

irregularities of terrain and forests vary unpredictably about the world. Instead we have simulated the ideal case, for in practice it is usually possible to move several feet in nonideal conditions to reach a line of sight that is essentially ideal.

### Acknowledgements

This study was supported by the Utah Agricultural Experiment Station. D. Verbyla did the computer programming, and he, T. L. Cannon, and R. Roeh collected the data.

AVERY, T.E., and BURKHART, H.E. 1983. Forest measurements. McGraw-Hill, Inc., New York.

AVERY, T.E. 1967. Forest measurement. McGraw-Hill, Inc., New York.  
 BELYEA, H.C. 1931. Forest measurement. John Wiley & Sons, New York.  
 HAIG, I.T. 1925. Short cuts in measuring tree heights. *J. For.* **23**: 941-944.  
 HUSCH, B., MILLER, C.I., and BEERS, T.W. 1982. Forest mensuration. John Wiley & Sons, New York.  
 LONG, J.N., and MOHAI, P. 1986. A simplified procedure for measuring tree heights directly from slope distance. *West. J. Appl. For.* **1**: 58-59.

## Bending of a conifer branch at subfreezing temperatures: implications for snow interception

R. A. SCHMIDT AND J. W. POMEROY<sup>1</sup>

*USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Laramie, WY 82070, U.S.A.*

Received November 23, 1989

Accepted February 19, 1990

SCHMIDT, R. A., and POMEROY, J. W. 1990. Bending of a conifer branch at subfreezing temperatures: implications for snow interception. *Can. J. For. Res.* **20**: 1250-1253.

Ice crystals in cells of frozen wood increase the wood's modulus of elasticity so that branches become more rigid at colder temperatures. As temperature increases after a snowstorm, melting of crystals within the cells allows increased bending of branches under intercepted snow loads. Measurements of the force that produced a 10-cm deflection of branch tips of subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) and lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) showed a linear decrease as temperature rose from -12 to 0°C. Model predictions for the bending of a tapered branch supported the hypothesis that increased bending can explain unloading of intercepted snow under certain conditions when warming occurs after snowstorms.

SCHMIDT, R. A., et POMEROY, J. W. 1990. Bending of a conifer branch at subfreezing temperatures: implications for snow interception. *Can. J. For. Res.* **20** : 1250-1253.

La présence de cristaux de glace dans les cellules de bois gelé augmente son module d'élasticité de telle sorte que les branches deviennent plus rigides à mesure que la température s'abaisse. Lorsque la température s'élève après une tempête de neige, la fonte des cristaux dans les cellules permet aux branches de plier davantage sous le poids de la neige accumulée. Chez le sapin subalpin (*Abies lasiocarpa* (Hook.) Nutt.) (*Pinus contorta* var. *latifolia* Engelm.), les mesures de la force associée à une flexion de 10 cm de l'extrémité des branches diminuent de façon linéaire avec une augmentation de la température de -12 à 0°C. La flexion d'une branche de forme conique, telle qu'estimée par un modèle, supporte l'hypothèse que dans certaines conditions une souplesse accrue entraîne la chute de la neige accumulée lorsqu'un réchauffement survient après les tempêtes de neige.

[Traduit par la revue]

### Introduction

Most who have brought a frozen Christmas tree indoors know that frozen branches become more flexible when warmed. Also generally well known is the fact that this increased flexure of warmed branches releases intercepted snow, a process central to the fatal demise of the main character in Jack London's (1908) classic story, "To Build a Fire." Yet hydrologists concerned with evaporation of snow from forest canopies (i.e., your authors) seem to have

overlooked the mechanism and how it influences retention of snow on branches. This paper presents a simple model of branch bending at subfreezing temperatures, based on field tests that estimated elasticity of a subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) branch over a temperature range of -12 to 0°C. Our purpose is only to show why the process should be considered in more detail, as it relates to snow interception.

More is known about the elasticity of dead wood as a construction material than elasticity of living wood in the tree branches and stems (e.g., Kollmann 1960). At temperatures below freezing, ice forms in cells of wood, stiffening both the living and dead material, so that elasticity depends on

<sup>1</sup>Present address: National Hydrology Research Institute, Environment Canada, 11 Innovation Boulevard, Saskatoon, Sask., Canada S7N 3H5.

temperature and moisture content (Partl and Strassler 1977). Static bending tests on spruce lumber with high moisture content show a linear decrease in modulus of elasticity as subfreezing temperatures increase to 0°C, with nonlinear variations above freezing temperatures. We found no reports of the modulus of elasticity measured on living branches at subfreezing temperatures.

