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Reclamation of Drastically Disturbed Lands

This book is a complete revision of the first edition with the same title. With a few exceptions, different authors than those of the first edition have written the chapters in this edition. These revisions follow significant changes in the coal mining reclamation requirements as a result of passage and implementation of the Surface Mining Control and Reclamation Act of 1977 (SMCRA, Public Law 95-87). Passage of this law essentially made many chapters of the first edition out of date by the time the book was published in 1978. The first edition (F.W. Schaller and P. Sutton, editors) was largely the result of proceedings from the Wooster, Ohio, symposium.

This edition is a cooperative effort of the American Society for Surface Mining and Reclamation (ASSMR) and the American Society of Agronomy as a part of mutual liaison activities between these two societies. Chapters and senior authors were suggested to the editorial committee by action of an ad hoc committee of ASSMR.

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25 Use of Mulches and Soil Stabilizers for Land Reclamation

MICHAEL R. NORLAND

National Park Service
South Florida Natural Resources Center
Homestead, Florida

I. INTRODUCTION

The use of a mulch or soil stabilizer is one of several treatment options in any plan for reclaiming drastically disturbed areas. Mulches or soil stabilizers should be used as an aid in reclamation and not as a substitute for proper use of other soil amendments, grading, and shaping for vegetating and stabilizing the area. This chapter focuses on the humid eastern USA, where many disturbed areas such as highway road banks, surface-mined areas, and construction sites in steep terrain have slopes that are very conducive to soil erosion prior to the establishment of a good vegetative cover.

Mulches or soil stabilizers can help control erosion caused by surface runoff prior to the establishment of vegetation. The value of these treatments is more evident on sites that have chemical, physical, or biological characteristics that delay the establishment of plants and limit their growth. Slick and Curtis (1985) identified the following stress conditions as the most detrimental to seed germination and subsequent plant growth and development: erosion, extreme diurnal surface and soil temperatures, lack of available moisture, and extremes in soil pH. These factors, along with the lack of nutrients and organic matter, make it difficult to establish and maintain a diverse productive vegetative cover that will meet reclamation standards. To alleviate these conditions and make the mine soil more favorable for plant establishment and growth, the disturbed area microclimate must be modified. In addition to the usual fertilizers and lime used in the revegetation process, the application of surface mulch can be used to modify plant growth conditions.

For this discussion, mulches are defined as organic or inorganic materials applied or left on or near the surface of the soil as a temporary aid in stabilizing the surface and improving soil microclimatic conditions for establishing vegetation. Mulches are used at the soil surface to: (i) prevent the loss of water by increasing infiltration, increasing the total and available water-holding capacity of soil, and increasing surface wetness; (ii) aid hi soil stabilization by reducing surface erosion by wind, water, and raindrop impact; (iii) increase soil organic matter or humus; (iv) reduce soil surface temperature extremes; (v) decrease stir-face crust formation by decreasing soil dispersing action of raindrops; (vi) increase structural stability, tilth, and permeability of soil; and (vii) reduce the germination and growth of weeds, resulting in improved microclimatic conditions for the growth of desired species. The organic materials may supply a limited amount of plant nutrients. Additionally, mulches may serve as a substrate for beneficial soil organisms such as earthworms and the microflora. Materials used as mulch include: (i) organic mulches (sawdust, bark, wood chips, animal manure, hay and straw, compost, sewage sludge, and other litter), (ii) inorganic mulches (plastics, rocks, and stones), (iii) chemical soil stabilizers, and (iv) preparatory crops. Soil stabilizers are organic or inorganic chemical products applied as water solutions to the soil surface. They form a protective film on the soil surface or infiltrate the soil and physically bind the soil particles together. A soil stabilizer temporarily stabilizes against wind and water erosion and prevents evaporation of water from the soil surface. Treatments can be used that combine mulch and a soil stabilizer. Additional detail on the use of mulches and stabilizers for highway revegetation is given in Booze-Daniels et al. (2000, see Chapter 35).

A number of products and materials are available, many of which have specific attributes and limitations. In order to select the best material to use, the basic characteristics of all available materials should be evaluated. Selection of treatment should be based on requirements for erosion control and on-site and climatic variables that may affect the establishment of vegetation and the cost of achieving the site-protection objectives. Mulches and soil stabilizers are distinct from other soil amendments. Other soil amendments can be organic and inorganic materials, such as lime, fertilizer, or manure that are incorporated into the soil root zone to make it more productive for vegetative establishment and growth (Slick & Curtis, 1985). Organic soil amendments are described in detail in Haering et al. (2000, see Chapter 24) while the basics of fertilizer and lime additions can be found in Fedkenheuer and Macyk (2000, see Chapter 22).

II. MULCHES

Mulches may be processed or unprocessed materials, including raw residues from agriculture or industry, processed residues, and manufactured products. These materials differ mainly in the physical characteristics of the individual pieces or fibers, solids, or liquids. Fibrous mulches are usually classified as long- or short-fibered. Long-fibered mulches include materials like straw, hay, shredded hardwood bark, and composted municipal solid waste, while short fibered mulches include hydromulch, wood fibers and cellulose, and paper. As a general rule, and within certain limits, long-fibered mulches are more beneficial and their benefits last longer than shorter-fibered mulches (Kill & Foote, 1971) Long-fibered crop residues decompose rather rapidly but are generally more effective in reducing surface flow and trapping sediment than short-fibered mulches. The effectiveness of short-fibered mulches can be improved by combining them with a tackifier or soil stabilizer. Solid mulches include animal manure, bark fragments, wood chips, sawdust, and municipal sewage sludge. Liquid or hydromulches may include animal, municipal, or industrial wastewater treatment sludges. The durability of mulch relates to its physical characteristics. Durability is defined as the length of time the mulch provides effective site protection. A discussion of the organic mulches and soil stabilizers commonly used follows.

A. Organic Mulches

Organic mulches are usually preferred to inorganic mulches because they are natural materials, sometimes providing the needed microflora and fauna, seeds, organic matter, and nutrients to the typically heterogeneous disturbed soil (Slick & Curtis, 1985) that is usually low in microbial activity. Organic residues from plant and animals that are on or in the soil are beneficial in the following ways (Follett et al., 1981):

1. Serving as the principal storehouse for anions essential for plant growth such as nitrates, phosphates, sulfates, borates, molybdates, and chlorides.
2. Increasing the cation exchange capacity of soils by a factor of 5 to 10 times that of clay. This is true for humified organic matter (humus). More available nutrient cations such as ammonium (NH_4), K, Ca, and Mg are thus absorbed by humus, thereby buffering the soil against rapid' changes due to acidity, alkalinity, salinity, pesticides, and toxic trace elements (heavy metals).
3. Protecting the surface soil against erosion by water and wind by reducing the impact of raindrops on soil peds and clods, increasing infiltration, reducing water runoff, increasing the soil's total and available water-holding capacity, and increasing surface wetness. Where hail is fairly common, surface organic mulch also reduces water and wind erosion by protecting soil peds and clods against destruction.
4. Supplying a C substrate for beneficial soil organisms such as earthworms, symbiotic N-fixing bacteria, and mycorrhizae.
5. Reducing extremes of soil surface temperature. Tlhis is especially true of organic residues used as surface mulch.
6. Decreasing surface crust formation by decreasing the soil-dispersing action of beating raindrops.
7. Reducing the crystallization and hardening of the plinthitic soil materials (laterite layer of soils that are rich in soluble Fe and Al). Humate complexes with Fe and Al resulting in reduced crystallization. Organic matter reduces hardening also by maintaining more uniform soil moisture.
8. Supplying to growing plants as organic residues decompose, small quantities of all essential plant nutrients, usually in time-sequence harmony with the needs of plants.
9. Making P and micronutrients more readily available over a wider pH range. This is a function of especially soil humus, a resistant decomposition product of soil organic matter.
10. Allowing application of selected herbicides. In certain instances, applications of postemergent herbicides on Histosols can be 50% greater than on

mineral soils. For other herbicides, application rates are determined partly by the percentage of organic matter, sand, silt, and clay in mineral soils. On coarse-textured soils with less than 2% organic matter, certain herbicides are not recommended for use; however, with increasing clay and increasing organic matter the same herbicides can be used.

11. Decreasing the negative effects of soil bulk density. Tillage pans or naturally indurated horizons in soils may be so dense as to reduce the rate of infiltration, decrease water storage capacity, and restrict normal root development. Organic residue additions and management can reduce soil hulk density as they decompose to humus and detritivores associated with their turnover mix and aggregate the surface soil. Mulches also help the soil retain moisture, which will lead to decreased mechanical impedance.

Raw residues from agriculture are often used as mulches, the most common are straw and hay. Straw mulch is composed primarily of stems of cereal grains such as wheat *(Triticum aestivum* L.) or oat *(Avena sativa L.).* These are applied at rates of 2 to 5 Mg ha-' after the disturbed area has been fertilized and seeded. The rate is typically adjusted based on slope, erosion potential, and other site-specific characteristics. Straw contains little or no N, so fertilization is necessary with this amendment. Straw decomposes rapidly, therefore it is important that the stems be as long as possible to prolong the life of the mulch. Resistance to wind or water movement may be increased by the use of asphalt or chemical tacks or by crimping into the ground with a disc. The use of straw or hay mulches may need to be restricted if the danger of transmitting a plant disease is high. When straw mulch is applied to a site, a nurse crop of the mulch species may be inadvertently seeded. Fortunately, in cooler climates the cover crop persists for only one growing season. Of greater concern are the seeds of weeds that also are brought to the mulched site. Straw usually contains undesirable species harvested with the straw or hay; undesirable plants may emerge and conflict with establishment of the desired plant species. Straw must be selected with the greatest of care to reduce the amount of weed seed introduced with this mulch. The use of native hay mulch has several advantages over straw mulches; if cut and dried properly native hay stems are longer and stronger than grain straw. It also contains seeds of native plants rather than cereal grains. These seeds are beneficial to the development of a diverse plant community on the disturbed area.

A straw or hay mulch effectively dissipates the energy of falling raindrops, thus minimizing the detachment of soil that is caused by the impact of rainfall. Erosion by surface runoff will be reduced if the straw and hay mulches make extensive contact with the soil surface; if the mulch is perched above the surface, sheet and rill erosion may occur beneath the mulch. Also, mulches will increase the rate of infiltration and decrease the rate of evaporation. Both are important in increasing the water availability for plant growth under drought conditions. Straw and hay mulch also may effectively reduce soil temperatures.

Other agricultural residues that may he used as mulches are peanut *(Arachis hypogaea* L.) hulls, corncobs *(Zea mays L.),* and bagasse, a residue from sugar cane *(Saccharum officinarum* L.) mills. Many of these materials need to be reprocessed before they can be used as mulch. In some cases, the pieces are reduced in size by grinding, shredding, or milling (hammer mill). Others need to be dried before being transported and applied. Packaging is an expensive measure that may not be justified unless there is a well-developed market for the mulch. Most agricultural residues are delivered to the application site in bulk. Municipal and industrial wastewater treatment sludges (biosolids) and animal manures also are commonly used as organic soil amendments (Haering et al., 2000, see Chapter 24), but in limited instances are used as surface mulching agents. However, composted biosolids and manures are commonly employed as surface mulches on disturbed lands as discussed below.

B. Use of Composts

Composting involves the aerobic mesophi ic and thermophilic decomposition of organic residues to a relatively stable humus-like material. Aeration is essential for encouraging specific microbial proliferation of bacteria, actinomycetes, and fungi to achieve rapid decomposition with minimum objectionable odors. Heat is generated by microbial activity. At the edges of the compost pile, mesophilic bacteria are very active at temperatures of 25 to 40°C and within the pile the thermophiles proliferate at 40 to 65°C. Special inoculum can be purchased for hastening microbial proliferation in composts, but it is not necessary since organic residues contain all essential microbes. The kinds of residues used for composts will determine the speed of decomposition and the quality of the finished product. Desirable materials for composting include those with a narrow as possible organic C/N as possible, although the ratio can he adjusted via addition of other high N organic materials (e.g., biosolids) or fertilizer N. The bulk C/N is a useful good indicator of compost fertility. The ratio of stable compost is usually less than 20: I . but may vary with the contents of the original composted material. If this ratio is low enough (12: 1) compost may be used as a fertilizer as well as a soil conditioner.

Compost can be derived from the biological decomposition of any solid waste. Decomposition may be brief or may have lasted several months, but the compost should be relatively stable to avoid undesirable odors. That is, the initial, rapid breakdown of the waste by microorganisms should be complete. Changes now taking place in the compost should be proceeding at a relatively slow rate. The original source of the organic matter may be anything from grass clippings to municipal solid waste to sewage sludge, but in each example the compost that results is an excellent soil conditioner. Compost has been found to enhance macronutrient fertility, improve soil structure, increase the infiltration of precipitation and the water-holding capacity, decrease bulk density, and increase the cation exchange capacity of the receiving soil, subsoil, or overburden.

Compost, as a low-cost soil fertilizer and conditioner, has received widespread use on degraded sites and agricultural lands throughout the world. It has been used for centuries in Asia and Europe on disturbed soils and agricultural lands. Its use on similar sites in North America is relatively new and has been limited. Recent research in the upper Midwest and Great Plains clearly reveals the benefits of compost additions to disturbed lands. The benefits of compost in these revegetation trials may be related to its ability to augment the water-holding capacity of the study site waste materials (Norland, 1993, 1994; Noyd et al., 1996, 1997). When a surface soil is not available for use in a rehabilitation program, compost is especially useful as an amendment to enhance soil structure and nutrient composition of the substitute materials. As a general rule, application rates should be approximately 25% by volume to impact soil structure.

C. Use of Natural Organic Soil Materials

Peats and mucks are used as both a mulch and organic fertilizer. When used as a soil amendment, there are two classification systems that may be used to describe peat; a commercial system and the soil taxonomic system (Follett et al., 1981). In the commercial system there are five categories:

1. Moss peat—mainly sphagnum and hypnum mosses. The fibers are readily identified because they have not been noticeably decomposed. This is the most acidic, most expensive, and most desirable of the peats in terms of use as soil amendment in this classification system.
2. Reed-sedge peat—a mixture of residues from reeds, sedge grasses, and cattails.
3. Peat humus—from advanced decomposition of hypnum moss and reed-sedge peat.
4. Muck soil—highly decomposed peat of any source, usually mixed with mineral soils (often marketed as topsoil).
5. Sedimentary peat—highly decomposed, colloidal, organic residues mixed with clay and sometimes marl. This peat has no value as an organic soil amendment.

In Soil Taxonomy, there are four suborders of Histosols used to describe organic soils. Fibrists, Hemists and Saprists are Histosols that are saturated long enough under natural conditions to limit agricultural operations, but vary in degree of fiber decomposition (Saprists/Hemists/Fibrists). Folists, on the other hand, are not saturated with water for significant periods of time. In general, Hemists and Saprists are much less desirable than fibrists due to their decomposed "mucky" nature, while Folists tend to be highly variable.

Residues such as hark fragments, sawdust, wood chips, and finely divided wood fiber from sawmills and other wood-processing plants have been used with good results. Raw or processed hardwood bark gained recognition as an excellent material for erosion control in the early 1970s (Yocum et al., 1971). The weight of the material and its interlocking rough fibers contribute to its effectiveness. Concern that toxic components of hardwood bark will affect the establishment and growth of plants has been overemphasized. Laboratory and field research has identified only a few minor hardwood species that have documented toxicities. Wood chips, sawdust, and pine bark are less desirable than hardwood bark, since they are light in weight and have a tendency to float in runoff water. If applied as mulch, tackifiers are used or the wood residues are incorporated into the soil.

The benefits of sawdust are reduced by the rapid digestion of this material by microbes and its undesirable C/N. Wood chips and bark fragments last much longer and are the more common form of wood residue used as a mulch or organic amendment. Equipment has been developed to apply these materials efficiently at costs competitive with other products (Emanuel, 1970; Sarles, 1973). Experience has shown those application rates of 56 to 94 m^3 ha-' or 1700 kg ha-' or more for bark, wood chips, and sawdust have provided acceptable protection for a variety of sites. The range of effective rates reflects variability in site conditions and seasonal weather patterns.

