

Sinking depths of black-tailed deer in snow, and their indices

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Sinking depths in snow of a captive black-tailed deer (*Odocoileus hemionus columbianus*) were recorded in old-growth, second-growth, and recently clear-cut forests. Data were collected over a wide range of snow conditions. Snow hardness was extremely variable, even within 30 cm, and only weakly correlated with deer sinking depths ($r = 0.52$ for upper crust hardness). Snow density in the upper 48 cm of the snowpack was a better predictor of deer sinking depths ($r^2 = 0.65$), but the best prediction was from density and hardness combined ($r^2 = 0.86$). Snow depth alone was a poor predictor, because the deer rarely sank to the bottom of the snowpack (9 of 630 cases). Two indices of sinking depth were evaluated: human sinking depth and Hepburn's index. Human sinking depth was both a simpler and better predictor, especially when snow hardness values $>256 \text{ g cm}^{-2}$ (deer static foot loading) were eliminated ($r^2 = 0.65$).

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La profondeur des pistes laissées dans la neige par un Cerf mulet (*Odocoileus hemionus columbianus*) captif a été déterminée dans des forêts âgées, des forêts nouvelles et des forêts récemment soumises à la coupe à blanc. Les données ont été recueillies dans une grande variété de condition. La dureté de la neige était extrêmement variable, même entre deux points distants de seulement 30 cm, et cette variable n'était que faiblement reliée à la profondeur des pistes ($r = 0,52$ dans le cas de la dureté de la croûte de surface). La densité de la neige dans les 48 cm supérieurs de la couche constituait un meilleur indice de la profondeur des pistes ($r^2 = 0,65$), mais le meilleur indice était cependant la combinaison de la densité et de la dureté ($r^2 = 0,86$). La profondeur de la couche constituait à elle seule un indice peu valable, car les cerfs s'enfonçaient rarement jusqu'au fond de la couche (9 cas sur 630). Deux indices de la profondeur d'enfoncement ont été évalués : la profondeur d'enfoncement d'une personne et l'indice de Hepburn. La profondeur d'enfoncement d'une personne s'est avérée un indice plus exact et plus simple à évaluer, surtout lorsque les valeurs de dureté de la neige supérieures à 256 g cm^{-2} (charge statique d'un pied de cerf) étaient éliminées ($r^2 = 0,65$).

[Traduit par la revue]

Introduction

Snow is a major factor influencing winter survival of black-tailed deer (*Odocoileus hemionus columbianus*) in some locations (Klein and Olson 1960; Bunnell *et al.* 1978; Jones and Mason 1983). Deep snow reduces net energy available (Harestad *et al.* 1982) by increasing energy costs of movement (Bunnell and Jones 1984; Parker *et al.* 1984) and reducing amounts of available forage by displacement and burial (Jones 1974; Harestad 1979). Snow depth, density, and hardness (Coady 1974) and animal leg length, foot loading, and velocity (Parker *et al.* 1984) interact to determine an animal's sinking depth and energy expenditure while moving through snow. Energy costs of walking through snow can be four to seven times greater than under snow-free conditions (Bunnell and Jones 1984; Parker *et al.* 1984) and can significantly modify the animal's daily energy expenditure (e.g., Bunnell and Harestad 1989).

Sinking depth increases the height feet must be lifted or generates drag and is a more revealing indicator of habitat suitability than is snow depth (Verme 1968). Snow density and hardness can modify sinking depth such that it is less than snow depth (Coady 1974; Jones 1974). Sinking depth itself should be considered relative to animal morphology, particularly brisket or chest height (Bunnell and Jones 1984; Parker *et al.* 1984).

As the density of a uniform snowpack increases, there is decreased penetration by the animal (Bunnell and Jones 1984), but increased resistance to forward movement (Parker *et al.* 1984). Hard, crusted snow can support a deer even when density

of the snowpack is low (Jones 1974). Generally, there is less penetration by the animal as hardness increases. Position of hard, crusted layers relative to softer snow layers is important because these may determine effective sinking depth (Nasimovich 1955; Pruitt 1959; Kelsall and Prescott 1971).

