CHAPTER

2

Forage and Biomass Planting

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Birdsfoot trefoil 2 wk after spring planting in Utah (drill rows run left to right). Credit: Jennifer MacAdam, Utah State Univ.

INTRODUCTION

Forage and biomass species offer many benefits for conservation. More specifically, these species can be grown for grazing, hay, silage, biofuel, or industrial use and are among land-use options available to generate economic return and provide other agroecosystem services. Once established, these perennial species protect soil from erosion, improve water infiltration, reduce runoff, retain nutrients that might otherwise enter a waterway, provide shelter and sustenance for wildlife, build soil organic matter, increase soil nitrogen (N) through root and nodule turnover, support food and biofuel production, ensure food security, add to farm income, and contribute to the quality of rural life.

One dilemma of any planting is that even though good management might be used, the establishment period has a risk of failure because of factors such as wind and water erosion, disease and insects, hard seed, slow seedling growth, weed invasion, drought, or frost. Every establishment is likely to have a short period of production and financial loss, as well as negative environmental impact; however, it is the long-term positive benefits that make these short-term negative impacts tolerable (Fig. 2.1). These up-front costs of financial expenditure, lost production, and environmental disturbance occur irrespective of establishment success or failure, so additional input to reduce the risk of stand failure is warranted (Bartholomew, 2005). It is well known that managers should rely on local data, previous experience, careful timing, and good management to minimize risk and economic loss. The literature is deficient in descriptions of establishment failures that frequently occur, most likely because it can be difficult to publish negative data.

This chapter summarizes the research related to the Purposes and Criteria of the practices described in the Natural Resources Conservation Service (NRCS) Conservation Practice Standard, Forage and Biomass Planting, Code 512 (January 2010) (Appendix I); (Maderik et al., 2006). We address the establishment of grasslands intended for the purposes listed in Code 512 (Fig. 2.2) and focused the synthesis on plantings in the cool-season (temperate), transition, and subtropical zones of the eastern USA, and included intensively managed grasslands in the West (Figs. 1.1 and 2.3). This includes establishment of grazed forest and agroforestry mixes, grazed or harvested cover crops, perennial seedings for wildlife, and interseeding of annual species into perennial warm-season pastures. This excludes rangeland establishment, which was reviewed by Hardegree et al. (2011). Also excluded were seeding cover crops where the sole purpose was grain production; the seeding of grain

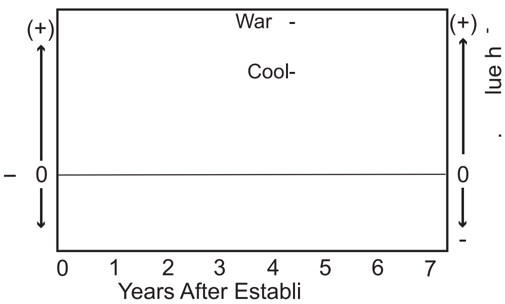

FIGURE 2.1. Change in economic return from production following a new seeding for perennial plants as they achieve and maintain full production. Cool-season species often establish faster than warm-season grasses, and may differ in some ecosystem services. Associated contributions to ecosystem services (e.g., soil erosion, soil carbon, wildlife, and social values) are not well known or been assigned economic values. A short-term loss of production and/or services can be justified by the likelihood of benefits over the long term.

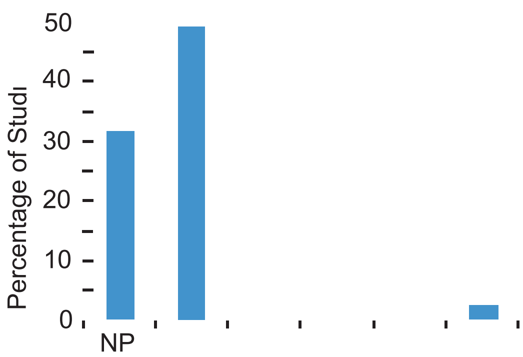

FIGURE 2.2. Percentage of 314 research publications on forage and grassland establishment based on the intended purpose. Purposes included no purpose stated (NP), improve forage production and animal nutrition (FP), balance forage supply (FS), improve water quality (WQ), enhance erosion control (EC), and biomass production (BP).

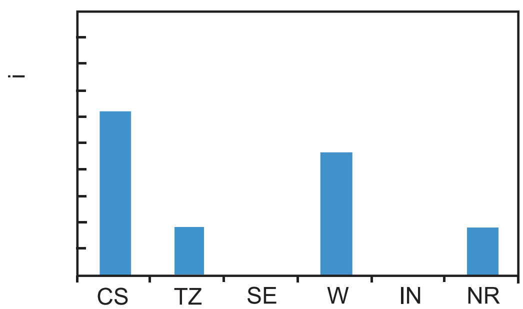

FIGURE 2.3. Percentage of 314 research publications on forage and grassland establishment based on the geographical region in which the research was conducted. Regions (see Fig. 1.1) included the cool season, mainly from northern and eastern states (CS), transition zone (TZ), southeast and subtropical (SE), west (W), international (IN), and no region stated (NR).

crops such as wheat (scientific names of all plant species used in this chapter are given in Appendix III) or corn where their secondary use might be for grazing; or Conservation Reserve Program (CRP) seedings, which were reviewed by Reeder and Westermann (2006).

In this chapter, establishment is defined as the period between seeding and utilization of the vegetation for its intended purpose, which is typically at the time full canopy cover is achieved. This period can be as short as 6 wk for rapidly establishing species in ideal conditions (e.g., annual ryegrass), or as long as 2–3 yr for slowly establishing species in a harsh environment (e.g., big bluestem). In broader terms, establishment commences when the seed is placed into the soil and continues until development of a mature canopy. After establishment it may take as long as 7 yr for a mixed-species planting to achieve equilibrium and develop spatial patterns that are typical of a mature canopy. At the other extreme, some definitions of *establishment* consider only the time until seedlings have achieved enough leaf area for photosynthesis to be in a positive energy and nutrient balance, which might take as little as 21 d after emergence for rapidly establishing species (Ries and Svejcar, 1991).

This chapter comprises 11 sections derived from the Code 512 "Plans and Specifications," and follows the sequence of decisions and operations necessary for a successful seeding. We begin with "Plans and Specifications," followed by the preplant operations, "Selection of Species and Cultivars," "Type of Legume Inoculant Used," "Seed Source and Analysis," "Fertilizer Application," and "Seed Coatings and Pretreatments." This is followed by the planting operations, "Site and Seedbed Preparation and Method of Seeding," "Climatic Factors Affecting Time of Seeding," "Rates of Seeding," and "Seeding Depth." We conclude with "Protection of Plantings," divided into the subsections "Postseeding Management" and "Weed Control."

PLANS AND SPECIFICATIONS

Code 512 requires preparation of plans and specifications for planting of each site or management unit. In some cases, planning should start 12 mo prior to the actual seeding. Elements necessary to meet the intended purpose include selection of species, type of legume inoculant used, seed source and analysis, fertilizer application, site and seedbed preparation, method of seeding, time of seeding, rates of seeding, protection of the planting, and supplemental water for plant establishment.

