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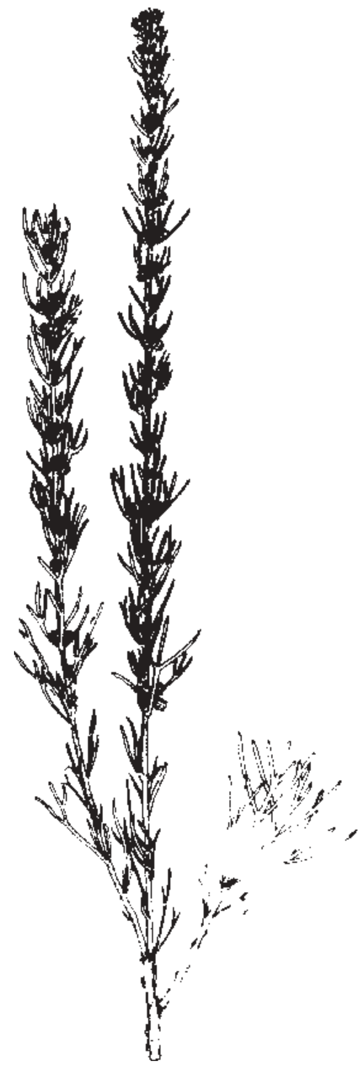
Chapter 7



Assessing Soil Factors in Wildland Improvement Programs

Soil factors are an important consideration for successful wildland range development or improvement programs. Even though many soil improvement and amelioration practices are not realistic for wildlands, their evaluation is an important step in selection of adapted plant materials for revegetation. This chapter presents information for wildland managers on: the importance of soils physical, chemical, and nutrient considerations in wildland restoration and rehabilitation; the basis for evaluating wildland soil suitability for plant growth; effects of management activities on soil factors; assessment of soil nutrient deficiencies in terms of plant needs; development of a fertilizer prescription; and principles of fertilization of wildlands.

The Need for Soil Improvement and Nutrient Amelioration

The Resources Planning Act document (USDA 1980a) and the Public Rangelands Improvement Act (U.S. Laws and Statutes 1978) indicate that public rangelands are producing less than their potential and many are in unsatisfactory condition. These conditions pose a risk of soil loss, desertification, and lowered productivity for large areas. Both the Resources Planning Act and Public Rangelands Improvement Act stress the need to correct the unsatisfactory rangeland conditions through intensified management and improvement techniques. Accomplishing the goals set forth in Resources Planning Act (USDA 1980a) and the Public Rangelands Improvement Act (U.S. Laws and Statutes 1978) will require rehabilitation of depleted wildlands and perhaps the development of marginally productive wildlands.

Intermountain wildlands—in particular rangelands—are no exception to the conclusions drawn by these two laws regarding lands producing below their potential. Managing for improvement of Intermountain wildlands, to date, has stressed: livestock grazing strategies, manipulation or elimination of shrubby species of vegetation to improve range productivity and wildlife habitat, and restoration of watershed stability. Management of soil factors that limit plant establishment and productivity has received little attention. Soil management has been limited because of possible negative cost-benefit ratios.

Wildland soils, especially those where water is the main limiting factor are not usually cultivated, amended by fertilization, or treated to improve their physical or chemical condition. Except for stabilization of human-degraded sites such as surface mined areas, or areas where downstream values are threatened, soil management on unstable areas of inherent low productivity has not been warranted because of excessive costs.

Rehabilitation of sites impacted by surface mining and the resultant spoils has required techniques such as topsoil replacement, terracing, liming, organic soil amendments, irrigation, and transplanting mature plants with specialized equipment. Another problem in the application of soil management technology to wildlands has been the fact that most of the information has been developed for the more fertile, productive, arable lands.

Basic Factors Influencing Soil Fertility, Productivity, and Reclamation Potential

Soil development is a function of climate, organisms, relief, parent material, and time (Jenny 1941, 1980). The ability of a specific site to produce vegetation is determined by the factors that influence soil formation as well as the history of land use (Klemmedson and Tiedemann 1995a). Suitability of the soil for plant growth is determined by those qualities and properties of the natural soil that physically, chemically, and biologically provide the necessary water and nutrients for growth and development of plants. Assessment of the soil's physical state will determine if the soil is suitable for improvement efforts. On eroded lands, for example, the loss of considerable quantities of soluble organic and mineral matter and nutrients accompanies the removal of surface soil layers (Klemmedson and Tiedemann 1995a). In addition to a loss of nutrient capital, removal of the more fertile surface soil layer may expose subsurface soils having abnormal pH (high or low) that can adversely affect nutrient availability.

Erosion also causes changes in productivity that may be difficult to compensate by additional fertilizer application. Such changes are caused by decreased water infiltration, decreased water-holding capacity of the soil, a less favorable root environment, and changes in soil temperature due to a difference in albedo and other factors. The quantitative effects of such changes are not well known (Flach and Johannsen 1981). Thus, assessment of soil factors will determine whether or not improvement would be beneficial or even feasible.

Soil physical properties are related to depth, texture, structure, bulk density, permeability to water, capacity to hold water, and depth to limiting layers. Slope, although not a soil physical factor, is an important consideration in determining the suitability of a site for revegetation and its productivity potential.

Chemical characteristics exert physiological stresses on plants through their effects on plant water relations, nutrient availability and uptake, and toxicity effects related to excess concentrations of certain chemical elements. Chemical characteristics that can be used to determine soil suitability include pH, salinity, and exchangeable sodium percentage. Concentrations of total and available essential plant nutrients in the soil are also an important determinant of soil fertility.

Measuring as many of these factors as possible will assist the land manager in determining wildland soil productivity potential and will provide the means to assess possible success or failure of proposed management or improvement efforts. Although a site may grade as "high" in all categories except one, positive results will not necessarily be realized. In fact, the one factor graded as "low" such as exchangeable sodium percentage or acidity might very well impede or prohibit all efforts to improve or rehabilitate a particular site.

In situations where rehabilitation is mandated, as in fire- or flood-ravaged watersheds, mined areas, or other massive disturbances, table 1 defines soil chemical and physical factors that must be considered if revegetation is to be successful. It will become apparent to

Table 1—Table for evaluating soil characteristics for productivity potential and possible improvement.

Soil property or quality	Level of suitability: Low (essentially unsuitable)	Moderate	High	Reference
USDA texture	Loamy sand, sand (<18% clay)	Clay, silty, clay, (>35% clay)	Sandy loam, sandy clay loam, loam, clay loam, silty clay, loam (18-35% clay)	Brady 1974
Soil structure	Massive, single grain	Platy, blocky prismatic	Granular	Soil Survey Staff 1962
Bulk density (g/cm^3)	>1.6 cc	1.4-1.6	<1.4	Daddow and Warrington 1983; Russell 1973; White 1979
Permeability (cm/hr)	(<0.5) or (>15.0)	5.0-15 and 0.5-1.5	0.6-5.0	Soil Survey Staff 1962
Available water-holding capacity (cm H_2O/ cm soil)	<0.08	0.08-0.16	>0.16	Brady 1974; Broadfoot and Burke 1958
Coarse frag content (%)/wt	>35	15-35	<15	Soil Survey Staff 1962
Depth to limiting layer (cm)	<50	50-100	>100	Soil Survey Staff 1962
Slope %	20-30	10-20	<10	USDA 1965a; Forest Service Handbooks 2209.21 and 2209.31
Organic matter (%)/wt surface soil	<0.5	0.5-2.0	>2.0	Donahue and others 1977; Foth 1978; Hendricks and Alexander 1957
pH	(<5.1) (>8.4)	(5.1 to 6.5) or (7.4 to 8.4)	6.6 to 7.3	Soil Survey Staff 1962
Salinity (mmhos/cm)[a]	>8	4-8	<4	Richards 1954
Exchangeable sodium percentage (ESP)[b]	>15	2-15	<2	Richards 1954

[a] Measured in terms of conductivity of saturated soil extract.
[b] ESP refers to exchangeable sodium percentage.

the reader that many of the soil characteristics are not feasible or practical to amend on wildlands despite the fact that reclamation technology may be presently in use in arable cropland settings.

Seeding or planting adapted species will be the primary feasible means for restoring vegetation, and hence soil stability, to most wildland sites. Despite our inability to alter some of the soil or site conditions, awareness and characterization of soil and site factors is one of the first steps in selecting adapted species.

The importance of each of the various properties that can be used to determine soil suitability (table 1) are discussed.

Soil Texture

The percentages of sand, silt, and clay determine the texture of the soil. Particle size and the percentage composition affect the packing arrangement and the amount of actual surface area per given unit volume of soil (Fairbridge and Finkl 1979; Millar and others 1958). The amount of surface area varies inversely with the size of soil particles.