Attempts to relate sinking depths to snow attributes have been plagued with sampling problems (review of Shank and Bunnell 1982) and there are few well-tested indices to deer sinking depths. Ideally, tame deer should be used to acquire comparable samples from a wide range of snow and forest conditions.

Objectives of this study were (i) to determine how snow density and hardness influence sinking depths of a captive black-tailed deer and (ii) to evaluate the accuracy of two potential indices of deer sinking depth (human, booted-foot sinking depth and Hepburn's (1978) index).

Study areas and methods

Sampling was designed to evade limitations exposed by previous workers. The basic sampling unit was an individual sinking depth and associated snow attributes. Coastal snow conditions can change within a day. To obtain sufficient replicates under similar conditions, sampling was limited to one deer. That deer was in its first winter, the age or period when most mortality occurs. Sinking depth samples are necessarily destructive, so plots were temporary; 10 sinking depths were recorded per plot.

Data were collected on 9 days selected during the period 22 January to 13 April 1984 to encompass different snow characteristics under stable weather conditions, i.e., minimal wind and precipitation and minor changes in temperature and solar radiation within each day. The days were representative of the range of snow conditions, but may not represent the frequency with which particular kinds of snow occur. Each day, sampling occurred in three or four habitats located on southern slopes (elevation, 950-970 m) of the subalpine Mountain Hemlock Zone (*sensu* Krajina 1965) in Mount Seymour Provincial Park,

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British Columbia. Dominant tree species included mountain hemlock (*Tsuga mertensiana*), amabilis fir (*Abies amabilis*), and yellow cedar (*Chamaecyparis nootkatensis*). The habitats were (i) a 200-year-old stand averaging 60% canopy closure as measured by moosehorn (Robinson 1947); (ii) an 80-year-old, second-growth stand with 90% crown closure; (iii) a 20-year-old stand with 36% crown closure; and (iv) a clear-cut area with no overstory cover. Extreme variability in snow conditions in the 20-year-old stand (air pockets around shrubs and small trees) influenced the behaviour and gait of the tame deer; therefore, trials using the deer were abandoned in that habitat. Measurements of snow characteristics and human, booted-foot sinking depth were made in all four habitats. Data on deer sinking depths and snow characteristics include 5 days of markedly different snow conditions in three habitats ($n = 630$); data on human sinking depths and snow characteristics include 9 days in four habitats ($n = 850$).

Sinking depths were determined for one captive black-tailed deer that had been bottle-raised and trained to a lead rope. During the 2-month period of measurement, at 7–8 months of age, the animal weighed 31.5 ± 0.4 kg. Brisket height, measured to the nearest centimetre from the ground surface, was 47 cm. Foot area was determined by photographic projection, as in Parker *et al.* (1984). This area included the bottom of the hoof and the phalanx up to and including the dewclaws. Standing posture foot loading (256 g cm^{-2}) was calculated from average foot area. All measurements of animal sinking depth were taken from tracks made at a consistent walking gait in undisturbed snow.

With the exception of 1 day in which weather conditions changed quickly and snow measurements were abandoned in two habitats, sampling with the deer occurred over a 6- to 8-h period in six plots in old- and second-growth stands and three plots in clear-cut areas. All plots were located on relatively flat terrain where the deer could take at least 10 steps without altering its gait.

Within each plot, the sinking depths of 10 individual deer tracks were measured to the nearest centimetre as the vertical distance from snow surface to the tip of the hoof track. Three hardness values were estimated using the snow penetration gauge (SPG) of Hepburn (1978): (i) hardness (g cm^{-2}) of any upper crust within as close a proximity as possible to each track, (ii) minimum load (g cm^{-2}) necessary to reach the same sinking depth as the animal, (iii) and depth (cm) attained by Hepburn's index of 1900 g cm^{-2} (the simulated foot loading of white-tailed deer, *Odocoileus virginianus*). Human, booted-foot sinking depth (weight, 81.5 kg; foot area, 294.06 cm^2 ; foot load, 139 g cm^{-2}) also was recorded near each deer track. Density (g cm^{-3}) of the entire snowpack was measured next to 5 of the 10 deer tracks with a Stevenson snow sampler (U.S. Department of Agriculture 1972). On 2 days, 49 samples were taken at a depth approximately equivalent to the animal's brisket height (48 cm) to compare the density of the upper snow layers potentially experienced by the animal with that of the entire snowpack. Snow depth was recorded at each deer sinking depth, hardness measurement, and density tube reading. To assess small-scale differences in snow depth and hardness, values ($n = 60$) were recorded on 1 day in the 80-year-old habitat on both sides of sampled deer tracks. Temperature of the air and upper (3 cm) snow layer and percent canopy cover were measured at each plot.