Important components of the planning process that are omitted from Code 512 are

1. Financial analysis of the costs and benefits for the planting, including a cash-flow plan.

2. Environmental analysis of the disruption to agroecosystem services, and the long-term benefits that can be expected.
3. Consideration of other improvement options. In some cases, a new seeding may not be necessary if sufficient plants remain that can be stimulated. Other adaptive management options such as fertilization (Chapter 5), appropriate harvest schedules (Chapter 4), or appropriate grazing methods (Chapter 3) can achieve grassland improvement in some situations. In these cases, agroecosystem services might be maintained by avoiding disruption resulting from re-establishment.
4. Identification and correction of management or environmental factors (e.g., poor drainage, weediness, low fertility, under- or overgrazing, or poorly adapted species or cultivars) that might have contributed to failure of the prior stand. For example, alfalfa plants release autotoxins to the soil that reduce root growth of alfalfa. Thus, alfalfa should not be seeded immediately following a prior alfalfa stand (Jennings and Nelson, 2002a, 2002b). Failure to complete this step increases risk of an unsuccessful establishment that will require another new seeding (Hopkins et al., 2000).
5. Consideration of additional operational details, including options for the use of seed coatings and pretreatments, and determination of the correct seeding depth.
6. The consideration of livestock production was implied in Code 512, giving the implication there is less emphasis on environmental conservation and the emerging importance of food sources and habitat for wildlife.

SELECTION OF SPECIES AND CULTIVARS

The most significant benefit of a new seeding is the introduction of preferred species or cultivars that were sparse or absent in the previous stand. One complexity in species selection is the number of options that exist. The 363 publications summarized in this chapter included 162 grassland species, comprised of 70 legume species, 79 grass species, and 13 forbs (Table 2.1; Fig. 2.4). Most species have many cultivars (e.g., as many as 1000 for alfalfa) that add to the complexity. Agronomic performance varies among cultivars. For example, in South Dakota, slowly establishing 'Vernal' alfalfa was more dependent on use of an oat companion crop for weed control than the faster establishing 'Saranac' (Hansen and Krueger, 1973). This said, the unavailability of a given cultivar, species, or even inoculum may severely limit a producer's options in a given year.

The selection of species for establishment is determined by the ultimate purpose of the land area. Formulating a seed mixture of desired species is based on variation in the establishment characteristics of the species used (Brar et al., 1991; Barker et al., 1993). Seeding rates used in mixed seedings integrate the relative establishment characteristics and the long-term botanical composition desired (Blaser et al., 1952). The literature has many examples of changes in botanical composition during establishment in response to the stand management (Skinner, 2005). Comparative analyses indicate species and cultivars can be ranked for rate of establishment and competitiveness during establishment (Blaser et al., 1952). However, the very large number of species and cultivars, the proportions in which they can be mixed, and their complexity of interactions within a variable environment have not been researched in detail, making selection of species mixtures as much art as science.

> "One complexity in species selection is the number of options that exist."

Species and the Code 512 Purposes

Livestock and Wildlife Nutrition and Health. In most cases, there is a trade-off between forage production and nutritive value for the purpose of livestock and wildlife nutrition and health (Collins and Fritz, 2003; Chapter 3 of this volume). Sometimes the most productive species (e.g., tall fescue or switchgrass) is not the highest-quality option. Less-productive species, such as timothy, blue grama, or white clover, may be suitable components of a pasture mixture through their contribution to forage quality. Some of these desirable species can be difficult to establish and maintain in the mixture. Nutritional needs of livestock are complex (Dougherty and Collins, 2003), but in general, the highest-quality forages will contain high energy and protein. Thus, the major criteria for species selection are the desired use

TABLE 2.1. Summary of the literature on responses of plant species to establishment practices. Most commonly researched species accounted for > 50% of the functional group.

Functional group	Most commonly researched species	Additional species	Total species	Total studies[1]	Percent of total
		Number			
Perennial legumes	Alfalfa, white clover, red clover	15	18	269	35%
Annual and biennial legumes	Subterranean clover, arrowleaf clover, winter pea, crimson clover, hairy vetch, sweet clover	46	52	93	12%
Cool-season perennial grasses	Orchardgrass, smooth bromegrass, perennial ryegrass, tall fescue, crested wheatgrass, timothy	28	34	169	22%
Cool-season annual grasses	Oat, wheat	7	9	62	8%
Warm-season perennial grasses	Switchgrass, big bluestem, indiangrass	30	33	143	19%
Warm-season annual grasses	Crabgrass, millet, sorghum sudangrass	5	8	13	2%
Forbs	Chicory, turnip, plantain	10	13	24	3%
Total			167	773	

[1]Includes 314 publications (47 reviews and 267 research papers), averaging 3.5 species per publication.

of the established stand and not their ease of establishment.

Current emphasis has expanded the list of desirable features of a forage mixture to include environmental and wildlife benefits, which involves more complex decision making. Even generalized species recommendations for wildlife are difficult because of the number of different species and the variability in their food and habitat requirements. There is increasing information on the dual-purpose supply of forage to domestic and wildlife species. Herbivorous wildlife (e.g., deer, elk, horses, etc.) have nutritional requirements similar to those of domestic livestock (Fennessey and Milligan, 1987), and well-managed grassland often has better forage quality than the vegetation they might usually encounter. An excellent review by Harper et al. (2007) lists 92 references describing the establishment and use of warm-season species for mixed wildlife and biomass production in the midsouth USA.

For some wildlife, habitat quality can be more important than nutritional value per se. In this respect, the dense stands of most well-managed forage grasses restrict nesting and feeding, with more open stands being preferred by ground-dwelling birds (Vickery et al., 2001). In contrast, many native prairie grass species grow as spaced bunchgrasses and offer excellent bird habitat. Grasslands used by wildlife must also support the insect and rodent populations used as food by certain bird groups. Similar to nesting issues, dense grassland stands may increase the cover for rodents and insects and reduce habitat quality for predatory and insectivorous birds such as owls, sparrow hawks, and meadowlarks (Vickery et al., 2001).

Studies also have shown that biodiverse vegetation with many flowering species usually supports more insects and consequently more bird species (Tscharntke and Hans-Joachim, 1995; Dupont and Overgaard Nielsen, 2006). In Minnesota, species-rich grasslands, especially those mixtures that included legumes and cool-season (C_3) grasses, supported greater insect diversity (Siemann et al., 1988). In addition to species selection, stand management (e.g., timing of mowing, grazing, or harvesting) can be important in allowing expression of flowering, as well as avoiding the disruption of nesting. Such management can be important to offset losses of species richness in the planting mixture (Siemann, 1998), yet management to allow flowering is usually in conflict with the goal of producing high-quality forage, because the highest nutritional value of most forage species occurs prior to flowers being formed.

We found little research on establishment of multispecies mixtures, especially those developed with the multiple purposes of livestock production, environmental conservation, and wildlife benefits. As mentioned above, the first step should be to design the best mixture to achieve the multiple functions, and then use the management needed to maintain the proportions. The method for establishing that desired combination may include sequenced seeding, beginning with a rapidly establishing species to hold the soil followed by interseeding other species to develop the desired mixture gradually. These diverse goals and species also require technical information for adaptive management of the landowner to maintain the mixture as designed to achieve the desired purpose. Unfortunately, there were few establishment studies that focused on these longer-term concepts or goals.