Because most of the important chemical reactions in soils take place at the surface of the soil particles (Jenny 1980), the amount of surface area per unit volume of soil is important in determining the interaction between plant roots and soils. The surface to volume ratio increases with decreasing particle size (Fairbridge and Finkl 1979; Millar and others 1958).

Texture also controls the rate at which water moves into the soil and the amount of water that can be stored in a given thickness of soil for plants to use. Clay provides the highest surface area, but if clay content is great enough to restrict air and water movement, these critical variables may limit productivity. Soils in the pure sand range have high rates of water infiltration but are low in productivity because they do not retain water or nutrients. The ideal substrate is texturally balanced soil in the loam range. Loam allows for a volume composition which leads to adequate surface area for nutrient exchange sites without compromising air and water space.

Texture can be measured qualitatively in the field by feeling slightly moistened soil. With training, an individual can learn to distinguish the major textural grades by this method. However, the most accurate procedure is to measure texture in the laboratory. For appropriate laboratory methodology, the reader is referred to Methods of Soil Analysis (Black and others 1965a,b).

Soil Structure

Soil structure refers to the "aggregation of primary soil particles (sand, silt, clay) into compound particles, or clusters of primary particles which are separated from adjoining aggregates by surfaces of weakness" (Millar and others 1965). The grouping or arrangement of particles exerts considerable influence on overall soil productivity through effects on water movement, heat transfer, aeration, bulk density, and porosity.

Variations in soil structure are: granular, crumb, platy, blocky, prismatic, and columnar, with a range of intergrades (Fairbridge and Finkl 1979). Structureless soils are either massive or single-grained. Massive soils are more or less compacted, restricting air or water movement. Single-grained soils, are generally excessively drained and low in nutrients. Soils with weak structure are susceptible to raindrop action and are potentially more erosive than soils with good aggregation.

Management considers structure to be one of the most sensitive of the soil characteristics. Machinery and grazing animals both have the potential to adversely affect the structure of the soil (Fairbridge and Finkl 1979; Gifford and Hawkins 1978; Soane and others 1981). In the case of soils high in clay, operating heavy machinery or livestock trampling may puddle the soil. When puddled soil dries, it may become impermeable to moisture, resulting in increased erosion potential and reduced availability of moisture to plants. Destroying structure of coarser soil materials also leads to increased erosion potential.

When prescribed fire is used as a management tool to eliminate residues, reduce competition, or eliminate unwanted vegetation, structure of the soil can be affected if the heat of the fire is great enough to remove litter and duff and expose the mineral soil to puddling and baking of the surface (Wells and others 1979). Prior to initiation of prescribed burning, it would be wise to conduct at least a field evaluation of the soil to determine if it may be susceptible to adverse changes in structure by fire management.

When structure is adversely affected by management, there are generally no economically feasible techniques for correcting the damage except elimination of the cause of the damage and allowing time for restoration of structure. Establishing vegetation on denuded sites will aid in restoration of structure (Fairbridge and Finkl 1979). Soil structure problems on small areas may be amenable to organic matter amendments to improve structure (Fairbridge and Finkl 1979).

Structure can be determined by trained personnel in the field where the overall characteristics of arrangement and aggregation of the soil separates in a profile can be assessed. But the most accurate assessment is by laboratory analysis.

Bulk Density (Volume Weight)

An important land management concern is the possibility of reduced vegetation productivity due to soil compaction (increased bulk density) by recreational vehicles, machinery, and livestock. Studies have shown the detrimental effects of soil compaction on the establishment and growth of range plants (Adams and others 1982; Lull 1959; Wilshire and others 1978). Bulk density of fine textured soils under heavy grazing use in Northeastern Colorado was 1.52 g/cm^3 compared to 1.34 g/cm^3 under light grazing (Van Haveren 1983). On coarse-textured soils, there was no difference between light and heavy grazing. Willatt and Pullar (1984) observed a direct relationship between stocking rate and bulk density.

Effects of soil compaction on plant growth are due to a complex interaction between many soil and plant properties, but for many situations there seems to be an upper limit or threshold bulk density value at which resistance to root penetration is so high that root growth is essentially stopped (O'Connell 1975). Restricted root penetration and elongation also reduces the volume of soil that can be exploited by a plant for essential nutrients and water, thereby causing a reduction in total growth. The established limits (table 1) are averages for intermediate textural grades (Daddow and Warrington 1983; Russel 1973). Bulk density threshold limits have been established for the various textural grades. The reclamation specialist is referred to Daddow and Warrington (1983) for limits based on specific soil textures.

Bulk density is easily measured in the field by trained personnel. See Black and others (1965a) for methodology. Laboratory procedures also determine bulk density.

Permeability

Permeability expresses the rate at which water is transmitted through the soil (Fairbridge and Finkl 1979). In the absence of precise values, soils may be placed into relative permeability classes through studies of bulk density, structure, texture, porosity, cracking, and other characteristics of the horizons in the soil profile in relation to local use experience. Soils with excessively high (>15 cm/hr) or low (<0.5 cm/hr) permeability are low in productive potential. High permeability soils have low water and nutrient retention capacity. In soils with low permeability, water has limited opportunity to enter the soil and the potential for surface runoff and erosion could be increased.

Operation of machinery and trampling by livestock have the potential to reduce permeability through their effects on soil structure and bulk density (Gifford and Hawkins 1978; Soane and others 1981). A review by Gifford and Hawkins (1978) indicates that grazing in some situations causes a marked reduction in infiltration rates of soils. Fire, in addition to altering soil structure, may result in the formation of water repellent layers that reduce infiltration and result in increased surface runoff (Tiedemann and others 1979; Wells and others 1979). In addition to increased erosion, reduced infiltration means less water available for plant growth. Prior to the use of prescribed fire, the potential for development of water repellency and other soil permeability problems should be evaluated. This would necessitate determining the soil texture to detect soils high in clay where soil sealing and puddling problems may arise from elimination of the litter and duff layers.

Permeability can be increased by mechanical treatments such as contour furrowing, terracing, pitting, and water spreading (Vallentine 1971). Specialized machinery such as the rangeland imprinter (Dixon and Simanton 1977) has also been used to promote increased water infiltration.

Permeability is best measured in the field with infiltrometers. Infiltrometers are generally of two types: double ring and rainfall simulators (Wisler and Brater 1959). The double ring infiltrometer is the easiest to set up, use, and interpret.

Available Water-Holding Capacity

Available water is the portion of stored soil water that can be absorbed by plant roots to sustain life. It is that portion of the water that remains in soil after excess water has drained away and the rate of downward movement has decreased materially (Veihmeyer and Hendrickson 1950). Available water-holding capacity depends on bulk density, soil texture, and coarse fragment content (Broadfoot and Burke 1958). See tables in Broadfoot and Burke for specific information on available water-holding capacity with soils of differing texture, bulk density, and percent coarse fragments. Soils in low and moderate ranges are inhibited from being highly productive simply because of their inability to store water and retain nutrients for plant use. Low water-holding capacity would be particularly restrictive to plant productivity in low to moderate precipitation zones or zones with irregular precipitation, especially when dry periods are long and unpredictable in their occurrence. This is the case in many areas throughout the Intermountain West.

Through effects on permeability, any management practice that results in reduced infiltration will cause an increase in surface runoff with the end result of reduced soil water storage.

The determination of available water-holding capacity is a laboratory procedure requiring specialized equipment.

Coarse Fragment Content

Coarse rock and gravel in soils include fragments greater than 2 mm in diameter. The size and amounts of coarse fragments in the soil influence nutrient storage capacity, root growth, moisture storage, water infiltration, and runoff, primarily through their dilution of the mass of active soil. The basis for the arbitrary limits (sizes and percentages) have been determined, taking into consideration interference with agricultural machinery (table 1). Thus, limits may not be as restrictive for seeding methods used to reclaim some rocky or stony wildlands.

Coarse fragments are easily measured using sieving screens of known dimensions.

Depth to Limiting Layer

The depth of soil available for root development will have considerable influence on the forms and types of plants that can inhabit a site (Jenny 1980; Kramer 1969). Shallow soils with restrictive layers near the surface generally can support only drought-tolerant or drought-avoiding plants that normally have shallow roots. A depth restriction may be bedrock, a hardpan or caliche layer, a high water table, a marked textural change (such as loam over gravel), or soil horizons having a limiting effect due to high bulk density or toxicity, such as high salinity.

