EFFECTS OF PRESCRIBED BURNING ON PHYSICAL PROPERTIES OF SOIL

Charles W. Ralston
School of Forestry
Duke University
Durham, North Carolina

Glyndon E. Hatchell
Southeastern Forest Experiment Station
Charleston, South Carolina

INTRODUCTION

One of my colleagues annually assigns a review of literature on effects of fire on soil properties to one of his unsuspecting forest management students. The normal and acceptable result--at least regarding soil physical properties--is a paper concluding that almost any position on fire effects can be documented by reports of reputable researchers. Experimental evidence can be cited to show that infiltration capacity, structural aggregates, macro and micro pore space, and incorporated organic matter are increased, decreased, or unaffected by burning forest, range, or woodland habitats.

Rational evaluation of such diverse effects of burning on physical properties of soil--and their implications in management--requires careful consideration of the kind of fire, the kind of soil, the kind of topography, and the other environmental conditions that produced the observed effects. Was it a prescribed fire or a wildfire? If prescribed, was it a light surface backfire or a heavy slash burn? Was the wildfire a surface headfire, or did it crown? Was the terrain flat and the soil sandy? Was it a silty soil on steep topography, an area with thick duff, or a peat soil? All of these questions, and others unasked, have a bearing on the degree of direct and immediate changes in soil properties at the time of burning and on subsequent, longer range, indirect effects of fire on physical characteristics of the ecosystem. If the literature

USDA Forest Service. 1971. Prescribed burning symposium proceedings. Southeast. For. Expt. Stn. pp. 68-84.

on fire effects is studied and interpreted with proper regard for the dominant variables in each instance, anomalous results can be understood, and an array of soil physical changes caused by burning can be provided for managerial value judgments.

IMMEDIATE EFFECTS OF FIRE

When a forest or range area burns, fuels are consumed, thereby heating the soil and producing alterations of surface ground covers. The magnitude of these effects largely depends on the oxygen supply during combustion and the amount and condition of the fuel supply.

Studies of Soil Temperatures During Burning

Intensities and durations of soil heating by prescribed fires for rough reduction are considerably less than those generated by slash burning or wildfires. Heyward (16) made comprehensive observations of soil temperature trends during 44 prescribed fires on longleaf pine flatwood sites near Olustee, Florida, and on well-drained upland longleaf types in southern Mississippi. Fires--both with and against the wind--in roughs up to 15 years old, seldom generated temperatures above 52° C. (125° F.) for more than 15 minutes at shallow (3-6 mm.) soil depths, and except for brief intervals (2-3 min.), maxima were below 121° C. (250° F.). The highest temperature observed 1 inch below the soil surface was 66° C. (150° F.). A typical temperature record of this study is shown in figure 1a.

Soil temperatures associated with slash fires have been the subject of several studies in Australia. The results of an experiment by Beadle (4) are given in figure 1b. Test fires ranged from a surface litter burn of 3/4-hour duration to a blaze fed by all of the shrubs and trees on the plot, stoked for 8 hours. The surface fire heated the soil to 50° C. (122° F.) at 1-inch depth, and the hottest fire, which approximated a land clearing operation or a severe wildfire, created temperatures near 223° C. (434° F.), 3 inches below the surface. Later measurements of temperatures under burning windrows of eucalypt slash and logs (9, 10, 18, 31) revealed peak temperatures from 666° C. (1231° F.) just below the soil surface to 112° C. (233° F.) at a depth of 8½ inches.

Effect of Soil Heating on Organic and Mineral Fractions

Once the range of heat intensities of various kinds of fires is recognized and approximate quantitative temperature limits are known, one may ask what happens to organic and mineral fractions of soils upon exposure to different heat levels.

Soil organic matter.--Progressive heat destruction of organic matter in four Australian soils, one from England, Merck's "humic" acid, and filter paper was observed by Hosking (17). Samples were heated in a muffle furnace at temperatures of 100° to 500° C.

for periods of 16 hours to 1 week. Major temperature-dependent stages of ignition were:

a. 100°-200° C.--nondestructive distillation of volatile organic compounds

b. 200°-300° C.--destructive distillation of up to 85 percent of organic substances

c. >300° C.--ignition of carbonaceous residues.