Additional data on human sinking depth and snow characteristics were collected using systematic sampling in the same habitats, including 20-year-old forest. Techniques were the same except that only one measure of hardness was used: minimum SPG load necessary to reach human sinking depth. Each transect was sampled across the slope and parallel to contours. Plots for human sinking depth and snow measurements were located 2.5 m apart on transects. All habitats contained 60 plots except clear-cut, which contained 40.

Results

Deer sinking depths versus snow conditions

The deer rarely sank to the ground (9/630), and snow hardness and density had much greater influence on sinking depth than did snow depth. Even at snow depths of <15 cm, deer sinking depth was less than the snowpack.

Limitations to potential relationships between deer sinking depth and snow hardness were also imposed by the SPG, which was capable of measuring values only between 211 and 3870 g cm^{-2} . Depending on snow conditions, the SPG sank from 0 to 27 cm by its weight alone (1.35 kg) with no force applied ($n = 10$). Extreme spatial variability further reduced predictability. Hardness values on either side of each deer track differed by up to 3307 g cm^{-2} , almost the range encompassed by the SPG itself (mean absolute difference = $177.1 \pm 1705.6 \text{ g cm}^{-2}$; $n = 60$). These differences occurred ≤ 30 cm apart. As a result, load required to reach at least deer sinking depth and measured deer sinking depth were weakly correlated ($r = 0.35$, $n = 550$, $p < 0.001$). Hardness of the first supporting crust layer was positively correlated with minimum load necessary to reach deer sinking depth ($r = 0.62$, $n = 550$, $p < 0.001$), but deer sinking depth and upper crust hardness were not strongly correlated ($r = 0.52$, $n = 550$, $p < 0.001$). In 78% of the observations, the minimum load necessary to reach deer sinking depth was within 5% of the measured hardness of the first (upper) crust.

Because hardness was extremely variable and difficult to measure accurately, hardness alone was a weak predictor of deer sinking depth. The tendency for deer sinking depths to decrease with increasing hardness was clearly expressed only at the extremes (Fig. 1A). In the four hardness classes illustrated, the mean values of all deer sinking depths (\pm SE) from least to greatest hardness were 13.8 ± 0.04 , 14.9 ± 0.9 , 14.6 ± 0.8 , and 9.8 ± 0.6 cm. There were no significant differences in sinking depth among hardness classes until hardness values exceeded 2048 g cm^{-2} ; that class showed significantly lower sinking depths than did the other three classes (Scheffé's test). At low values of hardness ($\leq 512 \text{ g cm}^{-2}$), only 5% ($n = 189$) of the deer sinking depths were $\leq 10\%$ of brisket height; at high values of hardness ($>2048 \text{ g cm}^{-2}$), 29% ($n = 166$) of values were $\leq 10\%$ of brisket height (Fig. 1A). Between the two extreme hardness classes, the proportions of deer sinking depths exceeding 40% of brisket height decreased from 28 to 16%.

Deer sinking depth as predicted by human, booted-foot sinking depth (Fig. 1B) showed patterns with hardness similar to those of measured deer sinking depth (Fig. 1A). Predicted sinking depths are from eq. 3 (see below); hardness measurements of Fig. 1B were collected during systematic sampling of human sinking depth and are independent of those in Fig. 1A. The effect of hardness, especially at extremes, is similar within two independent data sets encompassing 9 days of different weather and snow conditions.

Poor predictability using only hardness as an indicator of deer sinking depth is partially due to influences of density on sinking depth. The maximum deer sinking depth measured was 44 cm; brisket height was about 47 cm. Density of the entire snowpack (range, $0.15\text{--}0.62 \text{ g cm}^{-3}$) was significantly greater than that of the top 48 cm (range, $0.08\text{--}0.35 \text{ g cm}^{-3}$; $p < 0.001$, t -test). Across all habitats, the correlation between deer sinking depth and density of the total snowpack was weak ($r = 0.11$, $n = 343$, $p < 0.025$). The poorest correlation occurred in the second-growth forest ($r = 0.006$); the relation in the clear-cut habitat, where density of the entire snowpack was greater and less variable, was much stronger ($r = 0.70$, $n = 61$, $p < 0.001$).