Physical barriers such as carbonate layers (caliche) that develop in arid regions, and clay layers, can be broken up by ripping or deep chiseling (Vallentine 1971).

Slope

Slope is an important variable in the ability of a site to absorb and retain moisture. It follows that slope is a major determinant of the erosivity of a site—as slope increases, erosion potential increases. Also, as slope increases, the ease with which vegetation is established diminishes.

Slope steepness aggravates effects of management on soil characteristics. Changes in protective soil cover, structure, permeability, and bulk density that would not cause increased surface runoff and erosion on gentle slopes (<10 percent) could pose a serious threat to soil stability as slopes approach 30 percent. Effects of fire on physical soil characteristics and erosion are also amplified by increasing slope steepness (Tiedemann and others 1979; Wells and others 1979; Wright and Bailey 1982).

Organic Matter

All materials of vegetable and animal origin formed in or added to soil are collectively referred to as organic matter (Fairbridge and Finkl 1979). Most of the organic matter added to soils originates from dead plant parts in the form of litter on the surface and decomposition of roots below the surface (Fairbridge and Finkl 1979). Cultivated soils contain only 1 to 5 percent organic matter and Intermountain Great Basin semi-arid wildland soils would generally contain less than 3 percent (Foth 1978; Hagin and Tucker 1982). However, the small amount present can modify the soil's physical properties and can strongly affect its chemical and biological properties.

Organic matter is responsible for desirable soil structure. It increases soil porosity, improves water and air relations, and reduces erosion by wind and water. Chemically, organic matter is the soil storehouse and cycling center of most of the nitrogen (N), 5 to 60 percent of the phosphorus (P), and up to 90 percent of the sulfur (S) (Kowalenko 1978). Availability of nutrients, of course, depends on the rate at which organic matter is decomposed and incorporated into mineral soil. Also of importance is the capacity of organic matter to hold nutrient elements such as potassium (K), calcium (Ca), and magnesium (Mg), similar to the way that clays hold these elements in base exchange equilibria (Brady 1974). In addition, organic matter, by release of acid humus, aids in the extraction of elements from primary and secondary minerals.

The ratio of carbon (C) to nitrogen is an important determinant of nitrogen availability. The normal ratio in undisturbed surface soil (upper 15 cm) is 10 or 12 to 1 (Tisdale and Nelson 1975). As the C:N ratio widens, nitrogen availability is reduced because microbes responsible for organic matter mineralization utilize the available N. Nitrogen fertilization should be considered when this ratio exceeds 12:1.

Depletion of soil carbon by long-term cultivation has been well documented for croplands (Jenny 1933). However, the picture for carbon depletion associated with grazing is not as definitive. Milchunas and Lauenroth (1993) compared soil carbon in grazed areas with that in ungrazed areas for 37 sites around the world. Soil carbon in grazed sites was greater or equal to that in ungrazed for about half of the sites.

Operation of machinery on wildland soils would be expected to incorporate surface accumulations of organic matter in the form of litter and humus. Increased mineralization of this organic matter would tend to create a wide C:N ratio, resulting in short-term reductions in N availability. Thus, it may be necessary to amend the soil with N fertilizer.

Intense fires have generally been shown to reduce organic matter content of the soil surface to a depth of 2 cm, but light or moderate intensity fires cause no change (Wells and others 1979).

There is presently no economically feasible or practical means for amending organic matter content of wildlands on a large scale. Restoration of vegetative cover by reducing grazing, or complete rest of heavily grazed lands, will help restore the organic matter level over time. Although untested on wildlands, nitrogen fertilization has proven effective in the cropland setting for maintaining organic matter levels (Tisdale and Nelson 1975). The potential for organic amendments to alter plant succession was demonstrated by Klemmedson and Tiedemann (1994, 1998). They studied areas inside and outside an abandoned sheep corral on degraded subalpine range of the Wasatch plateau in Utah to determine the influence of 37 years of use of the corral on soil and plant development. The corral had been abandoned for 15 years at the time of the study. Organic matter additions by animal dung significantly increased storage of organic carbon in vegetation, litter, and the 0 to 5 cm and 15 to 30 cm soil layers. Cover of meadow barley (*Hordeum brachyantherum*), a component of the predisturbance vegetation of the plateau was nearly 12 times greater inside the corral than outside. On a larger scale, adding sewage sludge to rangelands shows promise as a means of increasing production and ameliorating organic carbon of the soil (Fresquez and others 1990).

Organic matter must be measured in the laboratory by a qualified chemist or laboratory technician. It is measured as organic carbon by combustion procedures. With soils high in pH, it is important to distinguish organic carbon (that associated with organic materials) from the inorganic carbon associated with carbonate salts.

Soil Reaction

The pH, or degree of acidity of the soil, is an indicator of the chemical condition of the soil as it relates to plant nutrition (Allaway 1957). The full impact of low or high pH can be fully realized if it is understood that it represents the negative log of the hydrogen ion concentration. A pH of 4 has a 10-fold greater hydrogen ion concentration and acidity than pH 5. Optimal pH for nutrient availability is between 5.0 and 7.5, with greatest availability at about 6.5. High and low pH have a significant effect on nutrient availability (table 1). At low pH levels, mineralization of nitrogen is decreased and limited primarily to the formation of NH4-N as the only available N source (Dhaube and Vassey 1973).

In strongly acid soils (pH <5.0) plant establishment and growth may be adversely affected by toxic levels of aluminum (Al), manganese (Mn), and iron (Fe), and by deficiencies or low availability of calcium (Ca), magnesium (Mg), and molybdenum (Mo) (Donahue and others 1977) (fig. 1). In highly alkaline situations (pH 8.0 and above) the availability of certain other nutrients is depressed.

From a soil nutrient amelioration standpoint, P and iron (Fe) are likely to present more problems than other nutrients that become limiting such as Mn, copper (Cu), zinc (Zn), and boron (Bo) (Black 1957). The native supply of the latter four nutrients is apparently adequate to offset effects of low pH on availability. Nitrification is reduced at pH levels of 4.5 resulting in reduced nitrogen availability (Stevenson 1965). Then, too, at a higher pH unacceptable amounts of Mo will be released (Blackbourn 1975).

Fire is the principal management practice that exerts an impact on soil pH. Soil acidity is reduced in the surface soil by burning as a result of release of basic cations by combustion of organic matter and heating of minerals (Wells and others 1979).

The effect of pH on nutrient availability emphasizes the importance of this factor. Whether or not a pH adjustment can be accomplished practically may be the deciding factor for reclamation of a depleted wildland site from a soil improvement perspective. Problems with excessively low pH (rare in Intermountain rangelands) can be corrected by liming. For example, to increase the pH of a sandy loam from 5.0 to 6.5 would require approximately 3 metric tons/ha. See Fairbridge and Finkl (1979) for liming rate calculations.

More common to the Intermountain region are areas of soils with high pH. Most practically, these soil types are treated by selecting adapted species to seed or plant. If it is determined that a high pH is unacceptable, soils can be treated by acid or acid-forming compounds such as sulfur. Sulfur is slow but inexpensive and reasonably permanent. Alkaline soils are often harder to correct than acid soils because they may not only present problems due to the high pH, but are often saline (Tinus 1980). The reclamation of salt-affected soils may not be practical on arid wildlands since a large amount of water is required to leach salts.

The pH of a soil can be measured in the field with a colorimetric test kit or with a portable pH meter. It is one of the easiest and least expensive field measurements of soil chemical characteristics that can be made.

Salinity

The failure of plant establishment or depauperate, patchy growth of plants on salty soils has been recognized since man began to grow crops. Salts detrimentally influence plants by: limiting the availability of moisture (Miller and Doescher 1995), by osmotic inhibition (Bernstein 1961, 1963; Slatyer 1961), and by specific toxic effects on metabolic processes (Miller and Doescher 1995; Richards 1954). Availability of water is reduced because of the increase in solute suction of the soil water as salinity increases. Osmotic inhibition is thought to influence plant growth because of an excess of salts taken up from soils high in salinity (Bernstein 1961, 1963; Slatyer 1961). Specific toxicity is a detrimental effect on plant growth because of excessive accumulation of certain ions.