Overall conclusions were that heating at 450° C. for 2 hours or at 500° C. for ½ hour are required to remove 99 percent of the organic matter in the materials tested.

Now, if these results are compared with soil temperatures recorded for various prescribed burns, it is most unlikely that soil heating by prescribed fires for rough reduction causes major loss of incorporated organic matter. Some nondestructive distillation of volatile substances can be expected and abnormal drying of organic colloids will occur at shallow depths. Thus, light burning causes no detectable change in total amount of organic matter in the surface soils (14, 27), or slight increases have been noted and attributed to more rapid decomposition and incorporation of residual organic fragments on burned surfaces (26).

Temperatures recorded during prescribed burning of slash piles and in hot spots of wildfires are high enough to cause ignition losses of organic matter near the surface and substantial destructive distillation losses to depths of several inches. An example of organic matter depletion in severely burned spots during disposal of slash of a Douglas-fir logging operation in Oregon is given by Dyrness and Youngberg (14). The organic content of the surface 5 centimeters (2 inches) of soil was 4.2 percent in places where slash piles burned, whereas comparable surface layers in lightly burned or undisturbed timbered areas contained about 11 percent organic matter.

Mineral soil fractions.--Temperatures associated with light surface fires are insufficient to cause any appreciable change in properties of mineral soil particles, but the heat of more severe fires can cause irreversible changes in the structure of soil clays. Temperatures between 100°-200° C. drive off water that is strongly adsorbed between adjacent micelles of montmorillonite and illite clays; at 550° C., both of these groups--and the kaolin clays, as well--lose water derived from hydroxyl ions that are part of crystal structures of clay minerals (21). Loss of structural water permanently alters the shrinking and swelling properties of montmorillonite clays to the extent that heat-treated clay aggregates have soil moisture properties similar to sand or gravel.

Alteration of Ground Surface by Burning

In addition to heating the soil, fires remove part or all of the forest floor materials that buffer the soil from rapid changes in microclimate and from the churning action of falling raindrops. Therefore, in judging effects of burning, it is important to recognize variations in forest floor removal by different kinds of fires.

Ordinarily, prescribed fires for rough reduction will not remove all of the forest floor. Sweeney and Biswell (37) found that 76 percent of litter (O_1) and 23 percent of duff (O_2) horizons were consumed by four test fires in ponderosa pine types in California, and that in all cases, remaining materials were sufficient to cover the soil. After 10 years of study of prescribed burning in sawtimber stands of loblolly pine in the South Carolina flatwoods, Metz, Lotti, and Klawitter (26) reported one instance in which a winter fire consumed about 4,000 of 17,000 pounds per acre of surface organic matter, and that after 10 annual fires (winter or summer) 4,000 to 5,000 pounds per acre of organic fragments remained on the ground prior to autumn leaf fall.

The exposure of post-burn surfaces of slash fires and wildfires is variable both in degree and extent. Relationships between soil temperatures during burning and post-fire seedbed conditions for California woodland ranges were evaluated by Bentley and Fenner (6). Their observations--summarized in table 1--give a good description of burned surfaces after a hot fire.

Table 1

Seed bed condition	Maximum temperature during fire	
	Surface	2.5-cm. 1 inch depth
Black ash (surface covered by charred litter fragments)	177° C. (350° F.)	71° C. (160° F.)
Bare (litter consumed; no ash accumulation)	400° C. (750° F.)	177° C. (350° F.)
White ash (litter and heavy fuels consumed; thick ash deposits)	>500° C. (>1000° F.)	288° C. (550° F.)

Areal estimates of surface conditions after logging and slash burning in mature Douglas-fir given by Dyrness and Youngberg (14) were: undisturbed (17 percent), disturbed by logging (30 percent), lightly burned (45 percent), severely burned (8 percent). Obviously, fires can effect greater reductions in surface cover--including complete removal--than those cited, but these examples illustrate the fact that the impact of burning on surface cover is variable and that some restraint is needed when interpreting effects of fire on soil properties and site disturbance.