Density of the upper 48 cm provided a better indicator of deer sinking depth than did density of the entire snowpack. Analyses were extended to include density of the upper 48 cm of snowpacks >48 cm and density of the pack when the entire snowpack was <48 cm. Generally, the sinking depth decreased

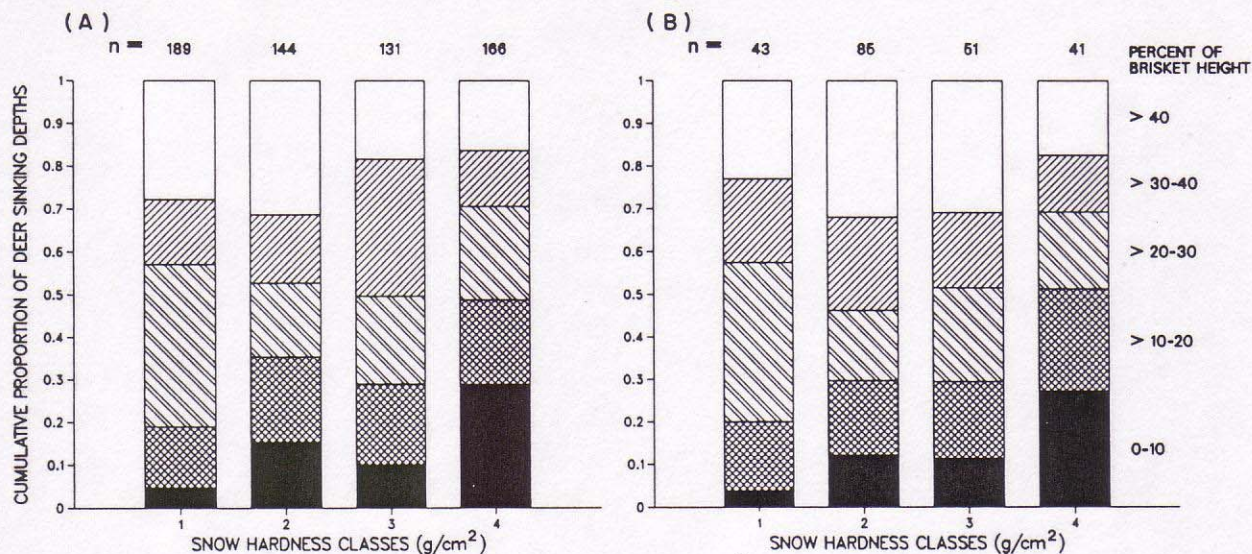


FIG. 1. The influence of snow hardness (SPG load reach to deer sinking depth, g cm^{-2}) on sinking depths of a black-tailed deer as measured (A) and predicted (B) using an index of sinking depth (eq. 3). Sinking depths are presented as percentages of brisket height. Hardness classes (g cm^{-2}) were as follows: 1, <512 ; 2, 513–1024; 3, 1025–2048; and 4, >2048 .

with increasing density. In the four density classes illustrated (Fig. 2), the mean values for all deer sinking depths (\pm SE) from least to greatest density were 18.3 ± 1.2 , 12.7 ± 0.6 , 13.2 ± 0.85 , and 9.4 ± 0.9 cm. Mean sinking depths of the two extreme density classes each differed significantly from the other three classes ($p < 0.008$, Scheffé's test). At densities $<0.20 \text{ g cm}^{-3}$, $\leq 9\%$ of deer sinking depths were $<20\%$ of brisket height; the percentage of these shallow sinking depths increased to 52% at densities $\geq 0.40 \text{ g cm}^{-3}$ (Fig. 2). Conversely, deeper sinking depths ($>40\%$ brisket height) represented smaller proportions of the observations as density increased: 52% at densities $<0.20 \text{ g cm}^{-3}$ and 9% at densities $>0.40 \text{ g cm}^{-3}$.