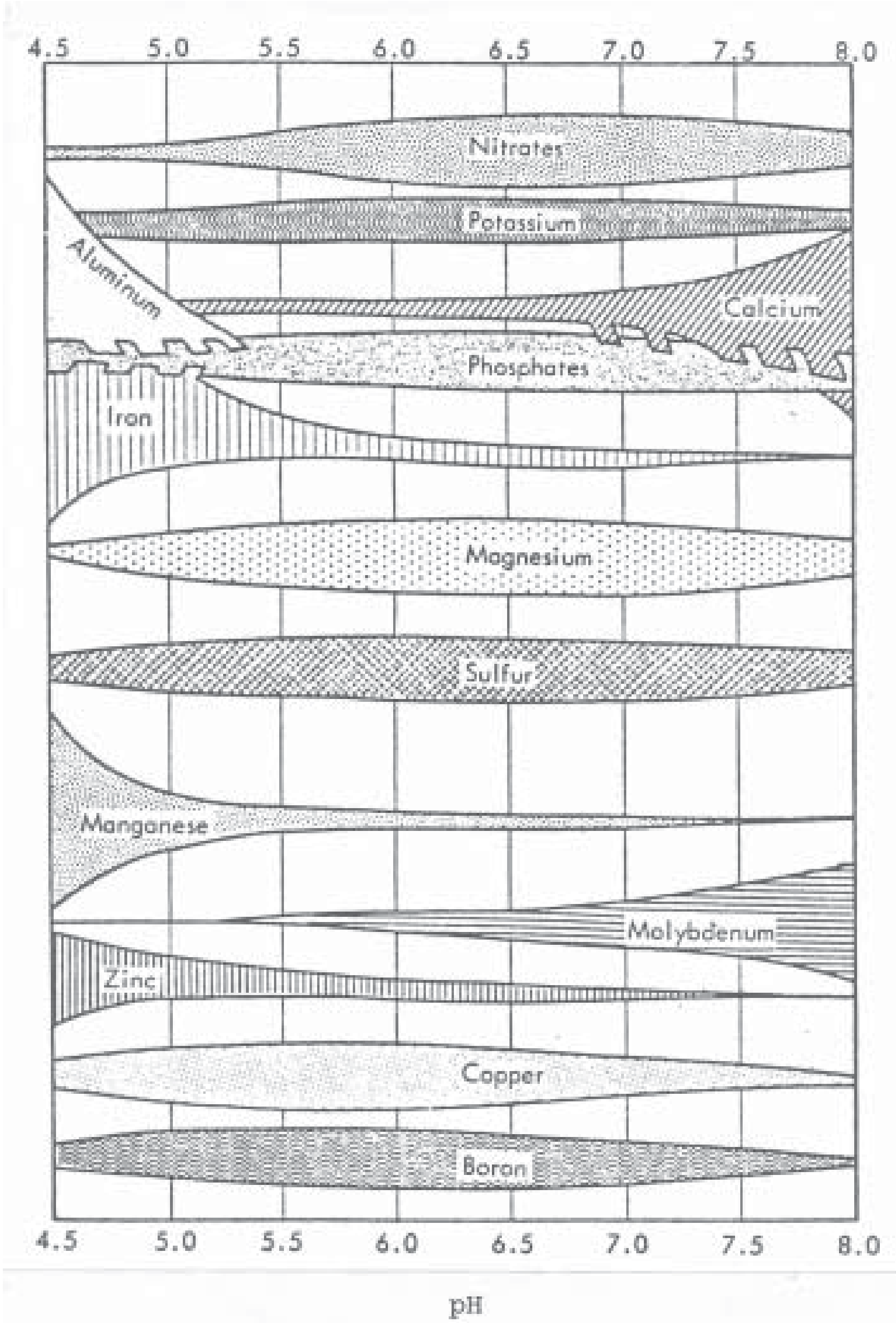


Figure 1—Effect of pH on nutrient availability. Modified after University of Kentucky Agricultural Station Soils Staff (1970).

Ions that are frequently found in high concentrations in saline soils include chloride, sulfate, and bicarbonate. At excessive levels, the influence of these ions on plant growth involves biochemical interferences and nutrient deficiency (Hagin and Tucker 1982; Miller and Doescher 1995). The effect of salinity on plant growth is scaled and based on agricultural crop response to various levels of salts (table 1) (Richards 1954; Scofield 1940). This classification of plant growth in relation to various salinity levels refers to the salt status of the soil in the active root zone. Surface layers may be highly contaminated by surface incrustations of salt, which is not a problem to established plants as long as salts are not later translocated to the root zone. Surface concentrations of salinity may, however, inhibit seedling establishment (Levitt 1980).

In agricultural cropping systems, fertilization of plants in saline soils may be beneficial by reducing the yield-depressing effects of salts, as long as the salinity level is within a low or medium range. In general terms, when the salinity is high enough to depress yield by 50 percent or more, fertilization will yield low returns (Bernstein and others 1974). However, an overall negative effect may result if fertilizers are not carefully selected. The added fertilizers may contribute to an increase in osmotic pressure of the soil solution because of added salts (Champagnol 1979). In the wildland setting, salinity problems are best solved by selecting plant materials that are adapted to grow well in those environments (Miller and Doescher 1995). Where there is a heavy crust of surface salt, it may be necessary to use container or bare-root planting stock since young plants developing from seed may be killed by high osmotic pressures. Soil tillage may also be used to incorporate the highly saline surface layer into the lower layers thereby diluting the osmotic effect and providing a more acceptable surface layer for seeding.

Salinity can be readily measured in the field with a portable solu-bridge test kit.

Exchangeable Sodium Percentage (ESP)

ESP refers to the proportion of the adsorption complex of a soil occupied by sodium. It is expressed as follows:

ESP = exchangeable sodium (milliequivalents/100 g soil)/ cation exchange capacity (cec) (milliequivalents/ 100 g soil) x 100

If a high proportion of the exchange sites are occupied by sodium ions, soils can become very alkaline (pH 8.5 to 10.5). The effect on soil structure is disintegration and disbursement that can lead to slow rates of infiltration or to impermeability. The exchangeable sodium percentage at which soils disperse is correlated to clay type. An ESP of 15 is a good approximation of the level at which dispersion occurs for most clays (Donahue and others 1977). Soils with ESP of 15 are referred to as sodic soils (formerly called black alkali soils). Soils within intermediate levels (2 to 15 percent) are rated as fair in terms of suitability. Sodic soils are the most difficult to reclaim and least likely to be worth the cost (Thompson and Troeh 1978). Therefore, selection of adapted plant species rather than soil management becomes the most applicable management tool. See USDA Agricultural Handbook No. 60 (Richards 1954) for methods of reclamation.

Exchangeable sodium requires a laboratory procedure for measurement.

Other Factors that Influence Reclamation Potential and Soil Suitability

Other variables such as parent material and aspect influence potential site productivity and the ease or difficulty of revegetation. Because there are several variables that affect soil development (and subsequent productivity), an individual variable such as parent material is difficult to quantify. However, as a general ranking, we would suggest a productivity potential array as: pumice<sand and sandstone<limestone<granitic and gneiss<volcanic ash<basalt.

Productivity potential by aspect (exposure) is also a complex parameter to quantify because it depends on the steepness of slope, latitude, and elevation. Exposure influenced soil moisture, nitrogen, organic carbon, and soil water retention in the Snake River Plains of Idaho (Klemmedson 1964). Northerly exposures were more favorable for plant growth than were southerly exposures as manifested in higher contents of nitrogen and organic C and higher levels of soil moisture and moisture retention. The interaction of slope position and exposure was more complex.

For the Intermountain area at low to mid-elevations, northerly and easterly aspects would be expected to be more mesic and, therefore, more productive than the southerly and westerly exposures. These exposures should also be easier to revegetate. However, at higher elevations such as the alpine and subalpine, this trend may be reversed because the southerly and westerly slopes receive more solar radiation resulting in a longer growing season than the north and east aspects.

Certain soil types are generally associated with a given vegetative complex. A detailed discussion of the soil/vegetation community or habitat type relationship is beyond the objectives of our effort in this chapter. The reader is referred to Daubenmire (1970), Klemmedson and Smith (1978), West and others (1978), Passey and others (1982), and Steele and others (1981).

Importance of Soil Nutrients to Plant Growth

Plant growth requires an adequate supply of all nutrients essential for the formation of tissue and for the various processes related to photosynthesis, energy transformation, respiration, and reproduction. Functions of the essential elements in plant metabolism are varied and complex with none having a simple, single function in the economy of plant growth and establishment. For example, nitrogen is a component of amino acids (proteins), vitamins, alkaloids, and chlorophyll. Nitrogen also controls growth and fruiting of most plants (Chapman 1966; Epstein 1972; Russell 1973). The micronutrient, iron, is a component of enzymes, oxidases, and peroxidases; it acts as a catalyst in the synthesis of chlorophyll; and it is an activator of biochemical processes such as respiration, photosynthesis, and symbiotic N fixation (Holmes and Brown 1957; Shaw and others 1975; Tisdale and Nelson 1975).