Forage Production and Seasonal Distribution. Pasture species, and to a lesser extent, cultivars, differ in their growth patterns during the year. Species with contrasting growth patterns can be seeded together in the same pasture or separately in adjacent pastures within a grazing system (e.g., Moore et al., 2004) for the specific purpose of modifying the seasonal pattern of forage availability and quality. Early- and late-maturing cultivars of orchardgrass grown in separate fields on a single farm will spread the harvesting time for hay. There are several situations in which the diverse growth patterns of grassland species can be used to complement each other to ensure forage supply for a longer time period. Usually, the objective is to provide a year-round supply of grazable forage to livestock; however, constraints from cold winters and dry summers reduce growth rates and prevent farms from achieving that goal. Thus, for most areas in the USA, farms are dependent on various systems to store forage (see Chapter 4). In such cases, species may be selected primarily for their ease of harvest and storage.

Optimal species for forage production differ among regions, districts, and even among fields within farms. Farmers should gain experience with new species and cultivars on small areas within their farms, because species and cultivar performance are sufficiently dependent on soil resources, slopes and aspects, livestock species, grazing management, and fertilization practices that their suitability can vary between adjacent farms. One strategy is for farmers to use mixtures of 3–10 species within a single sowing. Although this may increase the complexity of management to maintain each combination, the benefits of more species may include greater production and greater stability of livestock production (Blaser et al., 1952; Sanderson et al., 2004) or benefits to the environment and wildlife.

Legumes vs. Cool-Season Grasses. Most forage legumes have a higher temperature optimum for growth (25°C) than cool-season grasses (20°C; MacAdam and Nelson, 2003). Thus, in cooler conditions such as early spring or late autumn, cool-season grasses have a higher growth rate. In hotter conditions

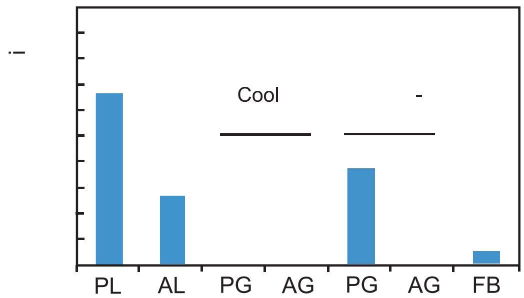

FIGURE 2.4. Percentage of 314 research publications on forage and grassland establishment based on functional group of species evaluated. Groups included perennial legumes (PL), annual and biennial legumes (AL), cool-season perennial grasses (PG), cool-season annual grasses (AG), warm-season perennial grasses (PG), warm-season annual grasses (AG), and forbs (FB).

Dairy heifers grazing a perennial ryegrass pasture in Idaho. Credit: Jennifer MacAdam, Utah State University.

during summer (after cool-season grasses have flowered and are growing in a vegetative condition), legumes will generally have higher production. One of the benefits of grass-legume mixtures, in addition to N-fixation by legumes, is their complementary growth patterns. In most cases, adapted legumes and cool-season grasses are planted together and will co-exist in perennial stands with good management. In some cases where legumes are lost from a stand, legumes such as red clover or alfalfa can be no-till or frost-seeded (broadcast) into established vegetation (Taylor et al., 1969; Wolf et al., 1983; Schellenberg and Waddington, 1997).

Cool- vs. Warm-Season Grasses. Cool-season grasses are adapted to cool, moist conditions, such as early spring and late autumn, whereas warm-season grasses are better adapted to warmer, drier conditions that prevail in summer (MacAdam and Nelson, 2003). In mixture, the contrasting growth and agronomic requirements of these grasses can make it difficult to retain both functional groups in the desired proportions. More commonly, these species might be planted separately as special purpose areas within a farming system to provide feed during a period of deficit (Moore et al., 2004). In the midwest, the options for special-purpose warm-season pastures are 1) planting annual crops such as sorghum–sudangrass or tef or 2) planting perennial pastures with species such as switchgrass, big bluestem, or indiangrass.

Autumn-Seeded Small Grains. Annual small-grain species suitable for forage production include oat, barley, wheat, rye, and triticale. These species can be planted in autumn after early harvest of soybean for grain, corn for silage, or winter wheat, with the specific purpose of accumulating forage for later in winter when it might be grazed (Sulc and Tracy, 2007). Species vary in their tolerance to winter cold. Oat plants are not very frost tolerant and need to be harvested or grazed before or soon after temperatures fall below −5°C to conserve yield and quality. At the other extreme, winter rye will survive most winters and have excellent early-spring growth.

No-Till Seeding Into Perennial Pasture. One option for pasture renovation is to no-till cool-season species such as white or crimson clover into existing pastures of warm-season (C_4) species such as bermudagrass. The primary benefits are to promote early- or late-season forage production and to improve forage quality. A common example in the USA is the establishment of annual or short-rotation (hybrid) ryegrass into bermudagrass (Swain et al., 1965). For the same purpose, ryegrass was no-till drilled into kikuyu pasture in northern New Zealand (Barker et al., 1990). Interseeding of cool-season grass or legume species into upright native warm-season grasses such as switchgrass or big bluestem has been less successful.

Soil Erosion

Grasslands have among the lowest rates of soil erosion compared to other land-use options (Owens et al., 1989). The mechanisms by which grasslands protect soil include, perennial vegetation that reduces rainfall impact on soil (Exner and Cruse, 1993), extensive root systems that die, leaving channels to enhance water infiltration, dense stands that slow surface water flow, dense and fine roots that hold soil particles, and greater earthworm numbers ensuring macropores for water infiltration (Owens et al., 1989). There is relatively little published information on differences in erosion among grassland species. One study found that adding smooth bromegrass to an alfalfa stand had no effect on the erosion rates from the vegetation (Zemenchik et al., 1996). The dense vegetation of tall fescue provides better soil cover and has less runoff than do native warm-season species (Self-Davis et al., 2003). In other studies, increased amounts of vegetative cover had the greatest effect on reducing erosion rates from pasture (see Chapter 4). If the vegetative cover is dense, relatively uniform, and has little or no bare ground present, the differences among species are negligible (Zemenchik et al., 1996).

Improve Soil and Water Quality

The most important characteristics relevant to the quality of runoff water are the concentrations of suspended sediments and dissolved nutrients, and the presence of bacteria such as fecal coliforms. Nitrate and pesticides can also leach through the soil and into the ground water. The volume of water and the concentrations of the suspended or dissolved materials affect the total amount of these materials lost from an area. Since there is very little vegetation on tilled seedbeds during early stages of establishment, newly planted areas are more susceptible to runoff and leaching than established stands. However, no literature was found describing any effects of species on erosion or water quality during establishment. One article reported that contour planting (perpendicular to the slope) of forages reduced surface runoff compared to planting down the slope, but no data were presented (Decker et al., 1964).

Established grassland vegetation significantly improves water quantity and quality compared to forest or cropland (Dabney et al., 1994; Owens and Bonta, 2004; Vadas et al., 2008; Owens and Shipitalo, 2009). The effects of pasture species on water quality are negligible compared to the effects of pasture cover, and the management of that biomass via defoliation and timing of fertilizer use. Any effects of established pasture species on water quality can largely be attributed to the density and uniformity of the final stand; all pasture species that are adapted to the environment and management will have beneficial effects on water quality and quantity.

