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Forest Regeneration Research at Fort Valley

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Abstract—*When G. A. Pearson arrived at Fort Valley to establish the first Forest Service Experiment Station he found many open park-like stands similar to those in Figure 1. Within two years, Pearson had outlined the major factors detrimental to the establishment of ponderosa pine seedlings (Pearson 1910). During the next almost 40 years, he wrote many articles on methods of cutting, tree planting, thinning, raising seedlings, natural regeneration and other aspects of forest management. His findings are contained in his landmark treatise, "Management of Ponderosa Pine in the Southwest" (1950). Gaines and Shaw (1958) summarize the first fifty years of research at Fort Valley. The following reviews Pearson's findings along with discoveries made since 1958.*

Introduction

Regenerating ponderosa pine in the Western United States is difficult. The primary obstacle to regeneration of this species throughout its natural range is drought (Curtis and Lynch 1957). Annual precipitation in the western and southwestern United States is generally adequate for tree growth, but erratic distribution during the year makes seedling establishment difficult. In the southwestern United States, annual precipitation in the ponderosa pine type varies from 38 to 64 cm (15-25 inches) (Schubert 1974). About half of this occurs as snow during the winter months and half as rainfall, primarily during a summer "monsoon" season during July and August. Spring and fall droughts are common. Shortly after tree planting in the spring, a drought period of up to 60 days or more may occur.

Figure 1. Open park-like stand of ponderosa pine in 1909. USFS photo 89806 by G. A. Pearson.

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Dry conditions coupled with competition from various herbaceous species, primarily perennial grasses, (Figure 2) effectively lowers soil water potential (**Ψ**) to a point where pine seedlings have difficulty extracting moisture from the soil. Natural seedlings that do not germinate until summer rains begin in late July and August face a very short period during which to become established before a fall drought. Growth of seedlings on volcanic soils is very slow. As a result seedlings are very susceptible to drought and frost heaving (Heidmann 1976, Larson 1961).

Obstacles to Regeneration

Soils

Regeneration problems are closely related to soils type. In the Southwest, forest soils are primarily volcanic or sedimentary in origin. Volcanic soils, derived from basalt rocks and cinders (throughout this paper volcanic soils will be referred to as basalt soils) contain high amounts of silt (60-70%) with the remaining fraction composed primarily of clay (Heidmann and Thorud 1975). On these soils, seed germination is usually adequate, but seedlings at the end of the first growing season are very small (3-5 cm tall, Figure 3). Small seedlings on these soils are highly susceptible to frost heaving (Heidmann and Thorud 1976, Larson 1961, Schramm 1958). In addition, on basalt derived soils, moisture becomes limiting when soil moisture content (SMC) drops below 10% and (**Ψ**) is approximately -2.0 MPa (-20 bars, Heidmann and King 1992, Figure 4). Frost heaving and moisture stress effectively prevent natural regeneration on these soils. There are indications, however, that first year seedlings growing on basalt soils on which litter has been burned are much larger in size and do not heave as readily as smaller seedlings (Sackett 1984).

Sedimentary soils, derived from limestone and sandstone parent material, in contrast, are much coarser in texture, often containing 65% or more sand-sized particles. In these soils, moisture does not become limiting until SMC drops below 1.5%, after which very small losses in SMC result in (**Ψ**) lowering dramatically (becomes more negative) (Heidmann and King 1992, Figure 4). First year seedlings on sedimentary soils are usually much larger than seedlings on basalt soils; however, in greenhouse studies both container and bare-root seedlings seemed to survive as well or better on basalt soils (Heidmann and King 1992). Frost heaving is less of a problem on sedimentary soils, but will occur, especially if soils are compacted (Heidmann and Thorud 1975, Figure 5).

Moisture Stress

Although soil moisture is often limiting, seedlings can endure severe moisture stress and recover. Seedlings appear able to "shut down" physiologically during periods of moisture stress and resume physiological activity when soil moisture is replenished. Studies by Heidmann and King (1992) have shown that ponderosa pine seedlings grown for 134 days without watering have very low transpiration (ts) and stomatal conductance (gs) rates in addition to a dramatic reduction in net photosynthetic (pn) rates, but after re-watering, seedlings appear to recover rapidly. Heidmann and Sandoval 1900

Figure 2. Dense stand of Arizona fescue (*Festuca arizonica*) and mountain muhly (*muhlenbergia montana*) at Wing Mountain, AZ, in 1962. USFS photo by L. J. Heidmann.