SUBSEQUENT EFFECTS OF FIRE

While soil heating and surface cover removal are the immediate factors that effect varying degrees of change in soil properties, we are usually more concerned with longer lasting effects that may occur when burned areas interact with other physical factors of the environment over a period of time.

Considerable attention has been given to study of soil temperatures, changes in macro-pore space, and related properties (infiltration rates and air space), but the studies of major consequence are those that provide data on how fires affect surface runoff and soil erosion.

Soil Temperature Changes

Forest floor material acts as an insulator against soil temperature changes, reducing extremes and moderating rates of soil freezing and thawing. Temperature differentials between fully insolated, charred burns and shaded, undisturbed, forested sites can be appreciable (ca. 10^{o} C. at 7.6-cm. depth), but this response is diminished considerably (ca. 2^{o} C. at 7.6-cm. depth) if the burn also is shaded (5). When the objective of management is perpetuation of a number of subclimax tree species, the combined effects of temperature changes, reduction of weed competition, and soil exposure on burns is favorable for regeneration by natural or artificial seeding.

Macro-Pore Space, Infiltration Rates, and Aeration

Alterations in these related properties mostly depend on fire intensity and the amount of forest floor that remains after burning. When increases in these properties are reported, it is likely that intense heating has altered the crystalline structure of shrinking and swelling clays, thereby causing them to be more permeable to air and water movement (30, 34, 36).

If mineral soil is exposed, either by hot wildfires or by repeated moderate burning for long periods of time, as aggregates are dispersed by beating rain and pores become clogged with fine particles, decreases in macro-pore space, infiltration, and aeration can be expected (1, 2, 3, 5, 33, 41).

Singular reductions in percolation rates sometimes are observed after fires on sandy soils, and special mechanisms have been advanced to explain this phenomenon. Water repellent soils have been found beneath litter layers of unburned chaparral areas and at varying depths in soils of burned watersheds of this type (22). These layers resist wetting and impede downward infiltration of water and upward evaporation from lower soil horizons. Their existence is attributed to downward distillation and condensation of volatile hydrophobic constituents of litter materials (13). Excessive drying of organic colloids also may affect their rewetting capacity (the senior author has found that ovendried samples of A_1 horizons retain less water when remoistened than air-dry or fresh samples). Furthermore, if peat soil fragments are air-dried in the laboratory, they will float on water for prolonged periods (weeks); however, if steamed or boiled, they rapidly become rewetted. This behavior suggests that pores of organic colloids in such soils have shrunk to sizes where capillary conductivity is exceedingly slow and that vapor pressure gradients at pore entries are too low to permit rapid rewetting at ordinary temperatures.

When surface organic horizons are not completely consumed by prescribed fires, changes in pore space and infiltration may be too small to be detected. Thus, Metz, Lotti, and Klawitter (26) reported no change in these properties after 10 annual burns on the Santee Experimental Forest.

Surface Runoff and Erosion

The main impact of fire on the physical environment is the extent to which it removes surface cover and thus alters the partitioning of incident precipitation into surface runoff and infiltration components, thereby increasing the potential for soil loss by erosion.

The importance of forest floors in regulating runoff and controlling erosion was the subject of elaborate experiments by Lowdermilk (24). His conclusions were: (1) forest litter greatly reduced runoff, especially in finer-textured soils; (2) destruction of litter and exposure of bare soil greatly increased soil erosion and reduced the water absorption rate; (3) sealing of pores by particles suspended in runoff accounted for marked differences in infiltration between bare and litter-covered soils; and (4) water absorption capacity of litter is insignificant in comparison with its role in protecting maximum percolating capacity of soils. These conclusions are confirmed by work of Rowe (32) in natural stands of ponderosa pine and by his lysimeter experiments.