Carbon (C) Sequestration

Established grasslands have considerable potential for C sequestration. However, the actual sequestration achieved is more dependent on biomass management than on species selection (Skinner, 2008; Don et al., 2009). Harvesting more frequently and removing most of the aboveground mass can reduce the potential for C sequestration because root growth is reduced (Skinner, 2008). The primary mechanism for C sequestration in harvested or grazed forages is root growth, or more specifically, the relative rates of root growth and death/senescence (Frank et al., 2004). Senescent leaves and stems on the soil surface can be incorporated into the soil by microbial activity, however that process is slower than for ingestion and movement by earthworms.

Pasture species with high root mass, especially mass that is distributed deeper in the soil profile, have the potential for high rates of C sequestration. In switchgrass, for example, roots can account for 27% of total plant C, and plant crown material that is below ground can account for an additional 57% of plant C (Frank et al., 2004). Not only can the individual species affect root growth, the number of species may also be important. Skinner et al. (2006) found an 11-species pasture mixture had 30–62% greater root biomass than two- or three-species mixtures, and a greater proportion of roots were deeper in the soil. Even with this initial variation in root biomass however, their study did not find any differences in C sequestration among species mixtures after 4 yr.

Monocultures of six cool-season grasses and one warm-season grass averaged 60% more root mass than either alfalfa or red clover 2 yr after establishment (Bolinder et al., 2002). It was subsequently found that legumes allocated 43% of total carbon to roots and soil while grasses allocated 56% (Bolinder et al., 2007). Mixtures of legumes and grasses can have up to 73% of their C allocated to roots and soil (Bolinder et al., 2007). It can be concluded that species and cultivars that are productive and persistent will have better C sequestration potential than species that perform poorly, and mixtures are superior to monocultures.

Species for Biofuel or Energy Production

Many grassland species have been evaluated for biofuel or energy production, including, for example, prairie cordgrass, sugarcane hybrids, sorghum, barley, Canada wildrye, big bluestem, indiangrass, sideoats grama, and alfalfa

"…effects of pasture species on water quality are negligible compared to the effects of pasture cover"

> Certified seed of named cultivars is highly recommended

(Boukerrou and Rasmusson, 1990; Vogel et al., 2006; Boe and Lee, 2007; Dhugga, 2007; Lamb et al., 2007; Wang et al., 2008; Mangan et al., 2011). Although most grassland species have the potential for dual use as livestock forage and biofuel/energy, the contrasting requirements of these industries makes it likely that specialist species and/or cultivars will be necessary. In recent years, greatest interest has focused on switchgrass for biofuel/energy in much of eastern USA and the midwest (Vogel et al., 2002; Frank et al., 2004; Berdahl et al., 2005; Cassida et al., 2005; Mulkey et al., 2006; Boe and Lee, 2007; Vogel and Mitchell, 2008), however, miscanthus, giant reed (Clifton-Brown et al., 2001; Decruyenaere and Holt, 2001, 2005) and energy cane (Prine and French, 1999) also have high potential for biofuel/energy crops, but would be lower in dual-use potentials.

Plant breeders have found variation in the characteristics of many species proposed for use as biofuel/energy crops, and cultivars of some species are available in some regions (Berdahl et al., 2005; Boe and Lee, 2007; Murray et al., 2008; Wang et al., 2008). Typically, these cultivars have high yield potential, low fiber digestibility, low nutrient content, and consequently low ash content. To date, no genetically modified crop dedicated to biofuel/energy production is available; however, new information on the biochemical pathways suggests that scope for genetically modified cultivars is possible (Sticklen, 2007).

We found no published research evaluating effects of biofuel species on erosion, water runoff, or wildlife benefits during the establishment period. But recognizing the duration for establishment is relatively long, the risk would seemingly be rather high. This is an area needing research attention.

Cultivars

Selecting appropriate cultivars of a species can be as important as selection of species for optimum grassland performance. For example, one cultivar of annual ryegrass resulted in more severe suppression of a new alfalfa stand than other cultivars, when used as a cover crop during establishment (Sulc and Albrecht, 1996). Although intended as a companion crop to provide soil protection and weed competition during alfalfa establishment, the more vigorous annual ryegrass cultivars impaired growth of the developing alfalfa stand. Certified seed of named cultivars is highly recommended rather than variety not stated (VNS) seed. Several years of testing with red clover in Kentucky found only about 10% of seed lots of common red clover were as productive as certified seed (Olson et al., 2010).

Cultivars vary in many traits, and alfalfa cultivars, for example, show large variation that includes differences in insect and disease resistance, fall dormancy, winter hardiness, flowering date, and yield potential. Genetically modified alfalfa cultivars with genes for glyphosate (chemical and trade names are in Appendix IV) tolerance were first released in 2005. These were withdrawn from commercial sale in March 2007 while their environmental impact was investigated by USDA and again approved. Seed became nonregulated and commercially available again in January 2011. This glyphosate-tolerant technology will allow producers to better control weed competition during establishment (Hall et al., 2010). Once a weed-free stand is achieved, a well-managed alfalfa stand is relatively resistant to weed invasion.

Grazing tolerant alfalfa cultivars have belowground crowns and multiple stems per plant, resulting in improved persistence under grazing (Bouton and Gates, 2003). Similarly, white clover cultivars can show extreme variation in morphology, with large-leaved and erect types (e.g., ladino white clover) being better suited to hay production, and intermediate types (e.g., 'Durana') being better suited to grazing. The very-small–leaved prostrate types of white clover (e.g., Dutch clover) have low production and are unsuitable for most purposes. In contrast to their agronomic characteristics, most cultivars within a species have similar emergence characteristics, and differences in establishment are more likely caused by variation in seed quality than emergence rate per se.

Turf cultivars should never be confused or mixed with forage cultivars. In most cases, the yield potential of turf cultivars is much lower, tillering rates are higher, and leaf growth rates slower than those of forage cultivars.

Recommended seeding rates for turf cultivars are typically much higher than those for forage use. This is due to the need for more rapid and more uniform establishment in amenity areas than is necessary in forage stands, rather than any difference in the rates of emergence and establishment. Seed of turf cultivars of tall fescue and perennial ryegrass will likely be infected with an endophytic fungus that improves persistence of these species, but produces alkaloids that can be toxic to livestock and wildlife.

Many forage species are sold commercially as blends. For example, BG34® perennial ryegrass, StarGrazer® tall fescue, and Haymate® orchardgrass are sold as mixtures of several cultivars of their respective species. Although there may be benefits from genetic diversity in seeding mixtures of cultivars, this has rarely been addressed in the literature. The success of these blends can be attributed to both the component cultivars and the proportions of each that survive after establishment. Biochemical and molecular methods can document the establishment of an improved cultivar seeded into a stand where a "naturalized" population of the same species already exists (Hopkins et al., 2000). Invariably, improved cultivars do not contribute significantly to the resultant stand unless significant changes to stand management (e.g., increased fertilizer use) are made.

