

# Rocky Mountain Research Station Publications

[www.fs.usda.gov/rmrs/rmrs-publishing-services](http://www.fs.usda.gov/rmrs/rmrs-publishing-services)  
[www.fs.usda.gov/treesearch/](http://www.fs.usda.gov/treesearch/)

---

This is a legacy archive publication from the former Intermountain Research Station (INT) or Rocky Mountain Forest and Range Experimental Station (RM). The content may not reflect current scientific knowledge, policies, or practices.

This PDF may have been generated by scanning the original printed publication. Errors identified by the OCR software have been corrected; however, some errors may remain.

---

Questions or problems? Please email us:  
[SM.FS.rmrspubsreq@usda.gov](mailto:SM.FS.rmrspubsreq@usda.gov)

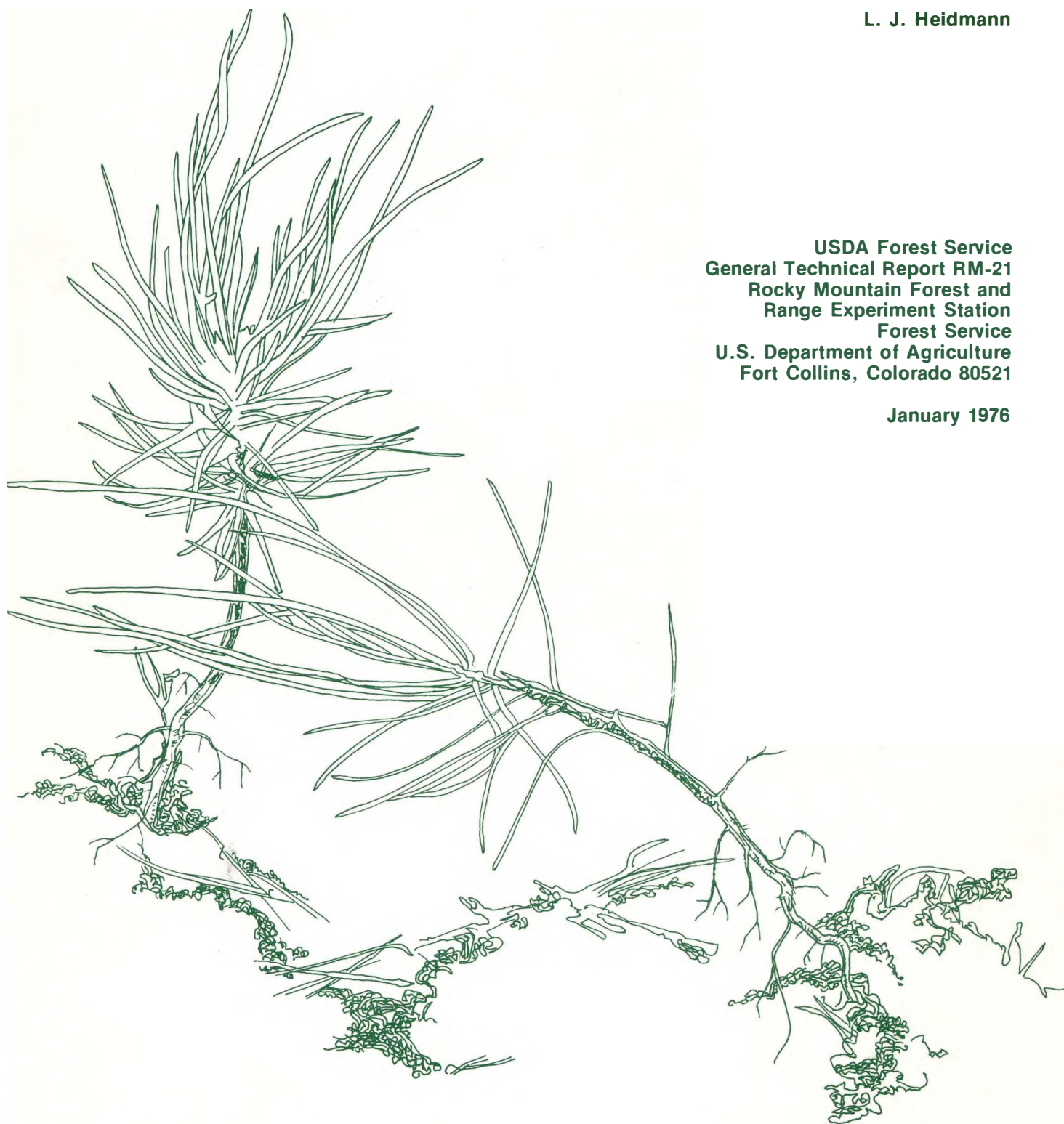
# **FROST HEAVING OF TREE SEEDLINGS:**

## **A Literature Review of Causes and Possible Control**

**L. J. Heidmann**

**USDA Forest Service  
General Technical Report RM-21  
Rocky Mountain Forest and  
Range Experiment Station  
Forest Service  
U.S. Department of Agriculture  
Fort Collins, Colorado 80521**

**January 1976**



### **Abstract**

Heidmann, L. J.

1976. Frost heaving of tree seedlings: A literature review of causes and possible control. USDA For. Serv. Gen. Tech. Rep. RM-21, 10 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.

Frost heaving of tree seedlings is more serious among seedlings less than 1 year old than among transplanted stock. It appears to be a surface soil phenomenon, and occurs because of a segregation of soil water which freezes into layers or lenses of ice. Lens formation causes an uplift of the surface soil and the tree seedling. Upon thawing, the tree remains in an extruded position on the soil surface while the soil recedes to approximately its original level. Segregation of the soil water occurs within the total matrix because of supercooling of the water in smaller soil pores and the water adsorbed on soil particles. The difference in freezing points provides the energy necessary to draw water to the ice lens and to lift the surface. Segregation of soil water is related to soil permeability and negative pressure on the water. A silty soil is more likely to heave because the right combination of permeability and tension can be developed. Heaving in a clay soil is determined to a great extent by the type of clay and the nature of the ions adsorbed by the clay particles. Heaving can be controlled by lowering the freezing point of the soil water, by restricting the water flow to the freezing front, or by cementing the soil particles together. Chemicals such as calcium chloride have been successful in reducing frost heaving by lowering the freezing point of the soil water. Dispersing agents, mainly sodium compounds, reduce heaving by plugging the soil pores, thus limiting water movement to the freezing front and subsequent growth of ice lenses. Cementing agents make the soil less frost susceptible by reducing the proportion of finer soil particles (clay and silt).