Efforts to model the mechanical structure of trees include a paper by Petty and Worrell (1981) who used both conical and paraboloidal descriptions of stem taper to arrive at the resistive bending moment of conifer stems under snow loads. They assumed  $7000 \text{ N}\cdot\text{mm}^{-2}$  as a mean modulus of elasticity of green softwoods. Archer and Wilson (1982) modeled branch movements during growth, using a segmented beam idealization to estimate the modulus of elasticity. McMahon (1975) presented an "ax head" branch model that tapers in the vertical as it spreads horizontally from its base, and from intensive measurements on six deciduous trees of different species, he showed that branch diameters increase as the  $3/2$  power of distance from the tip.

The mass of snow intercepted by a conifer branch increases as an S-shaped growth function of accumulated snowfall (Satterlund and Haupt 1967). Falling snow crystals rebound elastically from dry conifer needles at the beginning of a storm (Hoover and Leaf 1967). As crystals become lodged at the base of the needles, the percentage of crystals falling on snow already held by the branch begins to increase at an increasing rate, until the branch, with its needles and branchlets, is completely covered. Many falling crystals that strike the intercepted snow also bounce, and those striking near the edge of the snow cover often bounce off the branch (Kobayashi 1987).

Branch bending under the increasing weight of snow is not uniform. Curvature is greatest near the tip because of branch taper and the distribution of interception. Where intercepted snow causes bending that inclines the snow at a slope greater than its angle of repose, it fractures from the branch and often creates a cascade of snow as lower branches release snow under impact from the branch above. Cohesion of the intercepted snow and its adhesion to the branch and needles are certainly important in determining stability of snow on the branches (Miller 1966). Cohesive forces increase exponentially as snow temperature approaches the freezing point (Schmidt 1980), so that as a branch bends with warming, the forces that maintain the snow in place also increase, at least until melting occurs. However, this paper describes only the branch bending as a function of temperature, leaving the mechanical properties of snow at the point of release for future analysis.

### Measurements

We measured the bending resistance of one branch by applying a downward force 10 cm from its tip during diurnal temperature cycles in February and March 1988, first on a subalpine fir branch and then on a lodgepole pine branch (*Pinus contorta* var. *latifolia* Engelm.). For the 1.5-m fir branch, there were eight measurement times from 09:30 to 17:40 on 4 February that included both warming and cooling, over a temperature range of  $-11.3$  to  $-2.5^\circ\text{C}$ . Maximum rates of change in air temperature were  $0.3$  and  $-0.06^\circ\text{C}\cdot\text{min}^{-1}$ , at the beginning and end of the day's measurements, respectively. Fifteen measurements on the

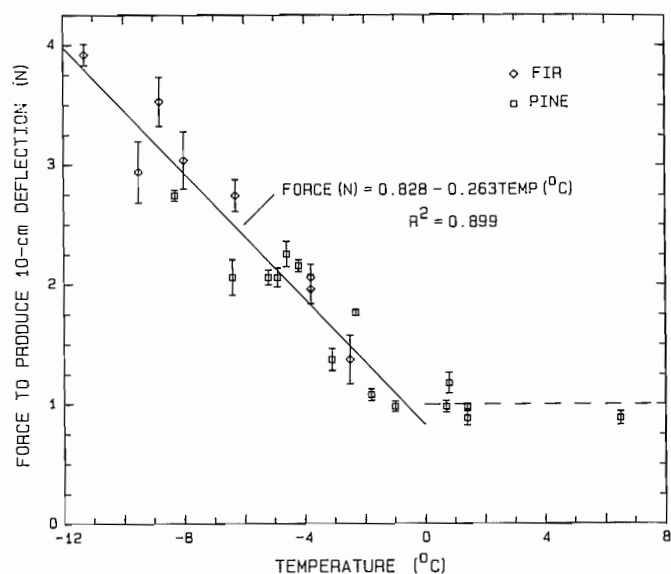


FIG. 1. A force gage attached 10 cm from the tip of each branch measured these loads required for 10-cm downward deflection of the branch tip. Temperatures were measured with a thermistor probe lodged in needles so it contacted the bark of the branch. Bars on each point represent the 95% confidence limits about means of 5 to 12 repetitions at each measurement time.

1.9-m pine branch, over 4 days, included temperatures from  $-8.5$  to  $6.5^\circ\text{C}$ . Again, warming and cooling periods were sampled, with the branch being both shaded and sunlit.