Past Research on Fertilization

Fertilization has been the most extensively studied of the soil management tools available to the land manager. Soil fertility is one of the few factors inherent to a site that can be implemented on a large scale as part of a wildland improvement program. However, fertilization of wildland sites on a large scale has not been practiced to date. High cost-benefit ratios are largely responsible for the limited use of fertilization on an operational basis. Herbage yield has been the primary basis to date for determining cost-benefit ratios. Other benefits have largely been overlooked. Consideration of other benefits may not bring fertilization of wildlands into profitability but they deserve consideration in decisions concerning the possibility of fertilization to improve productivity.

Fertilization may be helpful in emergence and survival of seeded species (Clary and Tiedemann 1984; Klock and others 1975a), but results are highly variable among species and climatic regimes (Vallentine 1980). Other potential benefits should be considered:

- Increased soil protection because of enhanced foliar cover and root mass (Carpenter and Williams 1972; Cook 1965; Tiedemann 1983)
- Enhancement of plant nutritional quality (Carpenter and Williams 1972; Duncan and Hylton 1970; Duvall 1970; Vallentine 1980)
- Improved plant vigor (Carpenter and Williams 1972)
- Desirable alterations of botanical composition (Duncan and Hylton 1970)
- Aid in the management of use patterns and movement of livestock and wildlife through improved nutritive value and palatability of forage (Brown and Mandery 1962; Carpenter and Williams 1972; Hanson and Smith 1970)
- Extension of the period of green forage (Hanson and Smith 1970; Holt and Wilson 1961; Vallentine 1980)

Of the studies we reviewed, there was little in common among them with respect to nutrient combinations, rates of application, test species, or length of study. Nor was there consistency in assessment of the soil nutrient status prior to treatment to determine the potential for obtaining a positive response. Responses vary by site, soil, and climate. Impressive responses in yield, forage quality, and plant vitality were observed in field trials by Eckert and others (1961a), Cook (1965), Bowns (1972), Baldwin and others (1974), Carpenter (1979), and Tiedemann (1983). Responses to fertilizers were positive in pot trial studies by Eckert and Bleak (1960), Hull (1962), Johnson (1969), Klock and others (1971, 1975a), Tiedemann (1972), and Tiedemann and Driver (1983). Carpenter and Williams (1972) provided a comprehensive synopsis of fertilization of rangelands. Vallentine (1980) is also an excellent source of information about range fertilization.

The application of fertilizer to wildlands has not consistently resulted in increased dry matter production. Some fertility studies have indicated negative responses related to plant competition and moisture availability. Depleted soil moisture reserves due to rapid growth of annual species were reported by Sneva (1978), Wilson and others (1966), and Kay and Evans (1965). In these trials the applied N increased competition between the annual grass, cheatgrass, and native perennial species which resulted in retrogression of the native species and increases in annuals. McKell and others (1959) noted the necessity of adequate soil moisture for plant growth on annual ranges. Applications of nitrogen made early in the growing season stimulated plant growth which in turn led to a faster depletion of available soil moisture, in fact, enough to retard the growth of summer growing plants. Addition of nitrogen to disturbed sagebrush steppe slowed the rate of succession and allowed annual plants to dominate through the fifth year (McLendon and Redente 1991).

Many of the fertility trials reviewed were undertaken without the benefit of soil nutrient concentration or availability assessments or characterization of soil physical and chemical properties. The lack of information on the status of nutrients other than those being tested and physical and chemical characteristics of the soil could lead to an unbalanced fertilization prescription. Because N is often the nutrient most limiting for plant growth in wildlands (James and Jurinak 1978), attention should be directed to enhancing the N capital. In addition to N, other macronutrients P and K and a secondary nutrient S are likewise important (Klock and others 1971, 1975). Fertilizers are most generally applied for their content of these four elements.

When single superphosphate is applied to amend phosphorus deficiencies, sulfur in the form of calcium sulfate is an accompanying, often overlooked, benefit. Single superphosphate contains 12 percent S. Treble superphosphate has only 1 percent S (Shaw and others 1975). In a series of field trials conducted by Cook (1965) to determine the effect of fertilizers on yield increase and forage quality, increases of the various factors measured were attributed to the primary nutrients. When complementary additions of N and treble superphosphate were applied, differences in some of the characteristics were striking: yield of crested wheatgrass was 18 percent over the N-only treatment, protein content 19 percent over the N-only treatment, and total digestible nutrients 16 percent over the N-only treatment. Smaller responses for the N-only treatments suggest further increases were deterred by lack of P or, perhaps, another limiting nutrient. Synergistic effects in the multielement treatments were undoubtedly occurring, but because pretest levels of available nutrients were not assessed, it is not known which nutrients were limiting. Actual amounts of S applied in these trials ranged from 1.5 to 6 lbs/acre (treble super-phosphate is 1 percent S). These amounts would be sufficient to amend low to marginally low sulfur deficiencies in soils (Tiedemann and Lopez 1983).

In a study by Bowns (1972) in which no soil nutrient assessment was made, large amounts of sulfur were added along with the primary nutrients, N and P, as ammonium sulfate and treble super-phosphate. Increased biomass, gross energy, and crude protein were attributed to N and P whereas S may well have been as important as a limiting nutrient. In the interior Pacific Northwest, sulfur has been shown to be almost as limiting as N (Klemmedson and Ferguson 1973; Klock and others 1971, 1975a; Tiedemann 1972).

One aspect of wildland fertilization that has received little emphasis is the differential nutrient requirements of various native plant species. Tiedemann and Klemmedson (1973) noted differential responses of four native grasses to deletion of individual nutrients in pot trials. In later trials, there were substantial differences in responses of a native grass Arizona cottontop and annual rye (Klemmedson and Tiedemann 1986). In pot trials with snow eriogonum, the only response was to the addition of N in soils that were severely deficient in both N and S (Tiedemann and Driver 1983).

Determining the Adequacy of Soil Nutrients

The complexity of soil chemistry and the necessity of proper and judicious use of chemical fertilizers support the need for soil assessment. A complete assessment also allows for characterization of site potential as it relates to specific plants and their range of adaptability—essential for planning best management practices to realize maximum sustained yield. Thus, the chemical and physical inventory serves to characterize wildlands and delineate those having potential for reclamation or improvement.

If there is assurance that other soil and environmental factors discussed in Section II: Basic Considerations are at reasonably optimal levels, the first step in development of a fertilizer prescription is determination of the total concentrations or availabilities of individual nutrients. Many fertilizer amendment studies and operations proceed with little information on concentrations of total or available soil nutrients. The result may be an erroneous interpretation of the results of such studies or operations. Liebig's law of the minimum and the Mitscherlich law (Stalfelt 1972) are often disregarded in decisions regarding fertilization (Klemmedson and Tiedemann 1995). The essence of these laws is that growth of a plant is dependent upon the amount of nutrient presented to it in minimum quantity (Odum 1959).

If more than a single nutrient is limiting in supply, the addition of one alone may produce only small increases in growth as compared to the addition of all that are limiting (Dean 1957). The added individual nutrients are effective only until another becomes limiting. The combined addition may actually produce a synergistic effect. A greenhouse pot study of orchardgrass yields as a function of three increments of N as urea, with and without addition of 57 ppm of S (fig. 2) demonstrates Liebig's law of the minimum

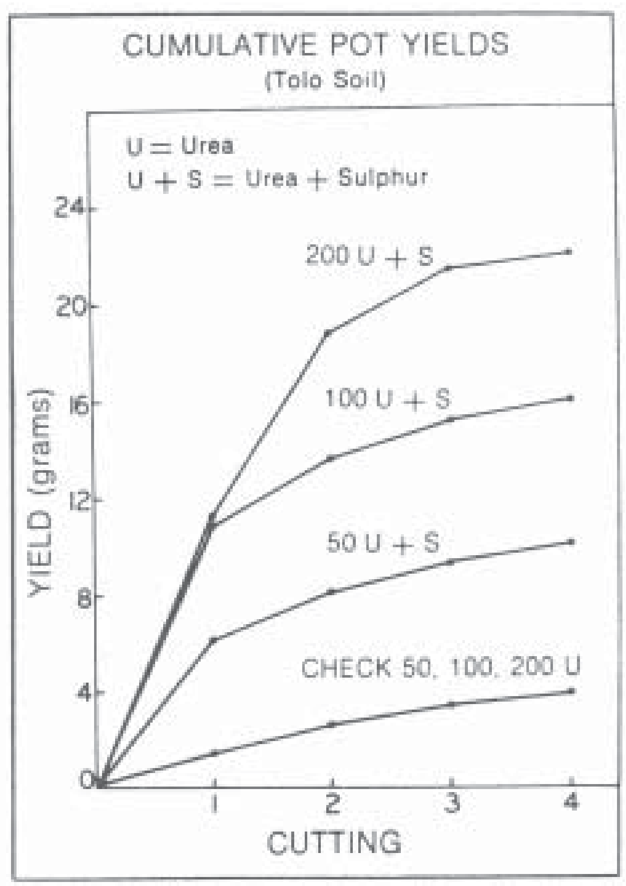


Figure 2—Cumulative yield of orchardgrass in response to several levels of urea and urea plus sulfur from Klock and others (1971).