Figure 3. Ponderosa pine seedling growing on bare volcanic soil at the end of summer 1957. Seedlings in this study were watered three times a week throughout the summer and are no taller than a toothpick. USFS photo by L. J. Heidmann.

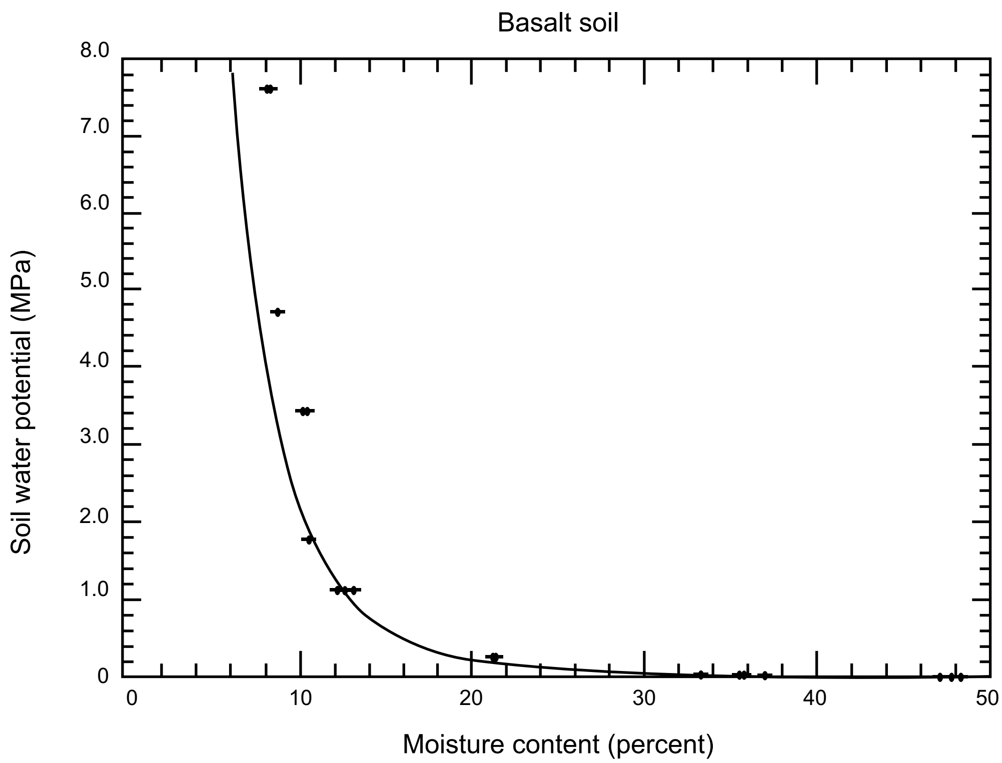
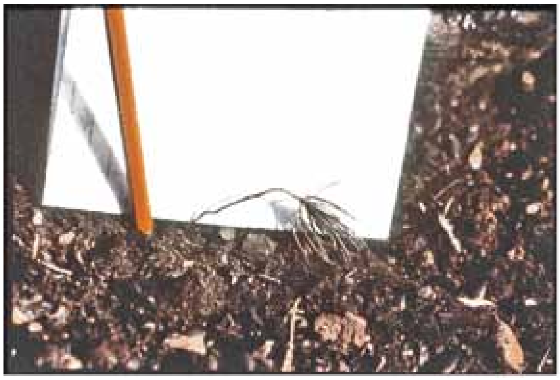


Figure 4. Soil moisture content (%) plotted against soil water potential in mega-pascals (Mpa) for a basalt soil in northern Arizona. One Mpa roughly equals ten bars of atmospheric pressure. Below 10% SMC water becomes more limiting for ponderosa pine seedlings.



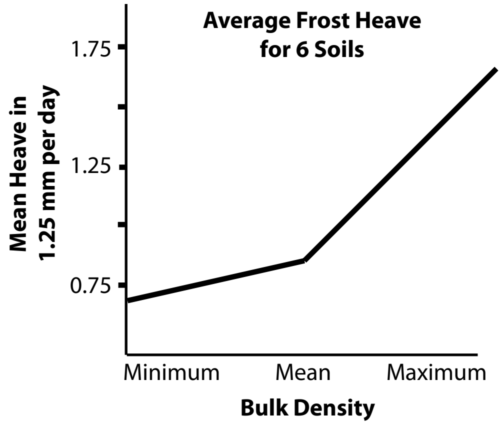


Figure 5. Mean frost heaving per day by soil bulk density for six soils in northern Arizona. Measurements were conducted in the laboratory using a specially designed freezing chest. USFS photo by L. J. Heidmann.