At each measurement time, 5 to 12 readings of a spring scale provided the average force required to deflect the branch tip 10 cm. The scale retained maximum force on a dial of 2 kg range, with 25-g graduations. Application of the test force 10 cm from the branch tip avoided the weak new growth, and the 10-cm tip deflection was chosen for easy reading on a meter stick pressed vertically into snow below the branch. A thermistor probe, placed in contact with the bark of the main branch, provided temperature readings on a digital meter with  $0.1^\circ\text{C}$  resolution. These data (Fig. 1) demonstrate the linear dependence of wood strength on subfreezing temperatures that is well documented in the literature. Moisture content was not measured.

Branch form, the relation between branch length and diameter, was similar for both species. Diameter increased as the  $3/2$  power of distance from the branch tip (Fig. 2), as noted by McMahon (1975) for deciduous species. Measurements of diameter are for the fir branch on which forces were measured, but for a different pine than that used in the force measurements of Fig. 1. Only the fir branch is used for the calculations that follow.

### Branch bending model

Following the suggestion of Petty and Worrell (1981), a model composed of short segments of constant cross sections provided estimates of the modulus of elasticity  $E$  from measurements in Fig. 1. We assumed circular-branch cross sections of radius predicted by the curve in Fig. 2. Deflections of each segment, produced by the bending moment of the test force times its distance from the segment, were calculated for 10-cm segments along the 150-cm fir branch, assuming a value of  $E$  of  $7000 \text{ N}\cdot\text{mm}^{-2}$ .

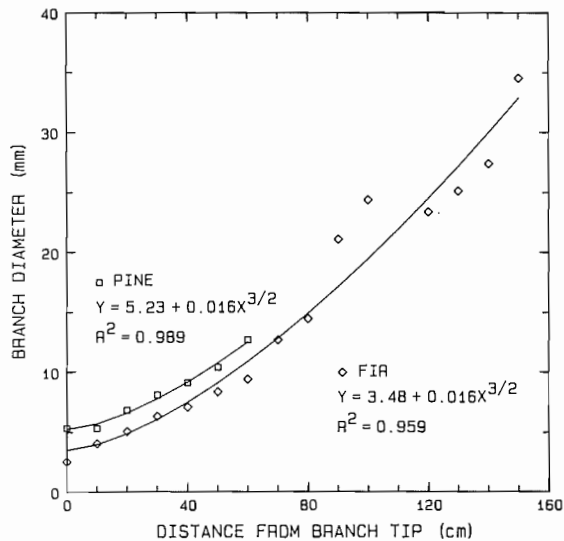


FIG. 2. In agreement with McMahon (1975), branch diameter increased as the  $3/2$  power of distance from the tip, for these fir and pine branches. (The fir branch plotted is the one on which forces were measured in Fig. 1; the pine is not.)

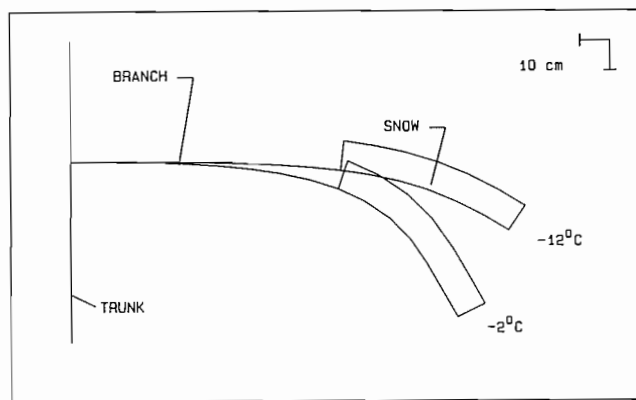


FIG. 3. Bending of the fir branch predicted by the segmented model, with an arbitrary snow load of 0.25 kg on each 10-cm segment from 90 cm to the tip, as temperature warms from  $-12$  to  $-2^{\circ}\text{C}$ .

Sketching the argument briefly, a branch segment of constant circular cross section, radius  $r$ , bends in a circular arc of radius  $R$ , such that the internal forces proportional to its modulus of elasticity  $E$  balance the external torque  $L$  that produces the bending. The equation describing this equilibrium is  $L = EI/R$ , where  $I = \pi r^4/4$  for a circular cross section. Bending-radius  $R$  is approximated by  $R = 1/(d^2y/dx^2)$  for  $R \gg 0$ , where  $x$  represents distance along the branch and  $y$  is displacement perpendicular to  $x$  (e.g., Stephenson 1952).