**Keywords:** Frost heaving, soil water segregation, supercooling, tree seedling mortality.

## **FROST HEAVING OF TREE SEEDLINGS: A Literature Review of Causes and Possible Control**

L. J. Heidmann, Silviculturist  
Rocky Mountain Forest and Range Experiment Station<sup>1</sup>

<sup>1</sup>*Central headquarters is maintained at Fort Collins, in cooperation with Colorado State University; author is located at the Station's Research Work Unit at Flagstaff, in cooperation with Northern Arizona University. Information contained in this paper is part of a Ph.D. Dissertation submitted to the University of Arizona, Tucson.*

## Contents

|                                                          | Page |
|----------------------------------------------------------|------|
| Introduction .....                                       | 1    |
| Mechanism of Frost Heaving .....                         | 1    |
| Factors Associated with Ice Lens Formation .....         | 2    |
| Segregation of Soil Water .....                          | 2    |
| Energy Requirements .....                                | 4    |
| Temperature Requirements .....                           | 5    |
| Permeability .....                                       | 6    |
| Controlling Frost Action .....                           | 6    |
| Dispersing Agents .....                                  | 7    |
| Waterproofing Agents .....                               | 7    |
| Cementing Agents .....                                   | 7    |
| Salts .....                                              | 8    |
| Nucleating Agents .....                                  | 8    |
| Altering the Radiation Balance of the Soil Surface ..... | 8    |
| Results of Various Control Experiments .....             | 8    |
| Summary .....                                            | 8    |
| Literature Cited .....                                   | 9    |

# FROST HEAVING OF TREE SEEDLINGS: A Literature Review of Causes and Possible Control

L. J. Heidmann

## INTRODUCTION

Frost heaving, one of the major causes of tree seedling mortality in many parts of the world, can occur in areas that have below-freezing temperatures, adequate soil water, and susceptible soils.

In northern Arizona, frost heaving may be the leading cause of ponderosa pine seedling mortality during the first winter. Larson (1961) found that frost heaving destroyed 52 percent of the seedlings in a seeding study during one night in October 1957. Larson (1960) noted in another study that only 5 percent of seedlings damaged by frost heaving survived compared to 20 percent for seedlings with no heaving damage.

With grass and brush seedlings, Biswell et al. (1953) frequently observed 75 percent or more mortality by frost heaving in California. Heaving was more severe on north slopes, and legumes were more affected than grasses. Heaving of legumes in Illinois is also a serious problem (Portz 1967).

In addition to plants, almost all objects in frost-susceptible soil, such as stakes, posts, poles, roads, and runways, can be moved upward by frost action (fig. 1).

Despite the fact that frost heaving is a serious problem, it has not been studied intensively by foresters or workers in other allied agricultural fields. Most of the basic information describing the heaving phenomenon is provided by engineers concerned about heaving of highways, runways, buildings, and other structures (Casagrande 1931; Beskow 1947; Grim 1952; Kersten 1952; Smith 1952; Aldrich 1956; Lambe 1956; Penner 1958, 1959; Low and Lovell 1959; Martin 1959). Work is also being done by scientists at the Cold Regions Research and Engineering Laboratory (CRREL) (Higashi 1958, Corte 1961, Chalmers and Jackson 1970, Kaplar 1971).

## MECHANISM OF FROST HEAVING

Frost heaving is a phenomenon involving the surface layer of the soil (Schramm 1958, Fahey 1973, Heidmann 1974). Schramm (1958), in explaining the heaving of tree seedlings, stated that an upper layer of coarse soil freezes solid because the pores are relatively large and the water in them freezes at close to 0°C. The frozen layer grips the tree stem tightly. Below the surface layer the soil has a finer texture

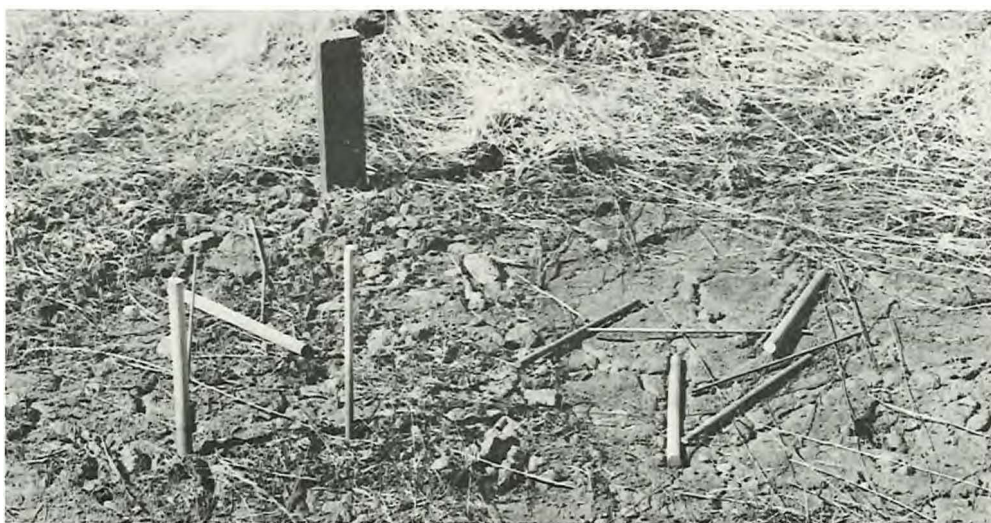


Figure 1.—Wooden dowels 0.31 to 1.27 mm in diameter. The dowels lying on soil surface heaved 10 cm in a few weeks' time.