However, in the sequence of things causing erosion, the crucial significance of vegetation lies in its effectiveness in preventing the dislodgment and suspension of soil particles--an event that must happen before erosion can take place. This truly profound characteristic of plant cover in preventing soil erosion--irrespective of high rainfall, steep topography, and soil type--is amply demonstrated by clear flows from mountain watersheds; but only when adequate cover of forest or grass is present. Further evidence of the role of vegetation in minimizing erosion is given by Langbein and Schumm (23) who postulate maximum rates of natural erosion for areas with annual rainfall between 25 and 35 cm. (10-15 inches), because increased vegetational cover causes a decrease in soil loss above 35 cm. and runoff is rare below 25 cm.

Since it is seldom possible to protect natural or managed forests indefinitely from disturbance by fire or other disruptive events of natural or manmade origin, further examination of studies on fire and erosion is warranted.

A *post mortem* analysis of conditions following a large wildfire in central Idaho (7) effectively illustrates the interactions of cover type, fire intensity, and slope gradient on incidence of accelerated erosion (figure 2). Greater fire intensities generated by heavy brush and slash fuels on cutover areas were believed to be the reason for a higher percentage of eroded plots (42 percent) on logged areas than were found on virgin forest land (28 percent). Also, needle cast from trees killed by severe ground fires gave a degree of protection to timbered areas that was absent on cutover terrain and in stands where crown fires occurred.

Although this study presents an excellent qualitative picture of interactions of fuel, fire, and environmental conditions producing the complex erosion patterns following a large wildfire, we must examine less drastic fire treatments on a quantitative basis, if we are to evaluate the soil loss from prescribed burning.

Some of our early records on this subject were initiated during the conservation wave of the 1930's, when conservation experiment stations were established at 10 locations representing major agricultural areas of the United States. Soil runoff and erosion were measured over a 10-year period from plots cropped both by conventional and conservative practices, with forest or sod plots serving as controls. Results of all stations were similar, and as shown in figure 3 (29), the essentially conservative nature of forest or grass crops is quite apparent.

Some of these experiments and later work present estimates of soil losses caused by woods burning (table 2). Although these erosion rates seem nominal when compared with those of agriculture, it is evident that annual burning does cause significant increase in soil loss, so the persistence of such effects after burning is discontinued, and levels of erosion considered acceptable as long-term loss rates are matters that deserve further inquiry.

Recovery Trends

It is reasonable to suppose that reduction in erosion rates after burning depends on how quickly surface cover is re-established. The scrub oak areas treated by Ursic (39, table 2) apparently had enough regrowth to be stabilized by the end of the third growing season. Ursic (38) also measured sediment production over a 3-year post-burn period on three old field watersheds with grass cover. On two burned catchments the maximum sediment yield was 2.9 tons $ac.^{-1}$ (44 cm. 1000 $yr.^{-1}$) during the first year after burning, 0.26 tons $ac.^{-1}$ after 2 years (4 cm. 1000 $yr.^{-1}$), and 0.023 tons $ac.^{-1}$ (0.35 cm. 1000 $yr.^{-1}$) in the final year of study.

After a 4,500-acre fire that killed a ponderosa pine forest near Deadwood, South Dakota, Orr (28) measured runoff and erosion from plots on two watersheds, helicopter-seeded to grasses and legumes on top of winter snow. Trends of soil loss and vegetation density during the recovery period (1960-64) appear in figure 4. The author postulates that total ground cover of native and seeded vegetation must equal or exceed 60 percent density for minimum tolerable control of runoff and erosion.