Producers may prefer 'tried and true' cultivars over newer and often more expensive cultivars. Producers might successfully use a specific cultivar for specific conditions on their farm, but it may not be suitable for a nearby farm if grazing systems or hay management and fertilizer practices differ between the farms. In many cases cultivar selection depends on what is available at a local seed merchant.

The literature does not always support the superiority of improved cultivars over common or VNS seed of forage rye (McCormick et al., 2006), especially during establishment and

Birdsfoot trefoil 2 wk after spring broadcast seeding in Utah (compare to photo after spring planting). Credit: Jennifer MacAdam, Utah State University.

even later if the management does not use the superior feature. It should be noted that VNS seed could be an older cultivar or a new cultivar that does not have normal proprietary protections and guarantees. In another study, Lamb et al. (2006) found that older alfalfa cultivars had production similar to newer ones, except in more stressed environments and especially when persistence was challenged. Newer alfalfa cultivars had better persistence and productions in year 3 and thereafter (Lamb et al., 2006). Although, in general, cultivars of various grassland species showed very little difference in emergence rates, rates of germination and field establishment could be improved in bahiagrass by standard breeding methods (Anderson et al., 2009).

Species Mixtures

Another consideration to be made before planting is whether a single or multiple species stand is desired. Many new seedings comprise only 1 or 2 species, yet there are some benefits from establishment of biodiverse mixtures containing as many as 10 to 20 species (Sanderson et al., 2004, 2005). The literature is not clear on the benefits from complex mixtures, with results depending on the actual species used in the mixtures. Arguments against species-rich mixtures are the greater probability that one or more desired species are poorly adapted to co-establishment or specific environmental conditions, the greater management complexity of the resultant stand, and the unpredictability of the final botanical composition. There is some evidence that established grasslands may benefit from species-rich mixtures, especially on sites with highly diverse microenvironments such as mixed soil types, variable topography and soil fertility, patch grazing by livestock, and those subject to wide variations in weather that add stresses such as temperature, drought and flooding (Sanderson et al., 2002).

Spring-seeded birdsfoot trefoil 10 mo after planting in Utah (drill rows run top to bottom) (compare to photo after spring planting). Credit: Jennifer MacAdam, Utah State University.

Conclusion—Selection of Species and Cultivars

Code 512 emphasizes the selection of species and cultivars that are adapted to the site being planted. The characteristics to consider include climatic conditions; soil condition; landscape position; and any phytotoxic compounds, diseases, and insects that might be prevalent. The Code 512 Criteria place little emphasis on environmental or wildlife factors, but these were also included in this review because of their emerging interest. Changing climate, as evidenced by revision of the USDA Plant Hardiness Zone map in 2005 and 2012, may allow species that had once been considered unsuitable, to be suitable for some regions. This literature summary included 162 species (70 legumes, 79 grasses, and 13 forbs); however, just 28 of these species accounted for more than 50% of the research evaluated. The remaining species have potential for use in innumerable specialized situations and purposes, and additional research is warranted to explore these situations.

Selection of species and cultivars should also include the proposed use and management of the established stand. Some species and cultivars are better suited for grazing, and even within this designation, certain plant species are better suited than others for a particular animal species. Some species and cultivars are better used for hay or silage, and some are better used as biofuel/energy sources. Although it is desirable for grasslands to have multiple uses, the species and cultivars best suited for particular purposes generally do not have multiple-use options, e.g., the best alfalfa cultivars for hay production are likely poorly suited for grazing or biofuel use. Regrettably, characteristics that determine the suitability of a species for a particular use are not always associated with ease of establishment, and some desirable species can be difficult to establish.

The Code 512 Criteria emphasize that forage should meet the level of desired nutrition for the class of livestock. Forage species vary in their nutritional characteristics (e.g., digestibility, energy content, and protein content), and high-quality forages are essential for growing and lactating livestock (not so for mature and "dry" animals). The Code 512 Criteria also emphasize components of the forage mixture should have similar palatability; however, research shows this specification is often unrealistic or infeasible. Grasses and legumes are frequently mixed in pastures to achieve an optimal combination of herbage production through the entire season, plus benefiting from biological nitrogen fixation. Competitiveness of a species in a mixture is related more closely to production of herbage than to the quality or palatability of the herbage. This characteristic is likely the most critical for establishment success making the species selection of the mixture restricted to matching those that are similar in competiveness. Selective grazing due to different palatability is an inevitable feature of grazing mixed species that can be managed with rotational stocking (Chapter 3).

The Code 512 Criteria specify that species should be used that help meet livestock forage demand during times when normal production is inadequate. This specification is supported by the literature and deferred grazing (Chapter 3) or harvest of forage species suitable for hay or silage production may be required (Chapter 4). Selecting the species to establish for these purposes is important in the planning phase, and the establishment time or method may need to be altered to accomplish this goal. To date there is insufficient research on how each species provides the nutritional and environmental requirements of wildlife to make detailed species selections.

Another Code 512 Criteria is that species established for biofuel or energy production should provide the kinds and amount of plant materials needed for that purpose. This is supported by research, because some grass species are more suitable than others for cocombustion, cellulolytic fermentation, or other biofuel or bioindustrial application. Most research is based on use of perennials in monocultures that are harvested one or two times annually and are based mainly on biomass production and quality. Effects on the environment or wildlife remain unknown.

Code 512 Considerations specify establishing persistent species that can tolerate close grazing and trampling in areas where animals congregate, and where C sequestration is a goal, deep-rooted perennial species should

"…the species and cultivars best suited for particular purposes generally do not have multiple-use options"

TABLE 2.2. Legume species and their recommended commercial rhizobia species and current sources of commercial strains.

