack. Temperature stability beneath the snow, irrespective of air temperature, was achieved at a snow index value of 200 cm.cm^3 g^{-1}. This corresponds both to the *hiemal threshold* described by Pruitt (1970) and with Marchand's (1982) value for which a stable subnivean temperature was attained.

Thermal index, furthermore, was found to be highly correlated with the reciprocal of the effective thermal conductivity for a given snowpack thus establishing a sound, physical base for the use of thermal index measurements as an ecological tool.

Meadow vole mortality was experienced with low thermal index values which suggests that both the concept of the *hiemal threshold* and the determination of thermal index are biologically relevent. The relative simplicity and rapidity of the thermal index technique to quantify the insulative capacity of a very complex and heterogeneous substance such as snow suggests its use for many forms of ecological investigations during the period when the ground is covered with snow.

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