Substituting for  $R$  gives  $d^2y/dx^2 = L/EI$ , which is evaluated for each segment by assuming a value of  $E$ , computing  $I$  from the radius at the base of the segment using the curve of Fig. 2, and equating torque  $L$  to the force reading times the distance between the segment and the point of test force application, 10 cm from the branch tip. The authors will gladly supply more details upon request.

Summing the computed deflections of each segment gave the predicted displacement of the branch tip. Then, for several forces in the range shown by Fig. 1, adjusting the

value of  $E$  until the computed tip displacement matched the 10-cm test deflection produced the following relationship between elasticity and temperature:

$$[1] \quad E = 2650 - 842T$$

where  $E$  is in  $\text{N}\cdot\text{mm}^{-2}$  and  $T$  is the temperature of air surrounding the branch ( $-12 < T < 0^{\circ}\text{C}$ ). Estimated values of  $E$  near  $2600 \text{ N}\cdot\text{mm}^{-2}$  for temperatures above freezing are in the range reported by Archer and Wilson (1982) for white pine branches during the growing season ( $1640\text{--}3460 \text{ N}\cdot\text{mm}^{-2}$ ), but are less than the value assumed by Petty and Worrell (1981) for pine stems.

The increase in  $E$  to  $12\,750 \text{ N}\cdot\text{mm}^{-2}$  predicted by [1] for  $-12^{\circ}\text{C}$  corresponds to the increase in force required for 10-cm deflection at that temperature. Predictions of  $E$  by the segmented model were checked against a finite-element solution (see Acknowledgements), which gave  $E = 2815 - 894T$ , in close agreement with [1]. Both methods are simplifications of the complicated branch structure, but the finite-element technique offers more convenience and perhaps more accuracy and will be used in future work.

Figure 3 demonstrates how the segmented model predicts branch bending under a snow load, as temperature warms from  $-12$  to  $-2^{\circ}\text{C}$  and  $E$  decreases according to eq. 1. The assumed interception load, arbitrarily distributed uniformly over the 60 cm nearest to the tip, corresponds to 0.25 kg of snow on each 10-cm segment. This might be visualized as a snowfall with  $250 \text{ kg}\cdot\text{m}^{-3}$  density, 10 cm deep on each branch segment that is 10 cm long and 10 cm wide (covering needles and branchlets).

### Discussion and conclusion

The hypothesis that warming temperatures release intercepted snow through the mechanism of branch bending occurred to us during experiments on evaporation of interception. One bright, still morning when many trees in a lodgepole pine stand began to unload the night's interception almost simultaneously, no wind was detectable in the stand and air temperature was  $-6^{\circ}\text{C}$ , having risen rapidly from an overnight low near  $-25^{\circ}\text{C}$ . Previous explanations for unloading, by wind (Hoover and Leaf 1967) or with temperatures above freezing (Miller 1966), did not fit the situation. Based on the measurements and calculations of this paper, changes in elasticity with temperature seem a more likely cause.

Two consequences of the hypothesis are (i) branches can support more intercepted snow at colder temperatures and (ii) greater bending near branch tips may result in partial release of intercepted snow without disturbing snow nearer the trunk, which remains exposed to evaporation.

Assumptions made in developing the model obscure some interesting aspects of the problem, as pointed out by John G. Worrall (University of British Columbia) in review of this manuscript. The line drawn through the data for sub-freezing temperatures in Fig. 1 is undoubtedly an approximation, probably of a function that is stair stepped, as freezing occurs in discrete phases. Strength properties are not uniform across the branch cross section, as assumed, because the structure includes phloem and pith in addition to wood cells. A uniform temperature through the section, especially of larger branches, seems unlikely when air temperature is changing rapidly. The significance of moisture content and distribution of moisture within the branch adds

interesting complexity. Such refinements to the model may prove useful, for example, in explaining differences in unloading of intercepted snow on adjoining north and south aspects.

### Acknowledgements

Dr. Walter S. Chemielewski, University of Wisconsin-Platteville, kindly took time from his summer work at University of Wyoming to check the predictions of the segmented branch model, using a finite-element analysis. The efforts of M. Martinez in maintaining the facilities at the Fraser Experimental Forest, Colorado, under direction of Dr. C. Troendle, contributed to this work.

ARCHER, R.R., and WILSON, B.F. 1982. Apical control of branch movements in white pine: compression wood action. *Wood Sci. Technol.* **16**: 181-191.