Common name	Rhizobium species	Source and name of commercial strain
Alfalfa	*Sinorhizobium/Ensifer meliloti*	Nitragin A,[1] Dormal alfalfa,[2] N-Dure or Pre-vail alfalfa[3]
Bundleflower	*Rhizobium* spp.	CB 3126[4]
Clover, alsike	*Rhizobium leguminosarum* bv. *trifolii*	Nitragin B,[1] Dormal–true clover,[2] N-Dure true clover[3]
Clover, arrowleaf	*Rhizobium leguminosarum* bv. *trifolii*	USDA 2298,[4] Nitragin R/WR/O[1]
Clover, ball	*Rhizobium leguminosarum* bv. *trifolii*	Identical to alsike clover
Clover, crimson	*Rhizobium leguminosarum* bv. *trifolii*	Nitragin R/WR/O,[1] Dormal true clover[2]
Clover, red	*Rhizobium leguminosarum* bv. *trifolii*	Identical to alsike clover
Clover, kura	*Rhizobium leguminosarum* bv. *trifolii*	USDA 2126[4]
Clover, rose	*Rhizobium leguminosarum* bv. *trifolii*	WSM 1325,[4] Nitragin R/WR/O[1]
Clover, subterranean	*Rhizobium leguminosarum* bv. *trifolii*	USDA 2116,[4] Nitragin R/WR/O[1]
Clover, white	*Rhizobium leguminosarum* bv. *trifolii*	Identical to alsike clover
Cowpea	*Bradyrhizobium* spp. *'vigna'*	Nitragin EL,[1] Royal Peat–cowpea[2]
Crownvetch	*Mesorhizobium* spp.	CrV-1[4]
Deervetch	*Rhizobium leguminosarum* bv. *viciae*	DV-2[4]
Lablab	*Bradyrhizobium* spp. *'lablab'*	USDA 3605[4]
Lespedeza	*Bradyrhizobium* spp. *'lespedeza'*	Nitragin EL,[1] Royal Peat–cowpea[2]
Medic, barrel	*Sinorhizobium/Ensifer medicae*	WSM 1115[4]
Medic, black	*Sinorhizobium/Ensifer medicae*	WSM 1115[4]
Medic, burr	*Sinorhizobium/Ensifer medicae*	WSM 1115[4]
Medic, little burr	*Sinorhizobium/Ensifer medicae*	WSM 1115[4]
Medic, rigid	*Sinorhizobium/Ensifer medicae*	M 49[4]
Medic, Tifton burr	*Sinorhizobium/Ensifer meliloti*	Nitragin A[1]
Milkvetch, cicer	*Rhizobium* spp.	USDA 3811[4]
Mungbean	*Bradyrhizobium* sp. *'vigna'*	Nitragin EL,[1] Royal Peat–cowpea[2]
Prairie clover	*Rhizobium* spp.	USDA 3742[4]
Sainfoin	*Rhizobium* spp.	Sain-1[4]
Sulla	*Rhizobium* spp.	Hedy-2[4]
Sweetclover	*Sinorhizobium/Ensifer meliloti*	Identical to alfalfa
Tickclover	*Bradyrhizobium* spp.	CB 756[4]
Trefoil, big	*Bradyrhizobium* spp. *'lotus'*	USDA 3469[4]
Trefoil, birdsfoot	*Rhizobium/Mesorhizobium loti*	Dormal-trefoil,[2] Pre-vail trefoil,[3] BFT-1[4]
Vetches	*Rhizobium leguminosarum* bv. *viciae*	Nitragin C,[1] Nodulator,[2] N-charge,[3] V-1[4]

[1]EMD Crop BioScience, 13100 West Lisbon Avenue, Suite 600, Brookfield, WI 53005. http://www.nitragin.com/homepage. [2]BeckerUnderwood, 801 Dayton Avenue, Ames, IA 50010. http://www.beckerunderwood.com. [3]INTX Microbials, 200 West Seymour, Kentland, IN 47951. http://www.intxmicrobials.com. [4]Plant Probotics, 6835 Lindel Court, Indianapolis, IN 46268. tomwacek@yahoo.com.

be selected that will increase underground C storage. Research shows there is variation among species and cultivars in tolerance of trampling and close defoliation, and in the extent of root growth. However, there are also limitations in the extent to which grasslands species can express these traits in these harsh conditions, and management such as delaying defoliation and fertilizer use, can be as important as species selection in achieving those goals (Chapters 3–5).

Overall, it is clear that the choice of which species to establish is more dependent on the ultimate use of the stand than on the ease of establishment. Most grasslands are planted with perennial species intended for long-term use, e.g., hay or silage production, a riparian area or a grazing pasture, so the choice of species should be made carefully. Although there is usually a single predominant purpose, there are invariably other benefits and ecosystem services that are associated with grassland, and in most cases the landowner prefers to select species for their versatility in different situations. Flexibility allows the landowner to alter the use or apply adaptive management to correct problems such as using a pasture for hay in spring to control some weeds or grazing the pasture during fall to weaken the grass stand to plant a legume the following spring. But the adaptive management also depends on recognition of the problem and knowing the best ways to ameliorate the problem.

IMPORTANCE OF LEGUME INOCULATION

The presence of functioning nodules from the genera *Rhizobium*, *Bradyrhizobium*, *Mesorhizobium*, *Sinorhizobium*, or *Azorhizobium* on legume roots is critical for N fixation. In addition to the number of nodules per plant, the activity of these nodules combines to determine the rate of N fixation. There are unique rhizobia species for each legume species; however, some rhizobia species can infect several host–legume species. In general, where a legume species has not previously been planted, it is imperative to ensure that seed is rhizobia-coated prior to seeding. Where the given legume has previously been planted, there are usually sufficient naturalized rhizobia populations to ensure infection occurs; however the N-fixation rate for these populations can be considerably lower than for introduced strains that are available commercially.

Rhizobia are generally host specific and, therefore, selecting the correct strain for each legume species is critical for growing legumes that can fix atmospheric N. Red, white, ball, and alsike clovers can use the same rhizobia strain; however, arrowleaf, kura, rose, and subterranean clovers each require a unique strain. During years with high costs of N fertilizer, this advantage seems obvious; however, research in this field is on the decline (Brockwell and Bottomly, 1995). The inoculants and strains that are recommended for each legume species are summarized in Table 2.2. Because of the dependence on commercial production and marketing, it is becoming difficult to find commercial quantities of rhizobia inoculants for the less commonly used legumes, and generally inoculants for only alfalfa, white clover, and red clover are approved for organic use by the Organic Material Review Institute (OMRI).

> There are unique rhizobia species for each legume species

There are several difficulties in summarizing the literature related to rhizobia strains and giving recommendations for their use. Many studies (e.g., Jones et al., 1978; Prévost et al., 1987; Coll et al., 1989; Trotman and Weaver, 1995) report on strains collected locally, but not available commercially. In other cases a commercial inoculant might be listed in a research publication, but the specific strain(s) used is not reported or even known. The authors are aware of only four commercial companies in the USA that produce and sell inoculants for a broad range of forage legumes (Tables 2.2 and 2.3), and the specific strains in the product are usually not listed. References relating to rhizobia strain selection, evaluation, and the best treatment found in each respective study are summarized in Table 2.3. However, these strains are often not those commercially produced, which shows some disconnect between research and ultimate commercialization.

Rhizobia infection (i.e., the number of nodules) and the rate of N fixation (includes activity nodule^{-1}) are sensitive to biotic and abiotic stresses. Generally any stress that reduces photosynthesis or plant growth will reduce infection and subsequent N fixation. Drought, heat, desiccation, soil acidity, salinity, nutrient deficiencies, some pesticides, and residual N in the soil have been identified as major factors limiting rhizobia populations and their formation of nodules (Thies et al., 1991; Zahran, 1999).

Literature relating rhizobia to management and technologies, such as adhesives, pelleting, and cropping history is summarized in Table 2.4. Rhizobia must adhere to the seed to ensure the desired bacteria are near the seed when it germinates. The roots release chemical signals to the bacteria that lead them to infection of the root and subsequently effective nodulation. One study found that water alone was

TABLE 2.3. Rhizobia–legume references related to comparing optimum strains.

