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Infiltration, soil erosion, nitrogen loss and soil profile characteristics were measured on 36 sites representing land occupied by *Artemisia tridentata* ssp. *tridentata*, *wyomingensis*, and *vaseyana*. Infiltration, soil erosion, and nitrogen loss were strongly correlated but highly variable. Soil loss, but not infiltration or nitrogen loss was significantly different between subspecies. At Frenchglen infiltration rates were higher and soil erosion and nitrogen loss rates were lower for *A.t.* ssp. *vaseyana* sites than for *A.t.* ssp. *wyomingensis* sites. Infiltration rate decreased between plots as mean soil particle size decreased, organic ground cover decreased, bulk density increased, and extractable sodium increased.

Infiltration rate was especially low on sites with vesicular porosity in the surface soil. Soil loss, and for the most part, percent nitrogen in the runoff water increased between plots as bare ground increased, and vesicular porosity in the surface soil increased, but soil and nitrogen loss was negatively correlated with medium and coarse sand and coarse fragments in the surface soil, and with organic ground cover. Aridisols lost more soil than Mollisols, but only if sites dominated by surficial tephra were omitted from the analysis, did Aridisols show significantly lower infiltration rates. The nitrogen lost in the simulation does not appear to be large in comparison with either capital or yearly flux. Nearly all characteristics of the soil profile show either no significant differences between subspecies or they show a significant interaction between location and subspecies. The Frenchglen location had the greatest elevational differences between subspecies and most of the significant physical and chemical differences between subspecies, including greater depth of maximum illuviation, greater rooting depth, and in the surface soil, lower pH, higher organic matter, higher cation exchange capacity, lower base saturation and lower percent exchangeable sodium on higher elevation *A.t.* ssp. *vaseyana* sites than on *A.t.* ssp. *wyomingensis* sites and/or *A.t.* ssp. *tridentata* sites. In the deeper soil horizons at Frenchglen, *A.t.* ssp. *vaseyana* sites had lower pH and lower base saturation than *A.t.* ssp. *tridentata* sites.

Infiltration, Soil Erosion, Nitrogen Loss and Soil Profile Characteristics of Oregon Lands Occupied by Three Subspecies of *Artemisia tridentata*

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INTRODUCTION

Water is frequently the most limiting factor in natural plant communities and for many of man's activities. This is certainly true in the western U.S. where 145 million acres of rangeland are occupied by *Artemisia tridentata* (big sagebrush) (Beetle 1960). In these semiarid areas, water is also the principle mechanism of soil erosion and soil formation. Water has long been a subject of rangeland management research, starting even before Horton (1933) recognized the role of infiltration in the hydrologic cycle. In the decades since, the related phenomena of infiltration, runoff, and soil erosion have received considerable research attention. On rangeland, research has focused on the impact of grazing, especially abusive grazing.

Perhaps all rangeland watershed research has identified the study area in relation to geography, vegetation, and soils. Biogeography has developed as a science studying the physical site factors that cause and/or result primarily from differences in vegetation. Using a biogeographic approach, Blackburn et al. (1982) discussed ten broad vegetation types separately in their review of the grazing response of watersheds. A few studies go even further, making comparisons across several plant communities on a local or regional scale. Blackburn and Skau (1974) studied 29 communities in Nevada including eight identified at least in part by *Artemisia tridentata*. Buckhouse and Mattison (1980) studied ten habitat types from mixed steppe to mixed forest in Central Oregon. These included the *Artemisia tridentata/Festuca idahoensis - Agropyron spicatum* habitat type with and without *Juniperous occidentalis* (western juniper). Neither of these studies identified the subspecies of *Artemisia tridentata*, yet since Beetle and Young (1965) reported the third subspecies, there has been increasing recognition and use of subspecific taxonomy in *Artemisia tridentata* ecological study. Tisdale and Hironaka (1981) stressed the value of identifying these subspecies in synecology. *Artemisia tridentata* subspecies might serve as both hydrologic and ecologic indicators. The principle objective of this study was to compare rates of infiltration and soil erosion for lands occupied by three subspecies of *Artemisia tridentata*, *A. t.* ssp. *tridentata* (basin big sagebrush), *A. t.* ssp. *wyomingensis* (Wyoming big sagebrush), and *A. t.* ssp. *vaseyana* (mountain big sagebrush). The second objective was to assess the relative correlation of soil and vegetation site factors with rates of infiltration and soil erosion.

Nitrogen is probably the second most limiting factor, reducing plant (especially grass) production in much of the northern Great Basin (James and Jurinak 1978). Soil nitrogen is primarily tied up in organic matter and/or clay minerals (West and Klemmedson 1978) and is concentrated near the soil surface (Charley 1977). This combination of attributes causes nitrogen to be susceptible to erosional loss. The third objective was to compare rates of nitrogen loss from lands occupied by the three subspecies of *Artemisia tridentata* and to correlate this with the soil and vegetative site factors.

Most of the research linking *A.t.* ssp. *wyomingensis* to moderately deep soils at relatively low elevations; *A.t.* ssp. *tridentata* to sites with very deep soils that might be suitable for agronomy; and *A.t.* ssp. *vaseyana* to deep soils at higher elevations where soil moisture is generally available later in the summer; was done in Idaho (Winward 1970 and Hironaka and Fosberg 1979). Therefore, a fourth objective was to compare physical and chemical characteristics of soil profiles representing the three subspecies in Oregon.

LITERATURE REVIEW

Artemisia tridentata Ecology

McArthur (1978) summarized the current concepts of taxonomy within the section *Tridentatae* Rydb. of the genus *Artemisia*. In general he agreed with the earlier work of Beetle (1960) and Beetle and Young (1965). Winward (1980) followed the same view of sagebrush taxonomy as he applied it to Oregon. He listed three subspecies and one form of *Artemisia tridentata*, *A.t.* ssp. *tridentata*, *A.t.* ssp. *wyomingensis*, *A.t.* ssp. *vaseyana*, and *A.t.* form *spiciformis* (subalpine big sagebrush). His description of the taxonomy of *Artemisia* may be supplemented by the chromatographic identification techniques of Stevens and McArthur (1974), Kelsey et al. (1976) and Kelsey (1982), by the spectrophotometric technique of Shumar et al. (1982), and by the discussion of biogeography and management by McArthur and Plummer (1978).

Winward (1980) and McArthur and Plummer (1978) discussed the ecology of *Artemisia tridentata* and other sagebrush species and both were cited by Tisdale and Hironaka (1981) in their review of the ecological literature of the sagebrush grass region. Winward (1980), drawing in part from his Ph.D. dissertation (1970), indicated that *Artemisia tridentata* ssp. *wyomingensis* is the most xeric of the three subspecies. It generally occurs below 6,000 feet (1,829 meters) elevation on moderately-deep well-drained soils, which may be slightly calcareous to the surface. Grasses form the majority of the understory vegetation and most forbs are annual. There is a considerable amount of bare ground (five to 25 percent, even under pristine conditions), which cryptograms may occupy. Winward (1981) indicated that shrub cover ranges from eight to 23 percent with a mean of 18 percent. He also indicated that in as much as *Artemisia tridentata* ssp. *wyomingensis* plants occupy the more xeric sites which are more easily abused and slow to recover, a high percentage of *A.t.* ssp. *wyomingensis* sites are in low ecological condition.

Artemisia tridentata ssp. *tridentata* is a good indicator of potentially arable land because it occupies deep well-drained soils. As a result it is generally in small stands because most of the original large stands are now cultivated. More perennial forbs are found here and potential herbaceous production is from 1 1/3 to 2 times greater than on *A.t.* ssp. *wyomingensis* sites. Winward (1981) indicated that shrub cover ranges from 19 to 30, with a mean of 24 percent.

Artemisia tridentata ssp. *vaseyana* resides in the upper foothill to mountain areas from 3,500 to 9,000 feet (1,067 to 2,743 meters). It occupies deep well-drained soils with moisture available most of the summer. Winward (1981) indicated that herbaceous cover is very diverse and productive with three to four times more species and 1 1/2 to 2 times more production of grasses and forbs than on *Artemisia tridentata* ssp. *wyomingensis* sites. He also indicated that shrub cover ranges from 14 to 41 with a mean of 23 percent.

Winward (1982) has listed the habitat types for *Artemisia tridentata* in order from xeric to mesic first by subspecies of overstory and then by understory within each subspecies (table 1). Hironaka (1979) described all the above habitat types except *Artemisia tridentata* ssp. *wyomingensis* / *Festuca idahoensis*, *A. t.* ssp. *tridentata* / *Elymus cinereus*, *A. t.* ssp. *vaseyana* / *Stipa thurberiana*, *A. t.* ssp. *vaseyana* / *Elymus cinereus*, and *A. t.* ssp. *vaseyana* / *Festuca scabrella*. He was uncertain, however, whether the *A. t.* ssp. *wyomingensis* / *Sitanion hystrix* habitat type is climax, or seral to *A.t.* ssp. *wyomingensis* / *Agropyron spicatum* or *A. t.* ssp. *w.*/*Stipa comata*. Doescher et al. (1982) described the *Artemisia tridentata* ssp. *wyomingensis* / *Festuca idahoensis* habitat type in Oregon. Culver (1964) described the *Artemisia tridentata* / *Elymus cinereus* association and although he did not identify subspecies of sagebrush, he did find this association on sites with either greater effective rooting depth or greater effective moisture which would indicate either *A. t.* ssp. *tridentata* or *A.t. ssp. vaseyana*. Hironaka (1979) lists *A. t.* ssp. *tridentata* / *Elymus cinereus* for Idaho, Oregon, and Washington.

Mueggler and Stewart (1980) described an *A. t.* / *Festuca scrabrella* habitat type for Montana. They did not break this out by *Artemisia tridentata* subspecies but indicated that the overstory may be either *A. t.* ssp. *wyomingensis* or *A. t.* ssp. *vaseyana* depending on elevation. In addition, Hironaka (1979) described the *A. t.* ssp. *tridentata* / *Festuca idahoensis*, *A. t.* ssp. *vaseyana* / *Stipa comata*, and *A. t.* ssp. *vaseyana* / *Symphoricarpos oreophilus* / *Carex geyeri* habitat

Table 1. Habitat types of *Artemisia tridentata*.

Artemisia tridentata ssp. *wyomingensis* / *Poa sandbergii*
Artemisia tridentata ssp. *wyomingensis* / *Sitanion hystrix*
Artemisia tridentata ssp. *wyomingensis* / *Stipa comata*
Artemisia tridentata ssp. *wyomingensis* / *Stipa thurberiana*
Artemisia tridentata ssp. *wyomingensis* / *Agropyron spicatum*
Artemisia tridentata ssp. *wyomingensis* / *Festuca idahoensis*
Artemisia tridentata ssp. *tridentata* / *Stipa comata*
Artemisia tridentata ssp. *tridentata* / *Agropyron spicatum*
Artemisia tridentata ssp. *tridentata* / *Elymus cinereus*
Artemisia tridentata ssp. *vaseyana* / *Stipa thurberiana*
Artemisia tridentata ssp. *vaseyana* / *Agropyron spicatum*
Artemisia tridentata ssp. *vaseyana* / *Festuca idahoensis*
Artemisia tridentata ssp. *vaseyana* / *Elymus cinereus*
Artemisia tridentata ssp. *vaseyana* / *Symphoricarpos oreophilus* / *Agropyron spicatum*
Artemisia tridentata ssp. *vaseyana* / *Symphoricarpos oreophilus* / *Festuca idahoensis*
Artemisia tridentata ssp. *vaseyana* / *Festuca scabrella*

Taken from Winward (1982).

types. Winward (Pers. Comm., Dr. A.H. Winward, Ecologist, Region 4, U.S. Forest Service), however, believes this last habitat type must be *A. t.* form *spiciformis* instead of subspecies *vaseyana*.

Winward (1970) found, in general, that increasing thickness of the A horizon correlated well with the trend toward cooler, more mesic habitats. Although soil bulk density and soil texture showed little relationship to *Artemisia tridentata* taxa, texture did correlate well with some herbaceous dominants. *Stipa comata* was associated with a sandy surface and *Sitanion hystrix* dominated on sites with a six inch (15.2 cm) upper layer of fine texture soil that otherwise had very similar profiles to *Agropyron spicatum* sites. Total organic matter, although variable, did average different amounts in habitat types of different subspecies. *Artemisia tridentata* ssp. *wyomingensis* habitat types had 3.6 pounds per square foot of solum (17.6 Kg/m^2), *A. t.* ssp. *tridentata* habitat types had 5.3 pounds (25.9 Kg), and *A. t.* ssp. *vaseyana* habitat types had 6.6 pounds (32.2 Kg). Presumably this may reflect differences in soil depth, productivity, and/or decomposition rates. In his table of average or representative soil profiles of *Artemisia tridentata* habitat types, he indicated depths of 22, 23, and 23 inches (56, 58, & 58 cm) for *A. t.* ssp. *wyomingensis* habitat types; 48+ inches (122+ cm) for *A. t.* ssp. *tridentata* habitat types; and 30+, 32+, and 25+ inches (76+, 81+, & 64+ cm) for *A. t.* ssp. *vaseyana* habitat types.

Sturges (1977) described three hill slope soil sites with the same parent material on which the soil depth, morphology, and moisture as well as the *Artemisia tridentata* subspecies varied in response to precipitation input affected by snow blowoff and drift. the *A. t.* ssp. *vaseyana* sites soil moisture recharged throughout the 244 cm measurement zone although withdrawal during the growing season was incomplete at mid and lower depths. On the *A. t.* ssp. *wyomingensis* sites recharge was negligible below 91 cm, but withdrawal corresponded to the entire recharge zone.

Hironaka (1979) listed soil families for most of the habitat types he described in Idaho (table 2). Daubenmire (1970) described soil profiles for his habitat types (subspecies not differentiated but he presumed *A. t.* ssp. *tridentata*) in Washington and found a predominance of those subgroups listed in table 3. The degree of disparity between the common soil subgroups found in Idaho and Washington is explained in the discussion by West et al. (1978) of the ecological indicator value of sagebrush within the pinyon - juniper woodlands of the central Great Basin. They concluded that over a wide area, the major sagebrush taxa do not correlate closely with higher soil taxonomic categories, even though both are largely influenced by climate. Yet these taxa have value as indicators of edaphic as well as other factors especially when their pattern is understood in local areas and when compensatory environmental factors are considered.

Infiltration

Parr and Bertrand (1960) wrote a classic article on infiltration in which they described factors influencing infiltration rates, methods of measuring infiltration, and theoretical considerations.

Table 2. Soil families for most of the habitat types of Hironaka (1979)

ARTRW/POSA 3	coarse-silty, mixed, mesic, Haploxerollic Durorthid.
ARTRW/STCO 2	coarse-loamy, mixed, frigid, Aridic Haploxeroll.
ARTRW/STTH 3	coarse-silty, mixed, mesic, Xerollic Camborthid; Typic Camborthid; or Durixerollic Camborthid.
ARTRW/AGSP	loamy, mixed, frigid, Xerollic Camborthid; fine-loamy, mixed, frigid, Xerollic Camborthid; coarse-silty, mixed, frigid, Xerollic Camborthid; coarse-silty, mixed, mesic, Xerollic Durargid; or loamy-skeletal, mixed, frigid, shallow, Xerollic Durorthid.
ARTRT/STCO 2	coarse-loamy, mixed, mesic, Xerollic Calciorthid or coarse-loamy, mixed, frigid, Typic Calcixeroll.
ARTRT/AGSP	loamy-skeletal, mixed, frigid, Xerollic Camborthid or fine, montmorillonitic, mesic, Xerollic Haplargid.
ARTRT/FEID	fine-silty, mixed, frigid, Calcic Pachic Argixeroll; fine-loamy, mixed, Argic, Pachic Cryoboroll; or fine-loamy over sandy, mixed, Argic Pachic Cryoboroll.
ARTRV/AGSP	loamy-skeletal, mixed, Lithic Cryoboroll or coarse-loamy, mixed, Typic Cryoboroll.
ARTRV/FEID	fine-loamy, mixed, Calcic Pachic Cryoboroll; loamy-skeletal, mixed, Calcic Cryoboroll; fine-loamy, mixed, Argic Pachic Cryoboroll or fine-skeletal, mixed, Argic Pachic Cryoboroll.
ARTRV/SYOR/FEID	fine-silty, mixed, Calcic Pachic Cryoboroll or coarse-loamy, skeletal, mixed, Typic Cryoboroll.

Table 3. Soil subgroups of *Artemisia tridentata* habitat types of Daubenmire (1970).

ARTR/POSA 3	Mollic Camborthid.
ARTR/STCO 2	Typic Haploxeroll, Calcic Haploxeroll, Typic Xerapsamment, Typic Xororthent, Mollic Camborthid, or Typic Vitrandept.
ARTR/AGSP	Mollic Camborthid or Calcic Haploxeroll.
ARTR/FEID	Calcic Haploxeroll or Lithic Mollic Camborthid.

More recently, Branson et al. (1981) devoted a chapter of their book Rangeland Hydrology to a general discussion of infiltration. Springer and Gifford (1980) described the spatial distribution of infiltration rates by reviewing the work of others and by using data reported earlier by Gifford (1972) and Gifford and Busby (1974).

Factors Influencing Infiltration

Several authors have described the importance of vegetation and/or litter for increasing infiltration rates. Branson and Owen (1970) found a highly significant correlation coefficient for percent bare soil and runoff. Tromble et al. (1974) had approximately twice as much crown cover on brush plots as on grass plots, and the extra protection significantly improved infiltration. Blackburn (1975) and Brock et al. (1982) found the greatest infiltration rate in the canopy zone of their sagebrush and honey mesquite respectively. Lang (1979) found that runoff (uninfiltrated precipitation) increased rapidly below a critical point of 75% ground cover. Meeuwig (1970), using a Rocky Mountain infiltrometer, found that plant and litter cover accounted for the greatest amount (73%) of the variance in infiltration. Dee et al. (1966) concluded that infiltration generally increased with increased stage of plant succession and with increased standing vegetation and litter. Rauzi and Kuhlman (1961) found that infiltration correlated with U.S. Soil Conservation Service (SCS) mapped range sites and Hanson et al. (1980b) presented SCS curve numbers (a runoff prediction tool) in relation to range sites of the Northern Great Plains. Shiflet (1973) explained range sites and their use.

In addition to the work linking the soil vegetation complex to infiltration, others have found relationships between specific soil properties and infiltration. Rauzi and Smith (1973) found that control of infiltration rate in the first 10 minutes was dominated by soils and that by 20 minutes grazing effects equaled soil effects. Tromble et al. (1974) and Blackburn (1975) found that antecedent soil moisture decreased the infiltration rate. Rauzi and Kuhlman (1961) found that infiltration rate declined more rapidly on sites with thin fine-textured soils and that texture, cracking, and cover were important factors. During prolonged rainfall, subsoil features dominated the control of infiltration. McGinty et al. (1979) found that infiltration rate was higher with lower bulk density and more surface depressions. Bodman and Constantine (1965) examined the role of particle size distribution in compaction. Akram and Kemper (1979) described the effects of varying the applied pressure and the soil water content on the resultant bulk density and infiltration rate. They also described the increase in infiltration rate caused by freezing and thawing and wetting and drying cycles. Blackburn (1975) studied sagebrush sites in Nevada and decided that the rate at which water will enter a soil landscape is governed mainly by the extent and soil surface horizon morphology of the dune interspace areas. He found 3 times higher infiltration rates on coppice dune. He also related higher infiltration to higher organic matter content (except for a few hydrophobic soils on juniper coppice dunes), lower bulk density (except for soils with vesicular porosity) coarser soil texture, more plant and litter cover, and less bare ground. Brock et al. (1982) found that water-stable aggregates and the interaction of soil aggregate stability with the amount of bare ground dominated in the control of infiltration on a deep Hardland range site in North Central Texas. McIntyre (1958) investigated microscopically the soil crusts formed by raindrop impact and discovered two layers, one compacted at the surface (0.1 mm) and another washed in layer, which also had lower porosity and permeability than noncrusted soil. Chen et al. (1980) used a scanning electron microscope to determine that soil crusts form in stages with fine particles being washed from the coarse ones before the coarse ones are washed away. Blake et al. (1973) applied 5 cm of tritiated water to soil with shrinkage cracks. They concluded that free water flowed down fine cracks in the A and B horizons, before reaching the C horizon or being absorbed into the ped walls.

Powell and Beasley (1967) studied the effects of soil erosion on subsequent infiltration rates and found that removal of surface soil increases the clay content of remaining surface soil but decreases organic matter and soil fertility. These factors influence degree of aggregation, aggregate stability, porosity, bulk density, and vegetative cover. As a result infiltration is slower except under extremely dry conditions with extensive cracking of the exposed clayey subsoil. The erosion-induced change in infiltration varies from site to site and by degree of erosion.

Theoretical Considerations of Infiltration

Since the Parr and Bertrand (1960) review of water infiltration into soils, much theoretical work has been done on the problem of infiltration. A brief review of empirical and simplified models of the infiltration process is given by Brakensiek (1977). Gifford (1976) applied 3 infiltration formulae to an assortment of his Rocky Mountain infiltrometer data from Utah and Australia. He had only limited success and concluded that field conditions often differ greatly from the assumptions used in deriving a given infiltration equation. This could cast some doubt on efforts to use these equations for "realistic" measures of integrated values for infiltration parameters over large areas, under semiarid conditions. Nevertheless, Gifford (1978 P. 115) continued to work with these equations and concluded that

> coefficients in Kostiakov's equation (1932) were related more to vegetation factors than to soil factors while coefficients in Philip's equation (1957) were more related to soil factors than to vegetation factors. The single coefficient in Horton's equation (1940) was somewhat intermediate, representing both vegetation and soil influence.

Later, Jaynes and Gifford (1981) applied infiltrometer data from many areas to Philip's (1957) equation. This equation has two coefficients (S and A), which have theoretical physical meaning and can be derived empirically to index infiltration curves for comparing infiltrometer data or for simulation modeling of small watersheds. Bond and Collis-George (1981) concluded that the apparent linearity of a measured cumulative infiltration-time relationship is not a reliable indicator of steady state, and that steady state infiltration can not be expected to be attained in finite time during infiltration into simple soil systems. Clothier et al. (1981) commented that time to initial runoff will lag behind time to incipient ponding if there is preferential flow into macropores. They used a device to measure sorptivity and wet front advance which supplies water to the soil surface at a slight suction. These measurements were compared with field profiles prior to ponding to support a constant-flux theory of infiltration developed by Philip (1973) and Philip and Knight (1974).

Hanks (1965) discussed the use of soil moisture properties to estimate infiltration rate on "fairly homogenous soils." Bruce (1972) concluded that soil water retention of sieved samples is significantly modified from natural soil except on coarse-textured organic matter-deficient soils. The bulk of his article, however discussed the use of water content-suction data to determine the hydraulic conductivity-water content relation calculated by numerous procedures as discussed by Brutsaert (1967).