(unpublished data) and Heidmann and Huntsberger 1990 (unpublished data) observed that ponderosa pine seedlings in a chamber in which the roots were sealed in plastic bags subjected to very high osmotic solutions of polyethylene glycol were able to absorb moisture from a saturated atmosphere through the seedling tops.

Heidmann (personal observation) found a ponderosa pine tree approximately 50 cm (20 in) tall growing in a small depression on top of a boulder, approximately 90 cm in diameter, in which there was a small collection of litter. The tree fell during examination since it had almost no root system. Although ponderosa pine is very drought tolerant, trees put on significantly greater height growth when moisture is plentiful.

Competing Vegetation

The combination of competing vegetation and inadequate soil moisture effectively restricts natural and artificial regeneration efforts on all soil types. The most severe competitors are spring-growing bunch grasses such as Arizona fescue (*Festuca arizonica*). This species has an extensive root system (Figure 6) that appropriates soil moisture from the upper soil layers at the expense of tree seedlings. In addition, fescue and other grasses contain growth inhibiting chemicals that restrict germination of pine seed and subsequent growth of seedlings (Rietveld 1975). The combination of dense grass root systems, growth inhibitors, low soil temperatures and low moisture until July or later make it very difficult for seedlings to survive (Larson 1961, Pearson 1950, Rietveld 1975).

Figure 6. Root system of Arizona fescue (*Festuca arizonica*). These roots are very dense and fibrous and can completely appropriate moisture from the upper 20 to 25 cm of soil. USFS photo by L. J. Heidmann.

Climate

In addition to erratic precipitation, wind is another climatic factor detrimental to establishment of tree seedlings. Strong winds are common throughout much of the ponderosa pine range. At or shortly after tree planting in the spring, plantation sites are subjected to warm days, very low humidity, little or no precipitation, and strong winds. Under these conditions, especially if site preparation is inadequate or lacking, tree seedlings desiccate very quickly.

Biotic Factors

Other elements affecting reforestation efforts can be combined under "biotic attrition." A whole host of insects, birds and mammals feed on ponderosa pine seed and young trees, and may effectively prevent tree establishment. The greatest threat comes from domestic livestock and large browsing mammals. If cattle or sheep are allowed to graze in newly established regeneration areas failure is sure to follow. In the Southwest, sheep have grazed forest land on Indian reservations since their establishment. Now, however, tribal leaders realize the necessity of protecting regeneration and recommend excluding sheep and cattle from regeneration sites (Arbab and Metteba, no date).

Other large mammals, such as mule deer (*Odocoileus hemionus*) and elk (*Cervus elaphus*), cause considerable browsing and trampling damage. Small mammals, such as gophers (*Thomomys* spp.) and rabbits (*Sylvilagus* and *Lepus*), cause severe local damage (Figure 7). Mice, particularly the white-footed deer mouse (*Peromyscus maniculatus*), consume vast amounts of seeds that fall to the ground, and Abert squirrels (*Sciurus aberti*) consume large amounts of cones as they mature on the tree (Larson and Schubert 1970).

Despite these adverse factors, ponderosa pine may be regenerated both naturally and artificially if proper procedures are followed (Heidmann and Haase 1989, Heidmann and others 1982, Hermann 1965, Schubert and others1970, Schubert 1974).

Figure 7. Planted ponderosa pine seedling showing rabbit damage. The seedling top has been clipped off. USFS photo by L. J. Heidmann.

Findings in the Last Fifty Years

Artificial Regeneration

Planting

For planting to succeed it is essential to have a thoroughly prepared site. Countless experiments over the years have shown that tree planting on sites where competing vegetation has not been deadened or removed is a waste of time and money. Several experiments were conducted at Wing Mountain, near Fort Valley, in the 1960s to test several herbicides for their effectiveness in killing perennial grasses and their effect on soil moisture.

In one experiment, soil moisture was studied at depths of up to 112 cm (44 inches) for two years on plots that had grasses, primarily Arizona fescue, either killed with herbicide or removed completely (Figure 8). Soil moisture was significantly higher on plots where grass was deadened than on plots with the grass removed or control plots where the grass was undisturbed (Figure 9), especially for the critical 0 to 20 cm (0 to 8 inches) depth. Under these conditions the grass serves as excellent mulch. This was especially true during the summer of 1962 (Figure 9) that had an unusual precipitation pattern. Each of the months from May to October received approximately 2.54 cm. (one inch) of precipitation and this generally came on one or two days (Heidmann 1969).