HOOVER, M.D., and LEAF, C.F. 1967. Process and significance of interception in Colorado subalpine forest. *In Forest hydrology. Edited by W.E. Sopper and H.W. Lull. Pergamon, New York.* pp. 213-224.

KOBAYASHI, D. 1987. Snow accumulation on a narrow board. *Cold Reg. Sci. Technol.* **13**(3): 239-245.

KOLLMANN, F. 1960. Die Abhängigkeit elastischer Eigenschaften des Holzes von der Temperatur. *Holz Roh- Werkst.* **18**: 308-314.

LONDON, J. 1908. To build a fire. *Century (Magazine)*, New York. [also, *Creative Education*, Mankato, MN, 1980.]

MCMAHON, T.A. 1975. The mechanical design of trees. *Sci. Am.* **233**(1): 92-102.

MILLER, D.H. 1966. Transport of intercepted snow from trees during snow storms. *USDA For. Serv. Res. Pap. PSW-33.*

PARTL, M., and STRÄSSLER, H. 1977. Temperatureinfluss auf das Biege- und Schlagbiegeverhalten von Fichtenholz. *Holzforsch. Holzverwert.* **29**: 94-101. [See National Agricultural Library Translation 24751, The influence of temperature upon static and impact bending behavior of spruce.]

PETTY, J.A., and WORRELL, R. 1981. Stability of coniferous tree stems in relation to damage by snow. *Forestry*, **54**(2): 115-128.

SATTERLUND, D.R., and HAUPT, H.F. 1967. Snow catch by conifer crowns. *Water Resour. Res.* **3**: 1035-1039.

SCHMIDT, R.A. 1980. Threshold wind-speeds and elastic impact in snow transport. *J. Glaciol.* **26**(94): 453-467.

STEPHENSON, R.J. 1952. *Mechanics and properties of matter.* John Wiley & Sons, New York.

## Jack pine budworm populations and staminate flowers

V. G. NEALIS

*Forestry Canada, Ontario Region, P.O. Box 490, Sault Ste. Marie, Ont., Canada P6A 5M7*

Received October 11, 1989

Accepted February 19, 1990

NEALIS, V. G. 1990. Jack pine budworm populations and staminate flowers. *Can. J. For. Res.* **20**: 1253-1255.

The relationship between jack pine budworm (*Choristoneura pinus pinus* Free.) and staminate flowers of its principal host, jack pine (*Pinus banksiana* Lamb.), is reviewed. Data from jack pine budworm outbreaks in northern Ontario are used to examine the relationship between the relative frequency of staminate shoots and the mortality of early- and late-larval jack pine budworm. Although there was some indication that early-instar budworm may be more successful at establishing feeding sites when flowers are abundant, there was no evidence that larval survival during the active feeding stages of the budworm was enhanced by the presence of staminate flowers. The assumption that staminate flowers greatly influence jack pine budworm population dynamics is questioned.

NEALIS, V. G. 1990. Jack pine budworm populations and staminate flowers. *Can. J. For. Res.* **20** : 1253-1255.

Le présent rapport examine la relation entre la tordeuse du pin gris (*Choristoneura pinus pinus* Free.) et les fleurs staminées de son hôte principal, le pin gris (*Pinus banksiana* Lamb.). Les données sur les infestations de la tordeuse du pin gris dans le nord de l'Ontario sont utilisées pour étudier la relation entre la fréquence relative des fleurs unisexuées mâles et la mortalité du premier et du dernier stades larvaires de la tordeuse du pin gris. Bien que les données laissent croire que le premier stade larvaire se trouve plus facilement des sites d'alimentation lorsque les fleurs sont abondantes, rien ne prouve que la présence de fleurs staminées améliore le taux de survie des larves pendant la période d'alimentation active. L'hypothèse que les fleurs staminées influencent énormément la dynamique des populations de la tordeuse du pin gris est mise en doute.

### Introduction

The jack pine budworm, *Choristoneura pinus pinus* Free. (Lepidoptera: Tortricidae), is a native defoliator of jack pine (*Pinus banksiana* Lamb.) in eastern North America. Populations of jack pine budworm fluctuate over a wide amplitude of densities. Where sufficient historical data exist, there is

a recognizable periodicity to these population fluctuations, with severe infestations occurring at intervals of 8 to 10 years (Benjamin 1956; Clancy *et al.* 1980; Volney 1988). These outbreaks last 2 to 4 years, and severe defoliation can cause a decrease in radial increment, an increase in top kill in dominant trees, and some mortality, especially in suppressed trees