The interacting effects of density and hardness were examined in two ways. One approach used plot means in multiple regression of deer sinking depth (DSD, cm) on density of the total snowpack (D , g cm^{-3}) and hardness of the upper crust (H , g cm^{-2}). Forty plots had five values of each of these variables; their means were used in eq. 1:

$$[1] \text{ DSD} = 23.03 - 29.13D - 0.003H \\ (n = 40; r^2 = 0.86; S_{y \cdot x} = 1.59; p < 0.05)$$

The second approach eliminated effects of upper crusting by using only those values for which upper crust hardness was less than static foot loading (256 g cm^{-2}). The relation between deer sinking depth and density of the upper 48 cm (D_{48} , g cm^{-3}) was then

$$[2] \text{ DSD} = -7.94 \ln D_{48} \\ (n = 57; r^2 = 0.65; S_{y \cdot x} = 2.99; p < 0.05)$$

Only 25 values of upper crust hardness between 256 and 512 g cm^{-2} were measured. Using a hardness threshold of 512 g cm^{-2} increased the value of r^2 modestly ($r^2 = 0.69$), but reduced the predictive capability of the regression ($S_{y \cdot x} = 3.34$).

Both density and hardness modified deer sinking depths (eq. 1). Density of the total snowpack was poorly correlated with sinking depth ($r = 0.11$); by restricting density measurements to ≤ 48 cm depth and eliminating effects of crusting, the influence of density was more apparent (eq. 2). The greatest depth to

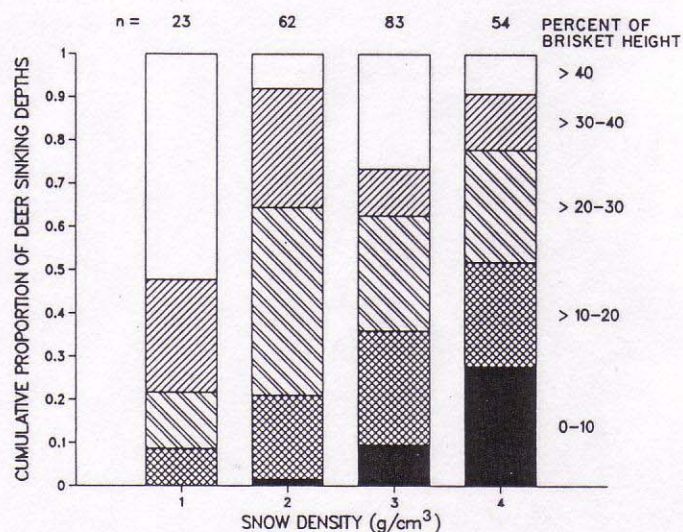


FIG. 2. The influence of snow density (g cm^{-3}) in the upper 48 cm of the snowpack on sinking depths of a black-tailed deer. Sinking depths are presented as percentages of brisket height. Density classes (g cm^{-3}) were as follows: 1, <0.20 ; 2, 0.20–0.29; 3, 0.30–0.39; 4, >0.40 .