To sample mulching techniques, an experiment found that a mulch of three rocks (Figure 10), placed around the stem of ponderosa pine seedlings, improved survival regardless of the site preparation treatment, but survival was highest on plots where all the grass had been removed (Heidmann 1963b).

In another experiment, several herbicides were studied for their effectiveness in killing perennial grasses, primarily Arizona fescue and mountain muhly (*Muhlenbergia montana*). The least expensive and most effective herbicide was dalapon (2,2-dichloropropionic acid) (Heidmann 1968a). Unfortunately, this herbicide is no longer available in the United States. In later experiments it was found that herbicides such as *Roundup* (glyphosate) are also effective but more expensive. *Roundup* kills both grasses and forbs (weeds) (Heidmann 1967, 1968a).

Figure 8. Soil moisture study at Wing Mountain, AZ, in 1962. Soil moisture was compared on plots with grass sprayed with dalapon, removed completely, or left undisturbed over a two-year period. USFS photo by L. J. Heidmann.

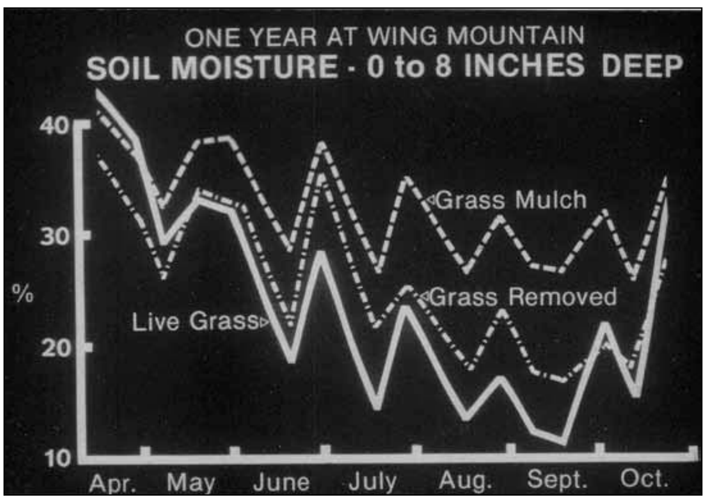


Figure 9. Soil moisture at Wing Mountain, AZ, for 0 to 20 cm depth comparing moisture on plots with dead grass, grass removed, and live grass, in 1963. USFS photo by L. J. Heidmann.

Figure 10. Mulch of 3-rocks placed around the stem of a ponderosa pine transplant at A-1 Mountain, AZ, in 1960. USFS photo by L. J. Heidmann.

At the Forest Service tree nursery at Albuquerque, New Mexico, two herbicides were tested for effectiveness in controlling weeds in nursery beds. Both *Goal* (oxyfluorfen) and *Modown* (Bifenox) sprayed over newly germinated ponderosa pine seedlings were effective in preventing establishment of grasses and forbs without damaging pine seedlings (Heidmann and Haase 1984).

Most site preparation methods in the Southwest have involved plowing or disking to get rid of grasses and forbs. These methods, however, do not result in as high a soil moisture as killing the vegetation and leaving the dead plants to serve as a mulch.

Seedlings

Seed Production

In a study of the Apache-Sitgreaves National Forest in which cone and seed production were studied in 1979, it was found that ponderosa pine produced an average of 25 pounds of seed per acre. Individual plots produced as much as 62 pounds of seed (Heidmann 1983a). This amount of seed (25 pounds per acre) is greater than the amount of seed estimated by Pearson (1950) for these soils. Twenty-five pounds of seed per acre is approximately six times the amount Pearson (1950) considered to be a bumper crop and is closer to findings by Larson and Schubert (1970) for basalt soils.

Heavy fertilization did not have an appreciable effect on the growth of ponderosa pine pole sized trees but it did significantly increase cone production and resulted in more frequent cone crops (Heidmann 1984). Application of urea ammonium phosphate at rates of up to 1,121 kg per hectare (1,000 lbs/acre) for four years resulted in good bumper cone crops in three of five years with seed production on individual plots of almost 1,000,000 seeds per hectare (400,000 per acre) (Heidmann 1984).