Miller (1969) investigated water flow and retention in layered soils. He found that infiltration rates will decrease in response to the wetting front reaching a coarse textured or coarsely aggregated soil because of the reduction in hydraulic gradient. This change in infiltration rate may be short lived, however, because once the wetting front has passed the coarse layer, hydraulic conductivity dominates in the control of infiltration and larger pore sizes, which decrease soil potential, increase conductivity. Infiltration rates may increase momentarily upon reaching a fine textured horizon because of the increased potential and hydraulic gradient, but will then decrease rapidly because of the reduced hydraulic conductivity. Aylor and Parlange (1973) developed an analytical model describing soil moisture profiles with a fine-textured soil over a coarser layer. Bruce et al. (1976) found that hydraulic characteristics and thickness of a coarser textured surface horizon dominated the determination of infiltration rate for the first 10-40 minutes for high intensity storms.

Infiltration rate into water repellent soil increases rather than decreases with time. Water repellency is caused by organic substances that increase the liquid-solid contact angles. However, the degree of water repellency is not directly related to the amount of soil organic matter, rather it is the chemical form that is critical. Coarse soil texture may also facilitate formation of nonwettable soil. The degree of water repellency is usually measured by timing the penetration of water drops or drops of other liquids with differing critical surface tensions. The water repellent layer is usually both discontinuous and variable in intensity, which results in irregular wetting patterns. Although these organic compounds may improve soil aggregation and structure, they may also lead to soil erosion if runoff is increased (Debano 1981).

Dixon and Peterson (1971) developed and tested a channel system conceptual model of infiltration which hypothesizes that water penetration rates and routes are largely a function of the prevailing combination of soil-surface openness and roughness. They found that biological activity near the soil surface increases these parameters and hence increases infiltration rate by an order of magnitude between a smooth surface with closed orifices and a rough surface with open orifices. The model of the effects of noncapillary-sized pores on infiltration developed by Edwards et al. (1979) and the infiltration results of Ehlers (1975) on soils with earthworm channels support the surface openness part of Dixon and Peterson's model. The surface roughness aspects of their model relate to release of soil air pressure. Soil air pressure has been studied by Phuc and Morel-Sextoux (1972), Linden and Dixon (1976), Jarrett and Fritton (1978), and Collis-George and Bond (1981).

Soil Erosion

Even though most streamflow in western U.S. rivers originates in forested mountains, most sediment originates on rangeland (Branson et al. 1981). They continued their discussion by pointing out the relative rates of water and wind erosion as affected by vegetative ground cover, phytomass, and mean annual precipitation; and by discussing the effects of soil characteristics and many aspects of soil and land management on soil erodibility.

Universal Soil Loss Equation

Smith and Wischmeier (1962) discussed the general nature of rainfall erosion stressing the mechanics of raindrop impact and splash, sheet, and microchannel flow as well as the basic factors affecting field soil loss. These include rainfall, soil erodibility, topography, cover and management, and erosion-control practices. Using these principles, they discussed the universal rainfall erosion equation which Wischmeier and Smith (1965) described in USDA Handbook No. 282 as the universal soil loss equation (USLE). A valuable tool in erosion research, this empirical equation

$$A = RKLSCP$$

predicts average annual sheet and rill erosion caused soil loss (A) from the factors primarily affecting it: R is the erosive potential of average annual rainfall in that locality; K is the soil erodibility factor; L is the length of slope; S is the steepness of the slope; C is the cropping-management factor; and P is the erosion-control-practice factor. Each of these factors has a body of empirical observations supporting its determination and use on croplands in the eastern U.S.

Though a powerful tool, the USLE has often been misused. Both its use and misuse were discussed by Wischmeier (1976). Since 1965, many people have improved and extended the USLE so that Wischmeier and Smith (1978) were able to write a conservation planning handbook for using the USLE in the West as well as East and under a variety of land management practices and land types including rangeland. Blackburn (1980) provides a good review of the USLE, its modifications, and applications to rangelands.

The job of improving the USLE has dealt in part with measuring and predicting the various factors. Ateshian (1974) developed simple empirical formulae for estimating the rainfall erosion index (R factor). However, derivation of the R factor applicable elsewhere would be inadequate for the Pacific Northwest because most of the erosion there is from winter events of rain on thawing ground, rain on snow, and rain on unfrozen ground without snow cover. Therefore, McCool (1976) developed an R_T factor that sums separate variables for winter and summer precipitation. A prediction equation for the soil erodibility (K) factor was developed by Wischmeier and Mannering (1969). This empirical equation has 24 variables that describe the texture, structure, morphology, and chemical nature of the soil. Using mostly these data, Wischmeier et al. (1971) developed a nomograph for predicting soil erodibility on farmland and construction sites. This nomograph used the variables percent silt, percent very fine sand, percent sand, percent organic matter, soil structure, and permeability. Holzhey and Mausbach (1976) explored the use of *Soil Taxonomy* (SCS 1975) to estimate K values for the USLE. They found good agreement between K values derived from the nomograph and K values assigned to soil series by hundreds of soil scientists and agronomists across the U.S.

Wischmeier (1975) explained how to estimate the USLE's cover and management (C) factor for undisturbed areas by first separating the total influence into three subfactors: type I—effects of canopy cover; type II—effects of mulch or close-growing vegetation in direct contact with the soil surface; and type III—tillage and residual effects of the land use. The type III value for rangeland depends largely on the root network in the topsoil, which in turn depends on the type of vegetation. The fiberous roots of grass are superior to the tap roots of many forbs. The effects of cover or mulch can be extended to include surface slatey fragments (Box 1981).

Johnson et al. (1980) used the USLE, including the above interpretation for the C factor, to compute potential soil loss on grazed and ungrazed areas subject to brush control treatment and no treatment on the Reynolds Creek Experimental Watershed in Idaho. Trieste and Gifford (1980) also used the USLE to predict soil loss on rangelands, but did so on a per storm basis using small plot (mostly a Rocky Mountain infiltrometer) data and had poor results. Their research approach was strongly criticized by Foster et al. (1981).

Other Erosion Research

In addition to the USLE, other soil loss predictive equations have been developed. Some are based on the physical mechanics of soil erosion and some are for individual storms on complex watersheds (Foster et al. 1977). These authors were interested in an erosion equation for individual storms that reflected difference along a slope, and differences between the surface and subsurface. They developed an equation that predicted soil detached by a combination of rill and interrill erosion.

Several authors have studied the relationship between various soil properties and soil erosion. Andre and Anderson (1961) found that soil developed from acid igneous rock was about 2 1/2 times more erodible than soil developed on basalt. Luk (1979) explained variations in erodibility by the resistance to compaction and dispersion of soil aggregates. Meeuwig (1971) found that although erosion was most closely related to the amount of cover, organic matter was the most important soil parameter affecting erodibility: organic matter in clay soils decreases erosion, but in sandy soils tends to increase erosion. Brock et al. (1982) found that sediment production is controlled primarily by an interaction of soil organic matter and amount of above-ground biomass or grass cover. Blackburn (1973) found that as organic matter and sand size particles increase, sediment production decreases. Farmer and Van Haveren (1971) concluded that overland flow erosion is influenced by the percentage weight of soil particles greater than 2 mm in diameter but splash erosion is affected by soil particles .06 to 2 mm diameter and by soil bulk density.

Alberts et al. (1980) found large differences in the size of soil aggregates and primary soil particles in rill and interrill sediment. They also found more sand in the eroded sediment than in the original soil matrix. Rill flow transported a greater proportion of larger particles as compared with interrill flow because of basic differences in the detachment and transport mechanisms. Yariv (1976) developed a model which explains observations that raindrop detachment is greatest for coarse and medium sand-size particles and lower for both larger and smaller particle sizes. Moss et al. (1979) found that raindrop-stimulated sediment transport in shallow water flow is relatively slope insensitive and can operate at very low slopes, but at high slopes of 20-30% it is overshadowed by the enormous innate transporting capacity of thin-water flows. In addition, on low slope, raindrops tended to suppress channel formation, promoting sheet-like flow of shallow water.

Others have investigated the soil itself, and some of their studies may relate indirectly to soil erosion. Wooldridge (1964) used mean size of the water-stable aggregates to "measure" soil erosion hazard and found organic matter content, pH, total porosity, and bulk density accounted for over 40% of the variation. Adams (1973) found that organic matter content had a dominant effect on bulk density. For a study of inorganic horizons of upland and alluvial soils in seven orders, Alexander (1980) found that organic carbon was the best predictor of bulk densities. Hamblin and Davies (1977) found that in silt soils, more organic matter led to better physical properties for plant growth and soil management including higher water holding capacity and porosity and lower compaction, breaking strength, and bulk density.

Long before the USLE, ground cover was recognized as influential in reducing soil erosion on rangelands (Craddock 1938, Osborn 1949, and Packer 1953). More recently numerous authors have found that increased ground cover of vegetation, litter, mulch, or cryptogams decreases erosion. This is true for grazed lands (Branson and Owen 1970, Gifford et al. 1970, Meeuwig 1971, Loope and Gifford 1972, Williams et al. 1972, Blackburn 1975, Kleiner and Harper 1977, McGinty et al. 1979, Wood and Blackburn 1981, Brock et al. 1982, and Wright et al. 1982) and for ungrazed lands (Meyer et al. 1970, Meeuwig 1970, Meeuwig 1971, and Singer et al. 1981).

Vegetation reflects the environment including soils and also effects the environment including its response to potential erosion events. Pfister (1981) explored the potential for using habitat types (Daubenmire 1968) for managing western rangelands. Buckhouse and Mattison (1980) concluded that habitat types and range condition are a more reliable index of soil erodibility than more broadly defined ecological land units. Others, also, have found success with vegetative means of land classification. Andre and Anderson (1961) related variation of soil erodibility with geology, geographic zone, elevation, and vegetation type in northern California. Osborn et al. (1978) found as much as 10 times greater sediment yields from brush-covered watersheds than from grass-covered watersheds. Buckhouse and Gaither (1982) measured potential sediment losses of 431 kilograms per hectare (384.6 lbs/ac) for grassland ecosystems but 1,284 and 1,572 kg/Ha (1,146 and 1,403 lbs/ac) for sagebrush and juniper ecosystems respectively. They also found that changes in potential sediment production reflected differences in ecological condition class and/or vegetative productivity class within ecosystems.

Grazing

As an indication of the extensive literature dealing with the subject of grazing and watershed management, a recent selected bibliography on grazing hydrology (Gifford and Springer 1980) includes 35 articles relating grazing to erosion and/or sediment. Twentyseven more discuss grazing and infiltration and an additional 11 relate grazing to runoff. Gifford and Hawkins (1978) and Blackburn et al. (1982 P. 1) reviewed the hydrologic impact of grazing on watersheds. They stressed the need for additional research that is long term in nature and describes range site, range condition, and grazing treatment carefully. The article by Blackburn et al. summarized the hydrologic effects of livestock grazing by stressing the direct effects of removing plant cover and trampling the soil, which in turn

> may (a) increase the impact of raindrops, (b) decrease soil organic matter and soil aggregates, (c) increase surface crusts, (d) decrease infiltration rates, and/or increase erosion.

Any of these developments may result in increased overland flow and decreased soil-water content. They go on to state that "existing studies show no hydrologic advantage to grazing a watershed lightly rather than moderately." Daubenmire and Colwell (1942) described some edaphic changes due to overgrazing in southwestern Washington. Gifford and Hawkins (1979) have, in a general way, modeled the grazing system impacts on infiltration rates.

Vesicular Porosity

Soils with vesicular porosity have been described in southern Spain, Morocco, and southwest Africa by Volk and Geyger (1970). Gifford (1976) mentioned a "hard setting vesicular crust which may be as much as 8 cm thick" in Northern Territory Australia. In the

United States, this vesicular porosity has been described in Nevada, where most research has been done, and in Washington, Oregon, California, Idaho, and Utah.

Hugie and Passey (1964) found vesicular porosity and attributed it to desiccation because they found it essentially absent when surface horizons were supersaturated or frozen. All their sites had well drained or moderately well drained silt loam, silty clay loam, or very fine sandy loam texture soils. The formation of polygonal surface soil patterns they attributed to alternate cycles of freezing and thawing followed by desiccation. Platey structure was also attributed to freezing, that is to the many fine horizontal frost lenses.

Miller (1971) used experimentation to find an explanation other than freezing and thawing for the formation of vesicular structure in silt loams in Washington. He found, also, that the vesicles remained air filled during irrigation. He observed this structure in the bottoms of irrigated furrows of soils with high silt content and low aggregate stability. In a laboratory experiment using heat, suction and repeated surface and subsurface flooding with tap water, which either did or did not have detergent added to reduce surface tension, he determined that vesicle formation was enhanced by increased drying before irrigation, by higher surface tension of the water, and by a greater number of irrigation-drying cycles. Vesicle formation was not influenced by the application of heat during drying and there was little difference between wetting the soil from the bottom and surface flooding.

Miller (1971) also noted a platey structure in the field and found that in the lab it developed first, but with repeated wetting and drying, the pore spaces between the platelets became spherical and the spheres became larger, especially in the upper half of the four centimeter column. He hypothesized that vesicles form in the spaces between the platelets because the air pressure, which equals the sum of the water pressure and the capillary pressure, exceeds the strength of the unstable saturated soils. The capillary pressure, $2\sigma/R$, (σ = surface tension of water and R = radius of curvature of interface) becomes large if either the surface tension is large or more importantly, the radius of curvature is small.

Miller (1971) concluded with indirect evidence that the vesicular porosity had little influence on infiltration rate because the decrease in infiltration rate through the season did not match the increase in vesicular porosity. Instead he attributed the low infiltration rate to the formation of the film which coats the surface of these soils. Although Springer (1958) didn't discuss this surface film, both he and Hugie and Passey (1964) mentioned the escape of air bubbles from the surface. I think the unstable soil is simply unable to prevent the escape of air bubbles as they get larger and perhaps closer to the surface. As a result this surface millimeter or two becomes devoid of pores.

If the crust is limiting infiltration, then, as Hillel and Gardner (1969) pointed out with theory and empirical evidence, the subcrust suction head will be greater with increased crust resistance during steady infiltration. It therefore seems likely that air pressure would not overcome the sum of capillary and water pressure until at or near saturation i.e. unless there was a percolation restricting layer below the vesicular layer. If so then the surface crust may initially restrict infiltration, but ultimately a subsurface horizon would anyway.

Blackburn (1975) found that the occurence and morphology of vesicular horizons correlated with restricted infiltration and was a more important variable in his combined analysis than any other variable in the regression equations he used to predict infiltration on four watersheds.[1] However, he did not attempt to explain the mechanism of this relationship. Like others, Blackburn associated vesicular porosity with low organic matter, high percent silt sized particles, poor aggregation, and instability.

Hugie and Passey (1964) found that the size of the polygonal units varies with soil drainage. They also classified their soil surface patterns as to prominence and whether the coarse particles were segregated. Eckert et al. (1977), Eckert et al. (1978), and Stephens et al. (1979) have developed a four part classification scheme with subclasses relating to coarse fragement segregation and other features. The nine study sites in their 4-year study of the "Properties Occurrence and Management of Soils with Vesicular Surface Horizons" are in the Humboldt Loess Belt, are all Argids, and have surface soil texture of sandy loams, loams, silt loams, and clay loams. On these sites, the four surface types are differentiated by

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[1]It could be argued, however, that using discontinuous arbitrary classes is inappropriate for multiple regression.

external polygon physiognomy, internal soil morphology, and thickness of the A11 horizon. The four types are genetically related to their microlandform so their microtopographic position helps identify them. The polygons are the tops of coarse and very coarse prisms that extend down through the entire A and in some cases into the B horizon. Apparently they are formed by recurrent soil shrinking and fracture along the same semi-vertical prism faces.

NITROGEN

Nitrogen is a macronutrient of prime importance to ecosystem productivity. In aquatic ecosystems, the nitrogen cycle can be altered by increased loading of inorganic or organic nitrogenous compounds, and this can lead to eutrophication (Wetzel 1975). West and Skujins (1978 p. 245) noted that the majority of the landscape is nitrogen limited most of the time, as are desert biological processes when expressed as functions per unit area of randomly-sampled surface. Nitrogen fertilizer has often been used to promote crop and range forage production. Even in semiarid regions where water is often thought of as the limiting factor, plants commonly respond to the addition of nitrogen fertilizer, especially with additional soil moisture (Sneva 1963, Sneva and Hyder 1965, Goetz 1969, Powers et al. 1973, and Wallace et al. 1978). James and Jurinak (1978 p. 231) concluded from work in the northern Great Basin that:

1. Indigenous soil nitrogen was severely limited to the growth of *Agropyron* and, to a lesser extent, to *Artemisia* and *Atriplex*.

2. Nitrogen fertilizer application gave increased yield and forage quality even in the year that soil moisture was exceptionally low.

3. Highly beneficial residual effects from nitrogen fertilizer can be expected for 2 or 3 years. The residual effect will be related to total moisture availability in any given year.

4. Efficiency of use of available soil water could be greatly enhanced by nitrogen fertilization of Great Basin Desert rangelands seeded with crested wheatgrass.

West and Klemmedson (1978 p. 15) gave a close description of the distribution of soil nitrogen in deserts including the northern Great Basin when they stated that:

> Estimates of relative importance and probably rates of transfer of nutrient elements can be obtained from the structural distribution of nutrients in the ecosystem. Presumably those elements in most limited supply will tend to exhibit marked concentration in places where organisms utilize them.

Charley (1977) discusses literature describing the concentration of nutrients under shrub canopies and toward the soil surface. Charley and Cowling (1968) found that biologically induced vertical gradients become sharper with increasing aridity. In these systems, soil nitrogen is concentrated toward the soil surface largely by the nutrient pumping effect of vegetation and by soil surface blue-green algae crusts, which are the major nitrogen fixers in desert ecosystems (Rychert et al. 1978).

West and Klemmedson (1978) indicated that the bulk of ecosystem nitrogen is contained in the soils and that most of this soil nitrogen is tied up in organic matter and/or associated with clay minerals and therefore not available for uptake by plants. Although not available, this nitrogen serves as a large pool in buffering against usage and loss (Wallace et al. 1978). Loss, incidently is mostly due to denitrification (Klubek et al. 1978), which is dependent on a variety of factors (Westerman and Tucker 1978) and is possible only for nitrogen which has first been ammonified (converted from organic compounds to ammonium ion) and nitrified (oxidized to nitrite or nitrate) and thus made available (Delwiche 1970). This pool of bound nitrogen is, however, very susceptible to erosional loss because it may be selectively removed by runoff or wind (Fletcher et al. 1978).

Several authors including Massey and Jackson (1952), Stoltenberg and White (1953), Sorensen and Porcella (1974), Fletcher et al. (1978), and Schreiber et al. (1980), have documented the increase in concentration of nitrogen from soil to sediment. This is ascribed to the association of nitrogen with clays and fine soil particles as documented by Bremner (1965), Chichester (1969), and Swift and Posner (1972) and especially with organic matter (Nishita and Haug 1973, Swift and Posner 1972, and Nagi 1980). In the Great Basin Desert, organic compounds contain more than 99 percent of the total soil nitrogen at all times (West and Skujins 1978). Fine soil particles and organic matter are selectively eroded because of their small size and low density respectively. Susceptibility to erosion is further enhanced by the concentration of nitrogen at and near the soil surface as discussed above.

The result of this selective loss was noted by Beadle and Tchan

(1955) who decided erosion was responsible for the removal of organic matter and nitrogen, because low values of both occur in eroded soils. Loss of fine soil particles and organic matter represents a reduction in the soil's capacity to conserve nutrient flushes because the cation exchange capacity is predominantly an attribute of soil humus and other colloids included in the clay fraction (Brady, 1974).

Although Sorensen and Porcella (1974), studying cool desert shrublands of Northern Utah, concluded that net removal of surface soil nitrogen by precipitation-caused runoff was insignificant on an annual basis; they based this on only one ten-month period. They measured total N carried in the natural runoff water at 1.50, 1.47, and 1.63 kg/ha (1.34, 1.31 and 1.45 lbs/ac) for 3 *Artemisia tridentata* plots with a protective crust of N fixing blue green algae. Dogan (1975) also measured losses of N by water erosion from runoff plots with a microflora crust. His measured losses ranged from 0.24 to 3.1 kg/ha/yr (0.21 and 2.77 lbs/ac/yr) with an average of 1.62 kg/ha/yr (1.45 lbs/ac/yr).

This short time period would be unlikely to include a large catastrophic loss of nitrogen by water or wind erosion as proposed and discussed by Woodmansee (1978) as part of his concept of "abiotically controlled pulse stability." Gifford and Busby (1973) collected the particulate organic material removed from a semiarid watershed during such a catastrophic event (approximately a 100 year event). They calculated the nitrogen losses from only the particulate organic matter as approximately 0.34 kg/ha (0.30 lbs/ac) in fine and 0.04 kg/ha (0.036 lbs/ac) in coarse materials (twigs, limbs, and cones). A catastrophic event might also be simulated with a Rocky Mountain infiltrometer as Gifford and Tew (1969a) did for detecting changes in runoff water quality (nitrogen not measured) on disturbed rangelands.

Rainfall Simulation

An infiltrometer is a collection of equipment including plot frames, a wind screen, and a rainfall simulator; all designed to apply a simulated rainfall to plots inside frames which allow the excess simulated rainfall to be collected and measured. Its purpose is basically twofold: 1) to allow comparison of two or more treatments or study areas under a constant rainfall; and 2) to determine the response of an area of interest to a rainfall event that is extremely infrequent. For both of these purposes, the rainfall simulator must approach as closely as possible the natural characteristics of the storm of interest.

Meyer (1979) listed and discussed 10 desirable characteristics of simulated rainfall including natural drop size distribution, impact velocity, rainfall intensity, and areal uniformity. Laws (1941) determined the impact velocity of various sizes of water drops when falling at terminal velocity. Laws and Parsons (1943) found a good correlation between rainfall intensity and raindrop size distribution at Washington, D.C. Wischmeier and Smith (1958) used these data to calculate the kinetic energy of natural rainfall of different intensities. McCool et al. (1978) found a similar drop size versus intensity relationship at Corvallis, Oregon and Pullman, Washington although the intensities were much lower. In addition, the Pacific Northwest data exhibit neutral skew and hence lower kinetic energy at a given intensity than the positively skewed drop size distributions of Laws and Parsons. From studies of the rainfall effects on soil erosion, Wischmeier and Smith (1958) concluded that the product of total rainfall energy of a storm and its maximum 30-minute intensity was the best single variable for predicting soil loss from cultivated fallow soil.