Recycled waste paper, often referred to as wood cellulose, makes desirable mulch that can be applied with a hydroseeder or hydromulcher. The fibers in this material are usually short, so the durability of the mulch may be less than that of materials with long fibers. Even when applied with a tackifier, particles tend to detach and float away on runoff water. Recycled paper is not as effective at reducing surface temperature or soil moisture loss as is mulch from wood residues. It contains no N and must be supplemented with N fertilizer. Decomposition rates are extremely fast and surface benefits of this mulch are short-lived. Recycled paper should not be used where surface runoff is a problem (Munshower, 1994). Reprocessed waste paper does have higher moisture content than processed wood fiber mulches. Moisture content should be considered in determining application rates from a predetermined air-dried weight per hectare. Further detail on use of hydraulic mulches and application techniques is given in Booze-Daniels et al. (2000, see Chapter 35).

Processed wood fiber mulches, prepared from selected woods, are widely used. They are applied to the soil surface with hydromulchers or applied as some type of woven erosion control blanket or mat. They are constructed of an organic material such as straw, fibers (excelsior), coconut (*Cocos nucifera* L.) fiber, jute, or burlap woven together or held in place by some woven material. They are designed to control erosion on slopes. Vegetation may be seeded under the mat or seed may be impregnated into the organic materials. Erosion control blankets are designed so that seeds germinate and stems grow through and above the mat. As the fabric ages, it becomes incorporated into the soil, decomposes, and loses its ability to control sediment loss from the slope. However, it is replaced by living plants that continue the control of erosion initiated by the mat. Variable amounts of straw or different types of biological materials may be used for different slope angles, overland flow rates, soil materials, erosion potential, or postdisturbance land use. Mats require close soil contact and are usually attached to the seedbed with large staples. The edges of the mat must be buried in the soil to prevent wind from lifting the blanket from the soil surface. If wind does get under the fabric, it destroys soil-mat contact, and effectiveness of the erosion control blanket is lost. The product is sold in bales that are easily handled and conveniently stored.

The degree of compaction during baling may influence the rate at which the wood fiber mulch can be added to the mixing tank in the hydromulcher. Rates of application that provide a mulching effect range from 1 to 2 Mg ha^{-1}. Lower application rates may be used, hut effectiveness of this material as mulch is proproportional to the rate of application. Low rates of application of wood fiber may increase the dispersion of seed in the slurry. Colored mulch will mark treated areas. The durability of this short-fibered mulch is short, even when the rates of application are high.

The value of other mulches in establishing vegetation may be compromised if, for the sake of convenience, a slurry containing a mixture of seed, fertilizer, and wood fiber is applied. Application of such a mixture provides an opportunity for some of the seed to be perched above the ground in a web of mulch. A tender, germinating seedling perched in this porous medium is vulnerable to extremes of temperature and to desiccation. The probability of seed damage or seedling mortality is related to the species being seeded, the amount of mulch applied, and the season of seeding. A more effective practice is to apply the seed and fertilizer first, and the wood fiber mulch subsequently. This procedure may be particularly useful in areas of low rainfall or when prolonged dry periods may occur.

III. PREPARATORY CROPS

Use of vegetative mulches in situ also should be considered in the humid eastern USA. Protection against erosion has been suggested as one of the most important reasons for cover or preparatory crops (Tisdale & Nelson, 1975). Quick-developing annual grasses such as rye *(Secale cereale L.),* wheat, Japanese millet *(Echinochloa crusgalli* var. frumentacea), and German millet *(Setaria italica* L.) are sown after adequate fertilizer and other soil amendments have been applied to support plant growth. Species of grasses are selected that are compatible with the season during which they will he grown. Also, the grass and legume species that will be the permanent vegetation is often seeded when the mulch grass is seeded. Care must be taken not to seed the fast-growing mulch grasses at so high a rate that it will he too competitive for the establishment of the permanent species.

The mulch grass provides a ground cover while it is growing and continues to protect the site after it has matured and died. Stubble mulch is another term used to describe preparatory crops and refers to the stems and roots remaining after growth of the crop. The root system of the mulches in situ anchors the dead stems and leaves of the plants in place so that they provide a protective mulch that may be effective for 1 yr. or more. Another possibility would be to seed the permanent grass and legume species in this mulch. Typically, the stubble mulches are seeded in the spring and the permanent vegetation cover interseeded during the fall of the same growing season. Under this condition, a seed-soil contact must be adequate to ensure seed germination. This can be accomplished with specific drill seeders to get seed into the ground.

Crop residues also are ideal for mulching purposes and to benefit soil productivity. Surface residues from summer crops and weed growth, if left undisturbed, may provide more protection than preparatory crops seeded in the fall (Tisdale & Nelson, 1975). Desirable crop residue management means the conservation of all organic material (roots, leaves, and harvest residues) on or near the soil surface. A good crop residue management system has several benefits including: (i) increased crop yields; (ii) less surface erosion by water and wind; (iii) more available soil moisture; (iv) more soil organic matter; (v) less soil compaction; and (vi) more desirable bacteria, actinomycetes, and fungi. Disadvantages of a crop residue management system include (i) more insects, disease (ii) weeds, and rodents; (ii) more wetness and coldness in the soil surface, resulting in slower germination; and (iii) more difficulty in getting good seed-soil contact, resulting in a nonuniform stand (Follett et al., 1981).

Green manures also are preparatory crops that have a beneficial mulching affect on the soil surface and subsequent permanent vegetative cover. A green manure crop refers to the growing of legumes, small grains, or other plants that produce an abundant root system and a large amount of aboveground biomass in a short time, which is subsequently plowed into the soil. This technique is used to increase soil organic matter while stabilizing surface soils and inhibiting development of weedy species. In most uses, the green manure crop is permitted to develop for one or more growing seasons before it is plowed under and the perennial vegetation is seeded. Decomposition of green manure crops is rapid, but the residual effects are considerable. Leguminous species are preferred as a green manure because these plants are N fixers and contribute N and N-rich organic matter to nutrient-deficient soils.

IV. SOIL STABILIZERS

The use of soil stabilizers for controlling erosion on drastically disturbed sites is a relatively recent development. At present, these materials are limited to use on problem areas where their relatively high cost is justified. The use of soil stabilizers also may be restricted by lack of information about rates of application for specific sites. Stabilizers are applied to the soil surface in water solutions. Most of them infiltrate no more than the upper 2.5 cm of soil and bind the soil particles together to form an erosion-resisting crust. Others form a thin film on the surface that provides temporary protection against soil movement. Soil stabilizers are often classified by their basic formulas, e.g., polyvinyl acetates, acrylic copolymers, elastomeric emulsions, and natural vegetable gums. Similar products may differ from each other because of additives mixed with basic formula. These additives may affect curing time, crust durability, and moisture infiltration rates.

There are many products available for use as soil stabilizers. Due to the large number of products on the market and the variations among products that have a similar basic formula, a discussion of soil stabilizers may become quite complex. Variables that may influence the effectiveness of stabilizers are: (i) dilution rate with water, (ii) soil properties and climatic conditions, and (iii) amendments added to the solution to aid in establishing vegetation.

Selection of a product should be based on intended use, cost, availability, and field-test results, if available. Reviews of laboratory tests that document the physical stability of soils treated with specific soil stabilizers will aid in the selection of a soil stabilizer or group of soil stabilizers for a specific site (Gabriels & DeBoodt, 1975). Standardized test procedures have been developed to determine resistance to water erosion, resistance to penetration, and compressive strength (Morrison, 1971). Weathering tests also may be used to compare products and treatments. Shallow flats filled with soil of known physical characteristics are treated with soil stabilizers and exposed to natural or artificial weathering (Kay & Mearns, 1973; Kay, 1976). The flats may be inclined at various angles or arranged to provide different exposures to the sun. Seed and fertilizer may be applied to the flats so that plant response to the treatments can be determined.

Recently, laboratory tests have been developed to evaluate those characteristics of product or treatment that may affect the establishment or growth of vegetation. The permeability of the soil crust to water or water vapor is important. Most soil-stabilizer treatments will not fill all soil pores, and moisture and air will move through the soil crust. The physical characteristics of both the soil and the treatment materials will determine the percentage of the total pore space that is filled during treatment. Measurements of loss of soil moisture and rates of infiltration reflect changes in porosity of the soil after treatment. The permeability of a crust to water vapor may affect the extent of evaporation losses that, in turn, affect the amount of soil moisture available for seed germination and plant growth.

An ideal soil stabilizer treatment would not restrict infiltration. How a treatment affects infiltration depends on both the product and the dilution ratio. Some treatments may actually increase infiltration during intense rainfall by preventing the detachment of fine soil particles that would ordinarily fill the pores of surface soil and temporarily restrict infiltration (Hendrickson, I 938).

Tough crusts can physically restrict the emergence of some plant species. Small-seeded grasses and legumes may have difficulty in penetrating tough crusts, large-seeded species of grasses would probably be less affected. Selection of species for seeding may be important when some soil stabilizers are used. After selecting a soil stabilizer for a site, the rate of application is determined after consideration of the configuration of the area, the soil type, and the expected interval between application and the development of an effective vegetative cover. The soil stabilizer should be applied on a weight basis (kilograms of dry solids per unit area) and at a standardized dilution rate to produce the type of crust that will reduce erosion and not prevent seed germination. Compatible amendments and seed are added to the solution, which is applied when the condition of both soil and atmosphere will complement the treatment. Strict procedural control should he observed on critical sites.

In the humid eastern states, all stabilizer treatments may be expected to become less effective with time because of a complex interaction among edaphic, climatic, and atmospheric variables. Generally, treatment with a soil stabilizer is expected to achieve effective control of erosion until the vegetative cover develops to a size and density that will protect the site. On many sites, such protection can be achieved within a 6- to 8-wk. period during the growing season.

Soil stabilizers usually require more precise preparation before applicationt than do mulches. One advantage of soil stabilizers is that all the materials required to establish vegetative cover could be applied in one operation, whereas, for many mulches, application of seed and fertilizer must precede application of the mulch. A secondary benefit from the use of soil stabilizers is a reduction in iced loss because of surface runoff, the soil stabilizer holds the seeds in place anti) they germinate. This fact is particularly important on extremely steep slopes. It also has been observed that soil stabilizers reduce friction in the hydromulcher's pipelines, pumps, and application hoses, thus reducing wear on these vital parts and making application of the slurry more efficient.

V. COMBINING MULCHES AND SOIL STABILIZERS

An attractive alternative to separate treatment with a mulch or soil stabilizer utilizes a combination of wood fiber or wood cellulose mulch and a soil stabilizer. In this combination, the desirable characteristics of the materials complement each other. Low rates of application of the combination should provide site protection comparable to that achieved by a high rate of either product used alone. The effective life of a wood fiber or wood cellulose mulch is extended when used in combination with a soil stabilizer. Many stabilizers also may be used as chemical tacks to hold straw, hay, or other light-weight mulches in place. The chemical stabilizer binds the individual pieces of mulch together and increases the resistance of the material to the movement of wind or water. The strength of the bond and the effective life of the treatment depend on the amount of soil stabilizer applied.

VI. TECHNIQUES FOR AND RATES OF APPLICATION

Uniform application of a mulch is critical to allow complete and uniform revegetation. Incorrect rates and distribution of the mulch material can impair the soil surface, delay seed germination and development, degrade the quality of surface- and ground-water, and evoke nuisance complaints from neighboring property owners (Slick & Curtis, 1985). Organic materials should be placed on soils in accordance with locally approved soil and water conservation practices. Such practices minimize the extent to which components of the material enter surface- and ground-water. They also minimize odors and provide for application to soils that will benefit the most.

Adherence to proper mulching rates and application procedures will greatly enhance success in establishing vegetation and in protecting the disturbed soil from erosion (Slick & Curtis, 1985). Surface preparation of the disturbed soil must be suitable for vegetation establishment. The landform designs and effects of hackfilling, grading, and topsoiling the disturbed surface for reclamation should be carefully considered. Some design and construction practices produce surface conditions that are not always necessary or appropriate for applying seed or mulch. Grading practices on some disturbed soils, especially those with a predominance of clay and silt particles, can actually hinder successful runoff control and vegetation establishment. Disturbing and grading wet or saturated disturbed soils or tilling and leveling dry material to a fine smooth finish alters the physical properties of the soil, creating compaction and other undesirable surface conditions. There is a tendency to unnecessarily finish, grade, or manicure the prepared surface. The surface should be left as rough as possible without disrupting the approved postdisturbance land use. Contoured furrow, ripped strips, or other rough tillage methods are preferable to the smoothly graded and harrowed surface. A properly roughened, cloddy, and loosened surface will enhance mulch adherence; reduce evaporation; provide numerous depressions that will intercept and slow surface runoff and retain moisture; create ridges that protect against abrasion by windblown soil; and provide pockets that trap and hold sediment, improve water infiltration, and benefit plant growth.

To maximize revegetation potential, slopes should he designed and constructed as flat as economically possible. As slopes become steeper, erosion control cost increases rapidly and the effectiveness and performance of control measures decrease. Slopes should be designed with gradients reduced to a degree that will provide mechanical stability with adequate rounding at both top and bottom and with appropriate transitional grading in between. The purpose of grading and shaping the slopes is to reduce the erosive forces of water and retain it on site fot use by vegetation.

Other important considerations in selecting a mulch or soil stabilizer are the cost at the point of application and the commercial availability of the equipment needed for application of the material. In selecting the equipment, consideration must be given to the terrain that must he covered. Wheel-type equipment cannot be used on very steep slopes; therefore, the equipment must have a range that will cover these areas.

A. Equipment Used

Methods of mulch application vary depending on form of mulch material and type of equipment and labor available. The method of application chosen depends on whether the mulch is fibrous, solid, or liquid as well as on its particle size, weight, and composition (Slick & Curtis, 1985). Uniform distribution at the desired rate and depth is essential. Poor distribution may impair seedling growth or leave part of the surface inadequately protected. Depth is somewhat difficult to control because of uneven surfaces. However, an absolutely even depth of mulch is not necessary as long as an average depth is obtained over the site. Mulching rates should be determined before the mulching operation and the equipment carefully calibrated to achieve the desired results. Commercial fiber mulches are often dyed with nontoxic fugitive green dye so that they are plainly visible when applied, aiding the operator in obtaining uniform coverage. Currently, mulches are spread manually and mechanically with either of three spreading mechanisms: rotary, pneumatic, and hydraulic. All three mechanical application systems can be used in spreading various fibers though solids are usually applied with a rotary spreader or pneumatic blower and some fibers and liquids with hydraulic spray. All types of mulch can be spread by hand.

Spreading or broadcasting mulch by hand is generally used in hard-to-reach, small (0.4-0.8 ha) areas, on harsh sites or steep slopes beyond the reach of a blower or hydraulic spray; and around trees and shrubs. The method is difficult, tedious, time consuming, and costly even on small areas. It is difficult to spread fiber evenly by hand, although leaves may be spread easily. Unchopped fiber spread by hand remains in place and is more effective than chopped, yet the manual labor required for such spreading is costly. Many types of mulch material are applied uniformly by mechanical means.

Physical characteristics of the mulch may be such that specialized equipment must be used if it is to be spread efficiently and economically. Rotarty pneumatic or hydraulic application requires products that are uniform in size and preferably free of trash, dirt, and dust. Mulching with rotary spreaders is common and involves the application of dry, fibrous and heavy, solid mulch by using a combination of conveyors, augers, rotary heaters, paddles, flails, centrifugal bladed disks, or spinners to broadcast the mulch to the rear or to one side of the machine. Lime/fertilizer spreaders, municipal spreaders, manure spreaders, modified stack processors, and tub grinders are conventional and modified equipment available in this category. Rotary spreaders are driven or pulled and work well on benches, terraces, and level or moderately rolling terrain adaptable to typical agricultural implements. Usually only two people are required on a rotary spreader operation. A third may be necessary if the mulch has to be tacked.

Pneumatic spreaders use an air stream to dispense mulch. Dry fibers or solid mulch materials are blown out of a discharge chute onto an area using air pressure generated by a motor-driven, high-pressure, paddle-wheel fan. An impactor is provided on some machines as an additional force to more efficiently propel heavier material. Some machines are equipped to spray a chemical adhesive (tackifier) on the mulch as it leaves the discharge spout. Fiber is spread more easily by blower than by hand. A blower shreds, cuts, and evenly spreads or scatters fibrous material. The mulch lies down in closer contact with the soil than dose hand-spread fiber. A fine-stemmed, baled, fiber mulch is preferable to loose mulch for pneumatic spreading. Wood fiber or cellulose can he applied with a blower but application in this manner leaves much to be desired. Leaves, even when damp, can be spread with a pneumatic spreader. Power mulchers and the Estes-type spreader (formerly manufactured by Estes Equipment, Inc., Winchester, KY) are examples of conventional and modified equipment available. Pneumatic spreaders provide the ability to cover inaccessible or steep slopes. They are drawn or driven along a road, terrace, or bench above or below the slope to be treated. They enable mulching of steep slopes without the water required for hydromulching (Slick & Curtis, 1985). Four people are usually required to operate pneumatic spreaders efficiently with a possible fifth person needed when it is necessary to tack the mulch.