Ponderosa pine seed retain viability for long periods of time if stored at low moisture contents (mc). Seeds collected and stored at Fort Valley for 27 years at a (mc) of 6.2% had a viability of 46% (Heidmann 1962).

Seedlings for planting should be grown from seed collected from an area near the eventual planting site that is similar in elevation and climate (Schubert and others 1970). Cones should not be collected from trees of poor form or which are obviously diseased. Seedlings should have a proper root/shoot ratio and should not be lifted from the nursery bed until they have a high root regenerating potential (RRP) (Jenkinsen 1980). Experiments conducted with trees raised at the Albuquerque USFS nursery (since closed) showed that for six National Forests in Arizona and New Mexico that the later trees are lifted from the nursery bed (for example, nearest to the time of planting), the greater the rate of survival (Heidmann 1982b).

Planting Procedures

Seedlings have been planted successfully utilizing both planting machines or manual methods (Figures 11a and 11b). Regardless of the method, seedlings need to be planted properly (Schubert and others 1969). Trees need to be kept moist until they are planted then the roots should extend straight down the planting hole and the soil needs to be compacted firmly around the roots. These are simple procedures that are necessary for success wherever trees are planted. In the Southwest, however, many plantations have failed over the years because of poor planting techniques.

Protection

Plantations need to be protected for several years from browsing and grazing mammals. Countless experiments over the years have proven that cattle and sheep grazing newly planted areas can effectively destroy the plantation. On the Navajo Indian Reservation, sheep were allowed to graze pine regeneration areas for decades. However, now grazing animals are excluded from regeneration areas (Arbab and Metteba, no date).

Experiments conducted at Fort Valley have shown that seedlings repeatedly browsed by cattle and/or deer can be protected from browsing using animal repellents (Heidmann 1963a, Figures 12a and 12b). Figure 12a shows trees in the foreground that have been browsed repeatedly over the years. They are the same age (38 years) as the trees in the background. Trees repeatedly browsed have an extensive root system and once released from browsing grow rapidly.

Natural Regeneration

Although Pearson suggested that natural regeneration could be obtained by leaving a prescribed number of seed trees per acre and following other procedures, attempts were unsuccessful. My first supervisor, Edward M. Gaines, told me when I arrived in Flagstaff in 1957 that no deliberate attempts to get natural regeneration in the Southwest had ever been successful.

Natural regeneration has generally not been successful on basalt soils primarily because first year seedlings are very small on these fine textured soils, and as a result, are highly susceptible to drought and frost heaving the first year, as has already been stated. On sedimentary soils seedlings have less difficulty extracting water from the soil because of larger soil pores and as a result seedlings grow to a much larger size the first year. These seedlings are much less susceptible to frost heaving. Seedlings with larger tops heave less readily than smaller trees (Schramm 1958). In order for successful natural regeneration on these soils, however, the following steps are essential:

1. Determine if a potential cone crop can be expected. Ponderosa pine cones develop over three years. The female flowers form the first season then the following spring they are pollinated and grow to about the size of a marble. The following year they are fertilized and grow rapidly until they mature in the fall. Thus, it is necessary to survey potential regeneration areas the year before

cones mature. Making cone counts using binoculars does this.

2. Next, a rodent census needs to be conducted to determine if the population of seed eating rodents is high. If it is, control measures need to be taken.
3. The regeneration area needs to be logged a year before seedfall leaving at least five seed bearing trees with an average diameter of 51 cm (20 inches).
4. After seedfall in the fall, run a harrow or disc over the site to cover the seed.
5. Exclude cattle for three to five years (Heidmann and others 1982).

Thousands of acres of ponderosa pine have been successfully regenerated on the Apache-Sitgreaves National Forest, for example, by following these procedures.

Figure 11a. Site of wildfire at Jones Mountain, AZ, approximately 64 km south of Flagstaff, AZ. Picture taken prior to tree planting in 1960. USFS photo by L. J. Heidmann.

Figure 11b. Site 19 years later after planting with 3-rock mulch. Success is obvious. USFS photo by L. J. Heidmann.