Over the years this parameter has received a great deal of attention, and while its utility has been acknowledged, it has also been challenged. Kinnell (1973) found that for identical rainfall intensities there are characteristic differences in momentum, kinetic energy, and kinetic energy per unit horizontal area of the raindrop between rain types, within rain types, and especially between different geographic settings.

Meyer (1979) remained dubious that either kinetic energy or momentum alone was an adequate parameter for comparison and stands by an earlier statement (Meyer 1965 p. 64) that

> until some parameter is proved to be adequate for comparison, this analysis suggests (a) that both the drop size distribution and drop-fall velocity of natural rainfall should be simulated as closely as possible and (b) that an appreciable sacrifice of either for the other is unwise. One of the parameters may be chosen as a guide, but its influence should be secondary to a comparison with actual raindrop characteristics.

Bubenzer (1979 p. 27) supported this conclusion by saying "There is no single, simple parameter that covers a wide range of conditions." He further concluded that

> when raindrop action is critical in the process, as in splash erosion or infiltration into an exposed soil, every attempt must be made to accurately simulate the drop size distribution, impact velocity and intensity of the natural erosive storms of the area.

Yet Hall (1970, P. 1104) said that,

> A general purpose rainfall simulator, combining control of application rates in both space and time with the reproduction of the drop size distributions and velocities of fall of drops observed in nature, has yet to be developed.

McCool (1979 p. 18) added that

> approximating natural drop-size and kinetic energy (terminal velocity) characteristics while retaining desirable intensity has been one of the most vexing problems in rainfall simulator design.

Rogers et al. (1967) concluded that the large errors in calculated kinetic energy caused by short term within storm variations in rainfall intensity and drop size distribution tend to balance out over a whole storm period. They also found that a wind speed of 8 miles/hr (12.9 km/hr) may increase the raindrop velocity enough to cause a 30 percent increase in the kinetic energy of rainfall. Kinnell (1973) found that while characteristic differences exist between rain types (the type of storm producing the rain), considerable variation in the relative dropsize distribution occurs within any one rain type. He also described differences in assessed erosive power of rainfall caused by differences in geographic setting and concluded that "it is questionable to apply the values obtained for a parameter from one location to another." Also, "in some instances a considerable portion of the total detachment ability of a storm may have been expended before significant transportation by runoff takes place." For this reason rainfall parameters alone are unlikely to be adequate as measures for predicting soil loss. Laflen said that "plot size is a limitation in every erosion study whether under natural or artificial rainfall conditions" (Laflen 1979 p. 104). Despite these problems, ". . . rain simulators as a research tool have long since proved their value" (Moldenhauer 1979 p. 91). If the main utility of comparing different soil-cover-management complexes is to derive an index rather than an absolute quantity then selecting a standard infiltrometer as an operational technique may be more useful, as Amerman (1979) contends. One such tool with a long history of standard use in Colorado, Utah, and Oregon is the Rocky Mountain infiltrometer described by Dortignac (1951) and used by Meeuwig (1965 and 1970), Thompson (1968), Gifford and Tew (1969a and b), Gifford (1979a), Williams et al. (1969), Gifford et al. (1970), Meeuwig (1971), Loope and Gifford (1972), Gifford and Busby (1974), Ponce (1975), Buckhouse (1975), Gifford et al. (1976), Buckhouse and Gifford (1976a, b, and c), Burton (1976), Busby (1977), Gaither (1980), Buckhouse and Mattison (1980), and Buckhouse and Gaither (1982).

Gifford (1979b) discussed the Rocky Mountain infiltrometer with Type F nozzles originally designed by V. D. Young (Parsons 1943) and computes a relative kinetic energy of 0.43 for simulated storms with the same size drops and rainfall intensity as natural storms. These natural storms would be high intensity convectional type thunderstorms with a mean drop size diameter of 3.7 mm and a terminal velocity of about 9.06 m sec^{-1}. The simulated raindrop impact velocity of 5.95 m sec^{-1} is lower because of the restricted fall height of only 2.2 m.

Meyer and McCune (1958) show a graph of the drop size distribution of rainfall at 2 1/2 inch/hr (6.35 cm/hr) and of the Type F nozzle. They also list a kinetic energy figure of 650 ft-tons/acre--inch (171.5 joules/m^2cm) for the Type F nozzle and figures in good agreement with Table 1 of Wischmeier and Smith (1958) for the kinetic energy of rainstorms of selected intensities. Using this table, a natural rainstorm of the intensity of an average Rocky Mountain infiltrometer simulated rainfall of 4.97 in/hr (12.62 cm/hr) has an energy of 1,146 foot tons/acre--inch (302.3 joules/m^2cm) and an average 100-year 1-hour rainstorm for all our sites of .79 in/hr (2. cm/hr) (see Table 5) has an energy of 882 ft tons/acre-inch (232.7 joules/m^2cm).

Using the kinetic energy relationship of Wischmeier and Smith (1958) and the above data, soil loss would be proportional to 0.19 for the Rocky Mountain infiltrometer, 0.07 for a 100-year 28-minute rainstorm, and 0.33 for a natural rainstorm of the intensity of a Rocky Mountain infiltrometer simulated storm. So the Rocky Mountain Infiltrometer yields a simulated rainfall which is about 3.8 times more intense than a 100-year 28-minute rainfall, and which has about 0.7 times the energy per acre inch or about 2.6 times the total kinetic energy, with about 2.7 times the erosive potential. The Rocky

Mountain infiltrometer should therefore be considered as a tool that gives an index to infiltration and erodibility under artificial conditions. Most of its long history of use especially in southern Utah may well have been under less artificial conditions, that is with more frequent natural rainfalls of higher intensities, but as a tool for yielding an index under "natural" conditions, the Rocky Mountain infiltrometer appears to be out of its range in Eastern Oregon.

STUDY AREA

Four locations in Eastern Oregon, Squaw Butte, Millican, Baker, and Frenchglen (Fig. 1), were chosen for comparison of lands occupied by the three subspecies of big sagebrush, *Artemesia tridentata* sspp. *tridentata*, *wyomingensis*, and *vaseyana*. At each location three sites for each of the three subspecies were identified on the ground by Dr. Alma Winward, a scientist with considerable experience observing sagebrush in these areas of Oregon.

The principal criteria used in site selection were vegetation, soils, and access. Dr. Winward tried to find sites in good to excellent ecological condition but this was often impossible. He also tried to find relatively homogenous sites with respect to soils and vegetation that fairly well represented the habitat types occupied by each subspecies. Because we would later use a Rocky Mountain infiltrometer, he tried to find sites easily accessible by road, with a slight slope of 2 to 10 percent, and with few large rocks that could interfere with placement of infiltrometer frames.

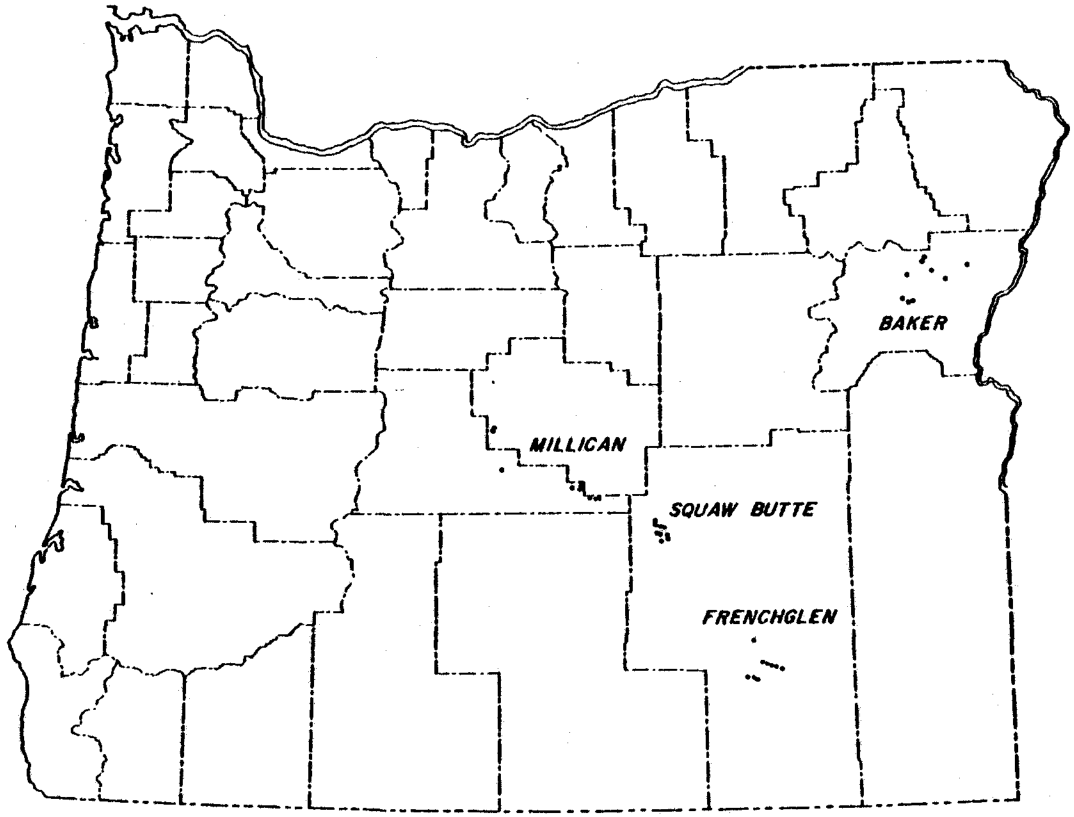


Figure 1. Location of study sites.

These criteria eliminated many sites initially considered, and some that were selected were of necessity somewhat marginal.

For a general overview of this region, one is referred to the Atlas of the Pacific Northwest, which presents many small scale maps showing various aspects of landforms, climate, vegetation, soil, and water (Highsmith and Kimerling 1979).

Geology and Soils

In order that results from this research might represent a large geographic area, the sites used in this research are widely spaced. They fall in three of the major geomorphic divisions of Oregon (Dicken 1965). The Squaw Butte and Millican sites are in the High Lava Plains division with sedimentary or igneous parent material of middle Tertiary or younger age (<26 million years). The Frenchglen sites are in the Basin and Range division with igneous parent material of middle Tertiary or younger age. The Baker sites are in the Blue Mountains Division with igneous or sedimentary parent material that is of Tertiary age or older (2-280 million years) (Walker 1977). The book *Geology of Oregon* (Baldwin 1976) was organized on the basis of these major geomorphic divisions. In addition to the normal soil forming processes working with the parent material in place, five of the Milliken sites have been heavily influenced by surficial deposits of Newberry Crater and/or Mazama pumice (tephra). The physical and chemical properties of pumice soils in Oregon are described by Youngberg and Dyrness (1964).

Although the US Soil Conservation Service is coordinating a cooperative soil survey in much of eastern Oregon, this is not yet completed. In the 1960's a reconnaissance soil survey for projecting long range irrigation water requirements was conducted in the Malheur Lake Basin covering the Squaw Butte and French Glen locations. This gives a very general description and classification approximately to the family level. By this survey, all but two of the sites would be placed in the hydrologic soil group with the highest potential for runoff (Lindsay et al. 1969). Instead of relying on this data base, the soil on each one of the sites was described and classified (Appendix I) according to definitions in *Soil Taxonomy* (Soil Conservation Service 1975).

Climate and Vegetation

The sites used in this research are widely dispersed and at different topographic positions. Therefore, climatic data for one location are only generally applicable for other sites. However, the Squaw Butte Experiment Station might be representative especially for the Squaw Butte, Millican and Frenchglen locations, in that it is centrally located at about the mean elevation, 4,500 feet (1371 m). This high desert station receives about 12 inches (30.5 cm) of precipitation annually with extremes of 6 and 17 inches (15.2 and 43.2 cm) recorded over a 34 year period. About 60 percent is fall and winter precipitation, often as snow and about 25 percent is rain in May and June. July, August, and September are dry. Mean monthly maximum temperature is 35° in January and 85° F in July (1.7° and 29.4°C). The temperature extremes recorded have been -24° and 104°F (-31.1 and 40°C) (Sneva 1977). The Baker sites are similar climatically. Although they are lower in elevation averaging 3,570 feet (1088 m), the mean annual rainfall at Baker is only 0.75 inch (1.9 cm) less than at Squaw Butte. For the Baker area too, more than half (55%) the precipitation falls in fall and winter. However, more of it falls in summer months especially in May and June (35%) (National Oceanic and Atmospheric Administration (NOAA) 1979-81).

Average temperatures for the High Desert city of Burns and the city of Baker are very similar, i.e., within a degree every month (NOAA 1979-81). However, one Baker *Artemesia tridentata* ssp. *tridentata* site is about 400 feet (122 meters) lower in elevation than Baker and the soil is warm enough to fall into the mesic soil temperature regime. Except for an *A.t.* ssp. *wyomingensis* and *A.t.* ssp. *tridentata* site at Frenchglen, all other sites are in the frigid soil temperature regime. However, all three *vaseyana* sites at Frenchglen and two of the three *vaseyana* sites at Millican are high enough in elevation to be in the cryic great group (Pers. Comm. Dr. Gerald Simonson, Professor of Soil Science, Oregon State University).

Due to the nature of this research project, sites are representative of *Artemesia tridentata* vegetation, which is described in the Literature Review section on sagebrush ecology. The habitat type and condition class at each site, as estimated by interpretation of present vegetation (Appendix 1), is varied. Therefore, the amount and form of herbaceous vegetation varies widely from one site to another.

Sneva (1977) correlated precipitation and temperature variables in many combinations with yields of mature crested wheatgrass. The highest coefficient of determination values were for July-May precipitation and March to May temperature. For the 1980 and 1981 growing seasons respectively the Burns weather station received 2.1 inches (5.3 cm) more and 0.9 inches (2.3 cm) less than the long term average precipitation in the July-May catchment periods. Baker received 2.23 and 4.45 inches (5.7 and 11.3 cm) more for these periods. Baker also appears to have had warmer springs (National Oceanic and Atmospheric Administration (NOAA) 1979-1981 and NOAA 1973). These data help to explain the general observation that herbaceous vegetation has been abundant during these two summers of field research.

Miller et al. (1973) shows the maximum precipitation intensity expected for given storm durations and return periods. Using his maps and the formulae presented, the expected two-year and 100-year 28-minute storm has been calculated (Appendix 2) for each site. Gaither (1980) cites similar precipitation amounts for his Eastern Oregon study area and devotes a chapter of his thesis to an explanation of its probable underestimation.

Hanson et al. (1980a) found at the Northwest Watershed Research Center in southwest Idaho that the two-year six-hour precipitation value listed by the Precipitation Frequency Atlas of the Western United States (Miller et al. 1973) was correct for low elevations (about 3,600 ft. or 1,100 m) but for high elevations (7,000 ft. or 2,134 m), they found precipitation intensity values twice as high as the atlas indicated. Using this information, the high elevation Frenchglen site which is at about 7,000 ft could receive a storm of 2.32 inches (5.89 cm) in 28 minutes (our overall average artificial rainfall) about once in 25,600 years. This is of course an extreme extrapolation from mapped data and should be considered only a rough estimate especially since the coefficient of determination (r^2) listed in the atlas is 0.76.

Chapter I

Infiltration on Lands Occupied by Three Subspecies of Big Sagebrush

Infiltration on Land Occupied by Three Subspecies of Big Sagebrush

Abstract

High intensity (12.6 cm hr^{-1}) short duration (28 min.) rainfall events were simulated in the shrub interspaces of twelve sites representing each of three subspecies of big sagebrush, *Artemisia tridentata* ssp. *tridentata*, *wyomingensis*, and *vaseyana*. Sites were distributed equally in four widely spaced locations in eastern Oregon. Due to large variability and interaction with location, differences between subspecies were insignificant except at one location. Infiltration decreased between plots as mean soil particle size decreased, organic ground cover decreased, bulk density increased, extractable sodium increased, and especially as vesicular porosity in the surface soil increased. When sites with surficial pumice deposits were omitted, infiltration was higher on Mollisols than on Aridisols and higher on Borolls than on Orthids.

Introduction

Infiltration is the most important process in both the study of hydrology and the management of watersheds, especially arid and semiarid watersheds which rarely produce subsurface flow. Infiltration partially controls soil moisture storage, which is the most critical environmental factor determining plant growth on rangelands. Infiltration rate becomes important when precipitation intensity is high or snowpack melt is rapid. Runoff may reduce potentially effective moisture. Runoff water is also of great interest both for its potential use and possible flood damage. Surface runoff is also responsible for significant soil erosion in semiarid rangelands. Surface water affects detachment of soil particles by raindrop splash and is both the medium of movement and the force behind rill and gulley erosion.

Infiltration is a combination of two processes, absorbtion and percolation. Vegetation can be very influential in promoting infiltration, especially in the later stages when percolation dominates the process. In addition to increasing surface detention, which allows more time for infiltration, vegetation provides soil organic matter and root channels which improve soil structure and porosity. It also provides ground cover, that protects the soil from raindrop impact. The force of raindrop impact can lead to raindrop splash erosion and subsequent "sealing" of bare soil surfaces as macropores become clogged by small detached soil particles (McIntyre 1958).

Vegetation also reflects the effective environment and has long been used to classify land types and environmental conditions. Through the years the technique has been refined and the units of classification defined more precisely.

Recently the concept of using habitat types as a classification tool on western watersheds was promoted by Buckhouse and Mattison (1980) and Pfister (1981). The success of this concept depends on how well phytosociology reflects watershed parameters, for example ground cover, above and below ground plant structure and phytomass, and soil structure, depth, texture and organic matter.

Artemisia tridentata (big sagebrush) is widespread in western North America, potentially covering 145 million acres (Beetle 1960). Although land is commonly classified as sagebrush or even big sagebrush land, there is obviously a great deal of variation in 145 million acres. Since Beetle and Young (1965) reported the third subspecies, there has been increasing recognition and use of subspecific taxonomy in *Artemisia tridentata* ecological study. Tisdale and Hironaka (1981) stressed the value of big sagebrush subspecies in synecology. Winward (1982) briefly described the management implications of the various habitat types currently recognized for each subspecies.

Wyoming big sagebrush, *A. t.* ssp. *wyomingensis*, is the most xeric of the three, generally occurring below 6,000 feet (1,829 m) on moderately deep well-drained soils. Grasses form the majority of the understory vegetation and most forbs are annual. There is a considerable amount of bare ground, five to 25 percent even under pristine conditions, which cryptogams may occupy (Winward 1980).

Because *A.t.* ssp. *wyomingensis* occupies the more easily abused xeric sites, a higher percentage of them are in low ecological condition (Winward 1981).

Basin big sagebrush, *A. t.* ssp. *tridentata*, occupies deep well-drained soils. It is generally in small stands because the large ones were converted to cropland. More perennial forbs grow in these stands and herbaceous production is from 1 1/3 to 2 times greater than in *A.t.* ssp. *wyomingensis* stands (Winward 1980).

Mountain big sagebrush, *A.t.* ssp. *vaseyana*, resides in the upper foothill and mountain areas from 3,500 ft (1,067 m) to 9,000 ft (2,743 m) elevation. It occupies deep well drained soils with moisture available most of the summer. The herbaceous layer is more diverse with commonly three to four times more species, and more productive by 1 1/2 to 2 times than *A.t.* ssp. *wyomingensis* sites (Winward 1981).

My objectives were twofold: To look for characteristic differences in infiltration rates between sites occupied by the three subspecies, and to identify aspects of the soil and vegetation that control and/or indicate differences in infiltation rates.

Study Area and Methods

In four widely spaced eastern Oregon locations; Millican, Squaw Butte, French Glen, and Baker, three sites for each of the three subspecies were selected for a total of 36 sites. Each site was selected to be relatively homogenous and representative of habitat types in relatively high ecological condition. Most were classified as fair or good. However all but one of the *A.t.* ssp. *tridentata* sites was classified as in poor ecological condition, often because of cheat grass, *Bromus tectorum*, dominance. In general, *A.t.* ssp. *vaseyana* sites were in the best condition. To facilitate use of the Rocky Mountain infiltrometer (Dortignac 1951), each site was selected for nearness to a road, slight slope of 2-10 percent, and scarcity of large rocks that would interfere with placement of subplot frames. These criteria eliminated many sites initially considered and some that were selected were of necessity somewhat marginal.

The wide spacing for research locations was chosen to make the research applicable to wider geographic areas. Locations fall in three of the major geomorphic divisions of Oregon (Dicken 1965). Squaw Butte and Millican sites are in the High Lava Plains with sedimentary or igneous parent rock of middle Tertiary or younger age (<26 million years). Frenchglen sites are in the Basin and Range division with igneous parent rock of a similar age. Baker sites are in the Blue Mountains division with Tertiary or older (2-280 million years) igneous or sedimentary parent rock. Five of the Millican sites have been heavily influenced by surficial deposits of Newberry Crater or Mazama pumice (tephra).

All *A.t.* ssp. *wyomingensis* sites except one are Aridisols whereas all the *A.t.* ssp. *vaseyana* sites are Mollisols. All twelve *A.t.* ssp. *vaseyana* sites and half the *A.t.* ssp. *wyomingensis* sites are the / *Festuca idahoensis* (Idaho fescue) habitat type (Hironaka and Fosberg 1979 and Doescher et al. 1982). Three of the remaining *A.t.* ssp. *wyomingensis* sites are on the *A.t.* ssp. *w.* / *Stipa thurberiana* (Thurber's needlegrass) habitat type; two are on the *A.t.* ssp. *w.* / *poa sandbergii* (Sandberg's bluegrass) h.t.; and one is on the *A.t.* ssp. *w.* / *Stipa comata* (needle-and-thread grass) h.t. (Hironaka and Fosberg 1979). Half of the *A.t.* ssp. *tridentata* sites are on *A.t.* ssp. *t.* / *Elymus cinereus* (basin wild rye) h.t. (Hironaka 1979); three are on the *A.t.* ssp. *t.* / *Stipa thurberiana* h.t.; two are on the *A.t.* ssp. *t.* / *Agropyron spicatum* (blue bunch wheatgrass) h.t.; and one is on the *A.t.* ssp. *t.* / *Stipa comata* h.t. (Hironaka and Fosberg 1979).

Field work proceeded in three phases. In the first summer, 1980, vegetation and soils were described. Understory vegetation was surveyed with three 30 meter frequency transects of 10 1 x 2 foot (30 x 61 cm) plots each. Shrub density and canopy cover was measured with three 30 m^2 strip plots and three 30 m line intersects respectively. Soil pits were described and sampled by horizon. Soil on each site was classified at the family level according to standard U.S. Soil Conservation Service (1975) definitions. The following summer a Rocky Mountain infiltrometer (Dortignac 1951) was used on each site coarse to simulate and measure infiltration and soil erosion in shrub interspaces under high intensity precipitation. The 12.4 cm/hr simulated storms represented events with a return period of well in excess of 100 years.