(Corte 1961) and consequently smaller pores. The water in the smaller pores freezes at a lower temperature, resulting in a movement of water to a freezing line and formation of an ice layer. The ice layer pushes up the layer of frozen soil above, including the tree seedling. As the soil thaws, it recedes to its approximate original position, leaving the seedling extruded on the soil surface. Theoretically, only one freeze-thaw cycle is necessary for heaving to occur. In the field, however, time-lapse photography showed heaving is usually the result of a series of freeze-thaw cycles (Heidmann 1974).

An interesting facet of frost heaving as related to conifer seedlings is that on many soils heaving injury is almost exclusively confined to first-year seedlings. In Arizona, few ponderosa pine transplants (2-0 or older) heave. Haasis (1923), working near Flagstaff, noted that 98 percent of frost-heaved ponderosa pine seedlings were in their first year. Similarly, Schramm (1958) found that by October, in the coal fields of Pennsylvania, all persimmon (*Diospyros virginiana*), pine (*Pinus virginiana* and *P. rigida*), and oak (*Quercus alba*, *Q. bicolor*, and *Q. borealis*) seedlings which had germinated in the spring had been severed or pushed out of the soil. Not one of 400 pine transplants (*Pinus banksiana*, *P. strobus*, *P. sylvestris*, or *P. rigida*) of various ages planted on the same site the same spring showed evidence of heaving, however.

Schramm explained the differences by stating that pine transplants present a considerable surface to the wind at all times so that even gentle winds will cause the relatively stiff woody stem to sway. The swaying motion results in the stem being pushed against the wet soil and causes an air gap or ring to form between the soil and the tree stem. Subsequently when the surface soil layer freezes, it does not grip the tree stem. As a result, when the soil lifts during heaving, it rides up the stem of the tree. Deciduous seedlings, in a leafless state, do not present as large a surface area as conifers for the wind to act upon. Consequently they do not move back and forth in the wind as readily as pine transplants, and no gap is formed around the stem; thus, the frozen surface layer of soil can grip the stem and the tree heaves. Current-year pine seedlings heave because they have a much smaller aerial surface than transplants, and are probably more protected from the wind since the tops are closer to the soil surface. The stem is also more supple, so that instead of displacing the soil the stem bends at the soil surface and no gap is formed around the stem.

There are obvious differences between root systems of current-year seedlings and transplants. The transplanted seedling should have a considerably more extensive root system by the time the frost heaving season begins, which may anchor the tree. On a site

where heaving of first-year seedlings is excessive, however, none of the many 2-0 ponderosa pines planted in late September on several occasions have heaved appreciably (personal observation). Roots of trees planted in September grow little if at all, and consequently there is very little anchoring of the seedling.

Schramm's (1958) explanation of heaving of tree seedlings indicates that heaving is a surface soil phenomenon, probably involving no more than the upper 2 or 3 cm. Heidmann (1974) tends to confirm this hypothesis by showing that plastic "Ontario" tubes buried as little as 10 to 15 mm below the soil surface did not heave nearly as readily as tubes planted flush with the soil surface (fig. 2). In addi-



Figure 2.—Ontario tube containing a ponderosa pine seedling which did not heave completely out of the ground.

tion, wooden dowels "planted" in the soil with gaps between the dowel and the soil surface generally heaved less than dowels planted without gaps.

Studies by Fahey (1973) also indicate that heaving is closely related to soil surface conditions.

### Factors Associated with Ice Lens Formation

#### Segregation of Soil Water

Early researchers suggested that frost heaving resulted from an expansion of the soil water upon freezing. Taber (1929), however, pointed out that when water freezes there is an increase in volume of only 9 percent which could not explain the degree of uplift noted in many soils. In a series of classical experiments, Taber (1929, 1930) demonstrated that frost heaving was due to a segregation of water in the soil which froze into layers of ice. The amount of uplift was generally equal to the thickness of the ice layers in the soil. The segregation of soil water is the

result of a slow freezing process caused by a migration of water to a freezing front, resulting in the formation of ice lenses in the soil. This type of ice has been referred to as needle ice (fig. 3), stalactite ice, or comb ice (kammeis) (Schramm 1958).

Soons and Greenland (1970) duplicated the formation of needle ice in the laboratory. They found that ice needles 6.5 cm long were produced by the third day with an ambient temperature of  $-4^{\circ}\text{C}$ . A decline of soil water in the upper layers was noted, and a second layer of needles was initiated below the first layer and separated from it by a layer of soil.

Rapid freezing of the soil causes the soil water to freeze in place in the larger pores, and produces concrete frost. The uplift of the soil is only slight with rapid freezing.

**Freezing of water.**—Heat is evolved from all substances in the phase change from the liquid to solid state. In the case of water, this heat is called heat of fusion or crystallization. For each gram of water that freezes, about 80 calories of heat are released. The rate of freezing and thawing in soil varies with the temperature, pressure, and shape of the ice surface (Chalmers 1959). At a given pressure there is only one temperature at which these rates are equal. When salt is added to water, the freezing point drops because of an increase in osmotic pressure and a subsequent decrease in water potential.

If no ice is present, water can be supercooled. If ice is added, freezing will occur and ice will grow

rapidly until the latent heat evolved raises the temperature of the ice and water mixture to the freezing point (Chalmers 1959). The temperature of equilibrium depends on the curvature of the ice surface. For each temperature there is a critical radius of curvature at which ice and water are in equilibrium. A small ice crystal may have an equilibrium temperature below  $0^{\circ}\text{C}$ . The absence of an ice crystal with a critical radius allows water to remain liquid when it is supercooled (Chalmers 1959).