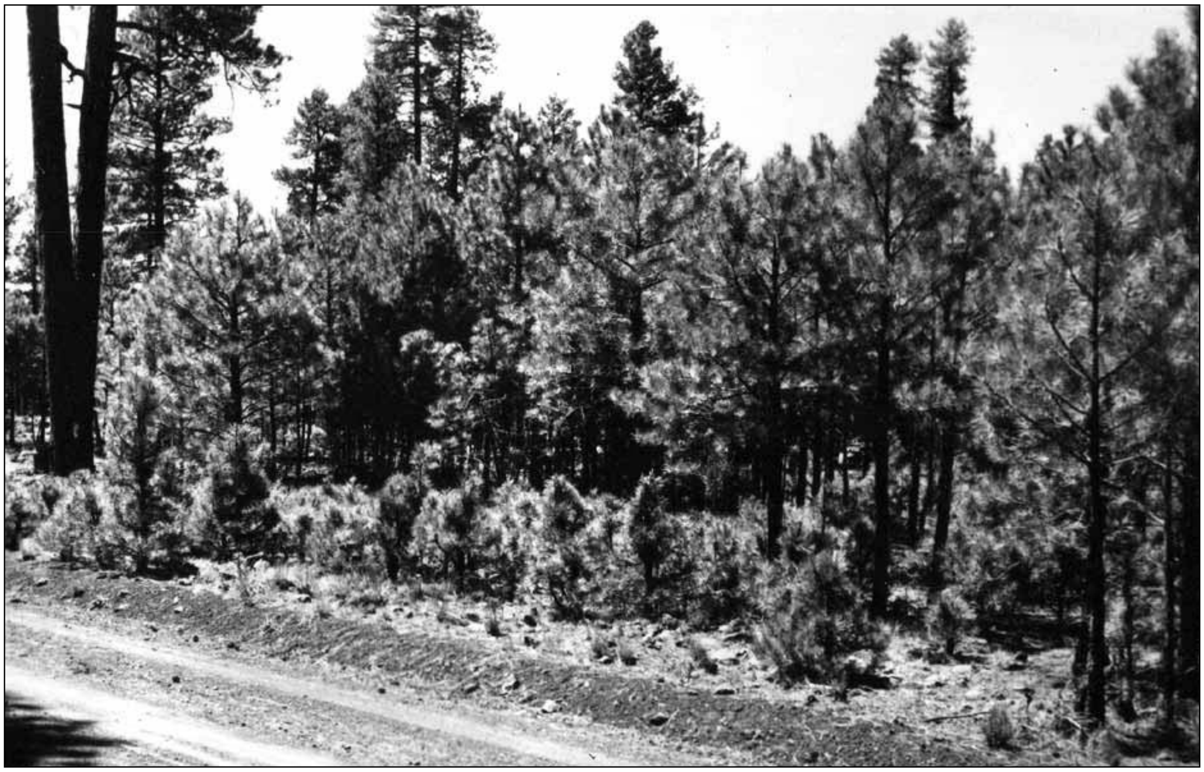


Figure 12a. Ponderosa pine in the foreground that have been repeatedly browsed by cattle or deer. Trees are the same age (38) as the trees in the background. USFS photo by L. J. Heidmann.

Figure 12b. The same site a few years after browsed trees were treated with deer repellents. USFS photo by L. J. Heidmann.

Basalt Soils

Sometimes useful information can be gathered by observation as well as from scientific experimentation. The author has observed that on areas where slash piles had been burned that first year ponderosa pine seedlings were six to eight times as tall as seedlings on unburned areas. The larger seedlings have a much greater chance of surviving frost heaving because heaving is inversely related to the size of seedling tops (Schramm 1958). It therefore appears that on basalt soils natural regeneration should be successful if the area is logged and slash burned before seedfall. However, the same steps prescribed for success on sedimentary soils should also be taken.

Frost Heaving

Frost heaving has been cited several times in this paper as a cause of seedling mortality. I became interested in frost heaving my first year at Fort Valley when I helped Mel Larson with a field study he was using for a master's thesis at the University of Washington (Larson 1961). This was a seeding study conducted inside a rodent proof enclosure at S-3, about six miles southwest of Fort Valley, where seed size and germination dates were related to survival. Beginning in June and throughout the summer, seedlings were watered three times a week, even during the rainy season. I took over the study for Mel while he was away at school. In early October 1957, 52% of approximately 1,000 seedlings heaved from the ground in one night. By spring of 1958 only a handful of seedlings were left. I was impressed by what had happened but did not think about frost heaving for a while because I was working on other things such as site preparation, planting, and animal repellents for controlling browsing by cattle and deer. Then, I read a paper by Schramm (1958) where he described heaving of coniferous and deciduous seedling on coal fields in Pennsylvania. He reported why very small seedlings heaved while seedlings with larger tops did not (true for coniferous species; larger deciduous species such as oak did heave). This piqued my interest but, once again, I did not think about the subject until I entered the University of Arizona to work on my PhD. I needed a dissertation subject and, even though my major was plant physiology, I decided to use a study of frost heaving for my dissertation. My dissertation director, Dr. David Thorud, who studied freezing of soils in Minnesota, helped me in this decision (Heidmann 1974).