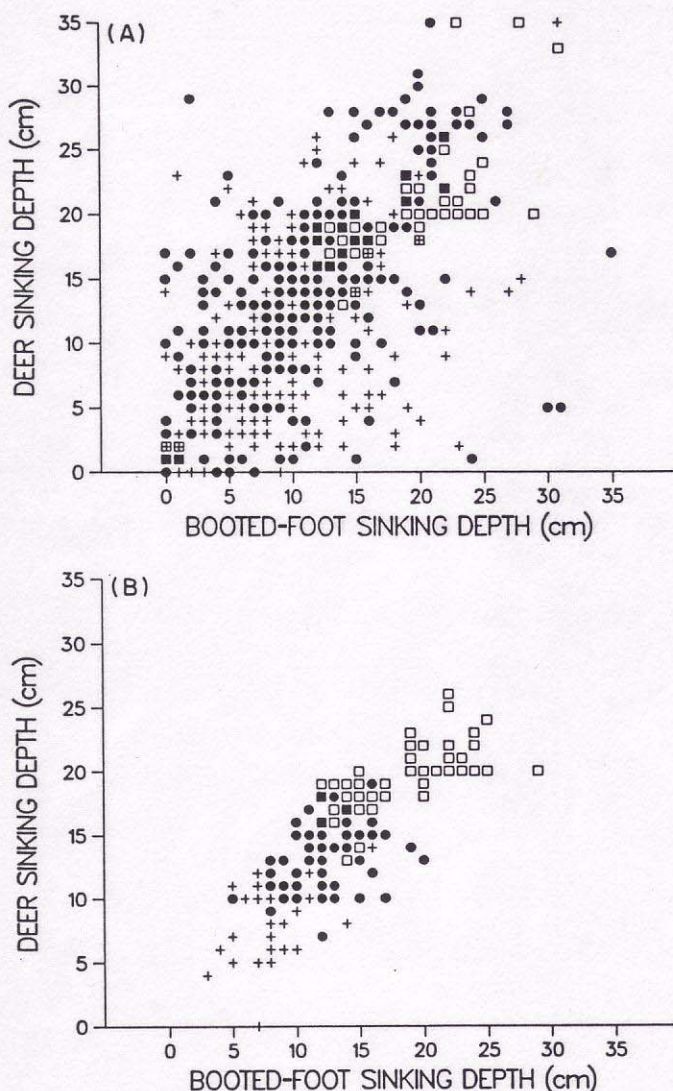
which the animal sank when density of the top 48 cm was measured (i.e., snowpack >48 cm) was 28 cm. To what extent the snow layers or individual crusts between 28 and 48 cm affected sinking depth is not known. There were no strong relationships between snow hardness and density ($r = 0.18$, $n = 273$, $p < 0.004$), nor between hardness and density per degree of snow temperature ($r = 0.46$, $n = 265$, $p < 0.001$).

Indices of deer sinking depth

Indices of deer sinking depth did not vary consistently with deer sinking depth (Table 1). Most relations using human, booted-foot sinking depth (seven of nine) were not significant within a habitat on a specific day ($p > 0.05$). By pooling data for all sampling days, the potential of this index was greatest in the clear-cut area ($r = 0.96$, Table 1). Combining data from all habitats per day gave significant relationships; the poorest

TABLE 1. Correlations between sinking depth of black-tailed deer and two indices of sinking depth (booted-foot and Hepburn's) within habitat and per day on Mt. Seymour, B.C., 1984

Habitat	Weather and snow conditions	Booted-foot index			Hepburn's index ^a		
		<i>r</i>	<i>n</i>	<i>P</i>	<i>r</i>	<i>n</i>	<i>P</i>
Old-growth forest		0.34	220	<0.001	0.32	270	<0.001
Second-growth forest		0.29	180	<0.001	0.29	300	<0.001
Clear-cut area		0.96	90	<0.001	0.77	120	<0.001
Day 1	-1 to 4°C, snowmelt from trees, strong crusting	—	—	—	0.78	140	<0.001
Day 2	-1 to 0°C, overcast, snowing, wet, crusting	—	—	—	0.51	60	<0.001
Day 3	-1 to +1°C, overcast, wet, very strong crusting	0.23	190	<0.002	0.32	190	<0.001
Day 4	-3 to -1°C, clear, dry, weak crusting	0.69	150	<0.001	0.41	150	<0.001
Day 5	-2 to -1°C, overcast, soft, sticky, weak crusting	0.66	150	<0.001	0.27	150	<0.001
All combined		0.62	490	<0.001	0.49	690	<0.001

^a1900 g cm⁻² (Hepburn 1978).FIG. 3. Relationship between booted-foot and black-tailed deer sinking depths in snow in old-growth (●), second-growth (+), and clear-cut stands (□) for all observations (A) and for observations when hardness was greater than static foot load (B). Eliminating all hardness measurements >256 g cm⁻² removes much of the effect of crusting.

correlation occurred during strong crusting (Table 1). Snow hardness appears to be a major factor affecting apparent relations between booted-foot sinking depth and deer sinking depth. Human sinking depth, like deer sinking depths, was poorly correlated with hardness. The best correlation between human sinking depth and snow hardness occurred in the old-growth forest ($r = 0.48$, $n = 220$, $p < 0.002$). By eliminating all values for which hardness could provide some support (i.e., >256 g cm⁻², deer static foot loading), the correlation between deer and human sinking depths over all habitats was improved from $r = 0.62$ to $r = 0.81$ ($n = 164$, $p < 0.001$, Fig. 3).