Hydraulic spreaders are used to apply wood fiber and cellulose. Tank trucks with gravity or pumped discharge and various forms of sprinkler irrigation are used to apply slurry and liquid sewage wastes. Spray applications are used most successfully with wood fiber or cellulose mulches applied with a hydraulic seeder, more commonly called a hydroseeder or hydromulcher. The main advantage of the hydraulic spray method is that mulch can he applied to areas that cannot be easily reached by other methods. The spreading distance is as much as 60 m from the machine depending on efficiency of the machine and wind conditions. The system is popular because of ease of application and because all materials needed for revegetation can be applied in one pass over the area. Disadvanages of the hydraulic spray equipment are that only a relatively small area can be treated with each load of material and a source of water must be readily available A considerable amount of time may he required in transporting or pumping water.

Liquid and slurry sewage wastes can he applied by self-propelled sprinkler irrigation equipment, such as a center pivot or a portable or traveling gun, which has a single large nozzle (1.9-5.1-cm orifice) with 552 to 690 MPa. With the travelling gun system, a large single sprinkler on a carriage is winched across the area, pulling a flexible hose through with sludge is pumped. An aerosol drift problem may occur with high-pressure sprinkler systems. Spray irrigation may involve the construction of distribution lines (either stationary or movable), the installation of pumping equipment, and time-cycle devices.

It is essential that some mulches, such as cereal crop straws, hay, leaves, wood fiber and cellulose, and other lightweight fiber materials, be anchored to the soil surface to assure protection of the soil. Some can be anchored as they are being applied. Where this is not possible, they should be anchored with a tackifier, such as asphalt, immediately after placement to minimize loss or movement. Coarser aggregates such as shredded bark have interlocking pieces that have a tendency to stay in place even on steep slopes. The size of area, mulch material, cost, and effective life of required treatment in combination should determine the anchoring method to be used. Whatever method is selected, it should effectively hold the mulch in place until vegetation takes over. The basic methods of anchoring mulches are manual, mechanical, and chemical (Slick & Curtis, 1985).

Manual anchoring is most applicable on small or critically sloping areas. It involves manually tying the mulch down with stakes or pegs, twine, string netting, or wire mesh. If stakes are used, they are driven usually on I .5-m centers with twine strung between stakes to form square, diamond, or cross patterns over the surface of the mulch. A variety of nets and mesh have been used including jute, baling wire, wire poultry netting, concrete reinforcing wire, chain link fencing, plastic fabrics, and twisted woven kraft paper. Nets and mesh should be anchored at enough points to prevent material from curling or whipping in a wind.

Mechanical anchoring is accomplished by pressing the fiber mulch into the soil by crimping, disking, or rolling. The average length of blown mulch fiber should be 15 cm and incorporated to a depth of 4 to 8 cm, which is sufficient to anchor but not bury it. Properly placed fibers should create a stubble effect that provides an excellent obstruction for wind saltation and surface flow. Straw, unless crimped, tends to perch rather than hind with the soil, al lowing rifling even on gently slopes. Fiber crop residues used for mulch should he new and pliable because excessively dry or rotten mulch is easily broken or cut in two. Machines for anchoring operate most efficiently on relatively level or moderately rolling land with slopes less than 3:1. On steep slopes, where machines are not suitable, mulch should be anchored with nets, mesh, or a chemical tackifier.

Crimping is accomplished with a specially designed crimper or with a conventional farm disc. These machines work best if the soil has been scarified to a depth of 10 to 15 cm during seedbed preparation because the blunt notched disks will not penetrate hard soil. Rolling or punchin g is done with a specially designed pronged roller. A conventional cheeps-foot roller is used on light soils. Punching may not be as effective as crimping because of the staggered arrangement of punched mulch compared to the "whisker dams" made by crimping (Slick & Curtis, 1985).

Chemical tackifiers are organic and inorganic chemical products applied in water solutions to lightweight mulches to hold them in place. Chemical tackifiers can be added to the mulch as it is applied. Adhesive injectors can be mounted at the mouth of the discharge chute to coat the mulch as it is ejected. Alternatively, hydraulic sprayers can be used in separate operation to cover the mulch after it is on the ground. Numerous chemical stabilizers are available. However, there Is insufficient knowledge about the comparative value of different products and about the most effective application rates for specific materials. Two broad classes of chemical stabilizers are recommended as tackifiers: polyvinyl acetate emulsions and acrylic copolymer emulsions. Recommended application rates are 95 to 190 L ha '. A dilution rate of 1:10 to 1:20 (1 part stabilizer-9 or 19 parts water) is suggested (Slick & Curtis, 1985).

The most commonly used chemical tackifier in the eastern USA is asphalt emulsion at a rate of 2300 to 4500 L ha-'. Caution must be exercised in using asphalt because it may retard germination and lower seedling emergence. Some plants react negatively to asphalt, while others react positively. Asphalt softens in hot weather and can be a sticky nuisance if allowed to drift onto traffic areas. It's black color helps increase soil temperature, and that may help to encourage growth in cool weather. Asphalt adhesives for application with mulch are usually liquid asphalt conforming to American Society for Testing and Materials (ASTM) Specifications D2028, designation RC-70 (ASTM, 1985) or emulsified asphalt conforming to ASTM Specifications D-77, grade SS-I (Slick & Curtis, 1985). The specifications currently used by the Natural Resources Conservation Service are:

I. Liquid asphalt rapid curing (RC-70, RC-250, or RC-800) or medium curing (MC-250 or MC-800) (apply 0.379 L m-2).
2. Emulsified asphalt (SS-1, SSk, SM-K, MS-2, RS-1, RS-2, RS-2K, or RS-3K) (apply 0.151 L m-2).

Rapid-setting materials (RS) are formulated for curing in approximately 24 h. Slow setting (SS) is formulated to allow adequate working time during dry hot weather. A higher number in the formula indicates a heavier residue. Emulsion can be applied either as a separate spray over the mulch or simultaneously with the mulch using the injection method. Some materials are applied from the top of a slope down with blowers equipped to spray a chemical tack on the mulch as it is being discharged. Application from the toe of a slope upward can create small dams that pond water on the surface of the mulch, causing some slumping, especially where the mulch helped maintain moisture at field capacity. Asphalt is nonporous, causing water to run off, but conserves moisture underneath it.

Chemical stabilizers also are used in combination with wood fiber and wood cellulose mulches more frequently than stabilizer alone. Assuredly, site protection obtained with low rates of the combined material is comparable to that obtained with high rates of either product used alone. A combination recommended and used in some eastern states is 189 L ha^{-1} of stabilizer mixed with a minimum of 560 kg ha^{-1} of wood fiber or wood cellulose (Slick & Curtis, 1985). Because they can be applied with a hydroseeder, chemical stabilizers have an advantage for tacking mulches on long steep slopes and other hard-to-reach places.

Materials such as hay, straw, or bagasse are delivered to the site in compact bales, and commercially available blowers apply the baled material. Truck-mounted mechanical dry blowers disperse large quantities of mulch, up to 18 Mg ha-1 (Munshower, 1994). Dry blowers have the capacity to cover large areas in a short period of time. These blowers may he equipped with an attachment that sprays a chemical tack on the mulch as it is being discharged. Native hay mulches must be distributed with a modified manure spreader or specialized hay spreader. To pass through a dry blower or hydromulcher, native hay mulches must be ground.

Because native hay mulch contains many leaves, flowers, and seed heads, it often contains a small amount of N. The concentration of this residual N is usually high enough that no fertilizer amendment or less fertilizer is required when compared to the use of cereal straw, paper, or wood residue mulches. If ground to pass through the dry blower or hydromulcher, native hay mulch may lose most of its desirable properties.

Many commercially available mulches, such as wood fiber and wood cellulose products, are designed for application by hydromulchers. Hydromulchers mix mulch with a fluid that permits spraying of the mixture over the site. The amount of wood fiber or wood cellulose that can be added to a hydromulcher is limited by the capacity of the pumps and circulation system. An 11.4-kL hydromulcher has the capacity to pump slurry containing 1100 to 1700 kg of wood fiber or wood cellulose. Two or more hydromulcher loads may be required to achieve the desired rate of application.

Field applications of animal manures, various composts, sewage sludge, and other solid wastes include; spreading of the solid wastes on soils using commercial spreaders, injecting a slurry of water and animal manures or sewage sludge directly into the soil, spraying the slurry of water and animal manures or sewage sludge on the soil surface and allowed to percolate into the soil, injecting a slurry of water and animal manures or sewage sludge into a sprinkler irrigation system and applying it to the soil, dehydrating the solid wastes and spreading on the soil surface. The slurry for the applications described above may come from an aerobic or an anaerobic waste pit, pond, ditch, lagoon, or debris basin (Follett et al., 1981). For the best results, animal manures, various composts, sewage sludge, and other types of solid waste should be incorporated into the soil after distribution by plow, disk, or chisel.

B. Rates of Application

The selection of the optimum rate and depth of a mulch is influenced by its intended use and the effectiveness of the mulch in modifying environmental factors associated with the site conditions (Slick & Curtis, 1985). Soil and seed protection, erosion control, and growth enhancement are the main purposes for use of mulch and are the most logical components on which to base application rates (Table 25-1).

An important consideration in the efficient use of mulch is that of mulch depth in relation to application rate (Slick & Curtis, 1985). Additionally, the particle size and correct amount of mulch are directly related to the proper depth at which to apply the mulch. For example, 103 m^3 of bark shredded in small chips will cover 0.5 ha to a 2.5-cm depth, while it would take 122 m^3 of chunk hark for the same coverage. Coverage with straw at 3.4 Mg ha^{-1} provides about a 2.5-cm layer. The rate and depth of application varies due to the type of material and particle size. Coarse and more bulky materials may be applied in greater depths than those of small materials that will compact. The selected material should be sufficiently loose and open for free circulation of air to favor development of vegetation.

The quantity of mulch needed at a specific site varies with soil surface and seeding conditions; species of plants to be seeded; and their requirements for ger-

Table 25-1. Common application rates per hectare.

Mulch type	Intended use		
	Seed cover	Erosion control	Plant mulch
Straw (Mg)	3.4-4.5	6.7	8.9
Hay (Mg)	4.5	6.7	8.9
Manure (Mg)	22.4-33.6	67.2-89.6	89.6-134.4
Hardwood bark (m3)	34.4	183.5	366.9
Softwood bark (m3)	34.4	183.5	366.9
Hardwood chips (m3)	38.2	204.9	409.8
Softwood chips (m3)	38.2	204.9	409.8
Sawdust (m3)	210.2	420.5	630.7
Leaves (Mg)	6.7	8.9	11.2
Composted municipal solid waste (Mg)	44.8		
Sewage sludge (Mg)	168.0		
Wood cellulose fiber (kg)	1681.5	3363.0	

mination, seedling emergence, and establishment (Slick & Curtis, 1985). Mulch should be applied at a rate that will provide the necessary protection for the soil surface yet not prevent seed germination and emergence. Cover mulches are usually applied at depths from 0.6 cm up to a maximum of 5 cm depending on the type and size of material. Depths greater than 5 cm will begin to significantly affect germination and emergence of seedlings. The optimum depth of mulch for seed cover is related to seed size. If the mulch is too thick or tightly matted, the seedlings may not have sufficient energy to penetrate the layer. The smaller the seed, the less energy available to emerge. For small-seeded species, such as weeping lovegrass *(Eragrostis curvula* (Schrad.) Nees) or timothy *(Phlewn pratense L.),* emergence is likely to be reduced where they are covered with more than 1.3 cm of solid mulches such as bark. In situations where higher rates of mulch are needed or required, increase the seeding rates of species with small seeds to compensate for the reduced emergence, or select vegetation species with larger seeds that would be compatible with higher rates. Compared to most of the grasses and legumes with smaller seeds, large-seeded species such as winter rye, or sorghum *Sorghum bicolor (L.)* Moenchl will emerge through a greater thickness of mulch. Mulch depths of 2.5 cm or more have been used to cover large seeds.

In general, light applications of cover mulch are more desirable than heavy applications. If the application is too light, however, the result is little or no improvement in soil protection, seed germination, or ground cover. Too much mulch may smother seedlings by intercepting all light or by forming a physical barrier that seedlings cannot penetrate. Heavy applications may prevent full circulation of the air that can lead to self-composting. The heat generated from composting kills the seed and prevents seedling growth.

When mulch is to be used alone as a temporary erosion control measure, the quantity of mulch needed at a specific site varies with the shape, slope, aspect, and roughness of the soil surface. Thicker applications are usually needed on bare soils, in drainage ways, on topsoil stockpiles, or during the dormant season when seeding is not practical (Slick & Curtis, 1985). The mulch should be deep enough to protect and hold the soil surface and increasing the rate usually gives increased protection. So, on steep slopes, mulch is usually applied to a depth of 5 to 10 cm to satisfy stabilization needs. High rates of mulch provide little additional reduction in runoff flow, but give greater surface protection from raindrop impact.

Crop residues applied at rates of 3.5 to 9.0 Mg ha-1 on agricultural soils reduce erosion. Wheat straw applied at 4.5 Mg ha-' on a 20% slope decrease runoff velocity by approximately two-thirds from 0.024 m s-' to 0.009 m s'. Runoff velocity for a 11.2 Mg ha' application is about half that for no mulch. Lower mulch rates effectively reduce erosion of fine sand, but not silt-size particles. Although smaller rates provide lesser surface protection, they still help. Heavier mulch application rates are required for establishing seedlings or woody plants than for seeded herbaceous covers to keep soils cooler for better woody plant growth and to control weed growth (Slick & Curtis, 1985). Mulches for individual shrub and tree plantings and group or row plantings are usually applied from 10 to 15 cm deep. The depth or thickness of the mulch to be applied will depend on the kind of mulch and the type of soil. Fine materials have better insulation properties than coarse materials, but when applied in a heavy layer, can affect aeration. When this happens, plants suffer. Thus, a mulch of sawdust should not be applied as thick as hay or bark. Additionally, a thicker layer of mulch can be applied to a light sand soil than to a heavy clay soil. It is always necessary for air to reach the roots in the soil.

Differences in site conditions, such as aspect, slope, weather patterns, and seasonal climatic variations, have an influence in determining a range of effective mulches and application rates. Aspect affects the choice of mulch color and dictates depth of application. The color and uniformity of mulch depth are critical because they have varying effects on establishment and growth of vegetation.

Adverse effects are usually related to seasonal variations in moisture and temperature. As a result, mulch rates must vary. A site with a north-facing slope usually requires less mulch for a particular purpose than a south-facing slope. In the spring on gentle north- and east-facing slopes, thin, light applications of a dark-colored material may be necessary to raise surface temperatures to speed up germination, but at the same time must be heavy enough to protect the soil surface and slope from seasonal precipitation.

If conditions are severe, such as those frequently encountered on harsh sites, steep slopes, or south- and west-facing slopes, mulching rates are usually increased. In summer seeding on south and west slopes, heavy rates of light-colored material may be necessary to reflect solar radiation, to reduce evaporation, and to lower midafternoon temperatures that affect seed mortality and optimum plant growth. In the fall and winter, heavy applications of most material may be necessary to insulate soils and plants subject to frost heaving. Different mulch colors and rates are usually associated with north and south slopes, long and short slopes, and steep and moderate to level areas. Slick and Curtis (1985) provided an example, 21 m^3 ha-' of bark mulch would he used on gentle, cool slopes, while 38 m3 ha-' might be necessary on steep, hot slopes. Mulching materials can be applied at any season of the year depending on conditions of mine soil and weather at time of treatment and the intended purpose for which mulch is being applied. Usually mulch is spread immediately after seed and fertilizers have been applied, unless it is part of a hydroseeding operation.

Under most circumstances, it is essential that seeding and mulching take place shortly after the earth-moving and grading process so that both the actual disturbed area and the length of time it is exposed are kept to a minimum. If reclamation takes place at a time when seeding is least desirable (summer, late fall, mid winter), mulches may be used to temporarily stabilize the soil until seeding can be done at a more favorable time. The temperature and amount of rainfall at time of application will affect site conditions and influence the efficiency of the mulch material. Sensitive field operations must be scheduled according to local weather patterns and conditions before, during, and after application. **In** some areas, adverse weather and soil conditions may hinder access and on-site travel. To spread solid or liquid mulches, soils must be dry enough to support machinery and avoid soil compaction. In early spring, the ground is often too wet; mud can impede the operations of both seeding and mulching. Mulching can he done during the spring after the immediate surface soil has dried out.