(Klock and others 1971). All treatments received adequate P and K. Orchardgrass yields with additions of N at 50, 100, and 200 ppm as urea were the same as the control (check) treatment. When S, at 57 ppm, was added with increments of 50, 100, and 200 ppm of urea, there was a continuous increase in plant yields. Similar results were obtained with bitterbrush on granitic soils by Klemmedson and Ferguson (1973). These studies highlight the importance of determining the supply of all soil nutrients prior to application of fertilizer amendments.

As with deficiencies, excesses of one or more elements, whether naturally occurring or induced, can have deleterious or negating effects in the nutrition of plants. Excessive application of fertilizers is avoided by assessing the soil fertility status beforehand.

Soil nutrient analyses are usually made by State Agricultural Extension Service Laboratories. These laboratories will provide instructions on sampling methodology, number of samples to collect, and preparation of samples for shipment. State Extension Agents can assist in the determination of the nutrients that need to be measured based on their experience. They can also assist with the interpretation of the results of soil analyses for nutrient content.

Total Nutrient Concentrations

Evaluation of total concentrations of soil nutrients provides an estimate of the long-term nutrient-supplying capability of a given soil. The soil substrate or parent material is the source of most elements required for plant growth. Among these are phosphorus (P), calcium (Ca), potassium (K), magnesium (Mg), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), and cobalt (Co). Decomposition and relative amounts of individual nutrients released depend on the nature of parent and soil material, climate, and the presence of organisms important in decomposition processes (Buol and others 1973; Hallsworth and Crawford 1965).

Soil phosphorus and sulfur, in addition to their important role in plant growth and physiological function, are important in the accrual of organic carbon and nitrogen (Walker and Adams 1958).

Nitrogen is unique in its accrual to the soil nutrient capital. Atmospheric nitrogen gas is the primary source of nitrogen for the soil (Stevenson 1965). However, the major storehouse of N is soil organic matter (Kowalenko 1978) and since organic matter is limited in semi-arid environments (Hagin and Tucker 1982; Klemmedson 1989), N is usually the major limiting nutrient. Nitrogen accrual to the soil occurs principally through the N-fixation process, whereby N is converted from the gaseous form in the atmosphere to forms usable by higher plants. Blue-green algae (*Nostoc* and *Anabaena*) in the surface soil, free-living bacteria (*Rhodospirillum*, *Clostridium*, and *Azotobacter*), legume symbiosis with *Rhizobium*, and actinomycete nodulation of several genera of wildland plants are principally responsible for this source of N accrual (Stevenson 1965). Klemmedson (1979) indicates that N-fixation by actinomycete nodulation occurs in species of eight western genera—alder, ceanothus, mountain mahogany, dryas, elaegnus, wax-myrtle, bitterbrush, and buffaloberry. Actinomycete nodulation and N-fixation also occurs in cliffrose (Nelson 1983).

Precipitation appears to represent a minor part of nitrogen accrual to agricultural soils—7 to 20 kg/ha/year (Stevenson 1965)—but may be important for wildland soils where N requirements are less. In some parts of the United States, however, the input of N by precipitation may be much lower—less than 2 kg/ha/year in the interior Pacific Northwest (Tiedemann and others 1978, 1980).

The atmosphere is an important source of sulfur from burning of fossil fuels and geothermal discharge (Strahler and Strahler 1973), with resultant deposition as dry fallout and precipitation.

While the normal ranges of total concentrations of nutrients in agricultural soils of the United States is readily available (table 2), such information is not generally available for wildland soils. However, levels would be expected to be at the lower end of the range given for agricultural soils, with the exception of such elements as Mg and Ca in arid land environments, where large reserves are held in the soil storehouse because of minimal leaching (Charley 1972). There are also exceptions for total N. Tiedemann and Furniss (1985) found N levels in excess of 0.7 percent in surface soils of curlleaf mountain mahogany stands. Tiedemann and Clary (1996) observed total N concentrations in excess of 0.4 percent in the upper 12 inches (30 cm) of soil in Gambel oak stands in north-central Utah.

Available Nutrient Concentrations

Of more immediate utility than total concentrations of individual nutrients is the determination of the available concentrations. Available nutrients normally represent only a minor proportion of the total nutrient capital. Available N (nitrate- and ammonium-N), for example, may represent 1 to 2 percent of the total organic N capital of the soil (Stevenson 1965). For available cations, the gap between total and available concentrations are usually much greater.

Table 3 presents values of low, marginal, and high availabilities for all of the soil nutrients essential for plant growth. Values are also presented for unacceptable levels that may be toxic to plants or in excess of

Table 2—Normal range of total concentrations of nutrients occurring in agricultural soils and soil factors for determining deficiency and excess (adapted from Tiedemann and Lopez 1983).

Element[a]	Total in soils	Soil type in which deficiency is likely	Notes	Reference
N	0.05 percent to slightly more than 0.5 percent in mineral soils	Sandy, especially in high ppt. area; low in organic matter	Rate at which N becomes available varies greatly and, hence, analysis for total N is usually of little help in determining immediate fertilizer practices. Excessive N can result in salt buildup.	Harding 1954; Jones 1966
P	0.09-0.13 percent	Weathered and acid; calcareous		Bingham 1966; Jenny 1930
K	1.7-2.5 percent	Light, sandy; acid; organic		Parker and others 1946; Ulrich and Ohki 1966
S	0.01-0.06 percent		High S concentrations occur in gypsiferous soils; neither total S nor reducible S significantly correlated (p = 0.05) with either plant yields or S uptake.	Burns 1967; Eaton 1942
Ca	0.1-2.0 percent in soils free of Ca carbonate; 1-25 percent in calcareous soils	Humid, sandy	Soils vary widely in content.	Chapman 1966; Millar 1955
B	2-100 ppm		B excesses occur in soils derived from marine sediments and in arid soils.	Bradford 1966; Krauskopf 1972
Cu	2-140 ppm	Alkaline and calcareous; leached, sandy soils; soils fertilized heavily with nitrogen; leached, acid	Excess Cu can occur in soils derived from Cu-ore sources.	Chapman 1966; Mitchell 1948; Reuther 1957; Reuther and Labanauskas 1966; Swain 1955
Fe	10,000-100,000 ppm	Calcareous, poorly drained manganiferous		Krauskopf 1972; Wallihan 1966
Mg	5,000 ppm	Acid, sandy; imperfectly drained; alkaline	Mg excess can occur in soils where more than 90 percent of CEC is saturated with Mg. No correlation between total Mg and a soil's crop-producing potential.	Embleton 1966; Kelley 1948; Prince and others 1947; Reichle 1970
Mn	0.2-3,000 ppm	Calcareous; heavily manured and limed; very sandy-acid	Total Mn is not a good measure for plant availability.	Krauskopf 1972; Labanauskas 1966; Swaine 1955
Mo	0.2-10.0 ppm	Highly podsolized soils with low Mo retention capacity	Availability of Mo highly dependent on pH.	Johnson 1966; Krauskopf 1972; Robinson and Edgington 1954
Zn	10-300 ppm	Acid-leached, sandy; alkaline; granitic, gneisses; organic soils; clays with low Si/Mg ratio	Zn availability is pH dependent; decreases 100-fold for each unit increase in pH.	Chapman 1966; Lindsay 1972; Swaine 1955

[a]B = Boron; Ca = Calcium; Cu = Copper; Fe = Iron; K = Potassium; Mg = Magnesium; Mn = Manganese; Mo = Molybdenum; N = Nitrogen; P = Phosphorus; S = Sulphur; Zn = Zinc.

legal limits. Toxic levels will often be a consequence of pH problems and can be moderated with liming amendments to adjust pH to acceptable levels. To determine the available supply of an element, concentration (ppm) must be converted to the decimal value by multiplying by 1×10^{-6}. This value is then multiplied by the weight of the surface 15 cm of soil, which is estimated at 2.2×10^{6} kg/ha. For available N (from nitrate), a high level of supply would equal 18 ppm (table 3). Multiplying 18 ppm by 1×10^{-6} and by 2.2×10^{6} kg/ha would equal 40 kg/ha of nitrate-N. Assuming 2 percent total N in plant tissue, this level of nitrate-N is adequate for production of about 2,000 kg/ha of forage.