Subplots were prewet until water began ponding and then were left for at least 30 minutes before beginning the run. Each run lasted 28 minutes with samples collected after three minutes and subsequent five minute intervals. Artificial rain was applied with three "F" type sprinkler heads and raindrops fell approximately two meters. Samples of applied rain and runoff were collected from each subplot and infiltration was determined by subtraction. By this technique, a small amount of water was counted as infiltration which in reality was retained as interception or surface detention. Runoff water was analyzed for sediment concentration which in turn was multiplied by total runoff to estimate total soil loss.

Eighteen subplots grouped into six plots were placed in representative shrub interspaces on each site. In each subplot, slope was measured with an Abney level and percent coverage of each surface soil morphology type was visually estimated along with surface pavement, litter, cryptogams, bunchgrass base, and canopy cover. Litter and bunch grass were combined to form the term organic ground cover. Training for occular estimation of cover was done in the field with a 100-point frame. Samples of the top 6-10 cm of each major surface soil type were collected from two locations on the site and these were analyzed in the laboratory to determine bulk density, percent organic matter, percent coarse fragments, and percent of medium and coarse sand, fine sand, silt, and clay in the fine-earth fraction.

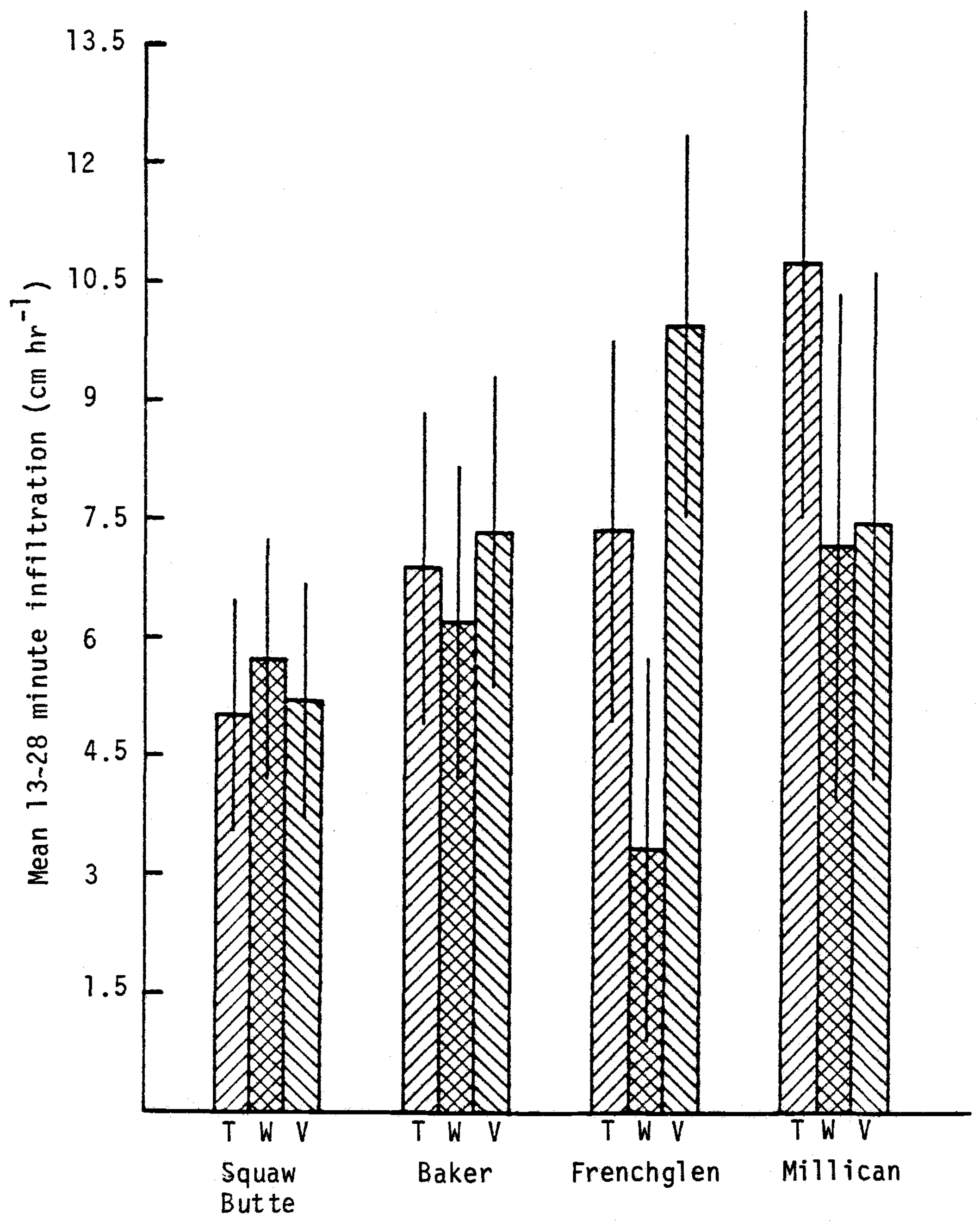
Bulk density was usually checked in the field using a modification of the excavation method (Blake 1965). This was always done when stable clods could not be collected. In the laboratory, bulk density was determined with the clod-in-parafin technique described by Blake (1965). Walkley-Black (1934) wet oxidation procedures were used to determine organic matter, and the hydrometer method of Day (1965) was used to determine particle size distribution. Soil profile samples from the previous summer were analyzed for organic matter, extractable sodium particle size distribution, and water retention at -1/3 bar and -15 bars pressure. Statistical analysis proceeded with multiple regression, analysis of variance (alpha = 0.1), and the multiple comparison procedure of Scheffe (Steel and Torrie 1980).

Results

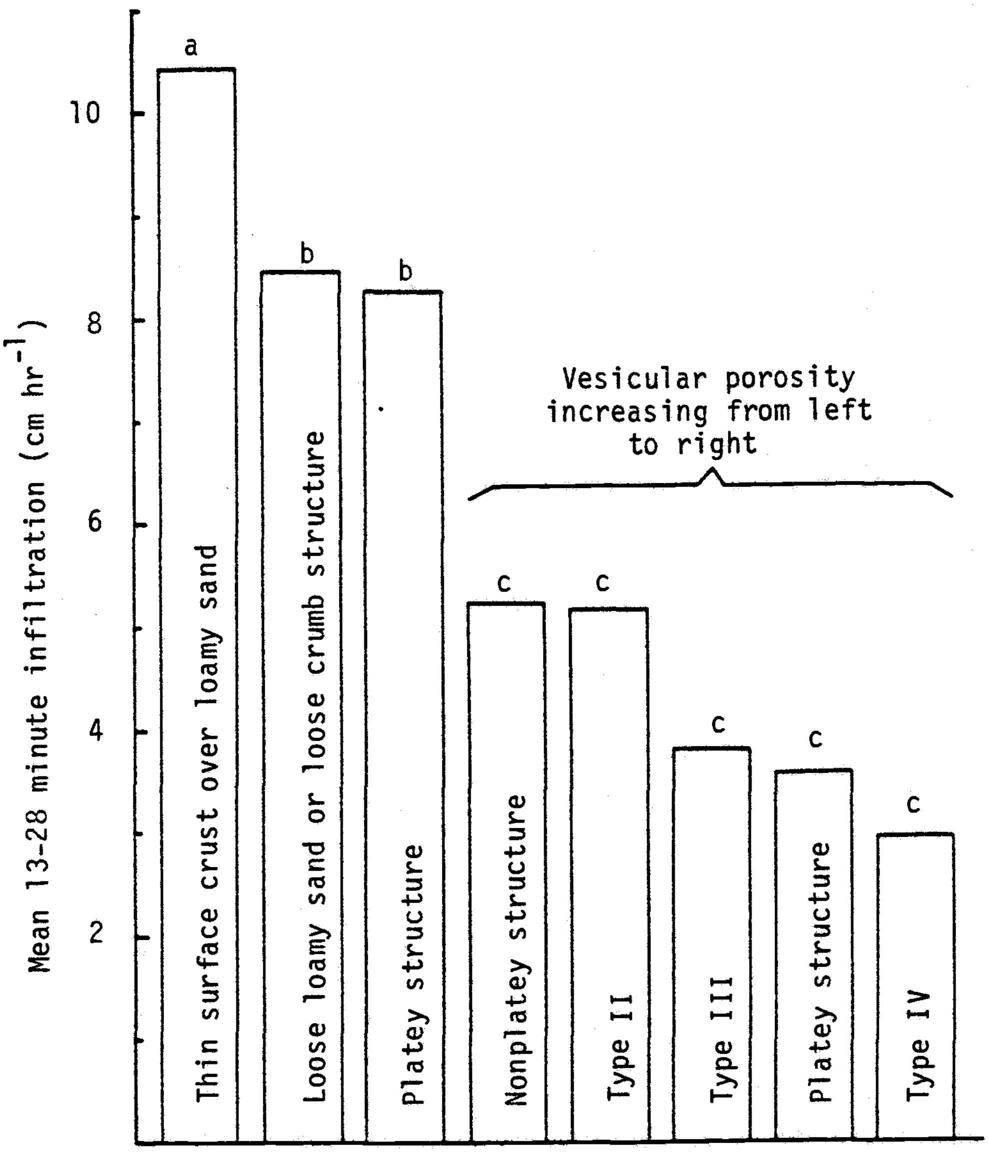
Average infiltration curves for the 36 sites were highly variable. Some sites showed almost no reduction in infiltration rate during the 28 minute run while others showed rapid reduction in water intake before infiltration stabilized. Analysis focused on the last 15 minutes of the 28 minute infiltration run (average final infiltration rate). Average final infiltration rates varied from less than three to more than twelve centimeters per hour. Habitat type and expected climax understory species showed no significant correlation with infiltration rates (see appendix 3 for analysis of variance tables). Although it appeared infiltration rates were

lower for lands occupied by *A.t.* ssp. *wyomingensis* , and for sites at Squaw Butte, these differences were not confirmed due to a significant interaction between location and subspecies (Fig. 1).
Differences between subspecies in infiltration rates were significant only at Frenchglen where sites occupied by *A.t.* ssp. *wyomingensis* had lower infiltration rates than *Artemisia tridentata* ssp. *vaseyana* sites.

Differences in infiltration rates could be partially explained by other site parameters. Surface soil with vesicular porosity had lower rates of infiltration, and in soils with vesicular porosity, infiltration rates appeared to be, but were not significantly lower in soils with more prominent platey structure and less prominent surface cracking (Fig. 2). Soils with a loamy sand texture had significantly higher infiltration rate than soils with loam, sandy loam, or silt loam textures (Fig. 3). Although Borolls appeared to have higher rates of infiltration than other suborders, differences were nonsignificant between soil orders or suborders. Using stepwise multiple linear regression, medium and coarse sand (.25 to 2 mm) in the surface soil within each subplot accounted for 23% of the variability in average infiltration rate during the last fifteen minutes (table 1). Combining organic ground cover with medium and coarse sand accounted for an additional 17% and adding fine sand (.05 to .25 mm) accounted for 3% more of the variation.
Variables that did not significantly improve multiple regression included bare ground, clay, silt, bulk density, organic matter, and

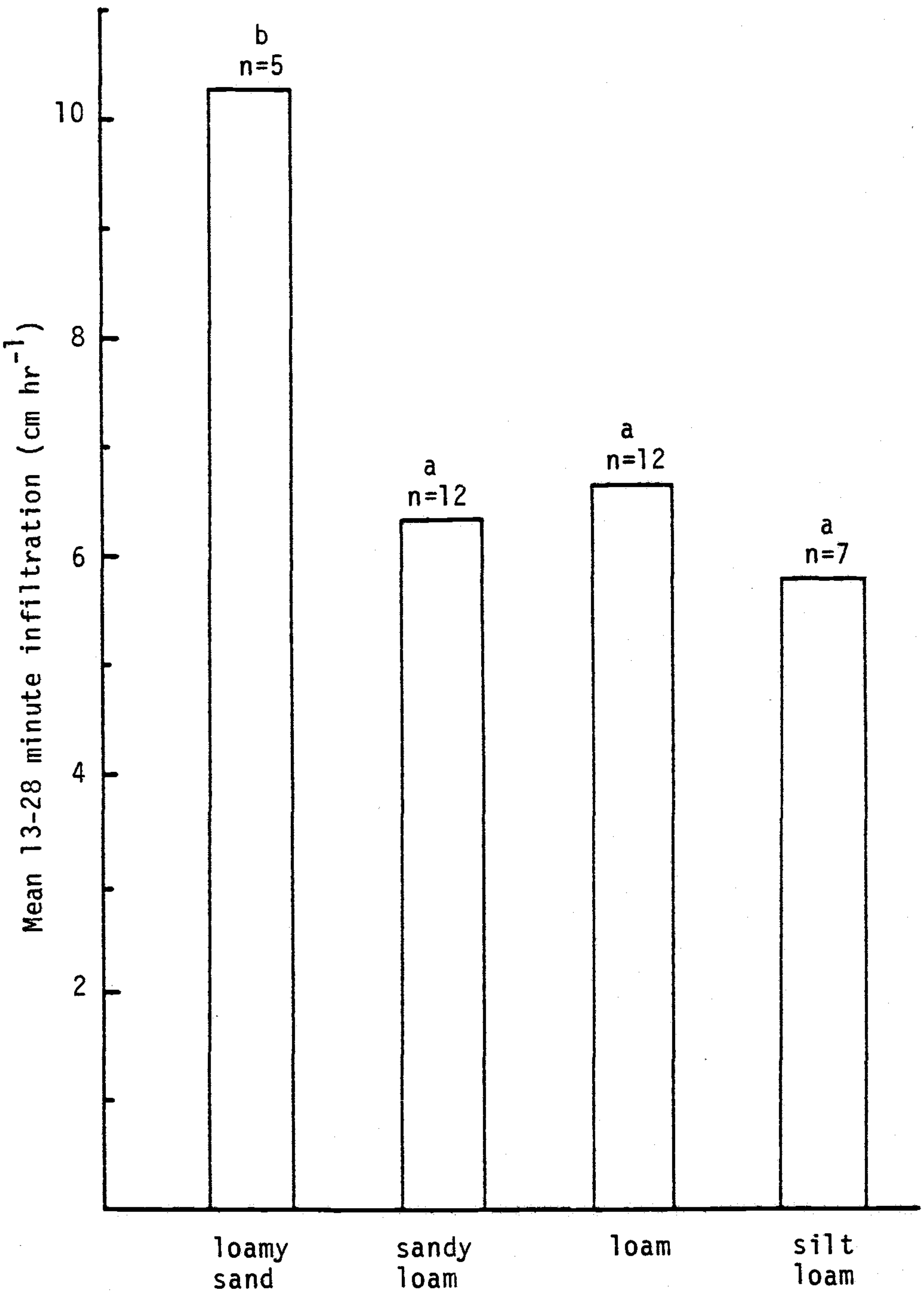


Chapter I
Figure 1. Infiltration by location and subspecies. T = *A.t.* ssp. *tridentata*, W = *A.t.* ssp. *wyomingensis*, V = *A.t.* ssp. *vaseyana*. At a location, subspecies with nonoverlapping confidence intervals are significantly different at the 0.1 level of probability.



Chapter I

Figure 2. Surface soil morphology and infiltration. Types II, III, and IV were described by Eckert et al. (1978); Type II has many well developed cracks, Type III has fewer well developed cracks, and Type IV has few narrow cracks. Surface soil morphological types with different letters are significantly different at the 0.1 level of probability as determined by Scheffe's test.



Chapter I
Figure 3. Surface soil texture and infiltration. Textures with different letters are significantly different at the 0.1 level of probability as determined by Scheffe's test.

Chapter I
Table 1. Regression analysis of soil surface and surface soil factors with infiltration rate during the last 15 minutes.

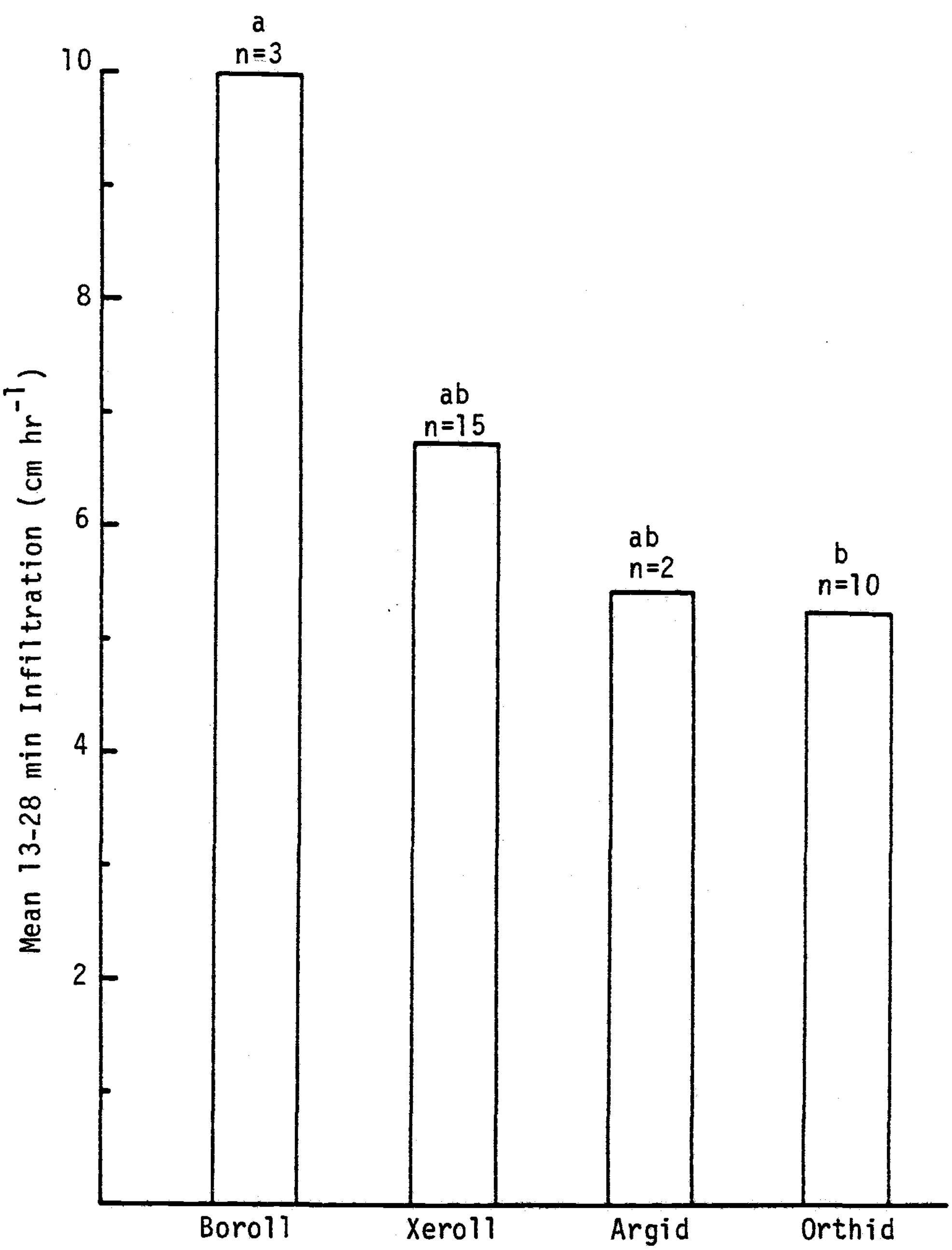
Site factor	Multiple r^2	Simple r
Medium and coarse sand (.25 - 2. mm)	.23**	.48**
Organic ground cover	.40**	.40**
Fine sand (.05 - .25 mm)	.43**	-.053NS
Bare ground		-.35**
Clay (< .002 mm)		-.34**
Silt (.002 - .05 mm)		-.27**
Bulk density		-.26**
Organic matter		.11**
Coarse fragments (> 2. mm)		.01 NS

coarse fragments. The amount of sodium in surface soils accounted for 11 percent of infiltration variability. Sediment concentration was also significantly related to infiltration ($r^2 = .32$).

Five sites in the Millican location with surficial deposits of tephra had higher infiltration rates than the other 31 sites. Because of this difference, some data analysis was repeated with these sites omitted. In that analysis, both soil order and suborder became significant descriptors for explaining infiltration rate. Mollisols had higher infiltration rates than Aridisols (7.25 and 5.29 cm/hr respectively) and Borolls had higher infiltration rates than Orthids (Fig. 4). In stepwise multiple linear regression, organic ground cover accounted for 29% of the variation and percent coarse fragments in the surface soil added just half a percent to the multiple r^2. Surface soil morphology and habitat type analyses were essentially unchanged.

Discussion

Shrub canopy zones generally have higher rates of infiltration than shrub interspaces because of differences in soil morphology, organic matter, and surface litter cover (Blackburn 1975, and Brock et al. 1982). This study, which examined infiltration in the shrub interspaces, can not be taken as an indication of the response of the site as a whole. Shrub cover appeared to be highest for *A.t.* ssp. *vaseyana* sites and lowest for *A.t.* ssp. *wyomingensis* sites, however, differences were not consistent and were complicated by significant



Chapter I
Figure 4. Soil suborders and infiltration omitting sites with surficial deposits of volcanic ash. Suborders with different letters are significantly different at the 0.1 level of probability as determined by Scheffe's test.

interaction with location.

Subspecific identify of big sagebrush and the dominant climax understory on a site may relate to factors that affect or are affected by infiltration rate. However, it is reasonable that vegetation indicators are not reliable indices of infiltration rate, as this study indicated, because climate and soil subsurface characteristics are the principal factors controlling vegetation. Subsurface soil horizons rarely have a direct effect on short duration high intensity rainfall infiltration, and climatic variation within location is narrow in relation to the variation in other site factors in these locations. Frenchglen is the location with largest elevational and probably therefore largest climatic variation and it is also the only location where different sagebrush subspecies reflect significant differences in infiltration. At Frenchglen, the three *A.t.* ssp. *vaseyana* sites were all above 5,600 ft (1707 m) while all three *A.t.* ssp. *wyomingensis* sites were below 4,900 ft (1494 m) in elevation. Infiltration data from the Millican location, which also had large elevational differences between sites, was complicated by surficial tephra deposits that increased infiltration.

Through work in Nevada it was found that lower rates of infiltration occur on soils with vesicular porosity (Blackburn 1975 and Eckert et al. 1977). When soils are nearly saturated, soil air tends to form spherical bubbles under the force of capillary pressure, $2\sigma/R$, (σ = surface tension of water and R = radius of curvature of the interface), which becomes large when the radius of curvature is small. This happens in many soils to some degree, but soils that allow bubbles to become large, forming vesicular pores, are unstable. These soils are silty. This may facilitate the detachment of soil particles which are then free to clog surface pores (McIntyre 1958). In this study, greater sediment concentration was found in runoff water from surface soils with vesicular porosity. In addition to their indirect effects; vesicular pores dampen the soil potential gradient by: 1. decreasing the effective surface area; 2. increasing the depth to which a given quantity of water must penetrate before being absorbed; and 3. by increasing the distance between the soil surface and the wetting front over which soil potential forces must pull. Surface soils with vesicular porosity are often immediately underlain by soil layers with a platey structure, which can inhibit infiltration by interrupting forces of soil potential. These may be underlain by a fine textured horizon, which may inhibit infilration by impeding percolation. Reduced permeability may be the primary reason why soils become saturated and vesicular porosity forms.