Spreading of animal, municipal, and industrial sewage wastes should be avoided when runoff or leaching potential is high. Even though wet ground does not interfere with liquid application, the extra water could result in greater nutrient leaching and runoff loses. Caution should be used when applying mulches to steep frozen or snow-covered ground. When applied under conditions leading to maximum spring snow-melt runoff, large amounts of organic materials or potential pollution can be transported from the land. Wind direction and velocity can be limiting factors sprinkler or spray and blower applications. They can cause uneven surface coverage and carry dust, mist, or unpleasant odors from material into areas of habitation. Moisture and temperature regimes dictate proper planting and mulching season and strongly influence results of mulching. Mulching for soil protection and seed cover could be scheduled so that moisture and temperature conditions are sufficient to germinate the seed and maintain seedling growth before adverse conditions occur. Additionally, the application of mulch can extend the seeding season and make more effective use of existing and future moisture. To do the most good, mulches should be applied well in advance of spring rains, active weed growth, and sunnier drought.

Materials used as plant mulches should be applied before active weed growth starts. If allowed to gain a strong foothold, weeds rob the plants of needed light, moisture, and nutrients. **In** summer applications, modifying the environment is most important because of the need to provide weed control, insulation, id shading. Applications in conjunction with fall planting of tree seedlings could be done well before the ground freezes. This will avoid alternative freezing and thawing that often results in seedlings being heaved out of the ground. the proper time for seeding, planting, and mulching will vary from one region to another in the East and with the species to be planted. In some areas, there are several appropriate times for seeding and planting. The advantages and disadvantages of these planting periods should be known.

VII. ECONOMIC CONSIDERATIONS

A. Cost of Adding Mulches and Soil Stabilizers

The costs of soil stabilizers may be readily obtained from dealers and conventual pumps or hydroseeders (hydromulchers) can be used to apply the material.

The ability of the hydromulcher to disperse a mulch, water carrier, dye, and a binding agent simultaneously contributes to the economy of operation of these machines in large-scale operations (Munshower, 1994). Agricultural or organic industrial wastes have a potential value as mulch, and their cost at the production site may be low. Some of these wastes must be reprocessed and packaged to make them suitable for application by conventional equipment. Others can be used without reprocessing or packaging, and can be transported to the site in bulk. Any rehandling of the material at the site prior to application may significantly increase costs. Physical characteristics of the mulch may be such that specialized application equipment must be used if it is to be spread efficiently and economically. Because almost all mulches are light and bulky, and large quantities are needed, transportation costs may prohibit their use in remote areas (Munshower, 1994). Munshower (1994) suggests that it may be cheaper to transport shredding devices to isolated areas to mulch organic products available on site rather than to haul organic matter to the target area.

The cost of labor and support equipment to service and operate conventional application equipment efficiently may be an important consideration in selecting an erosion-control material. A three-person crew can efficiently service and operate a hydromulcher. In addition to the hydroseeder, a supply truck is required to haul the mulch or soil stabilizer, seed, fertilizer, and other soil amendments. Blowers that apply straw, hay, or other baled mulches require a five-person crew and one or two supply trucks. Munshower (1994) states that the use of dry blowers on most disturbances is not economical because of the expense of the equipment. Additional equipment, such as a hydroseeder, is required to spread seed, fertilizer, and other soil amendments. This equipment may be operated by the five-person mulching crew.

Erosion control blankets or mats are expensive but effective. Their costs may be many thousands of dollars per hectare, but erosion reduction could represent up to 90% of soil loss on unprotected soils. The cost of erosion control blankets prohibits widespread use on most disturbed sites. They have been used successfully on steep slopes and erosion-prone soils throughout the world and may be the only realistic alternative on many slopes.

B. Cost-Benefit of Adding Mulches and Soil Stabilizers

Research data and experience provide a basis for making generalized comparisons of a few of the materials more commonly used in the eastern USA. Straw and hay are the most commonly used erosion-control materials. Considerable evidence exists for their effectiveness in erosion control when they are applied at rates of 2.2 to 4.5 Mg ha^{-1}. Applying an asphalt or chemical tack can minimize movement of the mulches by wind. The establishment of vegetation is often enhanced by the use of hay or straw mulch. The use of these materials has sometimes been restricted by contamination of the mulch with noxious weed seeds or with organisms that cause diseases in agricultural crops. Field studies indicate that hay, straw, or bark is essential to the establishment of grasses and legumes or extremely acid surface mine spoils (Vogel, 1975). The density of grasses and legumes on plots treated with lime and fertilizer was less than that on plots treated with lime, fertilizer, and mulch. It is believed that the mulch aids leaching of toxic ions by reducing the frequency of wetting and drying cycles of the surface. Greater surface moisture under thick mulch reduces the loss of soil moisture and accelerates leaching.

Wood fiber and wood cellulose mulches are used extensively in die eastern USA, the application rates are 1100 to 1700 kg ha-'. Their popularity is related to the ease of application and to the fact that all materials needed for revegetation can be applied in one operation. These materials are not as effective as straw or hay for controlling erosion. There is evidence that these mulches may reduce the percentage of seeds germinating and slow plant growth. The percentage of seeds germinating may be reduced when seed is suspended above the soil surface in a loose web of fibers and subjected to moisture stress during wetting and drying cycles. Higher seeding rates may be used to compensate for these losses or the seed can be applied in one application and the mulch in a second application. Slower plant growth has been demonstrated on areas mulched with wood fiber, but no specific cause of this delay has been identified (Plass, 1973).

The limited use of chemical stabilizers or of wood fiber with a stabilizer has produced inconsistent results. The number of materials used, variations in the rate of application, and the variahility in soils and climate make it difficult to generalize results for any of the stabilizers. There is evidence that a few materials have been more widely used than others are, and those agencies regulating the use of erosion control products have approved the use of several materials. This finding indicates that soil stabilizers are recognized as effective materials for controlling erosion. It is assumed that their use will expand as specific recommendations for effective methods of application are developed. Reductions in the loss of seed from surface runoff may enhance the establishment of vegetation. Materials that reduce evaporation or increase infiltration rates also would benefit plant growth. There is no evidence of chemical inhibition of germination or growth.

Residues from the wood-conversion industries are important mulching materials in some localities. Those that are supplied in bulk usually have a limited market area because of transportation costs. The lack of efficient application equipment also has restricted the use of these products. Recently, new equipment has been developed that will apply these mulches, as well as other agricultural or organic industrial wastes. Rates of application are often expressed in cubic meters, since waste from wood-processing plant show extreme variation in moisture content. Application rates relating to weight must be based on air-dry weight to assure uniformity. Residues from wood-processing plants may be effective materials for controlling erosion. The hardwood bark products are less subject to movement by wind and water than are wood chips. Wood chips are light in weight when dry, and may be moved by strong winds and runoff water. There is evidence Iliat plant establishment and growth is improved when mulches are used. Denitri cation is not a serious problem since individual particles are large and decompose slowly. If, however, the bark is mixed with the soil during seedbed preparation, approximately 30 kg of additional N is required.

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35 Establishment of Low Maintenance Vegetation in Highway Corridors.

J.N. BOOZE-DANIELS, W.L. DANIELS, AND R.E. SCHMIDT

Virginia Polytechnic institute and State University
Blacksburg, Virginia

J.M. KROUSE

University of Maryland
College Park, Maryland

D.L. WRIGHT

University of Florida
Quincy, Florida

I. INTRODUCTION

While surface mining for coal, aggregate, and other minerals is generally regarded as the major drastic disturbance to land in the USA, the disturbance associated with road building and similar urban related activities certainly approaches (or surpasses) mining in total annual impact. A small amount of land is disturbed by pipeline construction and reclamation of these areas is addressed in Fedkenheuer (2000, see Chapter 34), of this book. The cut and fill materials generated by the road building process are often quite similar to mining spoils and overburden and pose similar revegetation challenges. The major differences are that the highway disturbance occurs in long linear strips that often transect a variety of soil and geologic materials, and the cut slopes generated by road building often generate completely different microsites over very short distances. Mining sites, on the other hand, are much broader in their area of impact and usually encounter a relatively consistent mixture of soils and overburden that are returned to original or near-original contours. Despite these fundamental differences, the basic approach to revegetating highway sites is remarkably similar to that employed on mining sites, even though the long-term management implications are profoundly different.

Revegetation plans for highways must not only provide for erosion control and slope stability, but they must meet varying aesthetic demands of roadside managers and the traveling public. In certain roadside environments these goals are met through the establishment of mixed stands of herbaceous grasses and legumes with minimal inputs of fertilizers and other soil amendments. In other instances, particularly in the urban environment, pure stands of grasses along with ornamental plantings are required that necessitate higher levels of fertilizers, soil amendments, and management inputs. In general, highway revegetation specialists are expressing growing interest in the use of low-maintenance native trees and wildflowers in lieu of more demanding exotics, and the economics of right-of-way management are demanding that mowing, fertilization, and other management practices be limited whenever possible. The growing interest of citizens groups and regulatory agencies in off-site water quality impacts and the biodiversity issues associated with highway corridor management also are forcing this change in management perspective.

The successful revegetation of highway sites is dependent upon a thorough knowledge of the soil and site properties that must be stabilized, the plant materials to be employed, and how the plant/soil system must be managed with time to achieve the given revegetation goals. The biotic environments in old or newly constructed highway corridors in the USA vary in climax vegetation from semitropical with forests to grasslands to arid desert regions with sparse vegetative cover. The soil and geologic materials that must be revegetated also vary widely across the USA, but problems of low organic matter and water retention, compaction, and nutrient deficiencies or imbalances are universal across all disturbed sites.

From the viewpoint of environmental issues and aesthetics, two major problems are encountered in highway corridors: (i) erosion by wind and water during the construction phase before stabilization with vegetation, and (ii) concurrently controlling erosion and plant succession to a persistent vegetative cover requiring little or no maintenance beyond establishment. New construction disturbs natural contours, drainage areas, and climax vegetation to cause potential wind and water erosion and water quality impacts. The choice of erosion control practices to minimize off-site water quality impacts from construction sites in highway corridors depends on grading methods, slope preparation, soil surface conditions, soil amendments, mulches, species selection for mixtures, and upon obtaining a desirable, persistent vegetation through plant succession.

In this chapter we will review general concepts and approaches for evaluating site conditions, vegetation establishment, and long-term management of highway corridors. While many of the studies and concepts presented here are specific to certain regions of the USA, particularly the East, the principles developed and discussed should be applicable to all regions and highway corridors. The concepts and approaches described here can then be used to develop site-specific recipes of amendments, species, and management practices for the diversity of sites commonly encountered. The cut and fill slopes generated by highway construction pose unique challenges to the revegetation planner and a fundamental understanding of both site/soil conditions and plant community dynamics over time is critical for success. We also believe that many of the problems, interactions, and approaches discussed here also are applicable to the urban development environment.

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large amounts of fresh unweathered rocks and sediments that can be significant sources of Ca, Mg, K, and other nutrient elements as they rapidly weather in their newly exposed geochemical environment. Acid-forming sulfidic materials (Sobek et al., 2000, see Chapter 4) also are commonly encountered in deeper roadcuts in a variety of geologic settings, and can generate extremely harsh soil chemical conditions and associated runoff water quality complications as they oxidize.

It is important to note that the soil testing procedures and fertilizer/lime recommendation systems used by the majority of university and private-sector laboratories were developed and correlated for use on natural weathered surface soils and therefore may not accurately predict amendment needs for the roadcut environment. This is not to say that soil testing is not appropriate to highway revegetation efforts, but the results of a given test need to be specifically interpreted for their application to these types of materials. This is particularly true when unweathered sediments or soft rocks are being revegetated or the roadcut exposes sulfidic or other unusually reactive materials.

The cut/fill and site development operations for new highways or other construction activities may cause uncontrolled water flows and sediment loss from bare soil areas. Many small localized disturbed areas with seemingly insignificant losses of water and soil will often coalesce into massive and rapid flows of water with high sediment loads, causing severe damage in highway corridors as well as flooding and contaminating receiving streams. Even the initial slow flows of clear water from numerous small areas of disturbance within a highway development corridor can cause progressively larger erosive flows of water. Thus, it is imperative to minimize water flow and sediment losses from the initial stages of grading operations. Uncontrolled erosion also can severely degrade the site quality of the eroded area, particularly if applied topsoil. lime, and fertilizers are lost, or a less hospitable substrate is exposed.

Runoff during construction can be controlled or minimized iii five primary ways: (i) grade slopes as shallow as practical, (ii) decrease slope length, (iii) employ grading and soil management to encourage water infiltration and reduce runoff, (iv) immediately establish vegetative covers as the slopes are being constructed to hold soil materials in place and encourage water infiltration, and (v) use rock or concrete drains for containing and rapidly removing concentrated flows of water. While it is true that cut, fill, and median slopes in a given area will usually have contrasting physical properties, all slopes should be designed as shallow as practical, since the amount and rate of runoff during and after heavy rains is directly proportional to an integrated slope and flowpath length factor. The final slope gradient on a given area depends on many factors including right-of-way constraints, soil properties, the design constraints of the road itself, along with the relative cost of cut/fill alternatives. For example, micaceous and sandy soils are usually less stable on steep slopes than heavy-textured soils due to their lack of cohesion and corresponding low shear strengths; hence, such slopes should be shallow. Any extended slope on a site will increase its erosion potential, however, and during winter, minimal precipitation can cause severe rifling and erosion even on shallow bare slopes. The bottom line is that construction planning should encompass the design and grading of slopes, water quality problems that could potentially he encountered, and both the short- and long-range maintenance programs for any road corridor construction project.

A. Grading Cut Slopes

The relative erosion hazard from a cut slope and the ease of its revegetation will be largely dependent on how it is constructed. For long, sloping cuts, the grading operation should begin by establishing diversion ditches at the top of cuts to impede and disburse water from slopes above the area to be graded. Slopes should generally be no steeper than 75% (1.5:1), because the shallower slopes are less erosive and vegetation can more easily be established (Ostler & Allred, 1987). Duffy and Hatzel (1988) found that if the slope length is reduced by half, the amount of soil eroded was reduced by 70%. The steepness of cut slopes should be determined by the length of grade, soil and rock materials present, topography, width of highway corridor, and ease of establishing vegetation. For example, it is more difficult to establish vegetation on "hot" south-facing slopes than on "cool" north-facing or shaded slopes; hence, shallower slopes on sunny exposures would facilitate the establishment of vegetation (Wright et al., 1975).

Slopes steeper than 33% (3:1) should he benched or stair-step graded, left rough, or grooved. *Stair-step grading* may be used on any materials soft enough to be ripped with a dozer. In particular, slopes steeper than 50% (2:1) should be stair-step graded. The ratio of the vertical cut distance to the horizontal distance should be less than 1: 1, and the step should slope toward the vertical wall to catch sloughing soil, increase infiltration, and reduce runoff. The individual vertical cuts should generally not be more than 60 to 90 cm in soft soil materials and not over 100 cm in rocky materials (Blaser & Perry, 1975; Green et al., 1974; Perry et al.,1975; Wright et al., 1975). The heights and widths of the steps may vary within a cut. Soft rock and/or subsoil material is ideal for stair-step grading and rapidly establishing vegetation during grading operations. Areas in the mountainous region of the western USA use topsoil on the stair-steps where vegetation is desired because the infertile bedrock material weathers slowly and allows little water infiltration (Foote et al., 1970). In New Hampshire's sand and gravel soils stair-step terraces work well, especially if equipped with water diversions at the top of the slope (Kelsey, 1991).

Numerous steps or breaks in a cut-slope improve water infiltration and generally nullify sheet erosion, rifling, and pollution of runoff waters (Blaser et al., 1975). Sloughing and falling materials and precipitation intercepted by horizontal steps cover much of the lime, fertilizer, and seeds to promote germination and seedling growth, and enhance the establishment of a vegetative cover. Stair-step grading also augments encroachment of persistent leguminous vegetative cover, such as crownvetch *(Coronilla varia* L.) (Wright et al., 1975). Stair-step grading prevents an accumulation of mud and water at slope bases that usually occurs in drainage ways with the conventional smooth hard surfaces of cut slopes and bench grading.

All surfaces of cut slopes less than 50% (2: I) should he left rough and undulating with stones left in place. *Rough grading* generates a pattern of raised and low areas providing microenvironments that enhance establishment of vegetative cover. This technique has been adopted in many regions of the USA (Adams & Blaser, 1979; Huffine et al., 1981), and it is especially effective in drier climates. In the gravel and sand soils of New Hampshire, rough grading is discouraged, however, and tracking is encouraged as an alternative because it compresses the soil and creates appropriate microclimatic conditions (Kelsey, 1991).