Table 2.--Soil losses from burned and protected woodlands

Investigator	Location	Forest cover	Years of record	Annual PPT.(In.)	Soil loss (Tons $ac.^{-1} yr.^{-1}$)	Erosion[1/] (Cm. 1000 $yr.^{-1}$)
Meginnis (25)	Holly Springs, Mississippi	Scrub oak, burned	2	63.8	0.33	5.0
		Oak forest, protected	2	67.1	0.025	0.4
Daniel et al. (11)	Guthrie, Oklahoma	Woodland burned annually	10	30.6	0.11	1.7
		Virgin woodland	10	30.6	0.01	0.15
Copley et al. (8)	Statesville, North Carolina	Hardwood, burned semi-annually	9	46.5	3.08	47.0
		Hardwood, protected	9	46.5	0.002	0.03
Pope et al. (29)	Tyler, Texas	Woodland, burned annually	9	40.9	0.36	5.5
		Woodland, protected	9	40.9	0.05	0.8
Ferguson (15)	East Texas	Shortleaf-loblolly, single burn	1.5	--	0.21	3.3
		Shortleaf-loblolly, protected	1.5	--	0.10	1.5
Ursic (39)	North Mississippi	Scrub oak, burned and deadened	1st	65.1	0.51	7.8
			2nd	40.5	0.20	3.1
			3rd	50.5	0.05	0.8
		Scrub oak, protected	1st	65.1	0.21	3.1
			2nd	40.5	0.09	1.4
			3rd	50.5	0.03	0.45

1/ Assuming 1 cm. of soil weighs 65.6 tons $ac.^{-1}$.

Conditions following a single prescribed fire in southern pine types probably are given by Ferguson's example (15), table 2). Although the aggregate soil loss was greater from burned areas, the net difference in loss rate (1.7 cm. 1000 $yr.^{-1}$) was fairly low for the 18-month period, and most of the erosion presumably took place prior to leaf fall.

Viewpoints on Tolerable Erosion

Establishing a standard for maximum allowable soil erosion is a worthy but complex objective. If the goal is a loss rate on a national level equivalent to normal geological erosion prior to man's disturbance of the landscape, the estimate can only be obtained by inference. Accepting a current national rate of 6 cm. 1000 $yr.^{-1}$ for solid and dissolved loads discharged by rivers of the United States (20), Judson (19) estimates that our nation was eroding at a rate of 3 cm. 1000 $yr.^{-1}$ "before man started tampering with the landscape on a large scale."

Smith and Stamey (35) also tackled the problem of determining the range of tolerable erosion. They found sediment yields from 36 forest or grass control plots of erosion studies at 12 locations to be of the order of 0.05 to 0.30 tons per acre. These values were doubled to correct for short slope lengths of experimental plots in arriving at normal erosion rates for land protected by full permanent cover of from 0.1 to 0.6 tons per acre (1.5-9.1 cm. 1000 $yr.^{-1}$). In reviewing the rationale of SCS conservation planning standards of 0.5 to 6.0 tons per acre (7.6-91.4 cm. 1000 $yr.^{-1}$), they point out that available reserve depth of favorable, permeable material is a most critical planning factor. Thus, if a planning period of 1000 years is reasonable, the 6-ton-per-acre standard might be sound for deep, permeable, loess soils in Iowa, but a 3-ton annual loss rate would be most unacceptable for 41 cm. (16 inches) of favorable materials over intractable claypan soils of Missouri.

In considering these viewpoints on erosion standards, it may be observed that endorsing Judson's 3 centimeter per 1000 year prehuman intervention loss rate would, indeed, be conservative, as it virtually coincides with geological estimates of rock weathering rates in the central United States; thus, an equilibrium between soil loss by erosion and formation of new soil by weathering.

If we allow erosion from common forest practices to be judged by SCS planning standards, data of Ursic and Dendy (40) and those from other sources (table 2) are helpful in assessing the effect of burning on soil loss rates (figure 5). It is evident that soil loss from woods burning is within current planning limits[1/] for fire practices that are strongly discouraged, e.g., annual and even more irrational semiannual burning treatments.

1/ SCS planning standards were reduced to 0.25 and 3.0 tons $ac.^{-1}$ $yr.^{-1}$ in preparing figure 5 to allow for small watershed and plot sizes.

If prescribed burning is used as recommended in southern pine management, periodic fires for understory control, hazard reduction, and site preparation at the time of regeneration are less likely to cause runoff and erosion problems than the mechanical methods of site preparation and wildfires that would replace them.