The correlation of sodium with decreased infiltration may be an indication of the clogging effect of easily detached soil particles released by the dispersing action of sodium (Singer et al. 1982). However, two other explanations are possible: 1. Sodium induced dispersal may inhibit production or maintenance of stable aggregates, causing the soil surface to be less open; and 2. Sodium is more abundant on more arid sites which by their nature have lower infiltration rates.

Regression analysis that included tephra sites supports the work of Rauzi and Kuhlman (1961), who found more rapidly declining infiltration rates on fine-textured soils. All regression analyses, but especially the one omitting the tephra sites, support the conclusion that organic ground cover promotes infiltration (Meeuwig 1970, Branson and Owen 1970, and Lang 1979). This relation between infiltration and organic ground cover may partially explain the higher infiltration rates found on Mollisols and expecially Cryborolls. These soils have more organic matter in their epipedons. Increased organic matter can contribute to aggregate stability and a soil structure that is generally more favorable to infiltration. Soils with vesicular porosity are generally low in organic matter and are more frequently Aridisols.

Winward (1970) found that the occurrence of particular subspecies of big sagebrush did not correlate with soil texture. With this in mind, average infiltration rates in the last 15 minutes were adjusted for percent medium and coarse sand. Even with this adjustment, tests for differences by subspecies, location, and condition class were nonsignificant.

All these data should be considered as an index. Natural high intensity storms of low frequency in Southern Utah are exceedingly infrequent in Central Oregon and they may not be the cause of most runoff and soil erosion. Johnson et al. (1974) found that a large part of annual in-stream sediment yield was discharged in peak runoff events usually associated with prolonged rain, frozen soil, or rapid snow melt in winter or spring. The Rocky Mountain infiltrometer produces a simulated rainfall of about 12.6 cm/hr, which is excessively intense for Oregon (Miller et al. 1973). Also, because the fall height is low, terminal velocity is not reached and rainfall energy is low (Gifford 1979b). While reduced fall height partially compensates for the excessive rainfall intensity, a Rocky Mountain infiltrometer only partially simulates a natural event. However, The Rocky Mountain infiltrometer has been used extensively on rangeland by Meeuwig (1965 and 1970), Trieste and Gifford (1980), and Buckhouse and Gaither (1982) This extensive use allows comparison of data from vastly different ecosystems and treatments.

Conclusions

The process of infiltration is complex and is controlled by many factors. The same can be said for vegetation, which is influenced by many of the same factors. This correlation may aid managers in their attempt to understand rangeland hydrology, however, vegetation identification must remain only one of many tools. Subspecies of big sagebrush were not shown to be reliable indicators of infiltration rates. They reflect significant differences in only one of four locations and that location had large differences in elevation between sites occupied by *A.t.* ssp. *vaseyana* and *A.t.* ssp. *wyomingensis*. Observable site parameters that did relate to increased infiltration rates were the absence of vesicular porosity, loamy sand texture, and greater amounts of organic ground cover.

Chapter II

Soil and Nitrogen Loss from Oregon Land Occupied by Three Subspecies of Big Sagebrush

Soil and Nitrogen Loss from Oregon Land Occupied by Three Subspecies of Big Sagebrush

Abstract

Measurements of runoff and soil loss from simulated high intensity rainstorms are reported for shrub interspaces of three sites occupied by each of threee subspecies of *Artemisia tridentata* (big sagebrush) in each of four locations in eastern Oregon. *Artemisia tridentata* ssp. *wyomingensis* sites had significantly higher soil loss than *A.t.* ssp. *vaseyana* sites. Comparisons of means within locations showed nonsignificant differences between subspecies except at Frenchglen. Soil loss was positively correlated with runoff, percent bare ground, and vesicular soil porosity; but it was negatively correlated with medium and coarse sand and coarse fragments in the surface soil and with organic ground cover. Aridisols lost more soil than Mollisols. Habitat types did not appear useful for indexing soil loss from these sites. Surface soil morphology, however, correlated with large significant differences in soil loss and may be a useful index. Nitrogen loss was not correlated with subspecies of *Artemisia tridentata* but correlated with soil erosion and many of the soil features that affect soil erosion. Amounts of nitrogen lost in this simulation do not appear to be important.

Introduction

Soil loss rates under natural conditions are among the highest for semiarid shrublands (Branson 1975). Osborn et al. (1978) found as much as ten times greater sediment yields from brush covered watersheds than from grass covered watersheds. Buckhouse and Gaither (1982) measured potential soil losses of 431 kg per hectare for grassland ecosystems and 1,284 kg per hectare for sagebrush (*Artemisia* species) ecosystems in Central Oregon. Big sagebrush Artemisia tridentata) once dominated 145 million acres in western North America (Beetle 1960). Sagebrush ecosystems are diverse and widespread. This diversity suggests a finer classification is needed, such as the habitat types of Daubenmire (1968) suggested by Pfister (1981) for improved management of western watersheds. In recent decades, improvement in sagebrush taxonomy has enabled identification of three subspecies of *Artemisia tridentata*, each with distinct plant morphology and ecological requirements. Tisdale and Hironaka (1981) stressed the value of these subspecies in synecology and used them in classification by habitat types.

Artemisia tridentata ssp. *wyomingensis* (Wyoming big sagebrush) is the most xeric of the three big sagebrush subspecies. It generally occurs below 6,000 feet (1,829 m) on moderately deep well-drained soils which may be slightly calcareous to the surface. Bunchgrasses form the majority of the understory and most forbs are annual. There is a considerable amount of bare ground, 5 to 25 percent, even under pristine conditions, which cryptogams may occupy (Winward 1980). Because these sites are xeric and more easily abused, a high percentage of them are in low ecological condition.

Artemisia tridentata ssp. *tridentata* (basin big sagebrush) is a good indicator of potentially arable land because it occupies deep well drained soils. More perennial forbs are found on *A.t.* ssp. *tridentata* sites and potential herbaceous production is from 1 1/3 to 2 times greater than on *A.t.* ssp. *wyomingenses* sites (Winward 1980).

Artemisia tridentata ssp. *vaseyana* (mountain big sagebrush) resides in the upper foothill to mountain areas from 3,500 to 9,000 feet in elevation (1,067 to 2,743 m). It occupies deep well drained soils with moisture available most of the summer (Winward 1980). Winward (1981) indicated herbaceous cover is diverse and productive with three to four times more species and 1 1/2 to 2 times more production of grasses and forbs than *A. t.* ssp. *wyomingensis* sites.

In Idaho, Hironaka and Fosberg (1979) found *A.t.* ssp. *wyomingensis* mostly on Aridisols (mostly Camborthids), *A.t.* ssp. *vaseyana* entirely on Mollisols (Cryborolls), and *A.t.* ssp. tridentata on a combination of these soil orders.

This research was undertaken to assess the value of these subspecies as indicators of potential erosion and runoff. In addition, these parameters were related to other site factors including soil classification, surface soil morphology, texture, organic matter and ground cover of vegetation and litter.

Nitrogen is an essential macronutrient that is commonly limiting in semiarid ecosystems where vegetative growth is also water limited. Plants commonly respond to the addition of nitrogen fertilizer, especially with additional soil moisture (Sneva and Hyder 1965, and Wallace et al. 1978) which fertilized plants may use more efficiently (James and Jurinak 1978). West and Klemmedson (1978) indicated nutrients most limited in supply will be concentrated in places where organisms use them, such as the surface soil and under shrub canopies where nitrogen is commonly concentrated (Charley 1977). Charley and Cowling (1968) found biologically induced vertical gradients become sharper with increasing aridity. Nitrogen is concentrated near the soil surface by the combined biological processes of nutrient pumping by vegetation and fixation by soil surface blue-green algae crusts, the major nitrogen fixers in desert ecosystems (Rychert et al. 1978).

West and Klemmedson (1978) indicated that the bulk of ecosystem nitrogen is contained in soils and is tied up in organic matter and/or clay minerals making it unavailable for plant uptake. Although not available, this nitrogen serves as a large pool in buffering against usage and loss (Wallace et al. 1978). This pool of tied up nitrogen is very susceptible to erosional loss because it may be selectively carried off in runoff or by winds (Fletcher et al. 1978). Several authors (Massey and Jackson 1952, Stoltenberg and White 1953, Sorensen and Porcella 1974, Fletcher et al. 1978, and Schreiber et al. 1980) have documented an increase in concentration of nitrogen from soil to sediment. This is explained by the association of nitrogen with clays and fine soil particles, as documented by Bremner (1965), Chichester (1969), Swift and Posner (1972), and especially with organic matter (Nishita and Haug 1973, Swift and Posner 1972, and Nagi 1980). Even though medium and coarse sand-size particles are more easily displaced, fine soil particles and organic matter are selectively eroded because their small size and low density, respectively, increases their tendency to remain suspended in the runoff water. Loss of humus and colloids represents a reduction of cation exchange capacity. An additional objective of this research, therefore, was to assess the relative rates of nitrogen loss.

Study Area and Methods

Four widely spaced study locations were selected in three of the major geomorphic divisions of Oregon. At each location, three sites for each subspecies were studied, totaling 36 sites. Each site was located in a relatively homogenous stand in good condition, representative of common habitat types.

Soil loss sampling was done with a Rocky Mountain infiltrometer (Dortignac 1951) so sites were selected to be on slightly sloping terrain near a road and free enough of large surface soil stones that plot selection would not be unduly constrained. All but one of the *A.t.* ssp. *wyomingensis* sites were on Aridisols and all the *A.t.* ssp. *vaseyana* sites were on Mollisols. The lone *A.t.* ssp. *wyomingensis* site on a Mollisol was located very close to an *A.t.* ssp. *vaseyana* site, and neither site represented a large homogenous area.

In some locations, ideal sites were difficult or impossible to locate; however, a regression of plot slope with soil loss produced a nonsignificant coefficient of determination (r^2) of .012, and no significant difference was found between different condition classes.

Field sampling took place in three phases over two summers. Before mid-July in 1980, herbaceous vegetation data were collected with three 30 meter frequency transects of 10 1 x 2 foot (30 x 61 cm) plots each. Shrub density was determined with three 1 x 30 meter strip plots; and canopy cover was estimated with three 30 meter line-intercept transects. Following vegetation analysis, soil pits were described and samples analyzed in the laboratory for bulk density (Blake 1965), particle size distribution[1], and organic matter (Walkley and Black 1934).

In 1981 a set of three "F" type rainfall simulators were used to produce a high intensity (12.6 cm hr^{-1}) short duration (28 minutes) rainfall. This simulation should be considered as an index of potential rainfall. Raindrops did not fall far enough to reach terminal velocity, and rainfall of this intensity is far in excess of even the 100-year 28-minute rainfall expected for eastern Oregon (Miller et al. 1973). A high intensity was needed to produce runoff on some sites, and using a Rocky Mountain infiltrometer with these rainfall

[1]Particle size distribution was determined with a modified Boyucous (1962) technique as used by the Oregon St. Univ. Soil Physical Testing Laboratory.

rates makes these results comparable to other research done in Utah, Idaho, Colorado, and Oregon (Meeuwig 1965, 1970, and 1971, Thompson 1968, Gifford and Tew 1969 a and b, Williams et al. 1969, Gifford et al. 1970, Loope and Gifford 1972, Gifford and Busby 1974, Buckhouse 1975, Gifford et al. 1976, Buckhouse and Gifford 1976 a, b, and c, Burton 1976), Busby 1977, Gaither 1980, Buckhouse and Mattison 1980, and Buckhouse and Gaither 1982).

Infiltrometer sampling was conducted in shrub interspaces because Blackburn (1975) found that these areas produced greater amounts of runoff and sediment and because including shrub canopy zones would have greatly increased on-site variability. Plots were comprised of three 1 x 2.5 ft (30 x 76 cm) steel frames placed side by side in such a way that runoff water would drain out the lower end when the frames were partially driven into the ground.

The simulated rainfall was sampled with runoff after three minutes and then at five-minute intervals. Infiltration was estimated by subtraction. Sediment concentration was sampled with a quart (0.95 l) aliquot representative of the whole 28-minute run. Total soil loss was derived by multiplying sediment concentration by total runoff. An additional aliquot of approximately 175 ml was composited from the runoff water of the three subplots. This was immediately treated with 2-3 ml of 2 normal sulfuric acid and kept on ice until it could be frozen. Later, organic and ammonium nitrogen (but not nitrate or nitrite nitrogen) was determined with a macro Kjeldahl apparatus.

Before each run, percent canopy cover, bunchgrass base, litter, cryptogams, coarse fragments, bare ground, and each type of surface soil morphology was visually estimated in each of the 3 subplots of the six plots. For analysis, bunchgrass base, litter, and cryptogams were combined to form an organic ground cover term. Field training for visual estimation was done with a 100-point frame. At least 30 minutes before the run, each subplot was prewetted with just enough water to cause ponding.

On each site, two samples of approximately the top 8 centimeters of each surface soil morphology type were collected for laboratory analysis of clod bulk density, particle size distribution (Day 1965), percent coarse fragments, and organic matter. All surface soil morphology types that would not form a reliable clod, and most other types as well, were also field tested for bulk density using a modification of the excavation method (Blake 1965).

Multiple regression and analysis of variance was at the .10 level of probability with Tukey's procedure used for multiple comparisons of equal sample size and Scheffe's test used with unequal sample size (Steel and Torrie 1980).

Results and Discussion

There was a linear relationship (r^2 = .61) between total runoff and sediment concentration in the runoff water (Fig. 1), which causes a closer relationship (r^2 = .94) between total soil loss and sediment concentration. Therefore, all statistical tests were nearly

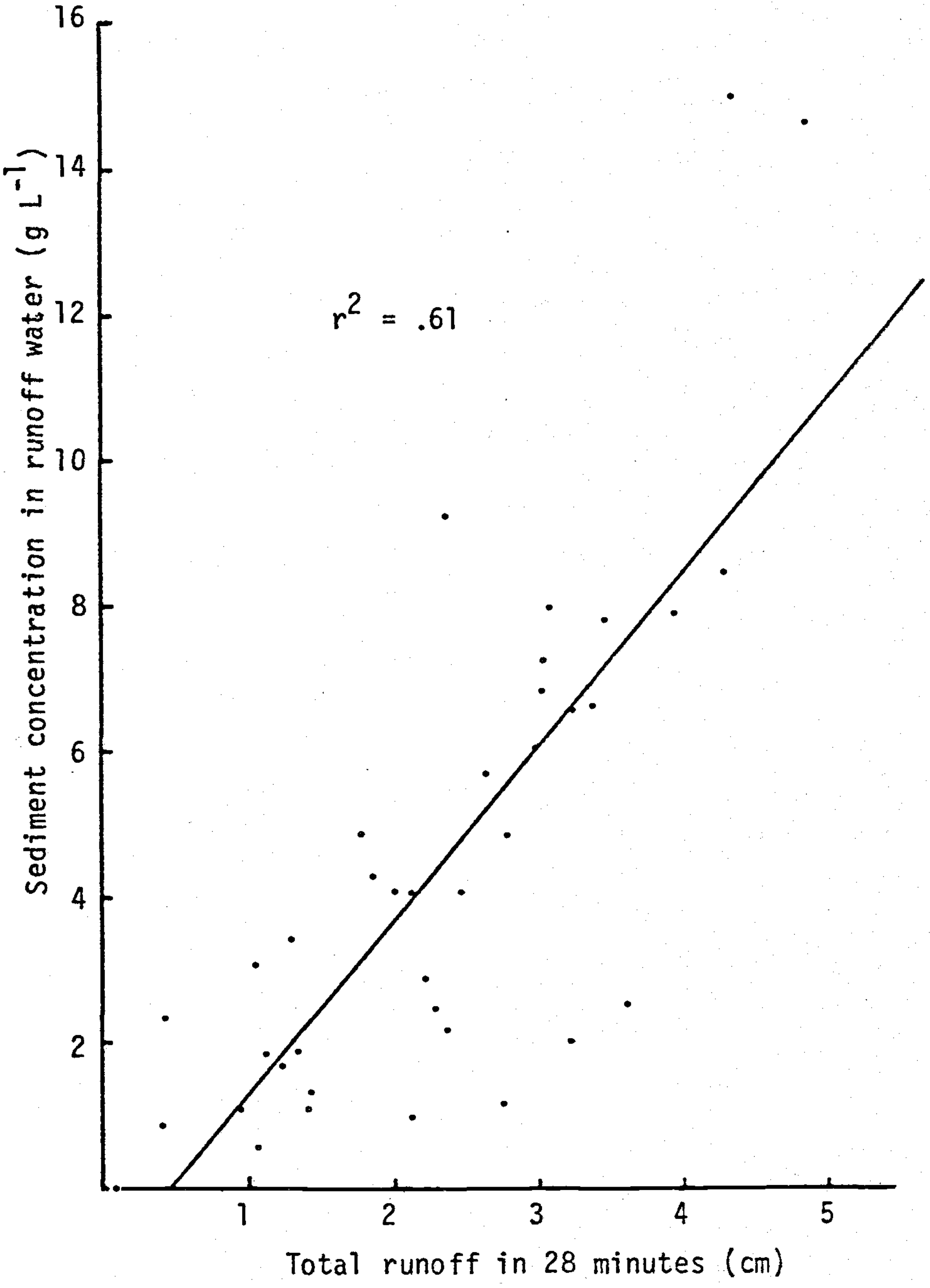


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Figure 1. Sediment concentration as a function of total runoff. The coefficient of determination (r^2) was calculated using a mean for each site.

identical for these two parameters, so discussion will focus on total soil loss.

Infiltration and soil erosion were highly correlated. Both infiltration and soil loss showed different patterns between subspecies at different locations (Fig. 2) (see appendix 3 for analysis of variance tables). Interaction was significant for infiltration but soil loss was great enough on some *A.t.* ssp. *wyomingensis* sites and low enough on some *A.t.* ssp. *vaseyana* sites to mask the interaction and indicate an overall significant difference between these two subspecies. Although soil erosion is a complex surficial process influenced both by natural conditions and land management decisions not considered in this research, it is apparently more sensitive to site differences than infiltration.

Subspecies of big sagebrush sort themselves mostly on the basis of climate and rooting zone soil moisture characteristics. Winward (1970) found different soil depths but not different surface-soil textures for the three subspecies in Idaho. Frenchglen sites have an elevational range greater than other locations, so the largely indirect hydrologic effects of big sagebrush subspecies distribution had ample expression there. The other three locations, however, exhibited no significant differences between subspecies in either infiltration or soil erosion.

Only three habitat types were represented by more than two sites. Idaho fescue (*Festuca idahoensis*) was the climax dominant in the understory of all *A.t.* ssp. *vaseyana* and half of the *A.t.* ssp.

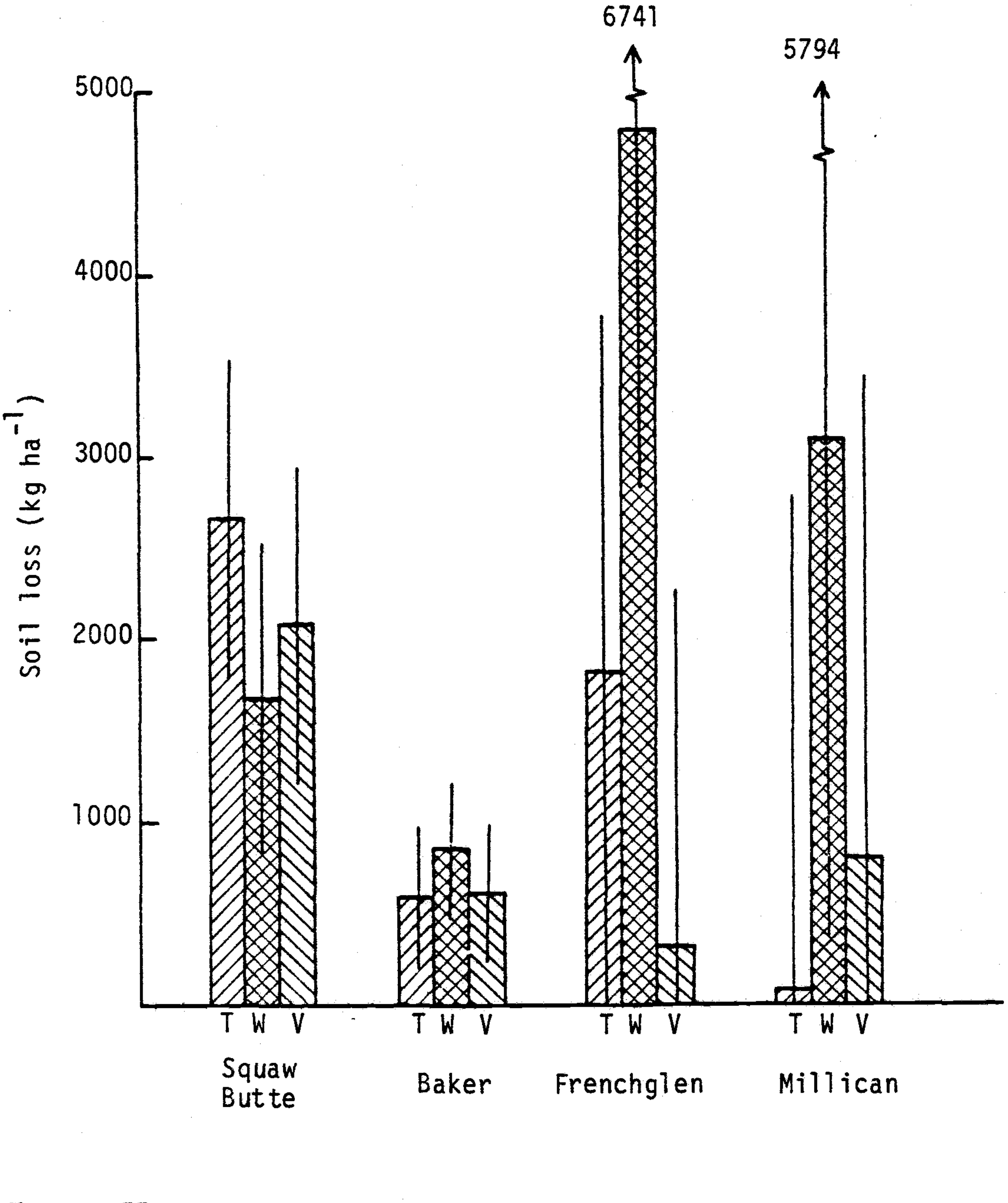

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Figure 2. Soil loss by location and subspecies. T = *A.t.* ssp. *tridentata*, W = *A.t.* ssp. *wyomingensis*, V = *A.t.* ssp. *vaseyana*. At a location, subspecies with nonoverlapping confidence intervals are significantly different at the 0.1 level of probability.

wyomingensis sites. These two habitat types had similar soil loss rates (Table 1). The *A.t.* ssp. *tridentata* / *Elymus cinereus* habitat type had a soil loss rate significantly higher than only the *A.t.* ssp. *vaseyana* / *Festuca idahoensis* h.t.. This difference could well be due to the generally poor condition of *A.t.* ssp. *tridentata* / *Elymus cinereus* sites. *Stipa thurberiana* (Thurber's needlegrass) was the climax dominant understory on a total of six sites of *A.t.* ssp. *tridentata* and *A.t.* ssp. *wyomingensis*. Analysis of sites grouped

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Table 1. Total soil loss on big sagebrush habitat types.