**Freezing of soil water.**—Water in the soil may freeze at a temperature below  $0^{\circ}\text{C}$ . According to Outcalt (1969), a wet soil surface will freeze if the surface can be supercooled to the ice nucleation temperature of about  $-2^{\circ}\text{C}$ . Freezing occurs when the equilibrium temperature of the soil surface descends to the ice nucleation temperature.

To maintain the growth of clear ice needles at a point, the vertical flow of water to the freezing front must match the fusion rate. That is, 1 g of soil water must be supplied for each 80 calories of heat flowing through the needles toward the soil surface. If either the heat flow to the surface becomes too large or the supply of water becomes limiting, segregation will stop and water will freeze in the soil pores. In most instances the soil surface layer dries slightly due to evaporation. Since segregation of soil water only occurs when the soil pores are near or above saturation, the surface layer freezes solid. It is because of the drying of the surface soil layer that, at all but the

Figure 3.—Example of ice layer often referred to as needle ice. When needle ice forms on the surface of the soil (as shown), it indicates that the soil is very wet.



wettest sites, needle ice usually wears a cap of frozen soil. The base of the cap is located at exactly the level where the water flux first equaled the fusion rate (Outcalt 1969).

**Supercooling of soil water.**—Soil water migrates to the freezing front due to the supercooling (Taber 1929). The nucleation temperature must always be below the freezing point. In pure water this temperature may be as low as  $-39^{\circ}\text{C}$  (Martin 1959). In ordinary tap water, the nucleation temperature is about  $-6^{\circ}\text{C}$  (Chalmers and Jackson 1970), but in the soil it is nearer to  $-2^{\circ}\text{C}$  (Outcalt 1969).

Nucleation of soil water is modified, since the water is present as separated small volumes, and the proximity of the soil-water interface lowers the temperature required to nucleate the ice. Edlefsen and Anderson (1943) demonstrated in a water-ice system that, if the pressure on the ice is constant, while the pressure on the water changes, the effect on the freezing temperature is:  $dT/dP = + 0.0824^{\circ}\text{C/atm}$  if the pressure is positive. A negative pressure lowers the freezing point.

In the soil, the freezing point is lowered because the freezing of water lowers the water content, which creates a tension or negative pressure at the freezing zone. In addition, the cations within the double layers of the hydration shell of soil particles, mainly the clays, are excluded from the ice which raises the osmotic pressure of the remaining water, thus contributing to the negative pressure (Martin 1959).

**Adsorbed water.**—Water adsorbed by soil particles freezes at a lower temperature than pure water (Taber 1929, Penner 1959). In a kaolinite clay, when the ice crystal has grown to within  $30 \text{ \AA}$  of the clay surface, the freezing point of the water molecules adjacent to the ice is depressed about  $0.4^{\circ}\text{C}$  below the freezing point of water at the center of the pore. When the crystal grows to within  $10 \text{ \AA}$  of the surface, the freezing point is depressed about  $4^{\circ}\text{C}$  (Martin 1959).

According to Low and Lovell (1959), exchangeable ions on the soil particles appear to be involved in water adsorption. In the earliest stages of adsorption, these ions form ion-dipole bonds with the water molecules; that is, they hydrate and thereby hold water to the mineral surfaces. The mineral surfaces also attract water, probably due to hydrogen bonding between the water molecules and the  $\text{O}^{2-}$  to  $\text{OH}^{-}$  ions on the mineral surfaces (Low and Lovell 1959).

Many authors (Taber 1929, 1930; Beskow 1947; Penner 1959; Chalmers and Jackson 1970) have pointed out the existence of a thin film of water between an ice layer and the adjacent soil particles. The water in this layer may not freeze until a temperature of  $-180^{\circ}\text{C}$  is attained (Jung 1931, cited

by Vershinin et al. 1960). Chalmers and Jackson (1970) stated that the layer of water between the ice and the soil particles has an equilibrium thickness. The thickness of the layer varies, and at a sufficiently low temperature it does not exist. If the soil water is supercooled, a little of the water layer separating the ice and soil will freeze, reducing the thickness of this layer below the equilibrium thickness. The equilibrium thickness can be restored by an influx of water from the unfrozen soil. A steady-state thickness of the water layer will be established, however, which is narrower than the equilibrium thickness, because as fast as water is drawn into the layer, water freezes on the ice lens. The layer of water is a region of negative pressure. The negative pressure would be eliminated by the influx of water if freezing were not continuous.

The freezing point of soil water is also related to the specific surface-to-volume ratio of ice, as demonstrated in the following equation (Chalmers and Jackson 1970):

$$\Delta T = \frac{A_i \sigma T_E}{V_i L}$$

where

$\Delta T$  = freezing point depression,

$A_i$  = surface area of the ice structure,

$\sigma$  = solid-liquid surface free energy per unit area,

$T_E$  = 273 K,

$V_i$  = volume of ice transformed, and

$L$  = latent heat per unit volume.

### Energy Requirements

For an ice lens to grow, water must move through the soil. This movement requires a pressure gradient, which can develop at the freezing front because of a free energy difference (Chalmers and Jackson 1970) given by:

$$P = \frac{L \Delta T}{T_E}$$

The energy required to lift the soil and draw water to the ice lens comes from the change in free energy ( $\Delta F$ ) (Martin 1959):

$$\Delta F = \frac{L(T_o - T_x)}{T_o}$$

where

- $T_0$  = freezing point of free water,
- $T_x$  = actual freezing point of soil water, and
- $L$  = latent heat of fusion (80 cal/g).

This equation demonstrates that, if the freezing point of water is not lowered and  $T_0 = T_x$ , then free energy is unavailable to lift the soil or to draw water to the freezing front. The greater the difference between  $T_0$  and  $T_x$ , the more energy is available for soil movement or heaving.

For freezing to occur in place, the ice must grow between the soil particles. Such ice growth can only happen if the radius of curvature of the ice is less than the radius of the pore channels (Chalmers and Jackson 1970). Soil water will freeze in place only below the temperature given by substituting the appropriate value for  $r$  in the following equation:

$$\Delta T = \frac{2\sigma T_E}{Lr}$$

where  $r$  = radius of pore, and other symbols have the same meanings as previously defined.