CONCLUDING REMARKS

It should be recognized by now that drastic changes in soil physical properties and removal of forest floor materials sufficient to cause significant increase in erosion rates can only be expected from severe fires or on sites where particular combinations of soil, topography, and rainfall confer high risk of damage. If recommended conditions for prescribed burning are observed, the danger of causing soil damage is negligible. Probably the most cogent summary of our topic is given by Davis (12) who notes:

> There is a tendency to overemphasize the unfavorable effects of fire on mineral soil by stressing extreme situations in frequency and intensity of burning. There should be no minimizing of the destructive and undesirable results of wildfires, and this applies both to occasional severe fires and to the cumulative deteriorating effect of frequent moderate fires. But it must also be recognized, and this is a point of large practical importance, that many fires have little total soil effect one way or another and some are beneficial. This fact permits a fairly wide range of choice in using fire in particular situations as a tool in forest management without risking significant soil damage.

There seems little reason to question this viewpoint at this time.

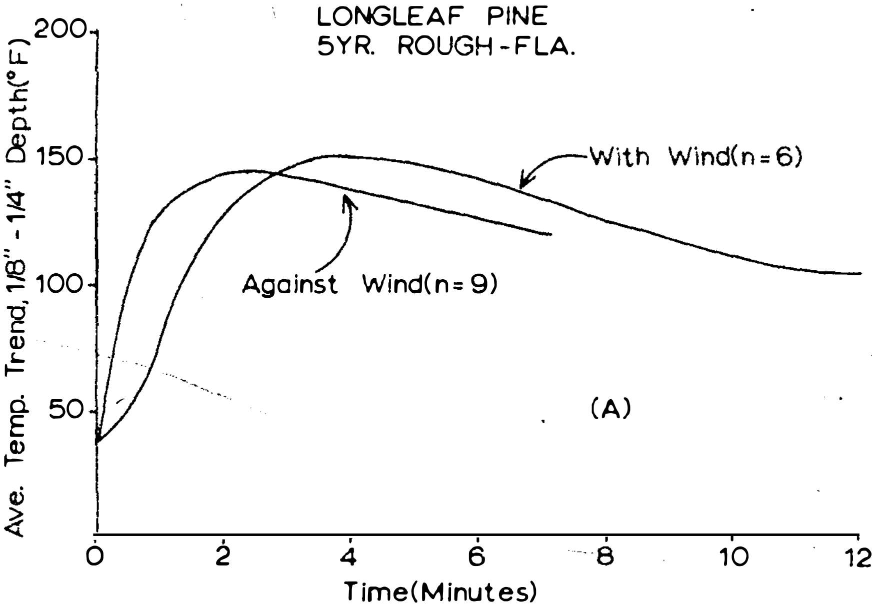

Figure 1A FROM: F. HEYWARD, 1938

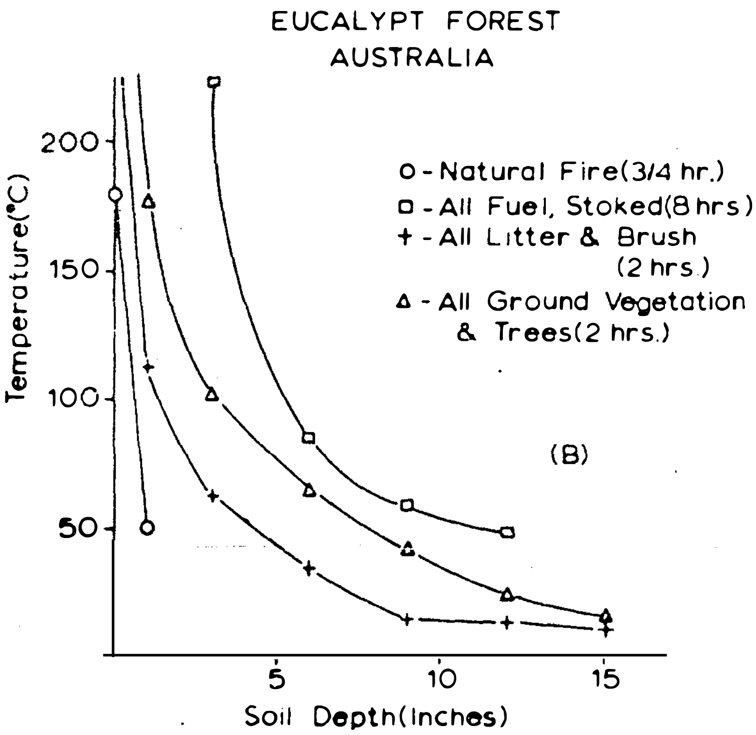

Figure 1B FROM: N.C.W. BEADLE, 1940