Habitat type	Number of sites	Total soil loss
A.t. ssp. *vaseyana/Festuca* [1]	12	912 a[4]
A.t. ssp. *wyomingensis/Festuca* [2]	6	1066 ab
A.t. ssp. *tridentata/Elymus* [3]	6	2226 b

[1]Hironaka and Fosberg (1979).

[2]Doerscher et al. (1982).

[3]Hironaka (1979).

[4]The same letter indicates nonsignificant differences at the 0.1 level of probability.

only by climax dominant understory showed no significant differences even though *Stipa thurberiana* sites had higher soil loss rates than *Elymus cinereus* sites. The low indicator value of herbaceous species is perhaps explained by Driscoll (1964) who worked in the closely associated central Oregon juniper zone and concluded that compensatory environmental factor interactions strongly influence plant community - soil relationships.

When soil classification was used directly to group sites, differences between suborders were not significant, but Mollisols lost significantly less (1103 kg ha^{-1}) soil than Aridisols (2342 kg ha^{-1}). The higher organic matter in the epipedon of Mollisols is influential in promoting infiltration with more distinct soil structure and in forming soil aggregates which are less easily eroded. In addition, higher organic matter may indicate greater plant growth which also protects the soil. On these sites Mollisols averaged 62% organic ground cover and Aridisols averaged significantly less, 35%.

The soil surface and surface soil variable most highly correlated with soil loss was percent organic ground cover. Three surface soil particle size descriptors, percent clay, percent coarse fragments, and percent silt were also significant in stepwise multiple linear regression analysis (Table 2). Other independent variables not useful in multiple regression are listed in Table 2 along with their coefficients of correlation.

Numerous studies have shown organic ground cover is critical in erosion control (Branson et al. 1981) because it breaks the impact of falling raindrops and forms sediment traps on the soil surface. Coarse fragments on the soil surface can have a similar effect (Eckert et al. 1978).

The correlation of soil loss with percent clay and silt appears to contradict observations that medium and coarse sand-size particles are most easily detached by raindrop splash. Yariv's model (1976)

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Table 2. Regression analysis of soil surface and surface soil factors with total soil loss.

Site Factor	Multiple r^2	Simple r
Organic ground cover	.20**	-.45**
Clay	.39**	.30**
Coarse fragments	.42**	-.19**
Silt	.47**	.23**
Bare ground		.49**
Medium and coarse sand (.25-2. mm)		-.41**
bulk density		.22**
organic matter		.19**
fine sand (.05 - .25 mm)		.05

**Indicates significance at the .01 level of probability.

predicts loss of medium and coarse sand-size particles on the basis of the high hydration energies of the minerals in smaller particles and the large mass of larger particles. However, the correlation of clay and silt with soil loss is in relation to the particle size distribution of the soil, not of the sediment. The correlation may reflect the rapid infiltration on sandy soils, for the coefficient of determination of medium and coarse sand with average infiltration in the last 15 minutes of the run was r^2 = .23. Rapid infiltration decreases erosion both by decreasing water available for runoff and by decreasing the probability of detachment of soil particles because the surface tension and viscosity of the soil water mixture at the soil surface is greater (Yariv 1976).

Five of the Millican sites had a surficial deposit of tephra, a lithologic discontinuity that is different from other sites. Therefore, stepwise multiple linear regression was repeated with these sites omitted. In that analysis, bare ground accounted for 32 percent of the variability in soil loss; again emphasizing the importance of ground cover. Coarse fragments in the surface soil increased the multiple coefficient of determination only slightly.

Morphology of the surface soil was perhaps the dominant influence on soil loss (Fig. 3). Both vesicular porosity and platey structure were associated with increased soil loss and with decreased infiltration. Eckert et al. (1978) described four types of surface soil morphology and their microtopographic position. Three of the four types occured in plots of this study. Type II is found on slope and coppice bench positions, has a very irregular surface, and deep, well-developed cracks separating polygons that are 5 - 8 cm in diameter. Type III is found on intercoppice microplains and has larger polygons with a flat top. Type IV has an almost unbroken flat surface with thin irregular cracks. All three types have platey structure, but vesicular pores are larger and well developed in type III and especially in type IV.

Although soil loss generally followed the trend set by decreasing infiltration, types III and IV were reversed. Cracks in type III probably facilitate infiltration whereas the almost level surface of type IV probably retards soil erosion by reducing the velocity of runoff water and allowing standing water to protect the

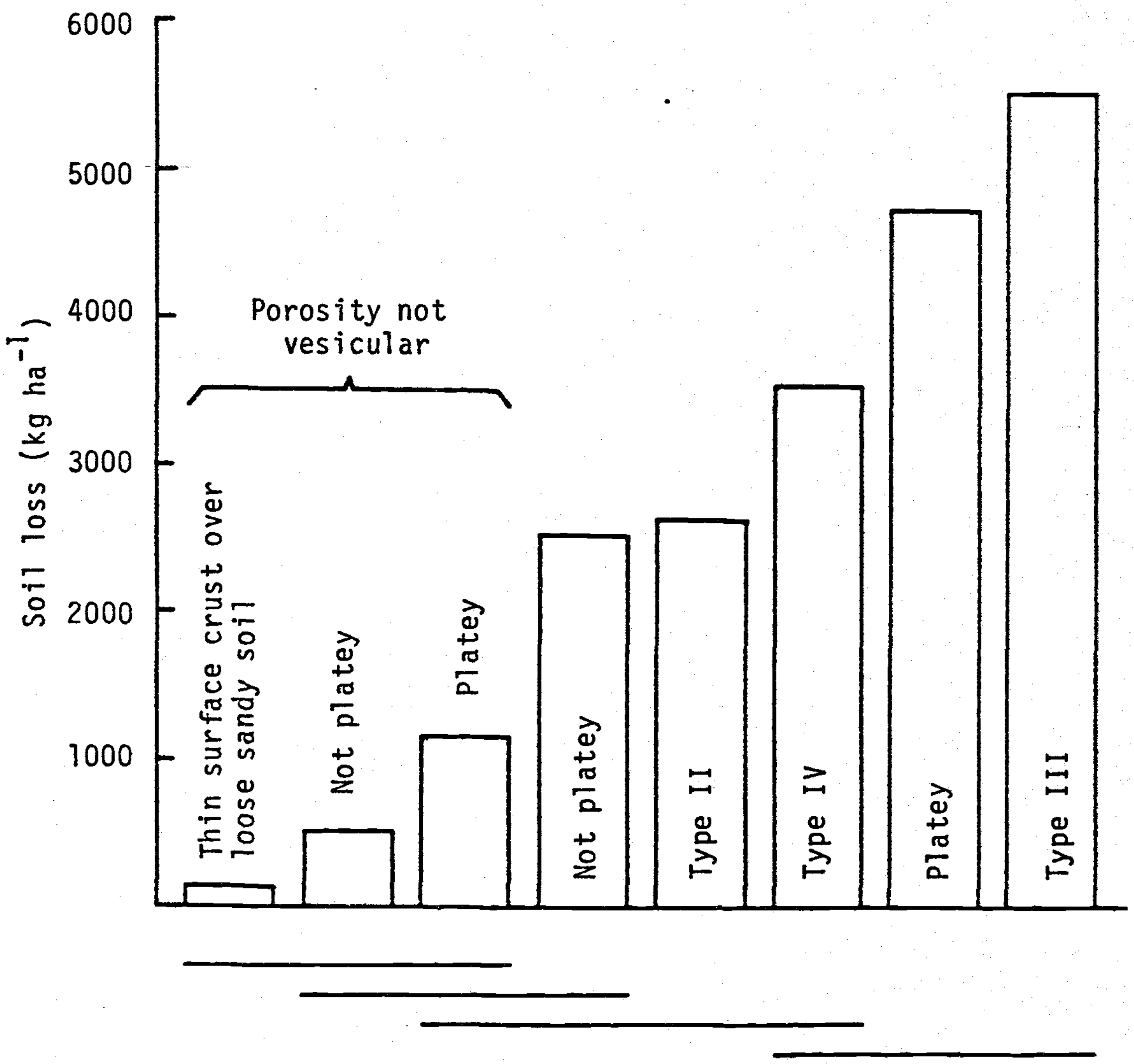

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Figure 3. Surface soil morphology and soil loss. There is no significant difference (probability = 0.1) between bars over any one line. Types II, III and IV were described by Eckert et al. (1978).

soil from falling raindrops as discussed by Fletcher et al. (1978).

Vesicular porosity is indicative of unstable soil structure that is easily deformed by trapped air. Vesicular soil horizons are generally high in silt content, low in organic matter, and poorly aggregated (Miller 1971 and Blackburn 1975). Instability leads to easy displacement by falling raindrops which may lead to clogging of surface pores and reduced infiltration as observed in this study and in the work of Blackburn (1975) and Eckert et al. (1978). Also, reduced infiltration may be the result of platy structure and/or a fine-textured horizon of reduced permeability below the surface.

Nitrogen loss shows a similar pattern to soil loss (Figure 4). However, no differences between subspecies in percentage nitrogen in the runoff water apply across all locations. At Frenchglen, *A.t.* ssp. *wyomingensis* sites lost more nitrogen than *A.t.* ssp. *vaseyana* sites. Similarity to soil loss data is illustrated by the significant correlation (r^2 = .55) between sediment concentration and nitrogen concentration in runoff water.

A multiple regression of nitrogen concentration in runoff water with the soil surface and surface-soil factors listed in table 2 produced the results in table 3. Results in these tables are very similar except that the simple coefficient of correlation for organic ground cover is lower for predicting nitrogen concentration. Presumably more organic ground cover indirectly decreases nitrogen

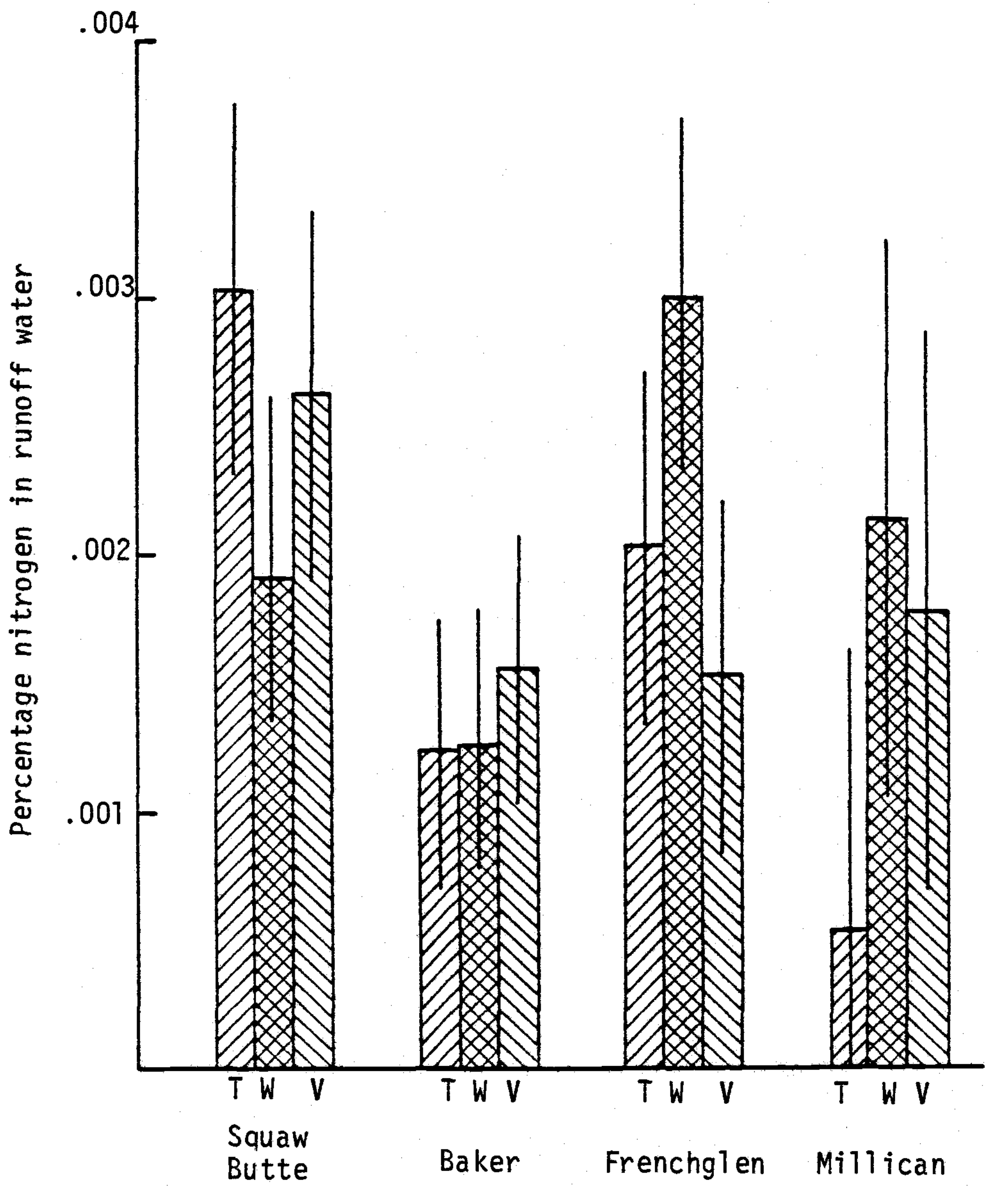

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Figure 4. Percentage nitrogen in the runoff water by location and subspecies. T = *A.t.* ssp. *tridentata*, W = *A.t.* ssp. *wyomingensis*, and V = *A.t.* ssp. *vaseyana*. Bars at a location with nonoverlapping confidence intervals are significantly different at the 0.1 level of probability.

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Table 3. Regression analysis of soil surface and surface soil factors with nitrogen concentration in runoff water.

Site factor	Multiple r^2	Simple r
Medium and coarse sand (.25-2. mm)	.17**	-.41**
Organic ground cover	.29**	-.35**
Coarse fragments	.31**	-.17**
Clay	.34**	.30**

concentration by decreasing soil erosion but also contributes a small amount of nitrogen to the runoff water.

The overall mean loss of nitrogen from a site was 4.34 kg ha^{-1}, with a high of 19.96 kg ha^{-1}. Although this is greater than the average nitrogen loss rates measured in natural runoff water (about 1.5 kg ha^{-1} yr^{-1} found by Sorensen and Porcella 1974, and 1.6 kg ha^{-1} yr^{-1} found by Dogan 1975) it is much less than rates of fertilizer application (33.6 kg ha^{-1}) reported by Sneva and Hyder (1965). It is also less than the average rates measured for cryptogamic crust fixation (7 kg ha^{-1} yr^{-1}) reported by Porcella et al. (1973), or (10-100 kg ha^{-1} yr^{-1}) by Rychert and Skujins (1974), and it is about equal to the net input from precipitation (4 to 6 kg ha^{-1} yr^{-1}) recorded by West (1978). In addition, the bound organic nitrogen which was most of what this study measured is not directly available to plants. West (1972) reported nitrogen in the standing crop biomass of vegetation on an Idaho desert sagebrush site was 251 kg ha^{-1}, and soil nitrogen was 5,200 kg ha^{-1}.

Conclusions

Land occupied by big sagebrush is highly variable in soil and vegetation characteristics and in its response to high intensity simulated rainfall. This rainfall caused more soil loss on *A.t.* ssp. *wyomingensis* sites than on *A.t.* ssp. *vaseyana* sites, and more soil loss on Aridisols than on Mollisols. Reduced runoff and soil loss found on some sites can be partially explained by abundant groundcover, a sandy surface texture, coarse fragments in the surface soil, and/or a surface soil morphology that is neither platy nor vesicular.

Differences between soil orders and surface soil morphology types point to the need for an even finer land classification than the habitat type promoted by Pfister (1981) and suggest soils must be included directly, as Bailey (1978) does for the landtype phase level of his hierarchial ecosystem classification system.

Nitrogen loss is highly correlated with soil loss, it appears to be influenced by many of the same factors, and it is not well correlated with subspecies of big sagebrush. Nitrogen loss from raindrop splash and sheet erosion on these sites does not appear to be critical.

Chapter III

Some Physical and Chemical Properties of Soils Occupied by Three Subspecies of *Artemisia tridentata*

Some Physical and Chemical Properties of Soils Occupied by Three Subspecies of *Artemisia tridentata*

Abstract

The three subspecies of *Artemisia tridentata* occupy qualitatively different sites. Wyoming big sagebrush, *A.t.* ssp. *wyomingensis*, typically occupies Aridisols; mountain big sagebrush, *A.t.* ssp. *vaseyana*, typically occupies Mollisols at a higher average elevation; and basin big sagebrush, *A.t.* ssp. *tridentata*, may occupy either. This study evaluated some physical and chemical characteristics of soils occupied by each subspecies in four widely spaced Oregon locations. Nearly all of the chemical characteristics showed either no significant differences between subspecies that apply across all locations, or they showed a significant interaction between location and subspecies indicating that analysis should proceed at each individual location. The Frenchglen location had the greatest elevational differences between sites and also had most of the significant chemical differences between subspecies. In the surface soil at Frenchglen, *A.t.* ssp. *vaseyana* sites had lower pH, higher organic matter, higher cation exchange capacity, lower base saturation, lower percent exchangeable sodium, and greater water retention at -15 bars than *A.t.* ssp. *wyomingensis* sites. Fewer characteristics of *A.t.* ssp. *tridentata* sites were significantly different. In deeper soil horizons at Frenchglen, *A.t.* ssp. *vaseyana* sites had lower pH and

base saturation than *A.t.* ssp. *tridentata* sites. Many of these characteristics are interrelated and differences in them are probably influenced by elevation-induced variation in climate.

Introduction

Vegetation and soil characteristics are interdependent integrators of environmental parameters. Where these characteristics are correlated over broad areas of the landscape, understanding the indicator value of vegetation can be useful to land managers. Habitat typing is one way of grouping plant communities into meaningful units. For example, Munn et al. (1978) described the correlation between soils, plant production, and some habitat types in western Montana. Using dominant or indicator species by themselves can also be useful. Tisdale and Hironaka (1981) summarized the autecology of major species in the sagebrush grass region of North America. Their review describes the autecology of big sagebrush, *Artemisia tridentata*; and its three subspecies, basin big sagebrush, *A.t.* ssp. *tridentata*; Wyoming big sagebrush, *A.t.* ssp. *wyomingensis*; and mountain big sagebrush, *A.t.* ssp. *vaseyana*. Winward (1982) stressed the utility of habitat types of these subspecies for ascertaining the site potential of rangelands.

Winward (1980) described the ecology of these subspecies in Oregon. *Artemisia tridentata* ssp. *wyomingensis* is the most xeric of the three subspecies. It generally occurs below 6,000 feet elevation (1,800 meters) on moderately deep well-drained soils that may be slightly calcareous to the surface. *A.t.* ssp. *tridentata* is a good indicator of potentially arable land because it occupies deep, well-drained soils. *A.t.* ssp. *vaseyana* resides in the upper foothill to mountain areas from 3,500 to 9,000 feet elevation (1,100 to 2,700 m).

It occupies deep well-drained soils with moisture available most of the summer. Herbaceous cover is most diverse and productive on *A.t.* ssp. *vaseyana* sites, which may have three to four times more species and 1 1/2 to 2 times more production of grasses and forbs than *A. t.* ssp. *wyomingensis* sites. Winward's Idaho work showed that increasing thickness of the A horizon correlated well with the trend toward cooler, more mesic habitats. Although soil bulk density and soil texture showed little relationship to *Artemisia tridentata* taxa, texture did correlate well with some herbaceous dominants. Total soil organic matter, although variable, appeared different in habitat types of different subspecies (Winward 1970). This presumably reflects differences in soil depth, productivity, and/or decomposition rates. Sturges (1977) described a hillslope with an *A. t.* ssp. *vaseyana* site experiencing recurrent snow drift accumulation and moisture recharge throughout the 244 cm measurement zone but incomplete soil moisture withdrawal during the growing season; whereas on the nearby though more wind swept *A. t.* ssp. *wyomingensis* site, recharge was negligible below 91 cm and soil moisture withdrawal corresponded to the entire recharge zone.

Hironaka (1979) listed the various soil families he found on sites dominated by the different subspecies in southern Idaho. All his *A. t.* ssp. *wyomingensis* sites were on Argids and the *A. t.* ssp. *vaseyana* sites were on Borolls. Subspecies *tridentata* sites were on either Argids or Borolls. West et al. (1978) discussed the indicator value of sagebrush within the pinyon-juniper woodlands of the central Great Basin. They concluded that over a wide area, the major sagebrush taxa do not correlate closely with higher soil taxonomic categories, as they are influenced largely by climate. Yet these taxa have value as indicators of edaphic as well as other environmental factors, especially when their patterns are understood in local areas and when compensatory environmental factors are considered.

This research was designed to analyze quantitatively some of the chemical and physical characteristics of soils supporting each of the three subspecies of *Artemisia tridentata* in widely spaced locations in central and eastern Oregon.

Study Area and Methods

Study sites were clustered in four widely spaced locations representing three of the major geomorphic divisions of Oregon (Dicken 1965). The Squaw Butte and Milliken sites are in the High Lava Plains division and have sedimentary or igneous parent rock of middle Tertiary or younger age (<26 million years). The Frenchglen sites are in the Basin and Range division and have igneous parent rock of similar age. The Baker sites are in the Blue Mountains division and have igneous or sedimentary parent rock that is of Tertiary age or older (2-280 million years) (Walker 1977). At each location, three sites represent each subspecies for a total of 36 sites.

Squaw Butte is representative of the climate of all four locations, for it is centrally located both geographically and elevationally. Sneva (1977) indicated annual precipitation averages 12 inches (30.5 cm) with extremes of 6 and 17 inches (15.2 and 43.2 cm) recorded over a 34-year period. About 60 percent is fall and winter precipitation, mostly snow, and about 25% is rain in May and June. July, August, and September are dry but subject to high intensity, low frequency thunderstorms. Mean monthly maximum temperature is 35°F in January and 85°F in July (1.7° and 29.4°C respectively).