Other procedures assess the adequacy of soil nutrients, but a detailed discussion is beyond the scope of this text. These other methods are briefly described below.

Visual Symptoms—Certain visual symptoms in plants are indicative of nutritional deficiencies. Some of these are easily diagnosed such as change

Table-3—Proposed guidelines for assessing fertility status of wildland soils[a] (adapted from Tiedemann and Lopez 1983).

Nutrient[b]	Availability Low	Availability Marginal	Availability High	Unacceptable levels of selected elements	Extraction method	References
	ppm					
Nitrate N	<9	9-18	>18		Water extract	Massee and Painter 1978; Stroehlein 1980
P	0-15	16-30	>30		Bray	Thomas and Peaslee 1973
P	<6	6-11	>11		Sodium bicarbonate	Ludwick and Rogers 1976; Massee and Painter 1978; Thomas and Peaslee 1973
K	<60	61-120	>120		Ammonium acetate or sodium acetate	Ludwick and Rogers 1976
SO_4S	<6	6-15	15-30	>30		Ensminger and Freney 1966; Massee and Painter 1978; Reisnauer and others 1973
B	<0.5	0.5-1.00	1.0-5.0 Sensitive crops may have visible injury	5-8	Hot water	Reisnauer and others 1973; Schafer 1979; Stroehlein 1980
Cu	0-0.2		0.2	10-40	DTPA	Reisnauer and others 1973; Schafer 1979; Stroehlein 1980
Fe	<2.0	2.0-4.0	>4.0		DTPA	Ludwick and Rogers 1976; Viets and Lindsay 1973
Mg	<25	25-50	>50		Ammonium acetate	Doll and Lucas 1973
Mn	0-0.75		>0.75	10-60	DTPA	Ludwick and Rogers 1976; Schafer 1979; Stroehlein 1980; Viets and Lindsay 1973
Mo	<0.1 (pH 6)		0.10-0.20	>0.3		Reisnauer and others 1973; Schafer 1979
Se				>2.0		Schafer 1979
Zn	<0.5	0.5-1.0	>1.0	20-40	DTPA	Ludwick and Rogers 1976; Schafer 1979; Viets and others 1979

[a]Selected trace elements should be analyzed from this list if they are a demonstrated regional problem. Many quantitative limits shown in this section are not supported by research findings.
[b]B = Boron; Cu = Copper; Fe = Iron; K = Potassium; Mg = Magnesium; Mn = Manganese; Mo = Molybdenum; N = Nitrogen; P = Phosphorus; Se = Selenium; SO_4S = Sulphate-sulphur; Zn = Zinc.

in leaf color, leaf scorching, or leaf deformation. Because they have similar nutrient requirements, deficiency symptoms within a specific plant family are generally quite similar. Plants of the goosefoot and mustard families, for example, have a high requirement for boron; members of the legume family are very sensitive to a deficiency of potassium (Donahue and others 1977). Pictorial descriptions of deficiency symptoms in plants for the essential elements are well documented; see Chapman (1966).

Tissue Analysis—For established plantings, tissue analysis may be used in conjunction with soils tests to develop a fertilizer prescription. Interpretation of tissue analysis results is more complicated than for concentrations of total and available soil nutrients. Also, information on nutrient concentrations in wildland plants and the relationships to soil nutrient status (sufficiency or deficiency) is negligible. Concentrations in tissue vary widely among species, plant part, and season. Interpretation may also be confounded by luxury consumption of certain elements. See Ulrich (1952) and Walsh and Beaton (1973) for more detailed information on tissue analyses and interpretations.

Greenhouse Bioassy—Another procedure for determining nutrient availability is greenhouse bioassy, such as the technique of Jenny and others (1950), commonly referred to as a pot trial study. This procedure is a practical way of determining nutrient needs for individual plant species using actual field soil samples. Although particularly applicable for study of macronutrient availabilities, it can also be used to assess micronutrients. This test involves determining biomass yield of a test species in response to deletion of individual nutrients from a full nutrient treatment. A control treatment (no added nutrients) is also established. Bioassay nutrient availability trials have the advantage that quantitative fertilizer prescriptions can be tailored to a particular species or mix of species being considered for revegetation purposes. A limitation of this method is that the effect of soil physical characteristics is not taken into account (such as permeability, bulk density). It also does not account for moisture limitations and the moisture/nutrient interactions that are encountered in the wildland setting. For a detailed discussion on methods and assessment of results for this technique, see Tiedemann and Lopez (1983).

Field Trials—Field experiments are a means of determining nutrient needs by actual on-site trials. Calibrating nutrient requirements to yields can be accomplished by carefully planned and executed outplantings. However, it should be kept in mind that recommendations based on field trials are site specific for the plant species tested. Standard guides to investigations of this type are available; see Hauser (1970) and Mukerjee (1960).

Development of a Fertilizer Prescription

The simplest procedure for developing fertilizer amendment needs is to match soil test results with the values presented in table 3. The amount of each element that needs to be supplied for low, marginal, and high levels of nutrient availability have been developed (table 4). To convert these values to actual rates of fertilizer application, the decimal value of the elemental concentration of a particular nutrient in the fertilizer is divided into the desired application rate of that element. For example, with N at low availability, there is a need to supply 56 kg/ha (table 4). The amount of ammonium nitrate fertilizer that must be applied is 56/0.32 = 172 kg/ha of actual fertilizer.

If more than one element is at a low level of availability, it will be desirable to apply a single fertilizer that contains as many of the limiting nutrients as possible. It should be noted that rates of more than one element cannot be controlled. We suggest keying application rate of other nutrients to the needed rate of application of N, P, or K to assure adequate amendment of these macronutrients. For example, in a situation where both N and S are at low availability, if the rate of ammonium sulfate application were based on sulfur needed (6 kg/ha), it would be equivalent to 25 kg/ha of fertilizer. Since this fertilizer contains 21 percent N (table 5), the rate of N application would only be 5 kg/ha—a 90 percent reduction from actual needs of 56 kg/ha. Ammonium nitrate could be used (in addition to ammonium sulfate) to achieve the proper level of N fertilization.

One important point to highlight in application of fertilizers is the need to maintain a balance of fertility. Application of an excess of one element will likely result in rapid depletion and limited availability of other elements. Voisin (1964) proposed a “law of correction of soil imbalances” that states that “any imbalance of available mineral elements existing or appearing in the soil because of the nature of the latter, as a result of removal in harvested crops, because of fertilizer application or for any other cause, must be corrected by application of the necessary fertilizing elements so that optimum balance among the soil elements is restored, producing high biological quality in the plant and the maximum yield compatible therewith.” In essence, any nutrient that is exhausted must be replenished and imbalances must be corrected.

Table 4—Fertilizer recommendations based on inherent status (table 3) (kg/ha) to be applied based on average soil bulk density (= 1.35 g/cm^3) (adapted from Tiedemann and Lopez 1983).

Nutrient[a]	Low	Marginal	High	Notes	References
N	56	17-22	0		Amburgey 1964; Massee and Painter 1978
P	29	22	15	To convert from P to P_20_5 multiply by 2.25.	Amburgey 1964
K	32	16	0	To convert from K to K_20 multiply by 1.20.	White 1979
S	6	2	0		Massee and Painter 1978
Ca	6				Viets and Lindsay 1973
B	1.7	0.8			Reisnauer and others 1973
Cu	5				Murphy and Walsh 1976
Fe	30	15		For acid soils—FeEDTA; for neutral soils—FeHEEDTA or FeDTPA; for alkaline soils—FeDTPA or FeEDDHA.	Wallihan 1966
Mg	7	3.5	0		Sirker 1908; Stone 1953
Mn	pH <7.0 6 pH >7.0 11	pH <7.0 3 pH >7.0 5	pH <7.0 5	Lime induced deficiency can be corrected by acidification.	Murphy and Walsh 1972
Mo	0.11	0.03			Murphy and Walsh 1976
Zn	11	6	0		Murphy and Walsh 1976

[a]B = Boron; Ca = Calcium; Cu = Copper; Fe = Iron; K = Potassium; Mg = Magnesium; Mn = Manganese; Mo = Molybdenum; N = Nitrogen; P = Phosphorus; S = Sulphur.

Table 5—Elemental composition of some common available fertilizers.