The detrimental practice of constructing slopes with smooth, hard surfaces gives a false impression of "finished grading" and a job well done; but vegetation often fails. Rough grading of slope surfaces with rocks left in place gives an "ugly" appearance to the novice, but encourages water infiltration, speeds up establishment of vegetation, and decreases the rate of water flow into drainage ways. In one study, roughened surfaces with topsoil or subsoil exposed increased soil moisture and decreased soil surface temperature, which increased germination, plant density, height, and protective cover (Woodruff & Blaser, 1970a). Slopes along older highways with smooth hard surfaces should be *grooved* (rather than tracked) to aid in re-establishing vegetation. The grooves should be 8 to 15 cm deep, parallel to the highway, and spaced 38 to 60 cm apart. Such grooves collect sloughing soil, seed, and soil amendments, and enhance the rate of obtaining a protective vegetative cover (Green et al., 1973a; Perry et al., 1975). Of the three types of slope surfaces discussed, rough and stair-step graded slopes are more desirable than smooth slope surfaces (with or without lateral grooves) for obtaining quick vegetative cover.

Gouging, a technique described by Jensen and Hooder (1979), generated mixed success in the loamy and sandy silts of Montana. An altered chisel plow with three fixed disc plow blades, 1.25 m apart, was pulled through soil to form surface depressions that were 75 to 90 cm long, 35 to 40 cm wide and 10 to 15 cm deep. The depressions help to control erosion and collect moisture that encourage plant growth at the bottom of the depression. There is usually poor vegetative establishment along the sides and between depressions. However, if an aggressive permanent species such as crownvetch *(Coronilla varia* L.) were used, the sides could conceivably be covered in a short period of time. This method can only be used in plowable shallow sloped sites.

B. Grading Fill Slopes

It is generally easier to obtain vegetative covers for erosion control on fill slopes than on cut-slopes because the less compacted rock and soil materials encourage water infiltration and root growth. This is only true, however, if the final lift of fill materials has been ripped or was placed in such a way as to avoid significant compaction. Soil erosion has been reported to be less of a problem on till slopes as opposed to cuts and cut-fill combinations (Missouri Highway Transp Dep., 1984; Sullivan & Foote, 1982). The common practice of blading and/or tracking fill slopes with a dozer is usually objectionable because resultant compaction inhibits water infiltration and aeration, causing poor growth. Also, seeds and fertilizer on such hard surfaces are apt to wash away. Tracking clayey and silty soil materials, especially when wet, causes severe surface compaction that augments water runoff and erosion. The weight and downslope slippage of dozers also causes soil materials to form hard clods between the cleats that are severed from soil contact. These conditions cause water to flow around and under the "cleated clods;" hence, during heavy rains surface water accumulates and the massive downflows on slopes cause severe sheet and gully erosion. The xeric environments associated with the severed "clods" make it difficult to establish vegetative cover. Tracking sandy materials on the other hand may be desirable if the tracks leave indentations perpendicular to the slope (Kelsey, 1991). Tracking with the bulldozer running parallel to the slope is especially objectionable since the vertical rills formed by the dozer tracks leave channels for accelerated water movement.

Water diversion structures should be constructed on each side of the fill lift to direct water movement off the slope. As lifts of the fill slope are constructed, the soil and rock materials falling naturally onto the slope surface should not be removed. Variations in inclination, compaction, and topography within a fill slope create desirable microenvironments for establishing and maintaining vegetation. Also, by allowing soil materials to fall naturally, the variable contours inhibit water runoff. Leaving fill slopes very rough with rocks falling naturally is desirable as it will often prevent movement or flow of soil material. This technique has been used to help stabilize slopes in Arizona. Duffy and Hatzell (1988) report that crushed rock of >4-cm particle size will protect surfaces from soil erosion. If rocks of >5 cm are removed, erosion increases by sixfold.

During fill slope construction, the slope area should be properly designed and constructed from the onset to make regrading of slopes unnecessary after seeding. Seedings should he made weekly or whenever the lift is elevated 3 to 4.5 m. The vegetation established at the base will detain suspended soil by slowing water movement from above as construction proceeds. Excellent vegetative cover to nullify erosion usually occurs from one seeding on rough, loose fill slopes; however, tracked compacted fill slopes usually have sparse vegetation due to poor establishment and erosion and frequently require several revegetation attempts to establish satisfactory vegetative covers. Smooth grading of the lower portions of fill slopes may he justified where mowing is necessary. However, fill slopes steeper than 2:1 should never be mowed.

C. Grading Medians

The grading of medians is similar to any cut or fill operation and shares the same problems associated with each operation; however, the median areas have their own unique set of problems. The median surface is often traversed during and after construction by heavy machinery, the soils are littered with construction debris as well as coarse fragments, and are subjected to concentrated water flows. simplistically speaking, the compacted surfaces of finished medians are poor environments for water infiltration and seedling establishment (Allmaras et al., 1973; Green et al., 1973a,b; Willis & Amemiya, 1973; Woodruff & Blaser, 970a,b).

Median design is dictated by the amount of water that will be captured from the road surface, and often does not promote the establishment of vegetation. For example, medians constructed in mountainous topography often become severely eroded because of accelerated water flow concentrated in "V"-bottom drainage ways, making it virtually impossible to establish a vegetative cover to reduce or prevent erosion. This accelerated flow of water causes severe gullying in drains and often plugs culverts and causes downstream pollution. In general, the slopes of medians should be as shallow as possible and flat bottoms up to 90 cm wide should be favored over "V"-shaped ditches. The latter concentrate and accelerate the flow of water, encourage erosion, and make it difficult to establish vegetation. As reported with the cut/fill slope, median slopes should be loosened and roughened with a spiked dozer blade or strong cultivation tool to leave furrows 5 to 10 cm deep and 15 to 25 cm apart, paralleling the drainage way. This will encourage water infiltration and establishment of vegetation.

Medians and drainage ways in level topography may be seeded, fertilized, and mulched without special erosion control measures. Lime (if needed) should be incorporated into the soil to a depth of 10 to 15 cm; seed, fertilizer and mulch should then he surface-applied.

In medians where considerable water flow is expected (generally not to exceed a depth of 5 cm), the ditch should be mulched with either straw (4500-6750 kg ha-') tacked with asphalt (750 L ha^{-1}) or woodfiber mulch (840 kg ha^{-1}). lined with geotextile related products, lined with gravel seeded with a grass, oil, even sodded. If sodding is selected, use high-quality sod, recommended fertilizer, lime, and other cultural practices as dictated by the region. For slopes in drainage ways where high-velocity water flow is expected, the only solution is the construction of concrete or asphalt ditches or the equivalent.

D. Topsoiling

This topic has been a source of controversy for many years in both the road. side and surface mining arenas. Research has commonly shown that subsoils or geologic materials can be successfully employed as growing media, and at times are favored. The key, as discussed earlier, is to understand how to test, interpret and treat the physical and chemical properties of the materials to be utilized as topsoil covers or seeded directly. Certainly, the ability to revegetate a site without a topsoil cover can generate considerable cost savings and will often justify the use of enhanced liming, fertilizer, and mulching amendments. In one study, Wright et al. (1978) compared the performance of vegetation seeded on rough graded subsoil with topsoil placed over the smooth subsoil, and found a fourfold ¡mprovement in vegetative cover for the rough-graded subsoil 90 d after seeding However, the use of topsoil can be advantageous for establishing vegetation in the following situations: (i) to cover xeric rocky environments, (ii) to cover and restrict root contact with soil materials containing high amounts of sulfides, (iii) where special ornamentals that demand especially good soil fertility and aer ation are to be planted, (iv) where a quality turfgrass lawn is desired such as at rest areas and highway corridors adjacent to urban areas, and (v) in prairie or wetland establishment where the topsoil contains required seed bank to help vegetate the site (Ostler & Allred, 1987).

Topsoil availability usually dictates application depths. For the previously described uses for topsoil, 25 to 50 cm of depth is ample. If using topsoil, the slopes should be as shallow as possible; topsoil will usually not adhere in place on slopes steeper than 2:1 (Blaser & Woodruff, 1968; Jacobs et al., 1967; Smith, 1973). The slopes should be rough-graded, stair-stepped, or grooved with undulations perpendicular to the slope. This encourages some mixing of the topsoil with the subsoil material to form a bond between the two. The stair-steps or grooves also reduce soil and water runoff. Ideally, when topsoil is applied to slopes, the final surface should be roughened. Another alternative is to apply the topsoil and then till it with grooves perpendicular to the slope and to a depth of 15 to 20 cm to insure bonding with the subsoil (Wright et al., 1975).

The economics and the potential problems commonly associated with topsoiled areas also must be considered. Topsoil ing is expensive and can delay seeding operations, which increases the possibility of erosion and water pollution. Also, most topsoil contains weed seeds that may cause dense weed canopies to shade out desirable species unless the area is reseeded or herbicides are applied. Also, topsoils in humid regions may he of poor quality (low in pH, fertility, and organic matter).

Potentially beneficial effects from topsoils on sloping cuts, fills, medians in highway corridors are often nullified by undesirable slope surface preparation and topsoil application practices. On slopes with hard smooth surfaces and those with vertical rills from prolonged exposure, topsoil ing is often useless because of severe sloughing and erosion. In general, topsoiling creates a fairly marked discontinuity in physical properties at the topsoil-substrate interface that tends to "perch" percolating water and frequently limits root penetration. Supersaturation at this interface often causes massive sloughing of the loose topsoil and its associated root mat after heavy rains.

Subsoil materials that are graded and amended often give more desirable seedbeds than topsoils. As compared with topsoil, the higher clay content of subsoils may provide high moisture availability and retain cations. Similarly, the lower silt content of subsoils often reduces sealing of surface pores, thereby reducing runoff due to increased water infiltration. However, subsoil materials that are very high (>35%) in clay content may he droughty and may have adverse chemical properties as discussed earlier. Experiments have shown that rough-graded subsoil slopes can be superior to topsoil for grass and legume establishment (Table 35-1). Plants grown in the amended subsoil performed better than those grown in the topsoil mainly because the subsoil's better water relations (Table 35-2) stop (Wright et al., 1976). Clayey clods from a roughened subsoil resisted breakdown and crusting and slowed down surface water movement allowing better infiltration than the topsoiled slope. Rough-grading of subsoil materials created a loose soil environment as noted by a decrease in bulk density and an increase in porosity when compared to the compacted subsoils for "finished" grading (Table 35-1).

The use of subsoils for direct seeding is an accepted practice and has proven successful for many regions of the USA (Green et al., 1973b; Iowa DOT, 1992; McCully and Bowmer, 1969; McCreery and Spaugh, 1977). Legumes such as crownvetch, alfalfa *(Medicago sativa L.)*, red clover *(Trifolium pratense L.)*, and white clover *(Trifolium repens* L.) are broadly adapted to subsoil materials that are properly graded anamended in the more humid regions (Carson and Blaser).

Table 35–1. Plant populations and vegetative cover as influenced by subsoil conditions, topsoiling, and fertilizer incorporation. Established May 1972 (Green et al., 1973b).

	Data recorded July 1972					
Treatments	Crownvetch plants m^{-2}	Grass plants m^{-2}	Vegetative cover, %	Bulk density[‡], g cm^{-3}	Total porosity[‡], g %	Crownvetch cover after 2 yr.
a) Subsoil smooth and hard with lime, fertilizer, mulch & seed surface applied.[†]	80 c*	160 c	22 c	1.76	42.1	100
b) Subsoil roughened & loosened, lime, fertilizer, mulch & seed surface applied.	440 a	800 a	72 a	1.38	51.4	100
c) Same as (b) except lime & fertilizer applied prior to working subsoil.	480 a	930 a	74 a	1.44	59.9	100
d) Same as (a) but with 10 cm of topsoil and all treatments surfaced applied.	180 b	680 b	66 b	1.42	53.0	100

* Means in a column followed by different letters are significantly different at the 5% level of probability.

† The subsoil pH was 5.3 at the date of seeding. The treatments were seed mixture (tall fescue at 84, redtop at 2, annual ryegrass at 6 and crownvetch at 22 kg ha^{-1}; 10-20-10 fertilizer at 1,120 kg ha^{-1}; lime at 4,480 kg ha^{-1}; woodfiber mulch at 480 kg ha^{-1}.

‡ Bulk density (wt vol^{-1}) and total porosity (pore space in %) were measured on the 0-3 cm soil layer.

Table 35–2. The influence of surface conditions of a subsoil with and without topsoil on plant density, vegetative cover, and height of cool season grasses. Established April 1974 (Wright et al.,1976).

	15 cm topsoil over subsoil				Subsoil alone			
Dates	May 1975			July 1975	May 1975			July 1975
Graded surface	Plants/ m^2	Vegetative cover, %	Height, cm	Vegetative cover, %	Plants/ m^2	Vegetative cover, %	Height, cm	Vegetative cover, %
Rough & Furrowed[†]	1,140 a*	39 a	8.3 a	100	1,520 a	38 a	8.8 a	100
Smooth finish grading	260 b	10 b	4.8 b	25	400 b	7 b	3.8 b	21

* Means in a column followed by different letters are significantly different at the 5% level of probability.

† Traversed perpendicular to slopes with a road grader with tiller feet. Lime, fertilizer, seed, and mulch were uniformly applied on the surface.

1963; Donald, 1963; Shoop et al., 1961; Wright et al., 1975; Zak et al., 1972). the Appalachian and Piedmont regions, crownvetch or sericea lespedeza *(Lespedeza cuneata [sericea]* Don.) have persisted for decades on various subsoil materials without any maintenance treatments. Their longevity is attributed to supplying needed lime and nutrients before seeding and the recycling of the various essential nutrients.

E. Soil Amendments

If the long term objective of revegetating highway corridors is to grow and maintain mixed stands of grasses, legumes, and other desired species with a minimum of fertilization and other amendments over time, then at establishment it is important to minimize N applications (<100 kg ha^{-1}) to favor legumes. Many local highway departments desire pure grass stands for aesthetic purposes, however, and higher establishment and maintenance rates of N are required to maintain stand density. It is equally important to insure that adequate P and K are applied to supply the stand's needs over time. While many subsoil and geologic materials may supply adequate K through release by mineral weathering, P will almost always be very low in the highway seeding environment and should he supplied in fairly high amounts ($\geq$300 kg P_2O_5 ha^{-1}) at seeding. Once a permanent stand is established and organic matter accumulates and turns over in the plant/soil system, nutrient cycling is relied upon for long term fertility maintenance of mixed stands. Fertilization regimes should be based on the known uptake demands of the particular vegetation mix employed and a rigorous program of soil testing. Post-establishment performance inspections should be used to confirm and fine-tune fertilizer recommendations for a given region.

The liming requirement for a given site will vary widely due to soil pH conditions and the type of vegetation to be established. Adapted and/or native grasses usually tolerate a wide range of pH. The legumes however, are less tolerant of acidic soils (pH $\leq$ 5.5). Sonic N additions may be required alter establishment. especially if non-native/adapted grasses are grown without legumes. If grasses are grown with legumes, N can be transferred to the grasses at a potential annual rate of 12.5-25 kg ha^{-1} (Mallarino et al., 1990) or more.

Semitropical legumes such as lespedeza species and crimson clover *(lrifolium incarnatum* L.) are tolerant of the high acidity, low Ca, low P, and high Al soil conditions common in soils in the humid southeastern USA (McKee et al., 1965a; Wright et al., 1975). Conversely, legumes of temperate origin require medium to high soil pH, with low Al availability and medium to high levels of P, Ca, Mg, and K. Except for a few specific roadside environments, other essential nutrients such as S and the micronutrients are usually adequate. Although applying higher amounts of macro- and micro-nutrient fertilizers may stimulate growth. the objective is to obtain a persistent protective cover rather than high yield. If the objective of the roadside manager is to grow moderate to high input species (such as pure grass stands), then N, P, and K are requ red at establishment and every three to five years to sustain acceptable density. Re-fertilization is commonly not required If legumes are incorporated into the stand at establishment, but may be necessary to maintain the desired species assemblage and limit the invasion of native perennials.

Fertilizers come in various forms for use on the roadsides and generally fall into several classes: (i) inorganics with a high content of soluble N, (ii) inorganics with a wide range of insoluble N for controlled release, and (iii) organic forms of various waste products. Controlled release fertilizers have been extensively investigated and are adequate for maintaining growth of pure stands of tall fescue (Mcllvaine et al., 1980; Schmidt and Rucker, 1988) over multiple seasons. The advantage of these types of fertilizers (which include sulfur-coated urea, urea formaldehyde, isobutylidene diurea and other formulations) is that the N is retained against leaching until the plant rooting system is developed for uptake.