### Temperature Requirements

The transfer of heat within soil is important in determining if frost heaving will occur.

With the onset of freezing conditions, water in the surface soil begins to freeze, and the heat released flows upward in response to the imposed temperature gradient. Water flows to the freezing front. When the water supply to the freezing zone is adequate, the amount of heat supplied by fusion is equal to the heat lost from the soil, and the freezing front remains stationary in the soil. If the supply of water is not adequate, the amount of heat lost from the soil is greater than that released by fusion, and the freezing front will move downward into the soil. In the former situation, ice lenses develop in the soil and heaving occurs. In the latter situation, water freezes in place and heaving does not take place.

Energy can be transferred by radiation, conduction, and convection. In the case of soil, the heat is transferred by conduction only unless water is moving within the soil voids (Aldrich 1956). The concept of heat conductivity describes a transfer of kinetic energy from the molecules of a warm particle to a cooler particle. The rate at which this heat is transferred is given by:

$$Q = K \frac{V_1 - V_2}{l} A$$

where

- $Q$  = rate of heat flow,
- $V_1 - V_2$  = temperature difference,
- $l$  = length,
- $A$  = cross-sectional area, and
- $K$  = coefficient of thermal conductivity.

The coefficient of thermal conductivity ( $K$ ) is a measure of the quantity of heat that will pass through a unit area of unit thickness in unit time under a unit temperature gradient. The  $K$  of the soil depends on its density, water content, temperature, texture, structure, and mineral composition (Kersten 1952).

The rate of frost heaving is independent of the rate of advance of the freezing front (Beskow 1947). The rate of heave is equal to the rate at which the water arrives at the ice lens. According to Chalmers and Jackson (1970), this rate can be given by:

$$R = \frac{k \rho_w P_{\max} - P_L}{\rho_i h_0 - h}$$

where

- $R$  = rate of frost heaving,
- $k$  = coefficient of permeability of the soil,
- $\rho_w$  = density of water,
- $\rho_i$  = density of ice,
- $P_{\max}$  = maximum suction pressure,
- $P_L$  = load pressure,
- $h_0$  = distance from the surface to the water table, and
- $h$  = distance from the surface to the ice lens.

Further, Chalmers and Jackson (1970) suggested that the following equation can be used to determine the rate of advance of the freezing front:

$$V = \left[ H_f H_u \rho_w L k \frac{P_{\max} - P_L}{h_0 - h} \right] \frac{1}{n \rho_i L}$$

where

- $H_f$  = (thermal conductivity of frozen soil)(temperature gradient below freezing front),
- $H_u$  = (thermal conductivity of unfrozen soil)(temperature gradient above freezing front),
- $n$  = volume fraction of the soil that is water, and
- $L$  = latent heat per unit volume.

Heaving is related to the rate at which water arrives at the freezing front, which depends on pressure differences that result from supercooling of soil water. The rate of advance of the freezing front thus depends on heat flow conditions.

## Permeability

Soil permeability largely determines the rate of water movement in soil, and ultimately whether or not the soil will heave. Permeability is a function of pore size, soil temperature, soil water tension, and type and amount of soil salts. The tension developed at the frostline largely depends on the pore size. Coarse-grained soils are highly permeable, but the flow of water is mainly governed by the tension developed. In fine-grained soils, the tension developed may be large, but the flow is limited by a relatively low permeability. The intermediate permeability and tension conditions in silt soils appear to be conducive to a high rate of frost heaving (Penner 1958).

Soil particle size influences frost heaving, since particle size influences pore size, which in turn affects permeability. According to Casagrande (1931), ice segregation can be expected in nonuniform soils containing more than 3 percent of grains less than 0.02 mm, and in uniform soils containing more than 10 percent less than 0.02 mm. No segregation was observed in soils containing less than 1 percent of grains smaller than 0.02 mm. Beskow (1947) stated that the maximum particle size which will produce measurable heave in 24 hours is 0.1 mm.

Frost heaving is influenced by the nature of the particles. Grim (1952) stated that soils consisting of very fine colloid-sized clay materials show little or no segregation during freezing. Heaving of clay soils, however, depends on the type of clay mineral present and the adsorbed ions.

Clay particles are surrounded by a diffuse double layer of ions within the contiguous water layer. The thickness of the double layer determines to a great extent the heaving characteristics. When two clay particles are less than 15 Å apart, the exchangeable ions are uniformly distributed in the interparticular space and do not separate into two diffuse double layers. Under these conditions there is an attraction between particles, so that they flocculate (Yong and Warkentin 1966). When soil particles flocculate, the result is more open pores for water movement, and segregation of ice into layers is likely. When the interparticular distance exceeds 15 Å, diffuse ion layers form with a resulting net repulsion of soil particles. The repulsion is caused by water being attracted between the particles, thus forcing them apart. In this case, water moves due to a water potential gradient since the concentration of ions is higher in the plane midway between parallel particles than in the outside solution (Yong and Warkentin 1966). When the soil particles become dispersed, heaving is reduced because the pores are smaller and water movement is restricted. Under these conditions, segregation of soil water is reduced.

The thickness of the double layer depends on the valence of the ion and its concentration. The lower the valence and concentration the thicker the diffuse double layer (Yong and Warkentin 1966).

Clays such as montmorillonite have a high surface area and adsorption capacity for certain cations, anions, and organic molecules (Grim 1952). In montmorillonite with sodium as the adsorbed ion, water can enter easily between all of the unit layers and build up to a thickness of at least 100 Å. Thus, even in the presence of large amounts of water, in which the water content would be in excess of the clay mineral content, there would be no fluid water. Such clays are largely impervious, and during freezing there is little or no concentration of ice in layers (Grim 1952).