My approach was to do a search of the world's literature relating to freezing of soils and frost heaving. It quickly became apparent that no work of a basic nature had been done in either forestry or agriculture. The overwhelming body of work had been conducted by scientists and engineers attached to the United States Army (CRREL, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire) who carried out most of their research in the Arctic, and by highway engineers. In addition, the Russians were doing a great deal of research (Heidmann 1976).

Next, I conducted a series of studies in the lab on the heaving characteristics of six soils from northern Arizona using a specially constructed freezing apparatus placed into a chest freezer. Several chemicals were tested for their ability to restrict water movement in the soil to a freezing front or their ability to lower the freezing temperature of the soil water and thus reduce heaving susceptibility (Heidmann 1975b, Heidmann and Thorud 1976). The chemicals were also studied to determine their effect on the germination of ponderosa pine seeds. Another major part of the study was to determine the effect of soil bulk density on the heaving of the six soils (Heidmann and Thorud 1975).

Tests were also conducted in the field inside the same enclosure used by Larson to study the heaving of wooden dowels and small plastic cylinders from the soil using a time lapse camera. The results from these studies are contained in six papers published by the USDAFS Rocky Mountain Forest and Range Experiment Station and in a dissertation from the University of Arizona (Heidmann 1974).

Frost heaving occurs because there is a segregation of soil water. Water migrates from lower soil depths to the surface where it freezes into lenses or palisade layers (Figure 13). Haasis (1923) described frost heaving on the Experimental Forest and included sketches but did not explore the basic cause. This water movement is a function of soil pore size, undercooling of soil water (soil water is at a temperature less than freezing), and soil surface temperatures slightly below freezing temperature (Heidmann 1976, Schramm 1958, Taber 1929, 1930). Soils with high silt contents are suited to heaving because the pore size is conducive to lowering the freezing point of the soil water that results in a negative pressure causing water to be drawn to the surface where it freezes into the lenses described. In order for ice lenses to form it is necessary that one gram of water arrive at the freezing zone at the surface for each gram of water that freezes. The result is that the surface of the soil is moved upward taking the seedling along with it (Figure 14).

Basalt soils studied in northern Arizona are high in silt content, often containing 60% or more (Heidmann 1975), with the remaining fraction clay and sand. According to Penner (1958), soils with high silt contents are ideally suited to heaving. Heaving is closely related to soil bulk density. Figure 5 clearly shows that for six soils studied in the laboratory in northern Arizona, the more the soil was compacted, the greater the rate of heaving, even in coarser sandy soils. The total water content for soils at minimum, mean, and maximum bulk density was the same, which indicates that at the minimum bulk density, there is considerable air in the soil pores that results in a broken water column restricting water flow to the freezing front at the soil surface. If water does not arrive at the freezing front as fast as it freezes then the soil freezes solid and no lenses are formed.

Methods to Reduce Frost Heaving

Since frost heaving is closely correlated with soil bulk density, the less the soil is compacted with heavy equipment