Organic fertilizers come in a variety of forms of animal, refuse, yard, and human biosolid wastes. Since most roadside soils are initially very low in organic matter, organic additions usually have profound effects on their productivity. In one study municipal heavy fraction waste (metal free garbage that had been ground) was incorporated into a subsoil median in Virginia. Four years after the soil was amended, the tal l fescue density was better than fescue that received only inorganic fertilizer at the beginning of the experiment (Booze-Daniels and Schmidt, 1994).

The use of sewage sludge biosolids holds promise as a long term fertilizer as well as organic matter source. It has been reported by several investigators that biosolids greatly enhance establishment and persistence of vegetation along roadsides. In Rhode Island, biosolids were applied at rate of 16 Mg ha^{-1} in a 1.3 cm thick layer in April over a mixed grass stand. Vegetation response and shallow ground-water quality were evaluated. The grass growth was favorable and ground-water quality was well within regulatory standards (Wakefield et al., 1981). Wakefield et al. (1981) also reported that the anaerobic cake form of biosolids performed better than biosolids stabilized by chlorination. Fresh biosolids at the rate of 48 Mg ha^{-1} gave the same results as aged biosolids when applied at twice the rate. Baker (1983), reported that wood-chip composted biosolids at 56 Mg ha-' applied to an existing stand of turf in October improved the stand density as well as protected it from droughty conditions associated with sandy soils. Calm and Homer (1985) reported the advantage of using biosolids prior to seeding. It can be applied with a hydroseeder on slopes to substitute for mulch and fertilizer, by subsurface biosolids injection, or through biosolids /soil mix at final grading. Wakefield et al. (1981) expressed caution over applying biosolids on steep slopes because it can slough into drainage structures and potentially runoff to surface waters. Both Cahn and Homer (1985) and Wakefield et al. (1981) reported that soil and water contaminants where biosolids was used were below acceptable levels, pathogens were not a problem, and public concerns should be addressed with educational programs.

The long term success of highway revegetation efforts is largely dependent on the development of a soil organic matter pool with associated macro- and micro-nutrients, particularly N and P, and the active turnover of organic debris into humus. The ability of the i niti al annual cover of "nurse" crop to scavenge and hold applied N and P fertilizers against leaching and adsorption losses is particularly important to the continued success of the stand, especially in high rainfall environments. During the subsequent litter turnover process, essential nutrients are cycled back to the plant community. Mulches and organic amendments can greatly accelerate organic matter accumulation, but significant amounts of organic matter will also accumulate naturally over time. However, this will occur only if the plant community is vigorous and producing annual biomass and if the important shredding and decomposing soil fauna and flora are present and active. In addition to benefiting soil fertility, organic matter improves the infiltration and water retention characteristics of the soil surface and greatly enhances the soil's resistance to further erosion.

F. Mulches, Binders, and Geotextile Related Products

Mulch and geotextile related products are used for temporary erosion control of bare soils and to simultaneously improve the soil environment for establishing vegetation quickly by augmenting germination and seedling growth. *Mulch* materials used on the roadside (also addressed in Chapter 25 of this book) most often include straw, hay, wood products (fiber, chips and hark), and paper products (made from recycled paper). The mulches can be classified as either long fiber (straw and wood bark) or short fiber (wood fiber and paper). In general, the long fiber mulches control erosion better than short fiber mulches, especially on steep slopes or areas subjected to rapid water flows. Long fiber mulches encourage better vegetative cover when the site is seeded during high stress periods, as in hot summers or wet winters (Iowa DOT, 1992; Jensen and Hodder, 1979; Wright et al., 1978). The other advantage to long fiber mulches is they persist and contribute to the mulching effect longer than the short fiber mulches (Duell, 1994). The short fiber mulches are often used in hydromulching/seeding operations, which makes them popular. The ability of paper mulch to control erosion has been a concern (Jensen and Hodder, 1979). Israelsen et al. (1980), determined in simulated rain tests that when paper mulch was subjected to 61 cm water ha^{-1}, rills formed in approximately I min.; however, when tacked straw was tested, rills were prevented for three hours. Of all the mulches investigated, tacked straw was rated the most effective, woodfiber the second, and a paper product third for controlling erosion as well as promoting vegetation establishment, especially on difficult sites. The use of mulch is unquestionably better than no mulch, with the exception of revegetating gravels with warm season grasses. Kelsey (1991) reports that the mulches actually inhibited establishment in this case.

Binders or tackifiers and *soil stabilizers* have been tested in the past with mixed reviews. In general. the binders are incorporated in the fiber and paper mulches or are applied over mulches to keep them from washing or blowing. The soil stabilizers are useful for short term treatments; however, seed germination problems have been attributed to their use (Perry et al., 1975; Wright et al.. 1975). The use of tacked straw on slopes with 840 kg ha^{-1} of woodfiber or 1,900 L ha^{-1} of asphalt has given exceptionally good and prolonged straw stabilization. Tacking straw with woodfiber gives excellent results in a two-step operation: (i) apply straw, and (ii) apply the seed-woodfiber-soil amendment slurry. This procedure gives results similar to the three-step operation: (i) applying the seed-soil amendment slurry, (ii) applying straw, and (iii) tacking with woodfiber (Wright et al., 1976).

It is imperative to apply mulches liberally in harsh environments, i.e., smooth, hard slopes and "hot" slope exposures, and to provide prolonged mulch stabilization, i.e., straw tacked with woodfiber for midsummer or winter seedings (McCreery et al., 1975; McKee et al., 1964 and 1965b). High rates of mulch materials are less important for rough, loose graded slopes since the roughness creates favorable microenvironments, aiding germination and growth.

Mulch materials and rates of application vary with season. During periods of water (too much or too little) and temperature stress, the long fiber mulches or higher rates of short fiber mulches are helpful to prevent erosion and to encourage vegetation establishment. The following guidelines are geared to the temperate regions, but can he adapted to other regions of the USA.

1. *Mulches for Favorable Seeding Season (Spring or Early* Fall)—Mulch with 3360 kg ha^{-1} of straw, 1680 kg ha^{-1} of woodfiber, or 30 m^3 of woodbark or woodchips. If slopes are stair-step graded or in a rough loose condition, the mulch rates may be reduced or even omitted on cool (shaded) slopes. Chemical binders need not be used during these favorable seasons, although straw may be tacked with 840 kg ha^{-1} of wood fiber on steep slopes.
2. *Mulches for the Warm Weather Season (Late Spring or* Summer)—During periods of moisture stress and high air and soil temperatures, long fiber mulches are recommended. Straw, woodbark, or woodchips are superior to woodfiber for conserving moisture and moderating temperatures to enhance germination and the establishment of seedlings. Straw on smooth, hard slopes and flat areas should generally be tacked with woodliber at 840 kg ha^{-1} or asphalt at 210 L ha^{-1}. When applied to rough loose soil, straw (3360-4480 kg ha^{-1}) need not be tacked under these conditions unless the areas have high winds, traffic, or steep slopes. Woodbark or woodchips (90-140m^3 ha^{-1}) should not generally be used on slopes steeper than 2:1. Woodfiber (1680-2240 kg ha^{-1}) can be used during the summer stress months; however, the higher rate should be used on slopes steeper than 2:1.
3. *Mulches for the Cool Season* (Winter)—Prolonged soil stabilization during winter (Nov. to Mar.) is imperative since protection from vegetative cover is not likely to he attained until spring. Wood fiber or paper mulches are not recommended for use in the winter. Persistent mulches to be used during hard freezing and thawing conditions include straw at 4000 kg ha^{-1} tacked with 840 kg ha^{-1} of woodfiber or asphalt at 210 L ha^{-1}, or woodbark or woodchips at 140 m^3 ha^{-1} without hinders.

Geotextile related products have appeared in force over the past ten years and are defined as "textile fabrics which are permeable to fluids such as water and gas" (Ingold, 1994). They consist of geogrids, geomats, geonets, geoblankets, and roving. Geomembranes have been used for erosion control but are not suitable for vegetation establishment as they are impermeable to fluids. These products are made of a variety of materials. Some are organic, synthetic or a combination of organic with synthetic materials. The geojutes (jute), and geonets (straw sandwiched between netting) have been used over the past 30-40 years; however, many of the geomats and geogrids are of newer technology. The success with all of these products lies with how they are applied. Faulty application can lead to greater erosion problems than where no products were employed. There must be good soil-product contact for erosion control and seed establishment; therefore, the soil must be graded smooth (not compacted), and stapling as well as overlapping application techniques should be used as specified by the manufacturer. Without these precautions, rills can develop under the product and seed can wash down the slope (Brede et al., 1987; Wright et al., 1976).

Excelsior mats (geomat) have been shown to control erosion as well as promote vegetative establishment and growth on various soil types and regions in the USA (Brede et al., 1987; Dudeck et al., 1970; Iowa DOT, 1992; Ostler and Allred, 1987). In Texas, a controlled geotextile related products test compared erosion control and vegetation coverage provided by a variety of products on two types of soil with 3:1 and 2:1 slopes (Godfrey et al., 1993). Most of the products tested controlled erosion better than no erosion control. However, the products with organic components such as straw, wood or coconut fibers promoted better vegetative cover. The spun monofilament polypropylene mat held the soil against erosion but also drastically inhibited vegetative growth. This group of investigators noted that seam separation and tearing at the slope bottom occurred for some products as they aged. The synthetic blankets have also been used by Palazzo (1989) to accelerate the germination of tall fescue seeding in a colder climate. Germination was accelerated, but the blanket must be removed prior to the spring flush or the vegetation is harmed. It was mentioned that the blanket could then be reused on other sites.

Roving is a new geotextile technology that consists of extruding continuous strands of fiberglass or polypropylene to cover prepared and seeded areas (Agnew, 1991). The material does not readily degrade, thus it becomes a permanent feature of the soil/root matrix. The material requires tacking with emulsi lied asphalt. Soil confinement systems or geogrids are usually the only option for sites where there is little hope for revegetation. These honeycomb-shaped geogrids are made of high-density polyethylene or non-woven polyester and are laid out on top of the site. The holes are filled with soil or gravel and vegetation is then established within the soil-filled spaces. Cost and application factors would most likely determine the use of most of these products.

G. Hydraulic Seeding, Mulching and Fertilization vs. Other Techniques

The use of hydraulic machinery to apply seed, mulch, and amendments has become popular and accepted in revegetating roadsides in the USA. The topic of applying mulches is also addressed in Chapter 25. The method allows for "one step" applications on steep slopes as well as flat areas. The technique is fairly straightforward for operators, and is rapid and useful on steep slopes, but there are several drawbacks:

- The greatest problem is that lime cannot be incorporated into the soil where most needed. This may be a limiting factor for long-term stand persistence. One way to "fix" the intrinsic problem is to ensure that the soil is rough graded (including flat areas) or stair-stepped prior to the seeding-operation.

As the site ages the soil will partially self-incorporate the lime and nutrients. This is not ideal, but incorporation is not always practical especially, on steep slopes.

- Hydraulic seeding and mulching as a "one-step" process requires up to 30% more seed than drilli ng or broadcast seeding (Iowa DOT, 1992) due to the paddle and pump agitation harming seed, fertilizer salt injury, and the seed failing to come in contact with the soil due to being embedded in the mulch (Zak et al., 1977). Thirty percent may be on the high side for seed loss estimate for aggressive species, but it is a good estimate for the less tolerant legumes, broadleaves, and prairie natives (Iowa DOT 1992).
- Legume inoculant must to be added to the hydroseeder slurry to insure adequate legume inoculation, but the *Rhizobia* are also sensitive to the pH and salt levels in the slurry. Whenever possible, inoculant should not be added to the slurry until just prior to seeding and the pH of the slurry should be maintained above 4.0 (Brown et al., 1983). In particular, the use of acid forming P-fertilizers should be balanced with lime additions if possible. The use of twice or three times the normal inoculum rate is also recommended.
- The use of controlled release fertilizers such as sulfur-coated ureas may be affected by the agitation and abrading action of the paddles and pumps. The fertilizer's coat may be compromised which would negate the desired controlled release of nutrients.

An alternative to hydraulic seeding techniques is the use of grass drills. These can be used only on tractor-accessible slopes; however, the advantage to this technique is that soil amendments in dry forms can be incorporated into the surface 10 to 20 cm prior to seeding. Conventional site preparation and broadcast seeding techniques can be used on gently sloping sites accessible by conventional tractors. No-till seeding has also been used in the prairie regions with success. The seed is drilled into killed stubble mulch of either a grain or existing vegetation (Ostler and Allied, 1987). The limited disturbance helps to conserve moisture as well as reduce weed competition. The disadvantage to this technique is that if the soil is compacted, the drilled seed establishes poorly.

H. Designing Seed Mixtures for One-Shot Seeding

The primary goal of roadside stabilization and soil erosion control is to quickly establish *persistent* plant species. Table 35.3 provides a list of plants that are likely to be used on roadsides in the USA. In this chapter, primary, secondary and persistent species are defined as the following:

- *Primary Species* consist of either grasses or broadleaves, annuals or short lived perennials, that germinate and establish quickly. These species are usually used to control erosion immediately, and are often referred to as companion, nurse, or temporary species. Annual ryegrass *(Lolium multiflorum* Lam.), Fairway crested wheatgrass *(Agropyron cristatutn L.)* and foxtail millet *(Setaria italica* L.) are examples.

Table 35–3. General rates (bulk) and seasons of seeding for species that are used in various states. Because state lines cross ecological regions, not all included species can be grown in every region within a state.

Species	Seeding Rate, kg ha^{-1}	Seeding Season			
		Spring	Summer	Fall	Winter
A. OH, IN, IL, MI, WI, IA, MO and MN					
Tall fescue (*Festuca arundinacea* Schreber)	50	x	x	x	x
Perennial ryegrass (*Lolium perenne* L.)	28	x	x	x	x
Kentucky bluegrass (*Poa pratensis* L.)	34	x			x
Annual ryegrass (*Lolium multiflorum* Lam.)	7	x		x	x
Redtop (*Agrostis alba*)	11	x		x	
Ladino clover (*Trifolium repens* L.)	7	x			
Strong creeping red fescue (*Festuca rubra* L. subsp. rubra)	45	x	x	x	x
Winter vetch (*Vicia villosa* subsp. *varia* L.)	45			x	x
Crownvetch (*Coronilla varia* L.)	22	x	x	x	
Birdsfoot trefoil (*Lotus corniculatus* L.)	22	x			
Cereal rye (*Secale cereale* L.)	100			x	x
Foxtail millet (*Setaria italica* L.) (German Millet)	28		x		
Alsike clover (*Trifolium hybridum* L.)	14	x		x	
B. VA, WV, TN, NC, KY, AR, MO, MD, DE, Southern OH, IN, and IL.					
Tall fescue	56	x	x	x	x
White clover (*Trifolium repens* L.)	5	x			
Japanese lespedeza (*Lespedeza strata* Thumb.)	7	x			
Weeping lovegrass (*Eragostis curvula* Schrader Nees)	22		x		
Bermudagrass (common) (*Cynodon dactylon* L.)	8		x		
Annual ryegrass	7	x		x	x
Crimson clover (*Trifolium incarnatum* L.)	22				x
Crownvetch	22	x	x	x	
Sericea lespedeza (*Lespedeza striata* (Murray) Hook. & Arn.)	40	x	x	x	
Kentucky bluegrass	55	x		x	
Strong creeping red fescue	45	x		x	x
Perennial ryegrass	28	x		x	x
Cereal rye	100				x
German millet	28		x		
C. ME, NH, VT, MA, RI, NY, PA, CT, and NJ.					
Tall fescue	50	x	x	x	x
Perennial ryegrass	11	x	x	x	x
Creeping red fescue	45	x	x	x	x
Red clover (*Trifolium pratense* L.)	11	x			
Birdsfoot trefoil	17	x		x	
Crownvetch	22	x	x	x	
Annual ryegrass	7	x			x
Cereal rye	100				x
White clover	6	x			
Creeping bentgrass (*Agrostis palustris* Huds.)	6	x			
Redtop	10	x		x	

continued

Table 35-3. Continued

Species	Seeding Rate, kg ha-¹	Seeding Season			
		Spring	Summer	Fall	Winter
Weeping lovegrass	11		x		
German millet	28		x		
Kentucky bluegrass	33	x		x	
D. Central and southern LA, MS, AL, AR, GA, SC, FL, west TN, east TX, and Coastal Plains of NC					
Annual lespedeza (Kobe or Korean)	22	x	x		
Bahiagrass (Pensacola or Wilmington) *(Paspalum notatum* Flugge)	45	x	x	x	
Bermudagrass (common)	11		x		
Brunswickgrass *(Paspalum nicorae* Parodi)	45		x		
Crimson clover	28			x	
Cereal rye	78			x	x
Seneca lespedeza	40		x		
Tall fescue (Piedmont only)	45	x		x	x
Weeping lovegrass	7	x	x		
German millet	28		x		
White clover	7	x			
Sudangrass *(Sorghum bicolor- (L.)* Moench	28		x		
Redtop	8	x		x	
E. AZ, NM, NV, southern CA, and west TX.					
Lehmann lovegrass *(Eragrostis lehmanniana* Nees)	2.2	x	x		
Sand dropseed *(Sporobolus cryptandrus* (Tor˙.) A. Gray)	1.1	x	x		
Sacaton *(Sporobolus wrightii* Munro ex. Scribn.)	22	x	x		
Black gramagrass *(Boute/oiia eriopoda* (Torr.) Torr.)	2.2		x		
Siberian wheatgrass *(Agropyron fmgile* (Roth) Candargy var. *sibiricum* (Willd.) Tzvel.)	2.2	x			x
Blue grama *(Bouteloua gracilis (H.B.K.)* Lag. ex Steud.)	3.3	x			
Indian ricegrass (Oryzopsis *hymenoides* Ricker)	2.2				x
Yellow sweetclover *(Melilotus qfficinalis* (L.) Lam.)	3.3	x			x
Crested wheatgrass *(Agropyron desertorwn* (Link) Schultes)	5.6	x			x
Smooth bromegrass *(Bromus inermis* Leysser)	5.6	x	x	x	
F. Eastern WA and OR, Ill, northern NV, and UT.					
Crested wheatgrass	5.6	x		x	
Smooth bromegrass	11	x		x	
Slender wheatgrass *(Elymus trachycaulus)*	5.6	x		x	
Streambank wheatgrass *(Elymus lanceolatus* (Scribn. & Smith) Gould)	8.9	x		x	
Hard fescue *(Festuca longrfolia)*	13.4	x		x	
Big bluegrass *(Poa secunda ssp. navadensis)*	11.2	x		x	