In montmorillonite with calcium, magnesium, and hydrogen as the exchangeable ions, the situation is different. When the alkaline earths of hydrogen are present as adsorbed ions, water enters between the layers with difficulty and forms thin layers of adsorbed water. In these clays, water present in relatively small amounts beyond about 40 percent of the dry weight of the clay is fluid. In such clays, ice may develop in layers if the water content is fairly high (Grim 1952).

Kaolinite particles are 100 to 1,000 times the size of montmorillonite particles, so their total surface area is relatively small. In addition, kaolinite has no interior surfaces but montmorillonite does. Because of the crystalline structure of kaolinite, only about half the total surface is likely to develop adsorbed water with a definite configuration. Therefore, at relatively low water contents, soils with kaolinite contain some fluid water (Grim 1952) and are susceptible to heaving (fig. 4).

## CONTROLLING FROST ACTION

There are several ways in which a soil can be made less susceptible to heaving. The most obvious is to prevent the freezing of the soil pore water. Another method is to reduce the permeability of the soil so that water cannot migrate to the freezing zone at a fast enough rate for ice lenses to form. A third is to cement the soil particles together with a bond strong enough to resist the expansive forces of frost action (Lambe 1956). It is also possible to prevent frost heaving by preventing the supercooling of the soil water. Finally, Cass and Miller (1959) suggested substituting a nonsusceptible soil for a susceptible one. This is not economically feasible as a forest management practice.

There are several ways in which the other methods may be implemented, however.



Figure 4.—Example of ice lens formation in pure kaolinite clay. The sample heaved 15 cm (200 percent) in 7 days. The closeup (right) shows little soil in the column, which indicates that the flow of heat to the freezing front was equal to the heat flow to the surface during most of the freezing period.

### Dispersing Agents

Dispersing agents for clay soils may be categorized as: (1) those that substitute sodium ions for exchangeable calcium, the latter being removed from the soil solution; and (2) those that, in addition, mask or reverse the positive charges normally found at the edges of the clay plates. Sodium oxalate is an example of the former, and sodium polyphosphates are examples of the latter (Cass and Miller 1959). Clay present in the system tends to become dispersed (because of the increased swelling pressure of the monovalent double layer) and migrates with the moving water to clog the pores, thus reducing the permeability of the soil (Cass and Miller 1959).

Most of the dispersants consist of a polyanionic group (phosphate or sulfonate) and a monovalent cation, usually sodium. Some of the anionic groups can remove any polyvalent cations by forming insoluble products, and others can become attached to the soil mineral surfaces. The sodium ions become adsorbed by the soil, replacing the removed polyvalent and exchangeable cations. The cation exchange (monovalent for polyvalent) and the anion adsorption expand the diffuse double layers around the colloids, thus increasing interparticle repulsion which tends to disperse the soil aggregates. Particles that do not stick together can be packed into a more orderly and denser structure. Attendant with im-

proved structure are higher density, lower permeability, and higher stability to water. By decreasing the size of the soil voids, dispersants also tend to lower the freezing temperature of the soil water (Lambe 1956).

### Waterproofing Agents

Soil mineral surfaces can be made hydrophobic with certain additives. One end of the additive molecule becomes adsorbed to a soil particle and the other end of the molecule is hydrophobic. As a result the soil becomes nonwetttable. Soil can also be treated with nonhydratable cations that are attracted to the negatively charged soil particles.

### Cementing Agents

A frost-susceptible soil may be made nonsusceptible by reducing the proportion of finer particles (clay and silt) by adding cements, or chemicals that cause flocculation. Synthetic polymers become attached to the soil mineral surfaces and link the particles together. Aggregation of soil particles can also be achieved by application of polyvalent cations such as iron ( $\text{Fe}^{+++}$ ) or aluminum ( $\text{Al}^{+++}$ ). The cations act by shrinking the diffuse double layer around the soil colloids enough to permit the particles to cohere.

Another phenomenon, ion fixation, results in aggregation of soil particles. If  $\text{Fe}^{+++}$  is added to a fine-grained soil, the iron replaces some of the exchangeable cations of the soil. This reaction tends to produce flocculation because interparticle repulsive charges are reduced. If the soil is dried, some of the iron ions link adjacent soil particles with a strong bond that is resistant to water. The iron ions become fixed and are no longer exchangeable (Lambe 1956).

### **Salts**

Salts lower the freezing point of the soil water. In addition, the presence of polyvalent cations in the system contracts the double layer. The salts, with their higher charge, are preferentially attracted to the mineral surface and find their equilibrium positions at short distances from the soil particles, which means that the double layer will be reduced in thickness and osmotic activity and the recharge mechanism will be suppressed (Cass and Miller 1959).

### **Nucleating Agents**

Supercooling of the soil water results in pressure differences and water migration to the freezing front. The addition of nucleating agents to the soil water will result in the water freezing at a higher temperature (there will be less supercooling of the water). If supercooling is prevented, the segregation process can be stopped.

### **Altering the Radiation Balance of the Soil Surface**

If the amount of heat lost from the soil is reduced, the temperature of the soil water may be maintained above the freezing point. The use of mulches, shade, or soil coatings may accomplish this objective.

## **RESULTS OF VARIOUS CONTROL EXPERIMENTS**

Lambe (1956) found that dispersants were effective in reducing frost heaving. Some of the more promising dispersants were: sodium hexametaphosphate, sodium tripolyphosphate, and tetrasodium pyrophosphate. Results using waterproofing agents such as polyethylene glycol were erratic and the costs were high. Cementing agents are expensive because too much material is needed to be effective. Ferric chloride, however, was effective at rates as low as 0.1 percent of the soil weight.

Chemicals that lower the freezing point of the soil water, such as calcium chloride, also appear useful

in preventing frost heaving. According to Smith (1952), applying calcium chloride at a rate of 2 percent of the soil weights protects silty soils from frost heaving. In clay soils, an application of 1 percent affords protection, and only 0.1 percent was required for graded mixes. After a period of 5 to 10 years, one-third to one-half of the chemical still remained in the soil.