Hepburn's index to deer sinking depth showed less reliability than did booted-foot sinking depth. Although significant relationships occurred by day and within habitat, most correlations were weak and there was no general relation (Table 1). Hence, for the prediction of deer sinking depth, booted-foot or human sinking depth (HSD, cm) was the more reliable index. Equations were generated for overall snow conditions (eq. 3; Fig. 3A) and for those in which snow hardness was <256 g cm⁻² (eq. 4; Fig. 3B):

$$[3] \text{ DSD} = 5.10 + 0.61\text{HSD} \\ (n = 490; r^2 = 0.38; S_{y \cdot x} = 4.85; p < 0.05)$$

$$[4] \text{ DSD} = 4.29 + 0.77\text{HSD} \\ (n = 164; r^2 = 0.65; S_{y \cdot x} = 2.87; p < 0.05)$$

Discussion

In the studies of Jacobsen (1973), Mattfeld (1974), and Parker *et al.* (1984), white-tailed deer, mule deer (*Odocoileus hemionus hemionus*), and elk (*Cervus elaphus nelsoni*) sank through snow to the ground. Snow characteristics other than depth did not influence sinking depth. In coastal areas, new-fallen snow is dense, experiences frequent rain-on-snow events or other melting periods, forms crusts, and apparently provides greater support. The black-tailed deer did not sink to the ground even when snow was only 15 cm deep.

No single snow characteristic strongly controlled or accurately predicted black-tailed deer sinking depths. Even when potential variation was reduced by using a single animal at one gait, extreme values of density and hardness interacted and either characteristic could have a pronounced effect. There was

a significant tendency for strong crusts ($>2048 \text{ g cm}^{-2}$) to reduce sinking depths, but it was variable and unreliable (Fig. 1). Similarly, densities greater than 0.40 g cm^{-3} strongly but inconsistently reduced sinking depths (Fig. 2). In areas of colder, drier snow or more stable weather conditions, snow density and hardness show strong positive correlation (e.g., Billelo *et al.* 1970). Within our samples, the correlation was weak ($r = 0.18$), reflecting the moist, changeable weather and extreme variation in hardness measurements.

Despite the lack of correlation and pronounced interaction, regression combining effects of both density and hardness accounted for 86% of the variation in deer sinking depths (eq. 1). When effects of hardness were eliminated (no upper crust $>256 \text{ g cm}^{-2}$), 65% of the variation in sinking depths was associated with density (eq. 2). Three points are evident. First, given the large spatial variability in hardness, particularly as compared to density, early efforts to rely on density as a predictor of sinking depth appear partially justified (e.g., Bunnell and Jones 1984), but will not be reliable in crusted snow. Second, some of the variation in sinking depth is a product of crusts or stronger layers within the snowpack (compare eqs. 1 and 2; eq. 1 uses upper crust hardness). Third, it is unclear what estimate of foot loading should be used in attempting to derive indices of deer sinking depth; doubling the foot loading threshold for eq. 2 increased r^2 slightly, but reduced $S_{y,x}$.

More reliable estimates of the influence of snow hardness on sinking depth will be difficult to obtain. The mean difference in hardness measurements $\leq 30 \text{ cm}$ apart was $177.1 \pm 1705.6 \text{ g cm}^{-2}$; the probability of these close measurements originating from the same distribution was >0.43 . Hepburn (1978) also noted that the hardness of snow layers could vary by a factor of three between samples in the same forest type at the same time. Given this variability, it is unlikely that the SPG measurements provide a good estimate of what is actually experienced by the deer even when taken close to the animal's tracks. The natural spatial variation eliminated any clear predictive relationship between snow hardness and deer sinking depth. Other workers have noted the same difficulty, but did not document the fine scale of the variability (Pruitt 1959, 1979; Kelsall and Prescott 1971; Antifeau 1987). In their behavioural index for adaptation to snow, Telfer and Kelsall (1984) included ability to select the most suitable conditions for locomotion and foraging within winter home ranges. They did not treat black-tailed deer, but ranked white-tailed deer as having the most adaptive behavioural traits within their system. Our data suggest that variability in snow attributes occurred over such a fine scale within a given habitat that deer would find it very difficult to select particularly favourable routes. The suggestion is supported by the erratic behaviour of deer in the 20-year-old stand, which forced us to terminate sampling there. Black-tailed deer exploit large-scale variability in snow cover (Bunnell and Jones 1984), but avoid areas of highly variable, unpredictable snow cover.