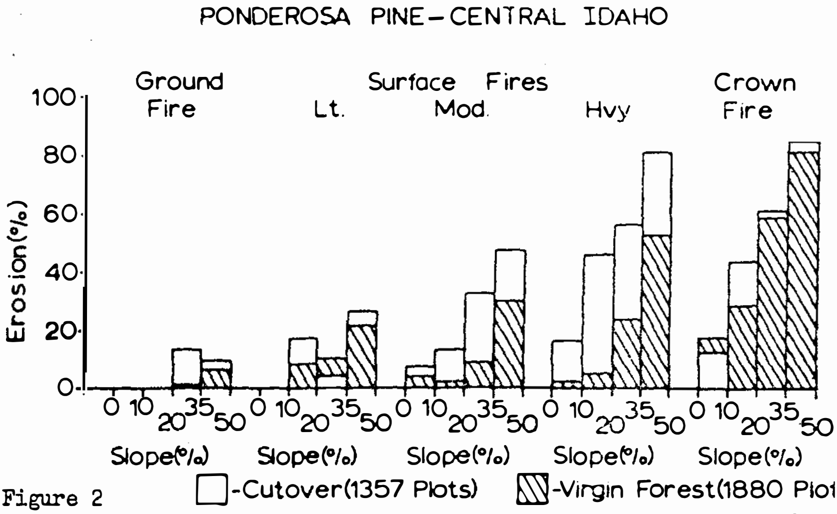

Figure 2

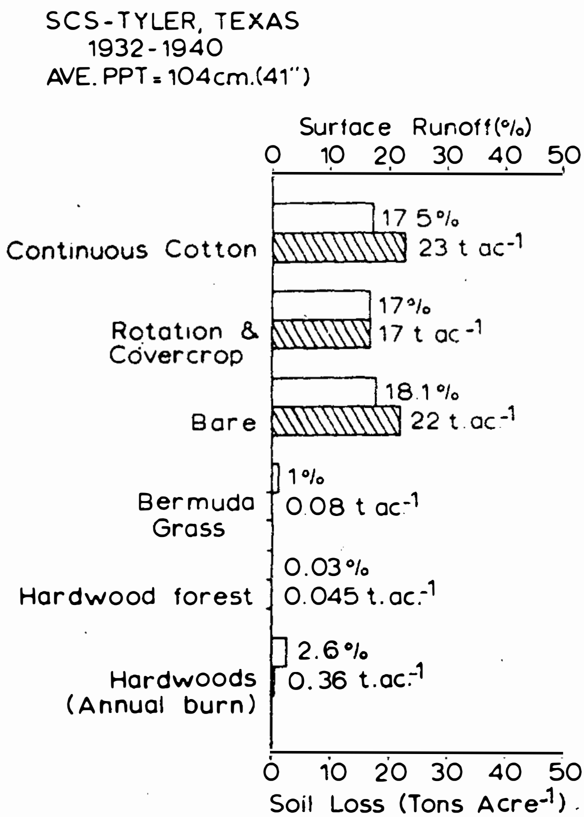

Figure 3 AFTER: POPE et al. 1946

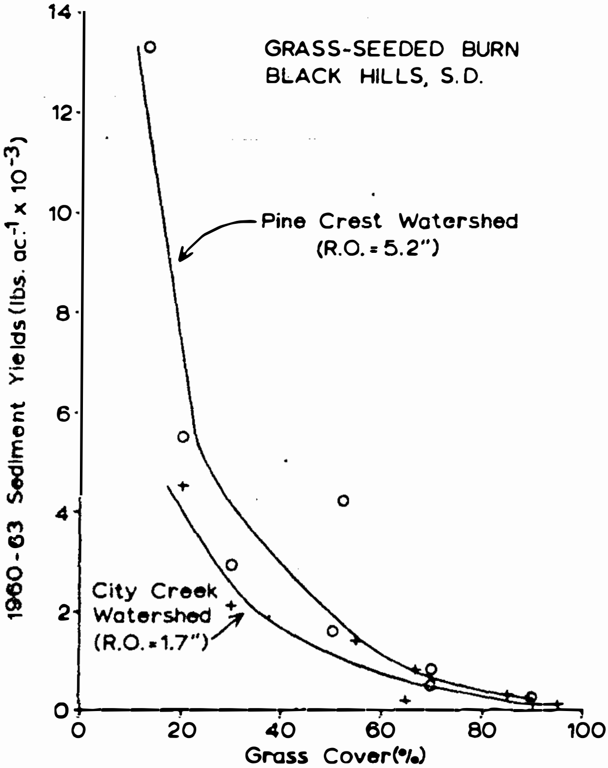

Figure 4 FROM: H.K. ORR, 1970

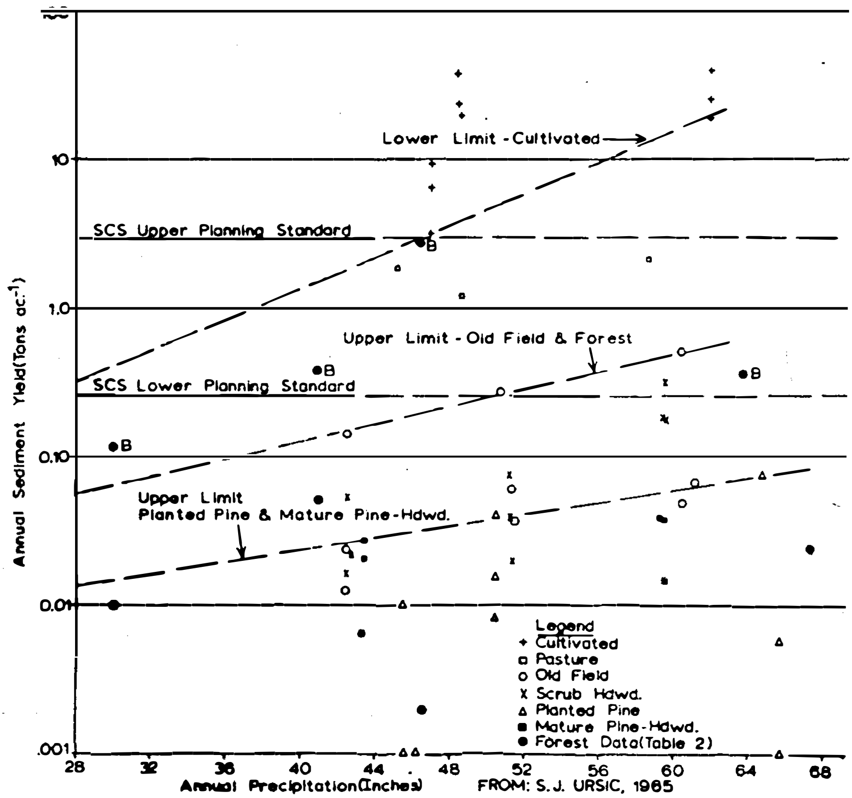
Lower Limit - Cultivated
SCS Upper Planning Standard
Upper Limit - Old Field & Forest
SCS Lower Planning Standard
Upper Limit
Planted Pine & Mature Pine-Hdwd.
Legend
+ Cultivated
▫ Pasture
o Old Field
x Scrub Hdwd.
Δ Planted Pine
■ Mature Pine-Hdwd.
● Forest Data(Table 2)
Annual Sediment Yield(Tons ac.$^{-1}$)
10
1.0
0.10
0.01
.001
28
32
36
40
44
48
52
56
60
64
68
Annual Precipitation(Inches)
FROM: S.J. URSIC, 1965

Figure 5

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