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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 Passage of this law essentially made many chapters of the first edition out of date by the time the book was published in 1978.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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35

Establishment of Low Maintenance Vegetation in Highway Corridors.

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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. Gradi ng 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).

Treatments	Data recorded July 1972					
	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 i 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 initial 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	
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	Winter
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 for mulation of specialized seed mixes that allow the use of pre-emergence or post-emergence herbicides to control broadleaf weeds without injury to the wild_ flower 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,*** *maximiliani*

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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