Vonnegut and Chessin (1971), working with nucleating agents, found that by coprecipitating silver bromide with silver iodide, solutions were formed in which bromide atoms were substituted for as many as 30 mole percent of the iodine atoms in the silver iodide structure. As the fraction of iodine replaced by bromine increased up to about 30 percent, supercooling was reduced by a factor of almost two.

Soil cover modifies soil temperature and subsequent heaving. Kohnke and Werkhoven (1963) found that 1.5 tons of wheat straw per acre resulted in 6.5 freezing-thawing cycles at the 1-inch soil depth in a silt loam soil, compared to 22 cycles in bare plots over a winter season.

Decker and Ronningen (1957) found that heaving of wooden dowels was related to degree of cover and species of vegetation present. Dowels heaved most in ladino clover (*Trifolium repens*) plots. No differences in heaving were attributed to variations in dowel diameter.

Gradwell (1960) noted that needle ice did not form under tussocks (grass clumps) in New Zealand. Krumbach and White (1964) observed that frost penetrated 12 inches in plots bare of vegetation in Michigan, compared to 3 inches in plots with a cover of alfalfa (*Medicago sativa*).

According to Thorud and Anderson (1969), white pine (*Pinus strobus*) litter samples had better insulating qualities than either red pine (*P. resinosa*) or oak (*Quercus* sp.) litter samples. Graber (1971) reported that the shading of white pine seedlings during the dormant and growing season reduced heaving losses.

## **SUMMARY**

1. Frost heaving of tree seedlings is a serious problem in areas which have below-freezing temperatures, adequate soil moisture, and susceptible soils.

2. Heaving of first-year seedlings is more severe than heaving of transplants.

3. Frost heaving is caused by a segregation of the soil water, which freezes into lenses of ice. The water segregates because of a lowering of the freezing point or supercooling of the soil water. Supercooling is the result of several factors, including adsorption and negative pressure. The difference in freezing points between free water and soil water at the ice line provides the free energy necessary to draw water to the line and lift the soil. The flow of water to the

freezing front is governed by the permeability of the soil and the negative pressure or tension developed.

4. Frost heaving may be controlled by lowering the freezing point of the soil water, restricting the flow of water through the soils, cementation of the soil particles, and by preventing supercooling of the soil water.

### LITERATURE CITED

- Aldrich, Harl P.  
1956. Frost penetration below highway and air-field pavements. Highw. Res. Board, Bull. 135, p. 45-62.
- Beskow, Gunnar.  
1947. Soil freezing and frost heaving with special application to roads and railroads. Swedish Geol. Soc. Ser. C, No. 375, 26th Yearb. No. 3, 1935. [With a special supplement for the English translation of progress from 1935 to 1946.] Northwest Univ. Technol. Inst., Evanston, Ill.
- Biiswell, H. H., A. M. Schultz, D. W. Hedrick, and J. I. Mallory.  
1953. Frost heaving of grass and brush seedlings on burned chamise brushlands in California. J. Range Manage. 6(3):172-180.
- Casagrande, A.  
1931. Discussion of frost heaving. Highw. Res. Board Proc. 11, Part 1, p. 168-172.
- Cass, L. A., and R. D. Miller.  
1959. Role of the electric double layer in the mechanism of frost heaving. U.S. Army, Corps Eng., Snow, Ice, and Permafrost Res. Establ., Res. Rep. 49, 15 p. Wilmette, Ill.
- Chalmers, Bruce.  
1959. How water freezes. Sci. Am. 200(2):114-122.
- Chalmers, Bruce, and Kenneth A. Jackson.  
1970. Experimental and theoretical studies of the mechanism of frost heaving. U.S. Army, Corps Eng., Cold Reg. Res. Eng. Lab., Res. Rep. 199, 23 p. Hanover, N.H.
- Corte, A. E.  
1961. The frost behavior of soils: Laboratory and field data for a new concept. Part 1: Vertical sorting. U.S. Army, Corps Eng., Cold Reg. Res. Eng. Lab., Res. Rep. 85, 22 p. Hanover, N.H.
- Decker, A. M., Jr., and T. S. Ronningen.  
1957. Heaving in forage stands and in bare ground. Agron. J. 49:412-415.
- Edlefsen, N. E., and A. B. C. Anderson.  
1943. Thermodynamics of soil moisture. Hilgardia 15(2):31-298.
- Fahey, B. D.  
1973. An analysis of diurnal freeze-thaw and frost heave cycles in the Indian Peaks region of the Colorado Front Range. Arctic and Alpine Res., 5(3, Part 1):269-281.
- Graber, R. E.  
1971. Frost heaving . . . seedling losses can be reduced. Tree Planters' Notes 22(4):24-28.
- Gradwell, M. W.  
1960. Soil frost action in snow-tussock grassland. N.Z. J. Sci. 3(4):580-590.
- Grim, R. E.  
1952. Relation of frost action to the clay-mineral composition of soil materials. Highw. Res. Board, Spec. Rep. 2, p. 167-172.
- Haasis, F. W.  
1923. Frost heaving of western yellow pine seedlings. Ecology 4:378-390.
- Higashi, Akira.  
1958. Experimental study of frost heaving. U.S. Army, Corps Eng., Snow, Ice, and Permafrost Res. Establ., Res. Rep. 45, 20 p. Wilmette, Ill.
- Heidmann, L. J.  
1974. An investigation into the causes and prevention of frost heaving of forest tree seedlings. Ph.D. Diss., Univ. of Ariz., 183 p. Tucson.
- Kaplar, Chester W.  
1971. Experiments to simplify frost susceptibility testing of soil. U.S. Army, Corps Eng., Cold Reg. Res. Eng. Lab., 21 p. Hanover, N.H.
- Kersten, M. S.  
1952. Thermal properties of soils. Highw. Res. Board Spec. Rep. 2, Frost action in soils: A symposium. NAS-NRC, Publ. 213, p. 161-172.
- Kohnke H., and C. H. Werkhoven.  
1963. Soil temperature and soil freezing as affected by an organic mulch. Soil Sci. Soc. Am. Proc. 27:13-17.
- Krumbach, A. W., Jr., and D. P. White.  
1964. Moisture, pore space, and bulk density changes in frozen soil. Soil Sci. Soc. Am. Proc. 28(3):422-425.
- Lambe, William.  
1956. Modification of frost heaving of soils with additives. Highw. Res. Board, Bull. 135, p. 1-23.
- Larson, M. M.  
1960. Frost heaving influences drought hardiness of ponderosa pine seedlings. U.S. Dep. Agric., For. Serv., Rocky Mt. For. and Range Exp. Stn., Res. Note 45, 2 p. Fort Collins, Colo.
- Larson, M. M.  
1961. Seed size, germination dates, and survival relationships of ponderosa pine in the Southwest. U.S. Dep. Agric., For. Serv., Rocky Mt. For. and Range Exp. Stn., Res. Note 66, 4 p. Fort Collins, Colo.