Material[a]	N	P	K	S	Mg	Ca	References
	- - - - - - - -	- - - - - -	- - - *Percent*-	- - - - - -	- - - - - -	- - - - -	
Ammonium nitrate	32.5						Fairbridge and Finkl 1979
Ammonium phosphate	11.0	48		3			Sulphur Institute 1982
Ammonium sulphate	21.0			24			Sulphur Institute 1982
Ammonium phosphate-sulfate	16.0	20		15.4			Sulphur Institute 1982
Calcium nitrate	15.5				1.5	19.3	Fairbridge and Finkl 1979
Copper sulphate				11.8			Sulphur Institute 1982
Phosphoric acid (liquid)		23-24				0.2	Fairbridge and Finkl 1979
Potash (potassium-chloride)			52				Fairbridge and Finkl 1979
Potassium magnesium sulphate			15-18	18-23	11		Donahue and others 1977
Potassium sulphate			44	18			Fairbridge and Finkl 1979
Single super phosphate		8-9		12		13-15	Fairbridge and Finkl 1979
Trebel super phosphate		18-20		1		9-13	Fairbridge and Finkl 1979
Urea	42-46						Sulphur Institute 1982
Zinc sulphate				13-18			Sulphur Institute 1982

[a]Ca = Calcium; K = Potassium; Mg = Magnesium; N = Nitrogen; P = Phosphorus; S = Sulphur.

Application of Fertilizers on Wildland Soils

Plant nutrients differ in the way they may be applied most effectively as fertilizers because of differences in their chemical properties, amounts required by plants, chemical and biological activity in the soil, and solubility, which varies according to their formula and physical condition (Cook and Hulbert 1957). The emphasis on proper application of fertilizers should be considered equally critical to the selection of fertilizers. Four reasons for this emphasis are elaborated upon here:

First, optimum time of fertilizer placement should coincide with adequate moisture availability. Nutrients are ineffective in dry soil. If leaching by water will not be the means by which nutrients are translocated to the root zone, fertilizers should be placed where roots have access to the nutrients (Cook and Hulbert 1957). For the Intermountain West, surface applications of fertilizers are most effective if applied in late fall after some precipitation has been received. This allows ample time for microbial transformations of fertilizer compounds such as urea and assures movement of mobile ions into the rooting zone.

Second, mobility of fertilizer elements and nutrient absorbing characteristics of the vegetation must be considered. For example, surface applications of phosphorus (an immobile nutrient) are likely to be more effective with shallow, fibrous-rooted species such as perennial grasses than plants with taproots such as forbs and shrubs. For fertilizer compounds with nitrate-N and sulfate-S, two relatively mobile nutrients, surface applications would be effective for perennial grasses, forbs, and shrubs.

Third, in fertilizer placement, a plant's demand for various nutrients at different stages of growth should be taken into account. Maximum demand for nutrients occurs in the young plant and early growth stages of perennials. Rapid growth can only take place when adequate enzymes are present and, therefore, only after the plant has absorbed a sufficient quantity of the minerals necessary for correct enzymatic function. However, the demand never ceases completely. Should some of the minerals become limiting at a later stage, damage and eventual plant death may occur. Seedlings should have ready access to nutrients for early growth yet direct contact with fertilizer could be detrimental because of the osmotic effect of salts depriving the seedling of water.

Fourth, application with regard to physical and chemical soil factors must be considered. The effect of pH on nutrient availabilities illustrates the importance of considering soil chemical properties. Fertilizers applied to soils with pH less than 5.1 or greater than 8.4 will not likely be effective in promoting plant growth because nutrients will become unavailable. Soil physical properties can also affect fertilizer effectiveness. A soil with a very slow infiltration rate, for example, may impede overall nutrient availability to plants, because little of the fertilizer will be transmitted to the root zone and will be vulnerable to removal by surface runoff.

Much of what we know about fertilizers and fertilization is based on agricultural practices that may not be suited to the wildland situation. Nevertheless, the basic concepts of plant-soil relationships are applicable. If it is decided that a fertilization program will be done, proper application is essential.

A number of application methods are available to the land manager. However, many of these are not practical in wildland settings. Broadcasting on the soil surface has been the most widely used method of applying granular fertilizer (Vallentine 1980). Where chaining, or other vegetation-clearing, soil-disturbing practices is employed, the prescribed fertilizers could be spread prior to clearing, thus allowing for some incorporation caused by the soil disturbance. The same recommendation would be appropriate for areas to be reseeded by drilling. Soil incorporation is particularly important for phosphorus fertilizers.

On annual grassland in California, helicopter application was considered fast and practical on rangeland too steep for ground application (Duncan and Reppert 1966). Spreading of granular and foliar fertilizer by airplane has likewise been a practical means of fertilizing wildlands, and at a much lower cost than with helicopters.

Foliar application of micronutrients and secondary nutrients in a wildland setting may be a practical and logical method for improving impoverished areas with identified deficiency symptoms. Foliar application may be particularly beneficial where nutrient uptake through the plant roots is restricted or where soil incorporation is prohibitive. Also, foliar application is the fastest way to correct deficiencies of micronutrients. Attempts to supply the major nutrient requirements such as N, P, and K by foliar application may not be successful because of the required high rates and repeated applications causing foliage scorching and increased expense (Hagin and Tucker 1982).

The addition of specific secondary nutrients or micronutrients to amend specific needs requires careful planning in their application because of the high cost involved and adverse consequences of toxicity due to excessive, uneven application. These minor and secondary elements are applied most economically at the same time as macroelements. The amounts needed (table 4) are generally so small that separate applications are difficult. One word of caution: the addition of specific micro- and secondary elements to take care of specific needs is applicable only in areas where soils are known to be severely deficient. The consequences of improper application can be devastating and protracted.

Some plant nutrients have been successfully applied by seed coating (Murphy and Walsh 1972). A number of benefits are realized: (1) even distribution of nutrients over treated areas; (2) nutrients readily available for a more even emergence and survival of seedlings; (3) assurance of more uniform stand establishment, often with less seed per acre; (4) most efficient in terms of labor and other application costs. One disadvantage is that seed coating cannot be used to build soil nutrient reserves. It is used primarily for early emergence and survival.

Conclusions

The foregoing information was given to provide an overview of the soil factors that affect the potential success of wildland rehabilitation efforts. It is obvious that it is not economically feasible to correct some soil conditions on wildlands. Even though there may be no economically feasible treatments for overcoming adverse soil conditions, it is important for rehabilitation specialists to be able to recognize these problems, and in some cases be able to quantify their magnitude. Although fertilization is a readily available technique for amending soil nutrients, it is considered to be a "high input" option (Marschner 1986). "The low input option, and perhaps the most feasible means of managing nutrient stress is to encourage the development of species that are either adapted to or can tolerate low nutrient levels, or those that can ameliorate N limitations by symbiotic N fixation" (Klemmedson and Tiedemann 1995).

There is a rapidly emerging understanding of the morphological and physiological features of plants that are adapted to grow and survive in nutrient-limited environments. Consideration of these adaptations in the process of selecting plants for revegetation should greatly improve chances for success in revegetation of nutrient-limited sites. Most species of a stress tolerant strategy tend to be small in stature (Grime and Hunt 1975) with an inherently slow growth rate, thereby, resulting in a low demand on the soil nutrient supply (Chapin 1980; Grime 1977).

Despite low nutrient absorption rates, species from soils of low fertility status maximize nutrient acquisition by maintaining a large root biomass, and high root:shoot ratios (Chapin 1980; Marschner 1986), increased length (Marschner 1986) and branching (Troughton 1980) of roots, strongly developed mycorrhizal associations (Mosse 1973), and greater root longevity (Chapin 1980).

Plants that fix N by symbiosis such as those of the legume family hold promise as a natural means of providing N to wildland plantings (Blackbourn 1975; Rumbaugh 1983). Several genera of native shrubs such as alder, ceanothus, bitterbrush, cliffrose, and buffaloberry are also known for their ability to fix atmospheric N (Klemmedson 1979; Nelson 1983; Righetti and others 1983). Although research on the effectiveness of these plants in improving the N supply of wildland sites is in its infancy, these plants hold promise of reducing or perhaps even eliminating fertilizer N amendment needs on wildlands in the future. Several herbaceous species of legumes such as alfalfa, yellow sweetclover, cicer milkvetch, sainfoin, and sulla sweetvetch are already in use for this purpose (Rumbaugh 1983).

Other chapters in this book address the issue of species adapted to vegetation zones and specific site conditions. The reader is also referred to Aldon and Oaks (1982), Monsen and Shaw (1983b), Tiedemann and Johnson (1983), and Tiedemann and others (1984b).