Continued

Table 35-3. Continued

Species	Seeding Rate, kg ha-1	Seeding Season			
		Spring	Summer	Fall	Winter
Western wheatgrass *(Elynms smithii)*	8.9	x		x	
Pubescent wheatgrass *(Elytrigia intermedia* subsp. *tri 'hophora* A.&D. Love)	4.4	x		x	
G. Western WA, OR, AK, and northwest CA.					
White clover	4.4	x		x	
Colonial bentgrass *(Agrosti.s* tenuis Sibth.)	3.3	x	x	x	
Creeping red fescue	22	x	x	x	
Perennial ryegrass	8.9	x	x	x	
Chewings fescue *(Festuca rubra ssp. commutata* Gaud.)	I 6.8	x		x	
Kentucky bluegrass	5.6	x		x	
Annual ryegrass	112		x	x	
Barley *(Hordeum vulgare* L.)	112				
Crownvetch	28	x			
H. ND, **SD,** MT, NE, KS, WY, CO, OK, central TX, and western MN					
Bromegrass *(Bromus* sp. L.)	14	x		x	
Intermediate wheatgrass *(Elytrigia intermedia* (Host) Neveski)	7.8	x		x	
Crested wheatgrass	14	x		x	
Kentucky bluegrass	30	x		x	
Perennial ryegrass	30	x		x	
White clover	5	x		x	
Reed canarygrass *(Phalaris arimdinacea* L.)	2.2	x		x	
Switchgrass *(Panicum virgatum* L.)	2.2	x		x	
1ndiangrass *(Sorghastrum nutans* (L) Nash)	2.2		x		
Sideoats grama *(Bouteloua curtipendala* (Michx.) Torr.)	2.2		x		
Little bluestem *(Schizachyrium scoparium* (M ichx.) Nash)	2.2			x	
Alfalfa *(Medicago* sp. L.)	1.1			x	
Red clover	7.8	x			
Hairy vetch *(Vicia villosa* Roth)	5.6	x		x	
Buffalograss *(Buchloe dactyloides (Nutt)* Engelm.)	14	x		x	x
Slue grama *(Bouteloua gracilis (H.B.K.)* Lag. ex Steud.)	4.5			x	x
Slender wheatgrass	1.1			x	
Green needlegrass *(Stipa viridula* Trin.)	7.8	x		x	
Western wheatgrass	2.2	x		x	
Green sprangletop *(Leptochloa dubia* (H.B.K.) Nees)	5.6	x		x	
Weeping lovegrass	4.5			x	
Sericea lespedeza	4.5			x	
Cereals (wheat, rye, oats, barley)	90	x		x	
all fescue	28	x		x	
Bermudagrass	*7*			x	

x

- *Secondary Species* consist of either perennial grasses or broadleaves that require moderate to high resource input, i.e. fertilizer, lime, mowing, etc. upon establishment and to remain persistent. Tall fescue *(Festuca arundi. nacea* Schreb.) and bermudagrass *(Cynodon dactylon* L.) are examples.
- *Persistent Species* consist of either perennial grasses, herbaceous broadleaves or woody perennials that are adapted species of the region. The climax species is often the persistent species; however, this is not always true (i.e., crownvetch in the temperate region). The persistent species requires low resource input once established. A persistent species transplanted from one region may not be considered persistent in that new region. This is also true of the primary and secondary species. Native prairie grasses are examples of species which are persistent in the Prairie region, but not necessarily in the humid temperate region. Because most persistent species are slow to germinate and establish, they cannot be utilized for immediate roadside erosion control, especially on slopes. For this reason, fast-establishing temporary species (companion or nurse crops) as well as secondary species are often added to the seed mixture. This strategy has been used successfully in many regions of the country. In the Appalachian and Piedmont region, crownvetch (the persistent species) is sown with cereal rye (primary species) and tall fescue (secondary species) in the early spring. The rye will germinate in one to four days (at 21°C) and quickly establishes to control erosion. The tall fescue will germinate in five to twelve days following seeding. As the rye declines the tall fescue assumes the erosion control duty. The crownvetch will slowly germinate over multiple seasons and eventually chokes out the secondary species and weeds.

In the Tall Grass Prairie region, the seed mixture design goal is to establish persistent native prairie grass and broadleaf species. As is true with crownvetch, some of these native species are slow to germinate and establish. Thus, when designing a one-shot mix, oats (primary species) are added to quickly control erosion as well as create shade. In this instance a secondary species is not recommended as they often compete with the prairie grasses for water and light (Harrington, 1991)

The success of any seed mixture design, either one-shot or multi-step seeding, must balance the following factors:

- *Competition:* The primary, secondary or persistent species should not compete with each other, especially during the establishment period. Perennial ryegrass *(Lolium perenne* L.) is an example. This cool season species germinates in 3-4 days after sowing, offers quick vegetative cover, is good for immediate erosion control; however, this species will inhibit the growth of the secondary and persistent species especially if the secondary or persistent species is a cool season plant (Duell, 1989; Foote et al., 1978). A simplistic approach to avoid plant competition and favor persistent species is to use a cool season primary with a warm season persistent or secondary species, or the reverse (Adams and Blaser, 1979; Wright et al., 1978). If competitive species must be sown together, use less seed of the primary species. For the sake of creating species diversity in the persistent stand, several persistent species can be sown in the same mix. Frequently, the species mix on one side of a roadway will be quite different than that on the opposing side, even when both were seeded with identical seed mixes, due to natural selection processes.

- *Time of Year of Establishment:* Soil and ambient temperature, soil moisture, and day length affect germination and establishment success of many of the roadside species. Yet, for the less tolerant species (usually the persistent species) it is important to identify which seasons are favored for optimal establishment. For example, centipedegrass *(Eremochloa ophiuroides* Munro Hackel) a warm season grass, is best sown in late spring in the Georgia Coastal Plain region, and crownvetch, a cool season legume, is best sown in the early spring in much of the USA. In the real world of road construction, species are not often sown at the ideal time. In these cases the seed mixture design is important. For example, if the goal is to establish a secondary cool season grass such as hard fescue *(Festuca ovina* var. *duriuscula (L.)* Koch), in fall in a cold location, cereal rye *(Secale cereale* L.) at a reduced rate could be used as the primary species. Both are cool season species but non-competitive because the rye and fescue would be germinating at slightly different times. In Montana, seed is not sown in the summer due to water stress, and erosion control should be accomplished through mulches (Jensen and Hodder, 1979).
- *Maintenance of Desired Species:* In some instances, usually in urban areas, the secondary grass species are desired as they can be frequently mowed, fertilized, and maintained to provide a uniform park-like appearance. If this is the goal, the seed mixture should include a primary species only if the time of seeding is during a stressful period for germination and establishment of the selected secondary species. During construction lapses the roadside must be seeded to bridge between construction periods. The contractor often elects to use primary species to temporarily control erosion. with the expectation that construction would resume before the annual grass or cereal species will senesce. If the length of down-time is questionable, the use of a secondary species would be prudent.
- *Varieties of Species:* Over the past twenty years many named varieties of roadside species have been developed. Many of these varieties were developed for uses other than the roadside environment; thus, care must be taken in recommending their use without testing. There are documented varietal differences among the grass species when grown in the roadside environment. Even among the tall fescues which share a narrow genetic pool, some varieties are more aggressive than others (Nahati et al., 1992).
- *Companion or Nurse Species:* The species used to initially control erosion and provide a hospitable environment for the slowly developing persistent species are usually primary species. However, secondary species can be used for this purpose, especially if the persistent species will eventually out-compete the secondary. Several fine fescues *(Festuca rubra* L., *Festuca ovina* L., and *Festuca ovina* var. *duriscula L.),* secondary species, have

been shown to he better companions for crownvetch than tall fescue, especially when the less aggressive varieties are used (Nabati et al., 1992; Wakefield et al, 1974).

I. Multi-Step Seeding and Fertilization

Due to the nature of roadside construction, seeding often occurs at less than optimal times. Complicated by the use of one-shot seeding/mulching/fertilizing techniques, less than adequate ground cover or complete failures commonly occur. Realization that the poorly revegetated site requires reseeding or renovation frequently comes after the site has been released from the contractor's responsibility and falls upon the local manager's budget. To avoid having to renovate previously seeded sites, problems sites (i.e. steep slopes, acid parent materials, shrink-swell clays, drought-prone soils) must be identified prior to the bidding process so that the contractor can use a multi-step seeding and fertilization technique instead of the one-shot technique. The advantage to this technique is that fertilizer can be supplied in split applications, which can reduce nutrient leaching, and weeds can be controlled at the appropriate time by use of herbicide, mowing, selective fertilization, or prescribed burning.

The principle of multi-step seeding is to apply specific seed and soil amendments in many steps over a period of time to take advantage of favorable conditions for establishing or stimulating desirable species and mixtures. The following examples of techniques have been shown to work in specific regions.

Summer Establishment Technique in a Humid Temperate Climate:
Step I. Establish a temporary canopy during the summer with foxtail millet (17-34 kg ha^{-1}), fertilizer (90-180-90 kg ha^{-1} N-P-K), and woodfiber slurry (1680-2240 kg ha^{-1}).
Step 2. During late summer-early fall sow cool season species with additional fertilizer (same rate used in step I). Frost or maturity kills the millet, providing an *in silo* noncompetitive mulch canopy (Wright et al., 1978).

Winter Establishment Technique in Humid Temperate Climate:
Step I. Establish a canopy during winter of cereal rye (11 kg ha^{d}), hard fescue *(Festuca ovina* var. *duriscula* L.) (90 kg ha^{-1}), fertilizer (90-180-90 kg ha-' N-P-K), and woodliber slurry (840 kg ha^{-1}) over straw mulch.
Step 2. Sow crownvetch with 180 P,O, kg ha^{-1} in the early spring. If the cereal rye remains competitive during the time of sowing, mow or use a non-residual herbicide to kill. The herbicide should be used only if the fescue has not germinated (Nabati and Schmidt, 1991).

Summer No-Till Establishment Technique of the Prairie Region:
Step 1. Establish a stand of oats *(Avena sativa* L.) (25 kg ha^{-1}) for erosion control, in the summer with fertilizer (30 kg ha' of each N, P_2O_5 & K2O).
Step 2. Use herbicide to kill off the stand, which will include weeds, In September.
Step 3. Burn off the dead material in April.

Step 4. Apply herbicide first of June to k ill sprouted weeds.

Step 5. Broadcast or drill the native prairie species; fertilize (0-35-55 kg ha $^{-1}$N-P-K).

Step 6. After the vegetation has been established in mid-summer, fertilize with 35 kg ha N. Nitrogen fertilization is withheld until after establishment because the N apparently stimulates the more aggressive species to the detriment of the less aggressive (Harrington, 1991; Iowa DOT, 1992; Masiunas and Carpenter, 1982; Morrison, 1981; Pauly, 1984).

J. Vegetation Renovation

Sparse vegetation on the roadside is commonly encountered for a variety of reasons. Low soil nutrient levels, erosion, use of unadapted and short-lived perennial species, weed competition, soil compaction, flooding, drought, and even vehicular accidents are among the long list of causes. No matter what was the cause, the problem should he corrected as soon as possible because as soil erosion proceeds, the cost of renovation can increase. If the vegetation density (excluding weeds) is greater that 50-60 percent, then fertilization, pH adjustment, dethatching, or burning are typically effective approaches to improve the density of the desired species. However, if the density is less than 50-60 percent then the site should be reseeded and amended.

- *Vegetation Density Greater than 50-60 Percent:* At this point in vegetative decline, the goal is to enhance the desired species by whatever amendments or cultural methods are available. For example, if a persistent legume is desired, the use of lime and low-N complete fertilizer may favor the legume over grasses. If permanent prairie vegetation is favored, then a prescribed burn may be in order (Harrington, 1991). To increase the density of a tall fescue stand, fall fertilization may be recommended.
- *Vegetation Density Less than 50-60 Percent:* Soil amendments alone are not sufficient to boost the vegetation. Thus, reseeding at 25% to 50% of the original prescribed seeding rate would be recommended. To insure that there is adequate soil/seed contact, the site should be scarified prior to seeding and seed should be broadcast or drilled, if possible, prior to hydraulic seeding. Wakefield et al. (1981) have shown that seed germination can be poor if the seed and mulch slurry remain suspended in the existing plant leaves instead of reaching the soil. Deletion of fiber mulch from the seed/fertilizer tank mix can compensate for this problem. In overseeding legumes into grasses, suppression of the grass by use of a herbicide (Gramoxone) prior to seeding crownvetch or hirdsfoot trefoil *(Lotus corniculatus* L.) is recommended (Stafford, 1982). Wright et al. (1978) found that the grass density should be less than 75% for hest legume overseeding. As with seeding most legumes, the manager should reduce the rate of N applied, adjust pH, and sow in the spring.
- *Vegetation Density Greater than 50-60 Percent and Erosion Present:* If the site is actively eroding the soil must be reworked to arrest the erosion. This

involves rough or stair-step grading, seeding, fertilizing (if required), and mulching (Green et al., 1973b; Wakefield et al, 1982). An area that failed the first time would be a candidate for the multi-step seeding technique to ensure establishment. Carpenter et al. (1977), found dint in some cases moderately eroded slope (46 cm gully) could be revegetated and erosion halted without reworking the soil. The slope was seeded with a mixture of crownvetch, red clover, and tall fescue. After one year, erosion was halted and by the third year the entire 16 m slope was completely covered.

III. WILDFLOWERS FOR LOW MAINTENANCE GROUNDCOVER IN HIGHWAY CORRIDORS AND OTHER DISTURBED SITES

A. Wildflowers on the Roadside

The popularity of wildflowers for low-maintenance groundcover underscores the fact that roadside plantings are now of interest to landscape designers and ecologists as well as highway managers and agronomists. Not surprisingly, the use of wildflowers for groundcover has tended not to focus on reclamation, but on other issues which wildflowers are perceived to enhance or promote (Ahern et al.,1992; Morrison, 1981; Roche, 1989). These issues include the use of wildflowers to reduce turfgrass acreage and decrease the associated costs of mowing, fertilizer, and pesticides. Attention has also focused on the desire to increase plant diversity, and to preserve natural habitat and wildlife in roadside areas by increasing the use of native species (NWRC, 1992).