Ability to predict snow conditions favourable to deer is further hindered because loads differ on the SPG and deer feet in their nature (dynamic in deer, static on the SPG) and duration (shorter in deer, longer on the SPG). These factors likely influence the modulus of rupture of snow so that the SPG does not index deer foot loading well, even at identical snow characteristics. However, the Swiss rammsonde penetrometer, which provides short, dynamic loads, provided no better correlation between measured hardness and human sinking

depths than did the SPG with human sinking depth (Hovey and Bunnell 1984).³

Hardness also reduced the predictability of both indices tested. Human, booted-foot sinking depth was statistically associated with deer sinking depth when only hardness values $<256 \text{ g cm}^{-2}$ were considered ($r^2 = 0.65$, eq. 4) and predicted similar patterns over a broader range of hardness (Fig. 1). Usually, the relation was poorer when all hardness values were considered; the high correlation ($r = 0.96$, Table 1) for the clear-cut area is potentially misleading. Of all habitats, the clear-cut area showed the most dramatic change in crusting over the winter. As a result, extremes of hardness were measured with few intermediate values; these conditions increased the apparent correlation.

Hepburn's (1978) index was generally less reliable than booted-foot sinking depth (Table 1). This failure reflects conditions in which the use of the SPG was limited: light unstratified powder and extremely hard or dense snow (Hepburn 1978). Both conditions occurred during data collection. Penetration gauges not only exhibit high variability (Kelsall and Prescott 1971; Coady 1974; Hepburn 1978), but the index of 1900 g cm^{-2} represents a much higher foot loading than that determined for the black-tailed deer in this study (256 g cm^{-2}). The SPG force of 1900 g cm^{-2} was chosen not to reflect static pressure, but a combination of gravity and the kinetic forces of locomotion for wild animals (Hepburn 1978). Static foot loading based on the average weight per foot in a standing animal is also only an index. During the normal walking gait, body weight is supported on two feet; in breakable snow crusts, animals may cautiously move only one leg at a time (Hepburn 1978). In combination with the forces of momentum, foot loading may therefore be increased substantially above a static index during locomotion in snow. Some compensation is provided, however, by the ability of deer to spread the toes and collapse the phalanx, thereby increasing the area of the foot and decreasing foot loading and sinking depth (Parker *et al.* 1984).

Foot area derived by our technique was 30.74 cm^2 . This differs little from a value of 31.17 cm^2 , which was derived using the simpler regression technique of Kelsall *et al.* (1980) developed for white-tailed deer. Because the young animal used in this study was controlled at a consistent walking gait, foot loading was probably less than that estimated for an adult white-tailed deer. The measured, static foot loading (256 g cm^{-2}) underestimates actual loading, but does provide an operationally defined and conservative estimate of the effects of foot loading on sinking depth. The actual threshold of hardness or foot loading at which sinking depth is modified primarily by density is unclear (e.g., the two thresholds evaluated in eq. 2).

Generally, attempts to index ungulate sinking depths by instruments, such as penetrometers, have generated weak relationships (Kelsall and Prescott 1971; Coady 1974; Eastman 1977; Hepburn 1978; this study). Attempts at combining measurements of individual snow layers have also been weakly predictive or very complex, thus reducing their utility as a simple tool (Pruitt 1959, 1979; Kelsall and Prescott 1971). The most accurate index is also the simplest, human sinking depth. Antifeau (1987) obtained an r^2 value of 0.96 between human and caribou sinking depths, whereas we obtained an r^2 value of

³F. W. Hovey and F. L. Bunnell. 1984. An analysis of the relative precision of three instruments used in measuring snow hardness. Unpublished report, B.C. Forest Service, Victoria.

0.65 between human and deer sinking depths. Possibly, human sinking depth does better at simulating short, dynamic loads than do available instruments.

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