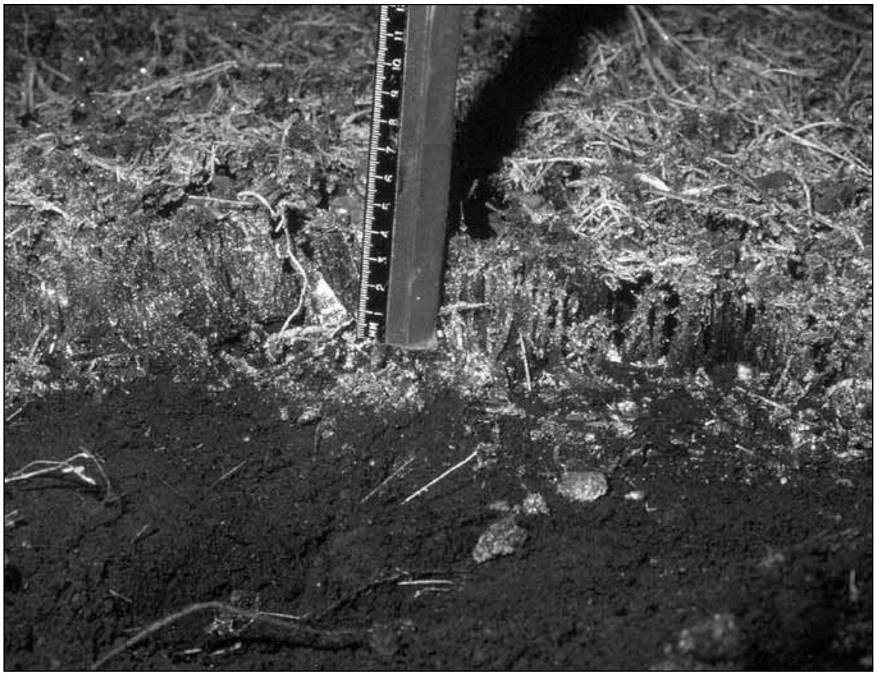


Figure 13. Example of frost action on basalt soil at Unit S-3 (Wing Mountain, AZ) during one night. This is an example of a 'palisade' layer of ice. Careful examination reveals extruded plant material on the surface.

Figure 14. A ponderosa pine seedling that has heaved from a basalt soil. The seedling is at least two years old because of the presence of needle fascicles.

prior to regeneration efforts the better the chances for success. Loosening the soil by disking prior to seedfall is beneficial. A harrow can be drawn over the site to lightly cover the seed after seedfall (Heidmann and others 1982). Certain chemicals, such as ferric chloride, cement soil particles together resulting in restricted water flow to the freezing front at the surface and thus reducing the formation of ice lenses (Heidmann and Thorud 1976).

Plant Growth Hormones

Plant growth hormones play an important role in the growth and development of plants. Several experiments with hormones were conducted over the years at Fort Valley. Seeds were treated with various hormones in an attempt to speed up germination. Results from these experiments were inconsistent. Gibberellic acid (GA4/7) was found to increase the height of ponderosa pine seedlings when applied as a root soak (Heidmann 1982a). A combination of GA 4/7 plus adenosine triphosphate (ATP) increased height growth nine times that of untreated seedlings.

Abscisic acid (ABA) is a plant growth hormone that controls dormancy in plants. Levels build up in the plant in response to day length. In the fall, when levels are high, growth of seedling tops ceases and a terminal bud is set. In the spring, when ABA levels are relatively low, buds break dormancy and top growth begins. The level of ABA in plants also tends to rise under stress. Equipment for studying hormone levels in plants is very expensive. In 1987 we found that hormone levels could be quantified by using monoclonal antibodies, a much less expensive process. We used this procedure to study ABA levels in stressed ponderosa pine in the greenhouse. Levels of ABA were six times higher in stressed seedlings after a ten week drought than in well watered seedlings (Heidmann and Huntsberger 1990, unpublished).

Dwarf Mistletoe

Dwarf mistletoe (*Arceuthobium vaginatum f. cryptopodum* (Engelmann) Gill), is the most destructive disease of ponderosa pine in the Southwest (Hawksworth 1961). In the 1960s it was estimated that 2.5 million acres of the 7.5 million acres of commercial ponderosa pine southwestern timberland were infected. The disease had been studied for many years but it was not until 1950 that a large pilot plant study was initiated to determine if the parasite could be controlled by silvicultural methods. Complete control was compared to limited control and light "Improvement Selection." After several treatments, it was determined that in order to control dwarf mistletoe by cutting, it was necessary to almost eliminate the entire overstory (Heidmann 1968b, 1983b). The mistletoe, however, is very slow growing and takes many years to kill host trees. For a comprehensive study of dwarf mistletoe in the Southwest, the reader is referred to Hawksworth (1961).

Summary

The humble beginnings at Fort Valley in 1908 eventually led to the establishment of the Forest and Range Experiment Station system throughout the United States. Many scientists have worked at Fort Valley in the last 100 years. Their findings are not only applicable to Arizona and the Southwest but around the country as a whole. In many instances scientists around the world have expressed interest in our findings. Drought and frost heaving are problems in most forested areas of the world. This paper has not discussed insects and disease, except for dwarf mistletoe briefly. These are problems of a global nature. One of our scientists, Frank Hawksworth, had a worldwide reputation as a mistletoe expert and Dick Tinus was equally well known for developing methods for raising container trees in greenhouses (Tinus and McDonald 1979). Who knows what the next 100 years will yield in the field of forest research?

Acknowledgments

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