Legume species	Rhizobium species	Comparison	Best strain or inoculant	Reference
Alfalfa	*Sinorhizobium meliloti*	2 strains; 2 CO_2 levels	A2 > NRG34	Bertrand et al. (2007)
Alfalfa	*S. meliloti*	2 strains	WSM419	Cheng et al. (2002)
Alfalfa	*S. meliloti*	4 parent/mutants	102F51, 102F34	Hardarson et al. (1981)
Alfalfa	*S. meliloti*	26 strains	WSM 826	Howieson et al. (2000)
Alfalfa	*Rhizobium leguminosarum*	3 strains	NS	Stout et al. (1997)
Alfalfa	*S. meliloti*	17 strains	CCBAU3013	Zeng et al. (2007)
Arrowleaf clover	*R. leguminosarum* bv. *trifolii*	16 strains; 3 pH	N fertilizer > 6A,6B,6C,9A,9B	Coll et al. (1989)
Arrowleaf clover	*R. leguminosarum* bv. *trifolii*	160 strains	W8-1, W9-4, W9-6 local strains	Trotman and Weaver (1995)
Arrowleaf clover	*R. leguminosarum* bv. *trifolii*	18 strains	Not identified	Trotman and Weaver (2000)
Cicer milkvetch	*R. leguminosarum, S. meliloti*	13 strains	B2 and 9462L	Zhao et al. (1997)
Cowpea	*R. leguminosarum* bv. *phaseoli*	3 strains; 2 carriers	Oil-based > peat-based inocula; 971A	Kremer and Peterson (1983)
Crimson clover	*R. leguminosarum* bv. *trifolii*	5 strains	K13, X95	Smith et al. (1982)
Faba bean	*R. leguminosarum* bv. *vicae*	67 strains	Strains effective on vetch and peas	Van Berkum et al. (1995)
Kura clover	*R. leguminosarum* bv. *trifolii*	18 strains	N fertilizer	Beauregard et al. (2003)
Kura clover	*R. leguminosarum* bv. *trifolii*	27 strains	3D1Y8, 3D1Y8(b)	Erdman and Means (1956)
Kura clover	*R. leguminosarum* bv. *trifolii*	+/− 1 strain	None	Seguin et al. (2001)
Mung bean	*Bradyrhizobium* spp.	40 strains	Eight effective on acid soils	Munns et al. (1979)
Sainfoin	Not reported	31 strains	Five experimentals = SM2 and 116A15	Prévost et al. (1987)
Subterranean clover	*R. leguminosarum* bv. *trifolii*	10 strains	NS (IST51, IST54 IST65, USDA 2156)	Rumbaugh et al. (1990)
Subterranean clover	*R. leguminosarum* bv. *trifolii*	33 strains	18 strains NS	Thornton and Davey (1983)
Subterranean clover	*R. leguminosarum* bv. *trifolii*	9 strains	X16, X47	Jones et al. (1978)

ineffective as a sticking agent for peat-based inoculant, but that gum arabic was an effective adhesive for ensuring nodule formation on white clover at both low and high levels of inoculation (i.e., 600 and 3000 rhizobia seed^{-1}, respectively; Waggoner et al., 1979). Formulations such as peat or pelleting, which provide physical protection to the rhizobia, or management techniques such as planting deeper to moisture should enhance nodulation (Walley et al., 2004). Nodulation was similar between liquid inoculum and peat-based inoculum for field pea (Hynes et al., 1995), but the liquid formulation was much easier to apply.

Under dry soil conditions, peat-based and granular formulations resulted in more nodules on field pea compared to a liquid formulation (Walley et al., 2004), which was attributed to physical protection of the rhizobia from heat and desiccation. Surface seeding was detrimental to rhizobia under dry conditions and planting at 16-mm depth optimized rhizobia survival, seedling emergence, and survival of arrowleaf clover (Rich et al., 1983). Exposure of rhizobia to 5 hr or more of sunlight or 2 wk in dry soil without germinating resulted in less effective inoculation (Alexander and Chamblee, 1965). Therefore, if seed are not preinoculated commercially, it should be inoculated effectively on the same day it is planted.

Contrary to Waggoner et al. (1979), seedling emergence and the resultant yield from lime-pelleted seed of red clover, white clover, and alfalfa did not differ from seed inoculated with rhizobia using water as the sticker agent (Olsen and Elkins, 1977). Similarly, lime pelleting containing rhizobia did not improve subterranean clover yield in the seeding year when compared to nonpelleted seed treated with a commercial inoculum on three of four soils (Williams and Kay, 1959). However, lime pelleting seed increased yield of arrowleaf clover in a nonfumigated soil over an otherwise equivalent fumigated soil, suggesting that pelleting assisted introduced rhizobia to compete with native soil microorganisms (Wade et al., 1972).

Encapsulating rhizobia into a seed coating helps protect the bacteria from environmental

TABLE 2.4. Summary of rhizobia responses to management and coating treatments.

Legume species	Rhizobium species (if stated)	Comparison	Best treatment	References
Alfalfa		Desiccation; sunlight	< 3 hr sunlight; < 2 wk desiccation	Alexander and Chamblee (1965)
Alfalfa		Two stickers	Lime pelleting = water	Olsen and Elkins (1977)
Alfalfa		+/− pelleting	Pelleting > nonpelleted	Vincent and Smith (1982)
Annual medics	*Sinorhizobium meliloti*	+/− N fertilizer; 1 strain	102G3 and 102A13 greatest occupancy	Zhu et al. (1998)
Arrowleaf clover	*Rhizobium leguminosarum* bv. *trifolii*	Two stickers	Pelgel gum arabic > water sticker	Rich et al. (1983)
Arrowleaf clover	*R. leguminosarum* bv. *trifolii*	+/− pelleting; rates	Lime pelleting = fumigation	Wade et al. (1972)
Hairy vetch		Cropping history	Inoculation beneficial 50% of time	Andrews (1940)
Lespedeza		Three timings; 3 N rates	Starter N increased growth; no effect of timing	Bender et al. (1988)
Pea	*R. leguminosarum* bv. *vicae*	Two formulations	Liquid = peat carrier; 128C56G strain	Hynes et al. (1995)
Pea		Cropping history	Inoculation beneficial 33–50% of time	Vessey (2004)
Red clover		Two stickers	Lime pelleting = water	Olsen and Elkins (1977)
Red clover		+/− pelleting	No differences	Vincent and Smith (1982)
Subterranean clover	*R. leguminosarum* bv. *trifolii*	13 coatings/ adhesives	Peat > broth; gum arabic > pelleting	Radcliffe et al. (1967)
Subterranean clover	*R. leguminosarum* bv. *trifolii*	Lime pelleting or band	Limestone band pH 4.6; NS other sites	Williams and Kay (1959)
White clover	*R. leguminosarum* bv. *trifolii*	Two stickers	Gum arabic adhesive > water	Waggoner et al. (1979)
White clover		Two stickers	Lime pelleting = water	Olsen and Elkins (1977)

stress. The literature is inconsistent on whether coating is beneficial for maintaining rhizobia viability or enhancing seedling vigor.

Competition between introduced and native strains of rhizobia can be one reason for inoculation failures (Thies et al., 1991). In Hawaii, on sites with moderate background populations of native rhizobia as low as 50 rhizobia g soil^{-1}, seed inoculated with rhizobia frequently showed no increase in yield. With a low background population of <10 indigenous rhizobia g soil^{-1}, however, rhizobia inoculation increased economic yield of several legumes 85% of the time (Thies et al., 1991). Pellet-coating seed increased the number of nodules plant^{-1}, N content, and seedling growth of alfalfa, whereas pelleting did not improve nodule formation on red clover (Vincent and Smith, 1982).