Ironically, attempts to reconcile these issues with a growing interest in roadside beautification over the past decade have frequently involved increased costs and the mass planting of introduced ornamental species. Despite this, wildflower establishment and maintenance techniques have developed rapidly, with the result that wildflowers are now an accepted part of highway landscaping, even though the rationale of their use has remained under sonic debate.

B. Regional Use of Wildflowers

The selection of species may be the most difficult issue affecting the use of wildflowers. Regional needs and expectations often play a decisive role in the selection process (Harrington, 1991; Munshower, 1994). In the midwestern and western U.S., a long-standing interest in the use of native prairie species has led to the establishment of prairie vegetation in highway corridors, and has proved to be overwhelmingly popular as well as technically satisfactory (Byler et al., 1993' Salac et al., 1978; Wallace and Logan, 1990).

But while many midwestern states have successfully utilized their native vegetation, which may tolerate a wide range of environmental conditions when planted in its native region, this has rarely been the case in the eastern states: where the native meadow vegetation is typically more habitat sensitive, where a greater variety of naturalized exotic species compete vigorously for opeto space (Harker et al., 1993; Krouse, 1994). Eastern highway corridors also tend have more acidic soils, more traffic, more air and litter pollution, and less user-perceived need for restoration of prairie vegetation than the midwestern states. These factors have encouraged the use of the most environmentally-tolerant and ornamental species, regardless of origin, for eastern highway wildflower plantings. In many respects, the use of wildflowers in the East has been handicapped by technical difficulties and failures involving weed invasion, the relative lack of adapted species, and a very limited regional seed production industry.

The use of wildflower species in the western and Pacific Coast states has developed somewhat differently from both the eastern or midwestern states. These regions have tended to use the most adapted species on roadsides, regardless of origin, although the demanding or restricted environments that prevail in these regions has reinforced efforts to utilize uniquely adapted native vegetation.

The wide-open spaces of much of the western and montane U.S. has accentuated the need for inexpensive and reliable plantings, rather than plantings made primarily for ornamental or ecological reasons. As a result, many western states have focused on maintenance practices to encourage wildflower species on roadsides, rather than more costly planting programs. New projects are often planted with a suitable base of grasses and forbs, and other species are expected to move in eventually. Occasionally, seed for these projects is harvested by transporting soil or cutting hay from nearby areas (Morrison, 1981; Munshower, 1994). These approaches are deemed successful to the extent that they satisfy local highway agencies, involve minimal cost, and are popular with highway users.

C. Wildflower Seed Mixes for Highway Corridors

At the minimum, wildflower plantings must control soil erosion, require little maintenance, be safe and attractive to motorists, and be inexpensive to establish. In all regions of the U.S., there has been an effort to identify species that satisfy these requirements, although some concerns have received more attention than others.

Soil erosion from wildflower plantings has received little attention, probably under the assumption that wildflowers control soil erosion at least as well as other broadleaf roadside plantings such as crownvetch and sericea lespedeza, which have been shown to be as effective as tall fescue and other grasses (Richardson and Diseker, 1961). Although native grasses are routinely included in wildflower seed mixes for ecological reasons in the Midwest and other regions of the U.S. (Prairie Nursery, 1995), their contribution towards short-term erosion control is doubtful, since most develop slowly during the critical establishment period; their added value to long term soil erosion has not been well documented. In the East, where grasses have often been suspected of being excessive competitive (Krouse, 1994) and detrimental to the floral display of wildflowers, the use of any grass species has been minimal. Despite this, there have been few reports of the excessive erosion from sites where wildflowers were relied upon for groundcover in the East. Presently, there is little perceived need to select wildflowers for maximum erosion control or to routinely include grasses for additional erosion protection.

The selection of wildflower species to reduce maintenance costs has also been given relatively little consideration, since wildflower plantings are usually mowed once or twice per year (sometimes never), and may be burned every 1-3 yr (rarely in the East) regardless of the composition of the planting. The formulation of specialized seed mixes that allow the use of pre-emergence or post-emergence herbicides to control broadleaf weeds without injury to the wildflower species chosen for the planting is currently under development (Dickens 1992; Erusha et al., 1991; Skroch and Gallitano, 1991). There have been few studies regarding the ability of individual wildflower species or mixes to suppress weed invasion.

The most important factors in the selection of wildflower species for roadside use throughout the U.S. have been economic and aesthetic. Species which cost more than \$100 ha^{-1} for seed are usually not selected for roadside use; the cost of seed mixes is rarely allowed to exceed \$1000 ha^{-1}. Uninteresting or unattractive species are virtually never selected for roadside use.

Species with large flowers and bright colors borne at the top of erect stems which bloom over extended periods of time are highly favored for use on roadsides. There is a preference for long-lived perennials, since annual species often fail to reestablish in permanent, unburned plantings. Bunch-type or weakly spreading species are preferred, so that the mix does not become dominated by a few colonial species. Also preferred for roadside use are species with moderate to low leaf canopy density (less competitive to other species in mix), vigorous growth (to stay ahead of weeds), a minimum height of 45 cm (to compete with weeds) and a maximum height of 120 cm (for roadside safety and visibility).

Because highway departments can rarely afford to plant wildflower seed mixes with more than 7 to 15 species, each species must make a significant contribution to the diversity of the planting. Typical mixes include species with contrasting colors which bloom at the same time, a floral and foliage display that changes through a long growing season, and as much live ground cover as possible during all seasons of the year.

A list of the most used and recommended species is included in Table 35-4. Virtually all of these species are available from seed producers or distributors. Species in bold tend to be of particular importance within their region of adaptation. Since this list was compiled with information provided by seed sellers and state agencies, and because the binomials are frequently obsolete and rarely include botanical authors, all names in current use have been included.

D. Soil Preparation & Wildflower Planting Methods

In contrast to bare soil situations where the rapid establishment of new groundcover is of overriding concern, the establishment of wildflowers usually focuses on the elimination of existing unwanted vegetation prior to seeding. One or two spray applications of glyphosate, perhaps tank-mixed with 2,4-D or another non-persistent broadleaf herbicide, is typically used to eliminate pre-existing vegetation. Other herbicides, including alachlor, benefin, eptam, metalochlor, pronamide, and trifiuralin have been successfully used when appropriate time for degradation has been allowed prior to planting (Corley and Smith, 1990, 1991; Dickens, 1992; Erusha et al., 1991). Meta-sodium and methyl bromide are soil fumigants used to kill existing vegetation and reduce soil seed

Table 35–4. Select list of wildflowers planted in U.S. highway corridors (commonly used species in bold type).

Genus	Species
Achillea	*filipendulina*, ***millefolium***
Agertina	*altissima*
Allium	*cernuum*
Ammi	*majus*
Amorpha	*canescens*
Anagallis	*arvensis*
Anemone	*canadensis, cylindrica*
Anthemis	*tinctoria*
Aquilegia	*caerulea*
Asclepias	*incarnata*, ***tuberosa***
Aster	***laevis,*** *ericoides*, ***novae-angliae,*** *oolentangiensis, patens, ptarmicoides, sericeus*
Astragalus	***canadensis***
Aurinia	*saxatilis*
Baileya	*multiradiata*
Baptisia	*australis*, ***leucantha, leucophaea,*** *tinctoria*
Bidens	*frondosa*
Cacalia	*atriplicifolia*
Calendula	*officnalis*
Callirhoe	*involucrata*
Campanula	*carpatica*
Camissonia	*cheiranthifolia*
Carphenophorus	*corymbosus*
Castalis	*tragus*
Castilleja	*coccinea*, ***indivisa***
Ceanothus	*americanus*
Centaurea	***cyanus***
Chamaecrista	***fasiculata***
Chrysanthemum	*carinatum*
Cichorium	*intybus*
Cirsium	*hillii*
Clarkia	***amoena,*** *concinna*, ***unguiculata***
Cleome	*serrulata*
Collinsia	*bicolor*
Coreopsis	***basalis,*** *floridana*, ***lanceolata, leavenworthii, palmata,*** *tinctoria, tripteris*
Consolida	***ambigua, orientalis***
Conoclinium	*coelestinum*
Cosmos	***bipinnatus, sulphureus***
Dalea	*purpurea, candida*, ***gattingeri***
Delphinium	*cardinale, gracilis*
Desmodium	*canadense, illinoense*
Dianthus	***barbatus***
Digitalis	*purpurea*
Dimorphotheca	*pluvialis, sinuata*
Dracopis	***amplexicaulis***
Eschscholzia	*caespitosa*, ***californica***
Echinacea	*angustifolia*, ***pallida, purpurea***
Erigeron	*speciosus*
Eryngium	***yuccifolium***
Erysimum	*x allionii*
Eupatorium	*altissimum*
Euphorbia	*corollata*
Euthamia	*minor*
Gaillardia	*amblyodon*, ***aristata, pulchella***
Gilia	*capitata, leptantha, tricolor*
Gypsophila	***elegans,*** *muralis, paniculata*
Helenium	*autumnale*
Helianthus	*annuus, debilis, giganteus, laetiflorus*, ***occidentalis,*** *maximilian*

Table 35–4. Continued

Genus	Species
Heliopsis	***helianthoides***
Hesperis	***matronalis***
Heterotheca	*subaxillaris, rutteri*
Heuchera	*richarsonii*
Iberis	*gibraltarica, sempervirens, umbellata*
Ipomopsis	***rubra***
Lathyrus	*latifolius*
Lavateria	*trimestris*
Layia	*platyglossa*
Lespedeza	***capitata***
Lesquerella	*gracilis*
Leucanthemum	***maximum, vulgare***
Liatris	***aspera, pychnostachya, spicata,*** *tenuifolia*
Linanthus	*grandiflorus*
Linaria	***maroccana,*** *reticulata, vulgaris*
Linum	***grandiflorum 'Rubrum', perenne, perenne ssp. lewisii***
Lithospermum	*canescens*
Lobelia	*cardinalis, spicata*
Lobularia	*maritima*
Lotus	*corniculatus*
Lupinus	*argenteus, densiflorus, diffusus,* ***perennis,*** *subcarnosus,* ***succulentus, texenis***
Lychnis	*chalcedonica*
Machaeranthera	***tanacetifolia***
Mentzelia	*lindleyi*
Mirabilis	*jalapa*
Monarda	***citriodora, fistulosa, punctata***
Myosotis	*sylvatica*
Nemophila	*maculata, menziesii*
Oenothera	*argillicola, biennis,* ***elator ssp. hookeri,*** *laciniata, glazioviana,* ***mcarocarpa,*** *pallida, rhombipetala,* ***speciosa***
Papaver	*nudicaule,* ***rhoeas***
Parthenium	*integrifolium*
Pedicularis	*canadensis*
Penstemon	*cobaea, digitalis,* ***grandiflorus,*** *hirsutus, palmeri,* ***strictus***
Phacelia	*campanularia, tanacetifolia*
Phlox	*carolina,* ***drummondii,*** *pilosa*
Physostegia	*virginiana*
Potentilla	*arguta*
Pycnanthemum	*virginianum*
Ratibida	*columnaris, pinnata*
Rudbeckia	*fulgida var. speciosa,* ***hirta,*** *subtomentosa*
Sabatia	*campestre*
Salvia	*azurea var. grandiflora,* ***coccinea, farinacea,*** *lyrata*
Sanguisorba	*minor*
Saponaria	*offinalis*
Senecio	*glabellus*
Silene	***armeria,*** *pendula*
Silphium	***integrifolium, laciniatum,*** *perfoliatum,* ***terebinthinaceum***
Sisyrinchium	*bellum*
Solidago	*nemoralis, rigida, speciosa*
Tradescantia	*ohioensis*
Trifolium	*incarnatum*
Verbena	*hastata, rigida, stricta, tenuisecta*
Vernonia	*cinerea, fasciculata, gigantea*
Veronicastrum	*virginicum*
Viguiera	*multiflora*
Zizea	*aptera, aurea*

reservoirs, but are costlier and less commonly used (Corley and Smith, 1991; North Carolina DOT, 1989).

Although the use of tillage to eliminate unwanted vegetation and to prepare soil for broadcast or drill seeding is common (Gallitano et al., 1992), the use of no-till seeders for this purpose is increasing. No-till seeders eliminate the need for tillage, and reduce both the expense and risk of soil erosion associated with roto-tilling, disking, or other conventional tillage practices. The reduction of soil disturbance associated with no-till seeders has often been reported to reduce weed seed germination and subsequent problems of weed infestation, though this practice may also reduce wildflower vigor (Ahern et al., 1992). Several no-till seeders manufactured for use with wildflower seed mixes are available which incorporate features that reduce the problems of seed segregation and bridging commonly encountered with general use broadcast seeders and no-till seeders (Morrison, 1981; Wildseed Farms, 1995).

The ability of wildflowers to tolerate drought and poor soil conditions has been widely misunderstood or exaggerated. As a result, the need to test and correct soil deficiencies prior to planting is often underappreciated. Although the wildflowers used for highway plantings are typically very hardy, they are usually less tolerant of pH extremes, salinity, and other adverse soil conditions than the grass species used in revegetation projects. Considering the much higher cost of wildflower seed than that of most reclamation species, the practical importance of testing and correcting soil deficiencies prior to seeding wildflowers would seem obvious, but is often overlooked.

To overcome the hostile subsoil planting conditions of many wildflower planting sites which are often low in nutrients as well as organic matter, the use of composted sewage sludge, composted municipal waste, and composted industrial waste has been increasing (Alexander and Tyler, 1994; Pill et al., 1994). Since these materials typically increase soil cation exchange capacity and water holding ability in addition to adding nutrients, these materials are associated with improved seedling vigor and survival. Despite these advantages, the cost of these products (tip to \$3000 ha^{-1} for materials, and \$1500 ha^{-1} for application/incorporation) has tended to Ii nit their general use.

Wildflower establishment by hydroseeding has been attempted by many highway agencies and contractors. Although useful for steep or inaccessible sites, hydroseeding has often proven unsatisfactory for seeding wildflowers (Byler et al., 1993). The size variation among wildflower seeds and the presence of awns, pappi, etc., causes seed tangling and mechanical damage in the spray tank. The use of paper or cellulose fiber mulch has also been observed to reduce the emergence of cotyledons and seedling survival; certain species often fail to emerge through fiber mulches. Because of these problems, hydroseeders must avoid certain species, use the cleanest seed (de-awned if possible, and free of debris), and increase seeding rates to compensate for reduced seedling survival (Harrington, 1991).

Cereal grain straw is among the most convenient, inexpensive, and readily available of seed mulching materials. Straw usually gives satisfactory results when used over broadcast seedings and when applied over wildflowers that have been hydroseeded without added fiber mulch. Although straw provides good soil erosion protection and poses little resistance to the emergence of wildflower seedlings, it invariably contains seed of weed species which may be difficult to remove after the planting is established. While little is known about the merits of other erosion control materials for wildflower establishment, it is likely that jute netting and other biodegradable open-weave materials may be useful alternatives to fiber mulch or straw.

IV. FUTURE RESEARCH NEEDS

Major areas needing additional research are:

- Identification of possible **persistent species,** especially for the humid temperate region, to expand the currently limited list. The search should focus on adapted species that require little management once established.
- Increasing the biodiversity along the roadsides has been a growing interest of ecologists. Animal populations are affected by the plant systems created along the highways. The prairie states are aware that the restoration and perpetuation of the native vegetation is important to the heritage of future generations. Research on how to increase roadside biodiversity as well as preserve the native species should be addressed.
- Use of **waste products** in the roadside environment, especially biosolids, municipal, and yard waste products.
- **Soil bioengineering** techniques; the use of live plant materials and specified soil matrices to construct living erosion control structures.
- Investigation of new **geotextile** related products with emphasis on geogrids.
- Establishment and dynamics of long term **nutrient cycling** regimes in the roadside environment.
- Determine if roadside **nutrient management** programs affect water quality and to evaluate management practices that could reduce the risk of nutrient loss.
- Since the use of **wildflowers** for low-maintenance groundcover has only been intensively studied for the past ten to twenty years in most regions of the U.S., few areas of research have been thoroughly investigated. The species listed in Table 35.4 comprise a small fraction of the species which might be developed for use; efforts to identify other adapted species, and to produce their seed on a commercial scale is certainly needed. Further investigation is also required to improve chemical weed control methods and define the tolerances of non-target species, and to determine the optimum pH and fertility needs of wildflower species.

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ing the literature over the past 30 years, it is apparent that the concern for energy conservation, soil loss, water quality, and hiodiversity issues has been a priority for state and federal support. John Krouse especially acknowledges the assistance of various highway planting agencies which provided informal reports and specifications that were used for the compilation of Table 35.4.

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