On each site the soil profile was described and sampled to a restricting layer or to a depth of 2 meters, and classified according to Soil Conservation Service (1975) definitions. Samples were generally collected from a representative part of the pit in the shrub interspace but near the edge of the canopy. Because of the island-interspace phenomenon described by Charley (1977) future work should more carefully standardize the location for soil sampling.

Description of the soil profile included depth and thickness of each horizon, moist and dry color, texture, structure, consistence, porosity, root abundance, horizon boundary morphology and an estimate of coarse fragment abundance by size. Bulk density of each horizon was determined by the clod and/or a modification of the excavation method (Blake 1965). A large sample (2-10 kg) from each horizon was air dried in a paper bag for later analysis. Samples down to and including the B horizon, or to a similar depth if there was no B horizon, were later split for chemical analysis by the soil testing laboratory of Oregon State University, and for physical analysis at the Squaw Butte Experiment Station. Results reported here refer to the top and bottom horizons of those analyzed.

The sample splits for chemical analysis were ground and analyzed for: 1. pH with a glass electrode pH meter (Jackson 1958); 2. extractable phosphorous with the sodium bicarbonate method (Olsen and Dean 1965); 3. extractable potassium, sodium, calcium, and magnesium with the ammonium acetate method (Peech et al. 1947); 4. organic matter with the Walkley-Black titration method (Walkley and Black 1934); and 5. cation exchange capacity with the ammonium acetate method (Shoemaker et al. 1961). From these measurements, percent exchangeable sodium and base saturation were calculated. In analysis, base saturation was constrained to an upper limit of 100%.

The remaining sample was sifted for determination of percent coarse fragments (>2 mm), and the fines were used to determine particle size distribution[1] (Day 1965) and water retention at -1/3 bar and -15 bars.

Water storage capacity was calculated using the difference between -1/3 bar and -15 bars water retention of disturbed samples, natural soil bulk density, percent coarse fragments, and soil thickness by horizon.

[1]Particle size distribution was determined with a modified Boyucous (1962) technique as used by the Oregon St. Univ. Soil Physical Testing Laboratory.

Results and Discussion

Although the three subspecies of big sagebrush tend to occupy different microclimatic zones and hence different elevational zones, the sites for the study areas did not reflect this difference adequately to be representative of the subspecies' central tendencies. The sites were selected instead to be representative of the subspecies in each location and the locations to be representative of a wider geographic region where the three subspecies overlap. As a result, sites of the three subspecies in the Baker location are not significantly different in elevation and there is a significant interaction for mean elevation between location and subspecies (Table 1) (see Appendix 4 for mean squares from analysis of variance tables).

Perhaps most surprising and also illuminating is the lack of significant differences in soil moisture storage capacity between subspecies. This is a strong indication that, although soils may be important, there is more to the total effective environment of the three subspecies. Elevational differences are greatest at the Frenchglen sites, and it is there that both total soil depth or rooting depth and depth to the horizon of maximum illuviation showed the pattern considered characteristic of the three subspecies. Soil depths are greatest for *A. t.* ssp. *vaseyana* and *A. t.* ssp. *tridentata* and the deep thick B horizons on *A. t.* ssp. *vaseyana* sites reflect the added moisture that comes with higher elevation.

Because of the significantly deeper B horizons at the Frenchglen *A.t.* ssp. *vaseyana* sites, other samples at these sites from

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Table 1. Some physical and chemical properties of soils occupied by three subspecies of *Artemisia tridentata* in four Oregon locations. Different letters between subspecies for a given characteristic in a given column indicate significant differences (a = .05).

	ssp. & F	Squaw Butte	Baker	French-glen	Millican	Mean
Elevation	T	1362a	1046	1392a	1199a	1250
	W	1382a	1097	1402a	1362a	1311
	V	1483b	1118	1920b	1666b	1547
	F	8.27*	1.03NS	14.66**	18.18**	35.36
	F'					6.53**
Depth of maximum illuviation (cm)	T	45.3	44.8	27.5a	29.5	36.8
	W	38.8	30.	29.3a	57.5	38.9
	V	37.2	59.3	77.7b	43.8	54.5
	F	0.60NS	0.91NS	14.45**	3.74NS	4.28
	F'					3.29*
Rooting depth (cm)	T	159.0	12.7	161.7b	99.7	136
	W	79.3	86.7	85.7a	141.7	98.3
	V	14.3	125.0	176.7b	73.0	122.2
	F	3.07NS	0.59NS	17.68**	0.97NS	2.44NS
	F'					2.25NS
Moisture storage capacity (cm)	T	18.5	9.0	20.1	7.4	13.8
	W	7.6	11.5	11.4	20.5	12.8
	V	10.9	18.6	18.7	10.9	14.8
	F	3.66NS	1.74NS	4.36NS	2.10NS	0.32
	F'					3.21*
Surface horizon						
-pH	T	6.87	6.87	6.97ab	7.10	6.95ab
	W	7.03	7.27	7.30ab	6.80	7.10a
	V	6.83	7.07	6.43a	6.63	6.74a
	F	0.69NS	1.24NS	9.74*	1.19NS	5.81**
	F'					1.83NS
-organic matter (%)	T	2.28	4.30b	3.42ab	0.72a	2.68
	W	1.67	1.85a	1.26a	2.43ab	1.80
	V	2.35	4.57b	7.81b	6.22b	5.24
	F	0.43NS	18.76**	9.54*	6.79*	18.35
	F'					4.18**

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Table 1. (Continued)

	ssp & F	Squaw Butte	Baker	French-glen	Millican	Mean
-cation exchange capacity (meq/100 g)	T	17.2	18.2	22.3ab	9.1	16.7
	W	13.5	20.2	15.2a	15.5	16.1
	V	16.0	23.5	29.1b	15.7	21.1
	F	1.32NS	3.54NS	17.05**	1.61NS	7.26
	F'					3.56*
-base saturation (%)	T	89.3	88.0	96.7b	99.0	93.2
	W	95.0	92.3	95.3	93.0	93.9
	V	91.7	92.0	71.3a	89.0	86.2
	F	2.31NS	0.22NS	22.04**	4.30NS	6.88
						4.92**
-percentage of exchangeable sodium (%)	T	0.67	0.53a	2.60ab	1.2	1.27
	W	1.6	3.83b	10.23b	0.97	4.16
	V	0.8	0.67a	0.47a	0.7	0.66
	F	3.27NS	37.83**	6.04*	2.22NS	12.30
	F'					4.72**
-phosphorus (ppm)	T	34.0b	19.7	28.0	6.7	22.1
	W	17.0a	10.7	12.7	23.0	15.8
	V	10.3a	33.0	28.3	9.0	20.2
	F	36.89**	2.15	1.79NS	1.29NS	1.19
	F'					4.63**
-potassium (meq/100g)	T	2.43	1.82	3.41c	0.92	2.14
	W	1.70	1.79	1.13a	1.68	1.58
	V	1.93	2.61	2.25b	1.57	2.09
	F	1.14NS	2.46NS	23.22**	1.17NS	3.95
	F'					4.65**
-salts (mmhos/cm)	T	.38	.32	.37	.25	.33
	W	.33	.33	.30	.37	.33
	V	.33	.32	.30	.30	.31
	F	0.75NS	0.03NS	0.96NS	2.85NS	0.30NS
	F'					1.09NS
-clay (%)	T	10.2	13.2	13.0	3.1	9.9
	W	7.6	15.7	12.6	11.8	11.9
	V	13.5	12.1	15.9	9.1	12.6
	F	3.85NS	0.37NS	0.89NS	1.50NS	1.15NS
	F'					1.27NS

Chapter III
Table 1. (Continued)

	ssp. & F	Squaw Butte	Baker	French-glen	Millican	Mean
-15 bar	T	12.21	12.06	15.30ab	6.33	15.30a
water	W	9.86	15.72	10.28a	11.25	15.70a
retention	V	13.43	14.05	19.61b	13.36	20.15b
(%)	F	0.65NS	2.36NS	5.83*	3.10NS	4.54*
	F'					2.33NS
Subsoil						
-pH	T	7.27	7.20a	7.53b	7.5ab	7.38
	W	7.80	8.47b	7.87b	7.9b	8.01
	V	7.30	6.90a	6.73a	7.0a	6.98
	F	3.17NS	24.79**	10.18**	5.72*	34.30
	F'					2.70*
-organic	T	0.85	1.21	1.86	0.36	1.07
matter	W	0.91	1.85	0.98	0.64	1.10
(%)	V	1.21	1.31	1.10	1.16	1.19
	F	3.08NS	1.33NS	1.65NS	2.82NS	0.24NS
						2.47NS
-cation	T	16.9	22.9a	21.4	9.9	17.8a
exchange	W	19.9	37.0b	27.5	20.1	26.1b
capacity	V	19.1	19.6a	23.1	14.0	19.2ab
(meq/100g)	F	0.47NS	9.13*	0.43NS	2.58NS	6.83**
	F'					1.18NS
-base	T	97.3	99.7	98.7b	95.7	97.8
saturation	W	96.7	97.3	92.7ab	96.3	95.8
(%)	V	96.3	97.3	83.7a	93.3	92.7
	F	0.05NS	0.58NS	6.58*	0.13NS	2.87NS
	F'					1.22NS
-percentage	T	1.37	1.00	3.00	2.67	2.01a
of ex-	W	8.69	13.63	5.13	5.97	8.42b
changeable	V	1.20	1.50	0.85	1.13	1.17a
sodium (%)	F	1.57NS	4.37NS	1.69NS	3.28NS	9.22**
	F'					0.89NS
-phosphorus	T	4.33	10.5	10.0	2.67	6.79
(ppm)	W	2.67	3.07	3.67	1.17	2.79
	V	8.33	7.33	4.67	2.67	5.75
	F	0.69NS	2.26NS	4.41NS	0.68NS	3.42NS
	F'					1.00NS

Chapter III
Table 1. (Continued)

	ssp. & F.	Squaw Butte	Baker	French-glen	Millican	Mean
-potassium (meq/100g)	T	1.91	1.35	2.17	0.80	1.56
	W	1.59	1.65	1.32	1.13	1.45
	V	1.96	1.08	1.56	1.26	1.64
	F	0.32NS	0.54NS	1.99NS	1.38NS	0.19NS
	F'					1.16NS
-salts (mmhos/cm)	T	.30	.28a	.37	.25	.30a
	W	.83	.77b	.42	.47	.62b
	V	.37	.23a	.25	.33	.30a
	F	0.88NS	36.33**	2.08NS	4.03NS	5.16*
	F'					0.64NS
-clay (%)	T	11.7	20.9	10.9	2.9	11.6
	W	10.8	30.0	21.2	20.3	20.6
	V	19.7	17.9	19.6	12.1	17.3
	F	0.55NS	0.68NS	1.52NS	1.92NS	2.09NS
	F'					0.74NS
-15 bar water retention (%)	T	11.61	16.89	13.46	8.57	12.63a
	W	12.50	26.22	31.64	14.68	21.26b
	V	16.22	13.78	17.90	11.42	14.83a
	F	0.47NS	4.83NS	3.99NS	1.27NS	14.45**
	F'					0.72NS

approximately the same depth as from the *A.t.* ssp. *tridentata* and *A.t.* ssp. *wyomingensis* B horizons were used in place of Frenchglen *A.t.* ssp. *vaseyana* B horizons for a comparison (not listed in Table 2) of chemical properties by subspecies. The only difference in significance of the results was that, organic matter was significantly lower in *A.t.* ssp. *wyomingensis* soil horizons than in *A.t.* ssp. *vaseyana* soil horizons of the same depth.

Nearly all of the surface soil chemical characteristics showed either no significant differences between subspecies as a whole or a significant interaction between location and subspecies indicating comparison analysis should proceed at individual locations. Most of the significant differences found in individual locations are at Frenchglen. In the surface soil at Frenchglen, *A.t.* ssp. *vaseyana* sites had lower pH, higher organic matter, higher cation exchange capacity, lower base saturation, lower percent exchangeable sodium and more water retention at -15 bars pressure than *A.t.* ssp. *wyomingensis* sites. Fewer characteristics of *A. t.* ssp. *tridentata* sites were significantly different. Potassium in the surface soil was highest on *A.t.* ssp. *tridentata* sites and lowest on *A. t.* ssp. *wyomingensis* sites. Lower pH and higher organic matter are probably a reflection of the higher precipitation and cooler temperatures at higher elevations. Lower base saturation and percent exchangeable sodium are probably a direct effect of increased leaching caused by the increased precipitation on *A.t.* ssp. *vaseyana* sites. Most of these surface horizon trends at Frenchglen are also reflected in the results for subspecies when taken as a whole, but only pH and -15 bar water retention clearly indicate a study wide significant difference.

Except for pH, subsurface horizon trends between subspecies were similar at all locations and therefore there were more study wide significant differences than in surface horizons. Subsurface soil characteristics with study wide significant differences between subspecies included CEC, percent of exchangeable sodium, salts, and -15 bar water retention. In the deeper soil horizons at Frenchglen, *A. t.* ssp. *vaseyana* sites had lower pH and base saturation than *A. t.* ssp. *tridentata* sites, and lower pH than *A. t.* ssp. *wyomingensis* sites.

Cation exchange capacity (CEC) showed a contrasting trend between subspecies at the two horizons. In surface soil, CEC appeared higher on *A. t.* ssp. *vaseyana* sites than on *A. t.* ssp. *wyomingensis* sites, although differences were significant only at Frenchglen. Whereas in the subsurface horizon, *A. t.* ssp. *wyomingensis* sites had significantly higher CEC than *A. t.* ssp. *tridentata* sites. This might be explained by a difference in importance of the relative proportion of organic matter and clay in the soil. Both provide exchange sites but organic matter levels are higher at the surface and clay levels are higher in subsurface horizons. Cation exchange capacity is significantly correlated with organic matter in the surface soils ($r^2 = .41$) and is significantly correlated with clay in deeper horizons ($r^2 = .50$). Organic matter in the surface soil was highest on *A. t.* ssp. *vaseyana* sites at all four locations, although significantly so only at Baker and Frenchglen. Mean clay content in subsurface soil is nonsignificantly highest in the *A. t.* ssp. *wyomingensis* sites and *A.t.* ssp. *vaseyana* sites have the highest surface soil clay content.

A soil physical characteristic which reflects some trends in the data of table 1 is percentage of moisture retained at -15 bars of potential. Water retention at -15 bars was significantly greater in surface horizons of *A.t.* ssp. *vaseyana* sites and in subsurface horizons of *A.t.* ssp. *wyomingensis* sites. These results probably reflect the nonsignificantly higher clay and organic matter in surface horizons at *A.t.* ssp. *vaseyana* sites and the nonsignificantly higher clay and significantly higher salts and percent exchangeable sodium in subsurface horizons of *A.t.* ssp. *wyomingensis* sites. Miller et al. (1982) found *A.t.* ssp. *vaseyana* to be the least water stressed of the three subspecies early in the summer but *A.t.* ssp. *wyomingensis* to be the least stressed subspecies late in the summer. Sturges (1977) found that both subspecies *vaseyana* and *wyomingensis* use soil moisture at the surface first and then at greater depth as surface soil moisture becomes less available.

Differences between locations were also very often confounded by significant interactions between location and subspecies, however subsurface horizons at the Millican sites had significantly lower organic matter, cation exchange capacity, potassium and -15 bar water retention than subsurface horizons at Frenchglen and Baker, and lower clay content than at Baker. This appears to be a result of the surficial tephra deposits which strongly influence many Millican sites

(Appendix 1).

As discussed above, many chemical characteristics are a function of elevation and are interrelated with each other. Table 2 presents four predictive equations for base saturation based on pH, organic matter, and cation exchange capacity. Overall, the equations for Frenchglen are better than those developed for all four locations combined. Although CEC is not significantly correlated with elevation (Table 3), base saturation, pH, and organic matter, in surface and subsurface soils are.

Chapter III
Table 2. Predictive equations and multiple coefficients of determination from multiple regressions for predicting base saturation (BS) with three independent variables; pH, organic carbon (OM), and cation exchange capacity (CEC).

Frenchglen		
surface soil	BS = −.93 x 0.25 pH x .03 OM x 0.01 CEC	r^2 = .84
subsurface soil	BS = .20 x .13 pH x .01 OM x .01 CEC	r^2 = .78
All sites		
surface soil	BS = 1.04 x .01 pH x .004 OM x .01 CEC	r^2 = .41
subsurface soil	BS = .10 x .17 pH x .61 OM x .06 CEC	r^2 = .70

Chapter III
Table 3. Coefficients of determination for elevation and soil chemical characteristics.

	r^2 (surface soil)	r^2 (subsurface soil)
Chemical characteristic:		
Base saturation	.23**	.35**
pH	.30**	.21**
Organic matter	.25**	.19**
Cation exchange capacity	.06	.03

Also potentially related to elevation, is the correlation of parent rock with some soil characteristics. Both surface and subsurface soils have higher organic matter and cation exchange capacities on Steens basalt than on alluvium, fanglomerate, or silicic vent rocks. However, soils from Steens basalt are at a higher average elevation.

Conclusions

As reported by others, and supported here with soil physical and chemical data, the three subspecies of *artemisia tridentata* tend to occupy different parts of the landscape. These differences tend to fit the elevational and soil depth pattern described by Winward (1980); however, there was a great deal of variability, and differentiating a *wyomingensis* site from a *vaseyana* site based on only these soil characteristics was not possible. Distribution of the subspecies is apparently dependent on a wide variety of ecological factors that are only partially reflected in the easily measured physical or chemical indices used in this research. Many soil profile characteristics are interrelated and significantly correlated with elevation. These elevational trends may be expected whether or not subspecies distribution boundaries are crossed.

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Appendix 1. Study area site descriptors and average 13-28 minute infiltration rate, total soil loss, and nitrogen concentration in runoff water.

Site[a]	Elev.[b]	Topo-graphy	Geology[d]	Soil family[e]	Habitat type[g]	Range Cond.[h]	Organic ground cover %	Infil-tration (cm hr^{-1})	Soil loss (kg ha^{-1})	Nitrogen con. %
ST1	4,400	0-5% N	Alluvium (Holocene)	Aridic Haploxeroll coarse loamy, frigid	t/ *Elymus cinereus*	P	41	4.7	2820	.00345
ST2	4,500	2-6% - (3.6%)	Alluvium (Holocene)	Xerollic Durorthid coarse loamy, frigid	t/ *Elymus cinereus*	P	17	3.7	1888	.00225
ST3	4,500	2-7% - (6.3%)	Alluvium (Holocene)	Aridic Haploxeroll coarse loamy, frigid	t/ *Elymus cinereus*	G	38	6.6	3301	.00342
SW1	4,400	3-7% N (4.7%)	Fanglomerate (Pleist. & Holocene)	Xerollic Durorthid coarse loamy, frigid	w/ *Festuca idahoensis*	F	33	7.0	770	.00093
SW2	4,500	3-6% S (4.5%)	Olivine basalt (Pliocene)	Xerollic Durorthid coarse loamy, frigid	w/ *Stipa thurberiana*	G	28	5.7	1718	.00208
SW3	4,700	3-12% SE (7.2%)	Alluvium (Holocene)	Aridic Durixeroll coarse loamy, frigid	w/ *Festuca idahoensis*	F	27	4.4	2655	.00273
SV1	4,900	5-10% WNW (8.0%)	Silicic vent rocks (Mio. & Pliocene)	Aridic Haploxeroll coarse loamy, frigid	v/ *Festuca idahoensis*	G	48	6.9	1096	.0023
SV2	5,000	3-15% WNW (8.8%)	Silicic vent rocks (Mio. & Pliocene)	Typic Argixeroll clayey skeletal, frigid	v/ *Festuca idahoensis*	G	29	4.5	2630	.00262
SV3	4,700	2-8% SE (4.8%)	Alluvium (Holocene)	Typic Durixeroll sandy, frigid	v/ *Festuca idahoensis*	F	28	4.2	2538	.00298
BT1	3,600	1-10% N (6.2%)	Alluvium (Holocene)	Aridic Haploxeroll loamy skeletal, frigid	t/ *Agropyron spicatum*	P	65	5.4	399	.00093
BT2	3,100	10-15% NW (10%)	Mafic plutonic rocks (Triassic)	Typic Argixeroll fine loamy, mesic	t/ *Agropyron spicatum*	P	68	7.6	636	.00132
BT3	3,600	1-10% S (9.8%)	Alluvium (Holocene)	Xerollic Durorthid fragmental, frigid	t/ *Elymus cinereus*	P	52	7.6	740	.00147

Appendix 1. (continued)

Site[a]	Elev.[b]	Topo-graphy	Geology[d]	Soil family[e]	Habitat type[g]	Range Cond.[h]	Organic ground cover %	Infil-tration (cm hr^{-1})	Soil loss (kg ha^{-1})	Nitrogen con. %
BW1	3,600	5-10% NE (7.6%)	Tuffaceous sed. rock (Plio. & Pleistocene)	Xerollic Durorthid clayey/sandy skeletal, fr.	w/ *Festuca idahoensis*	F	64	5.0	797	.00120
BW2	3,600	10-15% W (11.4%)	Tuffaceous sed. rocks (Plio. & Pleistocene)	Xerollic Durorthid fine loamy, frigid	w/ *Festuca idahoensis*	P	36	4.1	1060	.00118
BW3	3,600	1-8% - (7.0%)	Basalt & Andecite flows (Miocene)	Haploxerollic Durorthid coarse loamy, frigid	w/ *Festuca idahoensis*	G	39	9.4	692	.00141
BV1	3,900	10-25% E (12.3%)	Granite & Diorite (Triassic)	Pachic Argixeroll coarse loamy, frigid	v/ *Festuca idahoensis*	F	73	6.3	1288	.00250
BV2	3,500	7-15% W (8.9%)	Volcanic rocks (Permian & Triassic)	Typic Haploxeroll coarse loamy, frigid	v/ *Festuca idahoensis*	G	81	7.0	219	.00104
BV3	3,600	10-20% N (15.7%)	Volcanic rocks (Permian & Triassic)	Lithic Haploxeroll coarse loamy, frigid	v/ *Festuca idahoensis*	F	69	8.6	308	.00114
FT1	4,200	5-10% E (6.2%)	Alluvium (Holocene)	Pachic Argixeroll fine loamy, mesic	t/ *Elymus cinereus*	P	96	11.3	81	.00100
FT2	4,700	3-12% N (8.2%)	Steens basalt (Miocene)	Pachic Haploxeroll coarse loamy, frigid	t/ *Stipa thurberiana*	P	55	7.3	1024	.00193
FT3	4,800	1-6% - (5.4%)	Alluvium (Holocene)	Xerollic Camborthid coarse loamy, frigid	t/ *Elymus cinereus*	P	59	3.5	4342	.00318
FW1	4,300	2-10% NW (6.2%)	Steens basalt (Miocene)	Haploxerollic Durargid fine loamy, mesic	w/ *Poa sandbergii*	P	24	2.9	3699	.00330
FW2	4,700	5-15% NW (9.0%)	Steens basalt (Miocene)	Xerollic Camborthid loamy/sandy skeletal, fr.	w/ *Stipa thurberiana*	F	35	4.5	3159	.00257
FW3	4,800	5-13% NW (8.6%)	Silicic ash flow tuff (Pliocene)	Xerollic Dyrargid fine silty, frigid	w/ *Poa sandbergii*	F	17	2.6	7537	.00313