- Low, P. F., and C. W. Lovell.  
1959. The factor of moisture in frost action. Highw. Res. Board, Bull. 225, p. 23-33.
- Martin, R. T.  
1959. Rhythmic ice banding in soil. Highw. Res. Board, Bull. 218:11-23.
- Outcalt, S. I.  
1969. Weather and diurnal frozen soil structure at Charlottesville, Virginia. Water Resour. Res. 5(5):1377-1382.
- Penner, E.  
1958. The nature of frost action. Proc. Thirty-eighth Convention of the Canadian Good Roads Assoc., Tech. Pap. 53, p. 234-243.
- Penner, E.  
1959. The mechanism of frost heaving in soils. Highw. Res. Board, Bull. 225, p. 1-22.
- Portz, H. L. 1967. Frost heaving of soil and plants.  
1. Incidence of frost heaving of forage plants and meteorological relationships. Agron. J. 59:341-344.
- Schramm, J. R.  
1958. The mechanism of frost heaving of tree seedlings. Am. Philos. Soc. Proc. 102(4):333-350.
- Smith, H. R.  
1952. Remedies and treatments. Calcium chloride treatment of frost action. Highw. Res. Board, Spec. Rep. 2, Frost action in soils: A symposium. NAS-NRC, Publ. 213, p. 326-330.
- Soons, J. M., and D. E. Greenland.  
1970. Observations on the growth of needle ice. Water Resour. Res. 6(2):579-593.
- Taber, S.  
1929. Frost heaving. J. Geol. 37:428-461.
- Taber, S.  
1930. The mechanics of frost heaving. J. Geol. 38:303-317.
- Thorud, D. B., and D. A. Anderson.  
1969. Freezing in forest soil as influenced by soil properties, litter, and snow. Water Resour. Res. Center, Univ. Minn. Grad. Sch., Bull. 10, 41 p.
- Vershinin, P. V., B. V. Deriagin, and N. V. Kirilenko.  
1960. The nonfreezing water in soil. [O. Nezamerzaiushchei Vode V. Pochve] ACFEL Transl. 30, 10 p. U.S. Army, Eng. Div., Waltham, Mass.
- Vonnegut, B., and H. Chessin.  
1971. Ice nucleation by coprecipitated silver iodide and silver bromide. Science 174(4012):945-946.
- Yong, R. N., and B. P. Warkentin.  
1966. Introduction to soil behavior. 451 p. Macmillan Co., N.Y.

Heidmann, L. J.

1976. Frost heaving of tree seedlings: A literature review of causes and possible control. USDA For. Serv. Gen. Tech. Rep. RM-21, 10 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.

Describes phenomenon of frost heaving of tree seedlings and objects from the soil. Frost heaving is primarily a soil surface event resulting from a segregation of soil water which freezes into ice lenses. Suggested methods of control involve lowering the freezing point of the soil water or restricting water flow through the soil to the freezing front.

**Keywords:** Frost heaving, soil water segregation, supercooling, tree seedling mortality.

Heidmann, L. J.

1976. Frost heaving of tree seedlings: A literature review of causes and possible control. USDA For. Serv. Gen. Tech. Rep. RM-21, 10 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.

Describes phenomenon of frost heaving of tree seedlings and objects from the soil. Frost heaving is primarily a soil surface event resulting from a segregation of soil water which freezes into ice lenses. Suggested methods of control involve lowering the freezing point of the soil water or restricting water flow through the soil to the freezing front.

**Keywords:** Frost heaving, soil water segregation, supercooling, tree seedling mortality.

Heidman, L. J.

1976. Frost heaving of tree seedlings: A literature review of causes and possible control. USDA For. Serv. Gen. Tech. Rep. RM-21, 10 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.

Describes phenomenon of frost heaving of tree seedlings and objects from the soil. Frost heaving is primarily a soil surface event resulting from a segregation of soil water which freezes into ice lenses. Suggested methods of control involve lowering the freezing point of the soil water or restricting water flow through the soil to the freezing front.

**Keywords:** Frost heaving, soil water segregation, supercooling, tree seedling mortality.

Heidmann, L. J.

1976. Frost heaving of tree seedlings: A literature review of causes and possible control. USDA For. Serv. Gen. Tech. Rep. RM-21, 10 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.

Describes phenomenon of frost heaving of tree seedlings and objects from the soil. Frost heaving is primarily a soil surface event resulting from a segregation of soil water which freezes into ice lenses. Suggested methods of control involve lowering the freezing point of the soil water or restricting water flow through the soil to the freezing front.

**Keywords:** Frost heaving, soil water segregation, supercooling, tree seedling mortality.

*The use of trade and company names is for the benefit of the reader; such use does not constitute an official endorsement or approval of any service or product by the U.S. Department of Agriculture to the exclusion of others that may be suitable.*