Appendix 1. (continued)

Site[a]	Elev.[b]	Topo- graphy	Geology[d]	Soil family[e]	Habitat type[g]	Range Cond.[h]	Organic ground cover %	Infil- tration (cm hr^{-1})	Soil loss (kg ha^{-1})	Nitrogen con. %
FV1	5,700	10-20% N (13.2%)	Steens basalt (Miocene)	Typic Cryboroll fine loamy,	v/ *Festuca idahoensis*	P	74	10.3	418	.00138
FV2	6,200	6-12% N (9.3%)	Steens basalt (Miocene)	Pachic Cryboroll fine loamy,	v/ Festuca idahoensis	F	94	10.0	174	.00154
FV3	7,000	7-10% SSE (8.4%)	Steens basalt (Miocene)	Pachic Cryboroll loamy skeletal,	v/ Festuca idahoensis	P	85	9.6	332	.00165
MT1	3,600	1-5% S (4.3%)	Fanglomerate (Pleist. & Holocene)	Xerollic Durorthid[f] sandy, frigid	t/ *Stipa thurberiana*	P	35	9.6	155	.00103
MT2	3,700	1-4% - (3.1%)	Fanglomerate (Pleist. & Holocene)	Xerollic Durorthid[f] coarse loamy, frigid	t/ *Stipa thurberiana*	P	3	12.3	0	
MT3	4,500	4-5% N (6.0%)	Lacustrine sed. rocks (Pleistocene)	Aridic Haploxeroll sandy, frigid	t/ *Stipa comata*	P	45	10.3	74	.00058
MW1	4,500	5-15% N (8.9%)	Olivine basalt (Pliocene)	Xerollic Durorthid fine, frigid	w/ *Festuca idahoensis*	G	26	12.3	130	.00103
MW2	4,400	0-2% - (4.6%)	Lacustrine sed. rocks (Pleistocene)	Xerollic Camborthid coarse loamy, frigid	w/ *Stipa thurberiana*	P	21	2.8	8247	.00410
MW3	4,500	2-5% SW (4.4%)	Fanglomerate (Pleist. & Holocene)	Xerollic Camborthid[f] sandy, frigid	w/ *Stipa comata*	P	18	6.4	901	.00127
MV1	5,200	5-10% W (6.8%)	Silicic vent rocks (Mio. & Pliocene)	Typic Argixeroll coarse loamy, frigid	v/ *Festuca idahoensis*	F	23	5.1	1730	.00232
MV2	5,600	5-10% NE (6.7%)	Silicic vent rocks (Mio & Pliocene)	Argic Cryboroll[f] loamy skeletal,	v/ *Festuca idahoensis*	G	78	8.7	300	.00138
MV3	5,600	8-12% N	Silicic vent rocks	Lithic Cryboroll[f]	v/ *Festuca idahoansis*	G	51	8.5	377	.00163

Appendix 1. (Continued) Footnotes

[a]Each site is identified by a 3-character code; location, subspecies, site number:

Location:	Subspecies:
S = Squaw Butte	T = ssp. *tridentata*
B = Baker	W = ssp. *wyomingensis*
F = French Glen	V = ssp. *vaseyana*
M = Millican	

[b]1000 ft = 305 m.

[c]Slope range and aspect-number in ( ) is mean slope of plot surfaces.

[d]From Walker (1977) except that some alluvium was presumed too small to map.

[e]Mineralogy class on all sites is mixed.

[f]Sites strongly influenced by a surficial deposit of Newberry Crater or Mazama pumice.

[g]The letter/ signifies the subspecies of *Artemisia tridentata* in the overstory.

[h]Ecological condition class: P = poor, F = fair, and G = good.

[i]Organic ground cover = live and dead vegetation in infiltrometer plots.

Appendix 2. Precipitation depth duration frequency. Figures are in tenths of an inch (Miller et al. 1973).

St[a]	2y/6h[b]	2y/24h	100y/6h	100y/24h	2y/1h	100y/1h	2y/28m	100y/28m
S	6.5	12	15	26	3.8	7.4	2.9	5.6
MT1	7.5	15	16.3	28	5.0	8.1	3.8	6.2
MT2	7.5	15	16.3	28	5.0	8.1	3.8	6.2
MT3	6.8	13	15.5	29	4.1	7.1	3.1	5.4
MW1	6.8	13	15.5	29	4.1	7.1	3.1	5.4
MW2	6.8	13	15.5	29	4.1	7.1	3.1	5.4
MW3	6.8	13	15.5	29	4.1	7.1	3.1	5.4
MV1	8.0	16	17	30	5.4	8.2	4.1	6.2
MV2	6.8	13.5	15.8	27	4.2	7.9	3.2	6.0
MV3	6.8	13.5	15.8	27	4.2	7.9	3.2	6.0
BT1	6.5	10	15.5	23	3.0	8.9	2.3	6.8
BT2	7.0	11	14	23	4.0	7.3	3.0	5.5
BT3	7.0	12	16	24	3.8	9.1	2.9	6.9
BW1	6.5	10	15.5	23	3.0	8.9	2.3	6.8
BW2	6.5	10	15.5	23	3.0	8.9	2.3	6.8
BW3	6.3	12	14.5	24	3.8	7.5	2.9	5.7
BV1	9.0	16	18	30	5.8	9.2	4.4	7.0
BV2	7.0	12	16	25	3.8	8.7	2.9	6.6
BV3	7.0	12	16	25	3.8	8.7	2.9	6.6
FT1	6.0	10	14	23	3.1	7.3	2.4	5.5
FT2	7.0	14	16	27	4.4	8.1	3.4	6.2
FT3	6.5	12	15	24	3.8	8.0	2.4	6.1
FW1	6.5	12	15	24	3.8	8.0	2.9	6.1
FW2	6.5	12	15	24	3.8	8.0	2.9	6.1
FW3	6.5	12	15	24	3.8	8.0	2.9	6.1
FV1	7.0	14.5	16	27.5	4.6	7.9	3.5	6.0
FV2	7.5	15	17	28.5	4.8	8.6	3.6	6.6
FV3	8.0	15.5	18	30	5.0	9.2	3.8	7.0

[a]Each site is identified by a 3-character code; location, subspecies, and site number:

Location:
S = Squaw Butte,
B = Baker
F = French Glen
M = Millican

Subspecies:
T = ssp. *tridentata*
W = ssp. *wyomingensis*
V = ssp. *vaseyana*

[b]2y/6h stands for 2 year - 6 hour maximum expected precipitation (m = minutes).

Appendix 3. Analysis of Variance Tables

A. Average 13-28 minute infiltration (cm hr^{-1}) analyzed for differences by subspecies and location.

Source of variation	d.f.	Mean square	F	Significance of F
Main effects				
Location	3	555,490	2.88	.057 †
Subspecies	2	533,849	2.77	.083 †
2-way interactions	6	410,262	2.13	.087 †
Explained	11	472,340	2.45	.032 *
Residual	24	192,691		
Total	35	280,581		

B. Total soil loss (kg ha^{-1}) analyzed for differences by subspecies and location.

Source of variation	d.f.	Mean square	F	Significance of F
Main effects				
Location	3	5,185,545	1.83	>.100 NS
Subspecies	2	9,271,854	3.27	.060 †
2-way interactions	6	4,862,824	1.72	>.100 NS
Explained	11	5,752,480	2.03	.075 †
Residual	24	2,834,359		
Total	35	3,751,483		

Appendix 3 (continued)

C. Percentage Nitrogen in the runoff water analyzed for differences by subspecies and location.

Source of variation	d.f.	Mean square	F	Significance of F
Main effects				
Location	3	284.38	4.90	<.01 **
Subspecies	2	39.73	0.69	>0.1 NS
2-way interactions	6	148.66	2.56	0.048 *
Explained	11	165.87	2.86	.018 *
Residual	24	57.99		
Total	35	91.89		

D. Average 13-28 minute infiltration (cm hr^{-1}) analyzed for differences by subspecies at a location.

Squaw Butte:				
Subspecies	2	0.40	0.20	>0.1 NS
Residual	6	2.04		
Total	8	1.63		
Baker:				
Subspecies	2	0.98	0.27	>0.1 NS
Residual	6	3.60		
Total	8	2.95		
Frenchglen:				
Subspecies	2	33.64	6.16	.047 *
Residual	6	5.46		
Total	8	12.50		
Millican:				
Subspecies	2	12.00	1.23	>0.1 NS
Residual	6	9.72		
Total	8	10.29		

Appendix 3 (continued)

E. Total soil loss (g .232 m^{-2}) analyzed for differences by subspecies at a location:

Source of variation	d.f.	Mean square	F	Significance of F
Squaw Butte:				
Subspecies	2	374.99	0.97	>0.1 NS
Residual	6	385.51		
Total	8	382.88		
Baker:				
Subspecies	2	34.18	0.45	>0.1 NS
Residual	6	75.26		
Total	8	64.99		
Frenchglen:				
Subspecies	2	8451.	4.38	.075 †
Residual	6	1927.		
Total	8	3558.		
Millican:				
Subspecies	2	4011.	1.08	>0.1 NS
Residual	6	3727.		
Total	8	3798.		

Appendix 3 (continued)

F. Percentage nitrogen in the runoff water analyzed for differences by subspecies at a location:

Source of variation	d.f.	Mean square	F	Significance of F
Squaw Butte:				
Subspecies	2	97.53	2.07	>0.1 NS
Residual	6	47.12		
Total	8	59.72		
Baker:				
Subspecies	2	9.54	0.38	>0.1 NS
Residual	6	25.37		
Total	8	21.41		
Frenchglen:				
Subspecies	2	168.32	3.70	.093 †
Residual	6	45.51		
Total	8	76.21		
Millican:				
Subspecies	2	210.32	1.84	>0.1 NS
Residual	6	113.93		
Total	8	138.03		

G. Average 13-28 minute infiltration (cm hr^{-1}) analyzed for differences by habitat type:

Habitat type	2	121,960.	.471	.631 NS
Residual	21	259,098		
Total	23	247,173		

H. Total soil loss (g .232 m^{-2}) analyzed for differences by habitat type.

Covariables				
rainfall	1	.091	000	.991 NS
Habitat type	2	1883.	2.75	.088 †
Residual	20	685.		
Total	23	759.		

Appendix 3 (continued)

I. Average 13-28 minute infiltration (cm hr^{-1}) analyzed for differences by dominant understory species.

Source of variation	d.f.	Mean square	F	Significance of F
Dominant understory	2	2.7	0.35	>.1 NS
Residual	27	7.71		
Total	29	7.36		

J. Total soil loss (g .232 m^{-2}) analyzed for differences by dominant understory species.

Dominant understory	2	3409	2.32	.117 NS
Residual	27	1467		
Total	29	1601		

K. Average 13-28 minute infiltration (cm hr^{-1}) analyzed for differences by presence or absence of tephra deposits.

Tephra presence	1	29.32	4.26	.048 *
Residual	34	6.88		
Total	35			

L. Total soil loss (g .232 m^{-2}) analyzed for differences by presence or absence of tephra deposits.

Tephra presence	1	9,380,554	2.62	>.1 NS
Residual	34	3,585,922		
Total	35			

M. Average 13-28 minute infiltration (cm hr^{-1}) analyzed for differences by habitat type, but omitting tephra sites.

Habitat type	2	2.00	0.26	>.1 NS
Residual	19	7.56		
Total	21	7.03		

N. Total soil loss (kg ha^{-1}) analyzed for differences by habitat type but omitting tephra sites.

Habitat type	2	2,856,411	2.19	>.1 NS
Residual	19	1,302,114		
Total	21	1,450,141		

Appendix 3 (continued)

O. Average 13-28 minute infiltration (cm hr^{-1}) analyzed for differences by surface texture.

Source of variation	d.f.	Mean square	F	Significance of F
Texture	3	892,668	4.00	.016 *
Residual	32	223,198		
Total	35	280,581		

P. Average 13-28 minute infiltration (cm hr^{-1}) analyzed for differences by soil order.

Order	3	511,570	1.87	.18 NS
Residual	32	273,787		
Total	35	280,581		

Q. Total soil loss (g .232 m^{-2}) analyzed for differences by soil order.

Order	1	7254	3.88	.057 †
Residual	34	1867		
Total	35	2022		

R. Average 13-28 minute infiltration (cm hr^{-1}) analyzed for differences by soil suborder.

Suborder	3	565,024	2.23	.1043 NS
Residual	32	253,915		
Total	35	280,581		

S. Total soil loss (g .232 m^{-2}) analyzed for differences by soil suborder.

Suborder	3	3263	1.71	.184 NS
Residual	32	1905		
Total	35	2022		

T. Average 13-28 minute infiltration (cm hr^{-1}) analyzed for differences by soil order but omitting tephra sites.

Order	1	1,051,399	4.38	.045 *
Residual	29	240,149		
Total	30	267,191		

Appendix 3 (continued).

U. Total soil loss (g .232 m^{-2}) analyzed for differences by soil order but omitting tephra sites.

Source of variation	d.f.	Mean square	F	Significance of F
Order	1	10,856	5.76	.023 *
Residual	29	1,884		
Total	30	2,183		

V. Average 13-28 minute infiltration (cm hr^{-1}) analyzed for differences by soil suborder but omitting tephra sites.

Suborder	3	681,139	3.08	.044 *
Residual	27	221,197		
Total	30	267,191		

W. Total soil loss (g .232 m^{-2}) analyzed for differences by soil suborder but omitting tephra sites.

Suborder	3	4,165	2.12	.121 NS
Residual	27	1,963		
Total	30	2,183		

X. Average 13-28 minute infiltration (cm hr^{-1}) analyzed for differences by surface soil morphology class.

Morphology	9	11,516,119	45.14	.000 **
Residual	647	255,120		
Total	656	401,615		

Y. Total soil loss (g .232 m^{-2}) analyzed for differences by surface soil morphology class.

Morphology	9	80,432	35.28	.000 **
Residual	647	2,280		
Total	656	3,352		

Z. Average 13-28 minute infiltration (cm hr^{-1}) analyzed for differences by surface soil morphology class but omitting tephra sites.

Morphology	9	9,038,386	35.04	.000 **
Residual	548	257,934		
Total	557	399,809		

Appendix 3 (continued).

AA. Total soil loss (g .232 m^{-2}) analyzed for differences by surface morphology class but omitting tephra sites.

Source of variation	d.f.	Mean square	F	Significance of F
Morphology	9	69,278	25.96	.000 **
Residual	548	2,669		
Total	557	3,745		

BB. Shrub canopy cover (%) analyzed for differences by subspecies and location.

Source of variation	d.f.	Mean square	F	Significance of F
Main effects				
Location	3	295.64	5.58	.005 **
Subspecies	2	195.61	3.69	.042 *
2-way interactions	6	135.43	2.56	.047 *
Residual	24	52.99		

CC. Average 13-28 minute infiltration (cm hr^{-1}) analyzed by multiple regression.

Variable entered on step 1. is coarse sand.

Source of variation	d.f.	Mean square	F	Significance of F
Regression	1	58,226,018	191.73	.000 **
Residual	632	303,687		

Variable entered on step 2. is organic ground cover.

Source of variation	d.f.	Mean square	F	Significance of F
Regression	2	49,954,663	209.80	.000 **
Residual	631	238,109		

Variable entered on step 3. is fine sand.

Source of variation	d.f.	Mean square	F	Significance of F
Regression	3	35,920,410	158.92	.000 **
Residual	630	226,024		

Variable entered on step 4. is coarse fragments.

Source of variation	d.f.	Mean square	F	Significance of F
Regression	4	27,066,567	119.99	.000 **
Residual	629	225,580		

Appendix 3 (continued).

Source of variation	d.f.	Mean square	F	Significance of F
DD. Total soil loss (kg ha^{-1}) analyzed by multiple regression.				
Variable entered on step 1. is organic ground cover.				
Regression	1	431,814	156.87	.000 **
Residual	632	2,753		
Variable entered on step 2. is clay.				
Regression	2	419,769	198.85	.000 **
Residual	631	2,111		
Variable entered on step 3. is coarse fragments.				
Regression	3	301,144	149.61	.000 **
Residual	630	2,012		
Variable entered on step 4. is silt.				
Regression	4	252,664	136.90	.000 **
Residual	629	1,846		
EE. Average 13-28 minute infiltration (cm hr^{-1}) analyzed by multiple regression but omitting tephra sites.				
Variable entered on step 1. is organic ground cover.				
Regression	1	62,448,298	223.10	.000 **
Residual	552	279,913		
Variable entered on step 2. is coarse fragments.				
Regression	2	31,779,389	114.15	.000 **
Residual	551	278,406		
FF. Total soil loss (kg ha^{-1}) analyzed by multiple regression but omitting tephra sites.				
Variable entered on step 1. is bare ground.				
Regression	1	657,705	255.47	.000 **
Residual	552	2,574		
Variable entered on step 2. is coarse fragments.				
Regression	2	335,696	131.42	.000 **
Residual	551	2,554		

Appendix 3 (continued)

Source of variation	d.f.	Mean square	F	Significance of F
GG. Average 13-28 minute infiltration (cm hr^{-1}) analyzed by multiple regression with sodium, calcium, and shrub canopy cover.				
Variable entered on step 1. is sodium.				
Regression	1	1,025,071	4.18	.049 *
Residual	33	245,100		
HH. Average 13-28 minute infiltration adjusted for percent medium and coarse sand analyzed for differences by condition class.				
Condition class	2	2.84	0.70	>.100
Residual	33	4.14		
Total	35	4.06		
II. Average 13-28 minute infiltration adjusted for percent medium and coarse sand analyzed for differences by subspecies and location.				
Main effects				
Location	3	2.88	.88	>.100 NS
Subspecies	2	5.15	1.58	>.100 NS
2-way interaction	6	7.49	2.30	.075 †
Residual	24	3.26		

Appendix 4. Mean squares from analysis of variance tables for Chapter 3.

		Characteristics analyzed													
						Surface horizon									
Source	d.f.	Elevation	Depth of max. ill.	Rooting depth	Moisture storage cap.	pH	Organic matter	CEC	Base saturation %	% Exch. sodium	Phosphorous	Potassium	Salts	Clay	-15 bar H_2O
Level of Analysis															
All *locations:*															
Main effects															
Location	3	399.14	37.53	2221.2	36.09	0.133	6.82	154.6	55.59	24.14	178.3	1.31	.0031	70.98	40.7
Subspecies	2	318.25	1123.54	4533.9	12.04	0.464	38.21	88.0	231.36	42.04	123.4	1.206	.0015	24.44	49.0
2-way interactions	6	58.8	864.62	4178.6	119.30	0.146	8.71	43.1	165.40	16.14	480.4	1.422	.0054	26.83	25.1
Residual	24	9.0	262.64	1855.5	37.12	0.080	2.08	12.1	33.58	3.42	103.8	.305	.0049	21.19	10.8
Squaw Butte															
Subspecies	2	13.78	55.86	4783.	93.15	0.03	0.42	10.75	24.33	.73	447.0	0.41	.0025	25.6	9.8
Residual	6	1.67	92.50	1557.	25.46	0.05	0.97	8.12	10.56	.22	12.0	0.36	.0033	6.6	15.1
Baker															
Subspecies	2	4.33	645.	1550.	73.93	0.12	6.75	21.01	17.44	10.47	379.0	0.649	.00028	10.4	10.1
Residual	6	4.22	707.	2630.	42.49	0.10	0.36	5.93	78.44	.28	176.0	0.263	.0083	28.1	4.3
Frenchglen															
Subspecies	2	294.8	2428.	7141.	65.13	0.57	33.4	143.5	609.78	79.1	240.0	3.89	.0042	9.5	65.4
Residual	6	20.1	168.	404.	14.93	0.06	3.5	8.42	27.67	13.09	134.0	0.17	.0043	10.7	11.2
Millican															
Subspecies	2	181.8	588.1	3595.	137.6	0.17	23.78	41.90	82.11	.19	234.	0.51	.0102	59.4	39.0
Residual	6	10.0	157.1	2831.	65.6	0.14	3.50	26.01	27.11	.08	181.	0.43	.0036	39.3	12.6
All locations															
Parent rock	3	268.8					20.53	149.41							
Residual	19	45.8					5.51	21.10							

Appendix 4. (continued)

		Characteristics analyzed									
		Subsurface horizon									
Source	d.f.	pH	Organic matter	CEC	Base saturation	% Exch. sodium	Phos-phorous	Potas-sium	Salts	Clay	-15 bar H_2O
Level of Analysis											
All locations:											
Main effects											
Location	3	.0319	.974	253.2	69.81	10.87	43.69	1.034	0.0484	210.2	274.3
Subspecies	2	3.2103	.051	245.7	81.08	187.92	51.67	0.057	0.4193	247.6	383.5
2-way interaction	6	.2532	.530	42.4	34.53	18.06	15.16	0.35	0.0517	87.6	19.2
Residual	23[1]	.0936	.215	36.0	28.26	20.39	15.12	0.302	0.0813	118.3	26.5
Squaw Butte											
Subspecies	2	0.27	.11	7.11	0.78	59.05	25.44	0.122	0.2533	73.1	17.9
Residual	6	0.08	.04	15.15	16.33	37.61	36.67	0.379	0.2864	133.4	38.2
Baker											
Subspecies	2	2.02	.32	250.17	5.44	140.81	28.83	0.238	0.2513	116.3	123.3
Residual	6	0.08	.24	27.39	9.33	32.21	12.77	0.438	0.0069	170.0	25.5
Frenchglen											
Subspecies	2	1.02	.68	29.56	171.0	13.78	34.78	0.576	0.0219	91.3	269.5
Residual	6	0.10	.41	69.52	26.0	8.13	7.89	0.289	0.0106	60.0	67.5
Millican											
Subspecies	2	0.61	.49	78.43	7.44	18.30	1.86	0.171	0.0358	227.3	28.1
Residual	6	0.11	.18	30.36	56.67	5.59	2.75	0.123	0.0089	118.3	22.2
All locations											
Parent rock			3.14	198.37							
Residual			.50	29.53							

[1]Subsurface soil was not collected for analysis at BT-3.