It is a good practice to inoculate legumes each time they are planted, even when the same legume has been grown recently on the same field. Andrews (1940) tested noninoculated seed of vetch on 77 soils that had previously grown vetch. Half had a lower yield than those where seed had been treated with commercial inoculant. Vessey (2004) also reported positive alfalfa yield responses 33–50% of the time when inoculated seed was planted in fields with a prior alfalfa cropping history. Thus, inoculation of the seed just prior to planting is generally considered good insurance when planting legume seed, because of the more rapid growth rate of seedlings and better seedling vigor that usually occurs during establishment (Vincent and Smith, 1982).

Conclusion—Type of Legume Inoculant Used

General Criteria of Code 512 specify that legume seed should be preinoculated or inoculated with the proper viable strain of rhizobia immediately before planting, which

Cicer milkvetch 10 mo after spring planting in Utah (compare to birdsfoot trefoil 10 mo after planting). Credit: Jennifer MacAdam, Utah State University.

is supported by the literature. In addition, the literature supports making legumes self-sufficient for N supply in that legume seed inoculated with the proper rhizobia strain will improve establishment of forage and biomass crops by increasing seedling vigor, accelerating canopy closure, and ensuring earlier ground cover to reduce soil erosion and improve water quality. Properly inoculated legume seed will produce plants that are higher in protein than those from non-inoculated seed that can lead to improved nutrition and health of livestock and wildlife without the economic and environmental costs of N fertilization.

SEED COATINGS AND PRETREATMENTS

Seed coatings are a broad group of compounds that can be applied to seed to modify their germination and establishment characteristics. The most common coatings include rhizobia (for legumes), lime, nutrients, insecticides, fungicides, nematicides, and their associated adhesives. Invariably, these products increase seed weight by as much as 100% and reduce the amount of pure live seed (PLS) applied (seed m^{-2}) for a given seeding rate (g m^{-2}). Seed pretreatments contrast from seed coatings by modifying the seed and its coat, but do not appreciably affect the seeding rate. Seed pretreatments include deawning to improve seed flow for mechanical planting, scarification to improve water imbibition, seed priming and preimbibition to enhance early germination and emergence, and chilling to reduce dormancy.

Seed coatings were first used in China around 100 BC, and comprised seed pellets made from a slurry of ground horse bones, herbal extracts, silkworm droppings, and sheep dung (Gong et al., 2003). The modern coating and treatment options have been reviewed by Scott (1989).

Many coatings and pretreatments have been investigated as aids to germination; however, evidence in the research literature is inconsistent about the benefits these provide. Although seed coatings generally provide benefits to seedling emergence and protect the seed from adverse environmental impacts, in some situations the very nature of the coating can be a barrier to the environment and slow or delay germination. Generally, the benefits of coatings may be more evident when the seed and seedling are in a stressful environment.

The choice to use seed coating is affected more by the nature of the species than by the intended purpose for the grassland planting. Seed coatings used to enhance germination and the success of establishment can benefit all purposes. We found and summarized 15 publications that investigated seed coatings and treatments within a forage production context, but none investigated seed coatings and treatments for ecosystem benefits, specifically for soil or water conservation, environmental protection, wildlife, or C sequestration.

Seed Coatings

Lime coatings are the most common and can protect rhizobia viability during storage and benefit establishment indirectly through improved nodulation and subsequent N fixation. Most rhizobia carriers used in alfalfa seed coating add 10–30% to the seed weight. With spring-planted alfalfa in Minnesota at 16.8 kg PLS ha^{-1}, a lime-based seed treatment (RhizoCote®) increased the stand density by an average of 31% over the control in 5 of 14 field studies, with no difference measured in the remaining studies. This advantage was increased to 54% for 8 of 14 studies when metalaxyl, a fungicide, was also used in the coating. In 10 of these studies, yield the seeding year was increased by an average of 6.6% from the lime coat used in conjunction with a fungicide or pesticide (Sheaffer et al., 1988). This study also compared bare and coated alfalfa seed at the same seeding rate (16.8 kg ha^{-1}), which, in effect, added 34% weight $seed^{-1}$ because the coat reduced specific seed weight from 485 to 320 seeds g^{-1}. In this case, although the lower seeding rate was partially offset by greater seed emergence for the coated seed, the final stand density was reduced in only one of four studies. However, if fungicide or pesticide was added to the coating, the final stand density at the low rate was not statistically different from the control.

Lime coatings may have other less direct effects on seedling emergence by modification of seed texture. In the case of rough and/or fluffy seed, lime coatings can improve their flow through a seeder. In the case of aerial seedings, lime coating can increase seed weight (especially for

> "...legume seed inoculated with the proper rhizobia strain will improve establishment of forage and biomass crops"

> Factors most often related to seed vigor are seed size or weight, duration of seed storage, and the seed storage environment.

light seed such as orchardgrass) and contribute to a successful seeding by enhancing seed ballistics and ensuring seed actually hits the target area, and lands with greater force to improve seed to soil contact (Scott, 1989; Loch, 1993).

Many studies describe where fungicides, insecticides, and nematicides have been included in seed coatings. Having the chemical products near the germinating seed might give greatest protection. Greater benefit arose from use of fungicides as seed coats, but benefits also occurred for insecticides and nematicides where these pests were present (Sheaffer et al., 1988). In New Zealand, laboratory and field studies with white clover found seed coating containing the insecticides carbosulfan and isofenphos improved early seedling establishment when a native weevil was present, and a commercially available white clover seed treated with the insecticide, furathiocarb, increased seedling survival and yield for up to 13 mo after sowing (Barratt et al., 1995). In this study, carbosulfan caused rapid mortality of rhizobia, whereas isofenphos and furathiocarb caused no significant mortality of rhizobia (Barratt et al., 1995). Studies in New Zealand found no benefit to final stand for seed-coat applications of carbofuran or furathiocarb insecticides for no-till perennial ryegrass (Barker et al., 1990).

Of concern is the potential effect of insecticide use on nontarget organisms. In one French study, the effect of an insecticide (imidacloprid) seed coating on sunflower was investigated on subsequent nontarget pollinator populations of bumblebee (Tasei et al., 2001). When used at the registered dose in the greenhouse or field, there were no significant effects on bumblebee foraging and homing behavior, or on colony development.

Nutrients attached to the seed as a coating offer potential for early nutrition of the emerging seedling, but may raise the risk of incurring damage from the high osmotic potential of such solutes. The nutrient most likely to be of benefit is phosphorus (P). In Norway, P seed coatings of oat enhanced biomass accumulation up to 22% and grain set up to 15%, but had no benefit for grain yield (Peltonen-Sainio et al., 2006).

Seed Pretreatment

Hard seed is a common condition of natural plant populations, in which dormancy can be caused by an impermeable seed coat (Ghersa et al., 1997). The most common pretreatment in this case is scarification of the seed coat by physical abrasion or chemical weakening to allow easier movement of water or oxygen into the seed. Mild physical abrasion with sandpaper increased germination of white clover from about 3% to 70% (Burton, 1940). For cicer milkvetch, the best scarification treatment among 30 different time, pressure, and abrasion combinations reduced the percentage of hard seed from 54% to 1% (Townsend and McGinnies, 1972b). Most responses to scarification have been observed for legumes and other dicotyledonous species, but also are effective for some warm-season grasses, such as eastern gamagrass (Tian et al., 2002).

Many seed pods, seed coats, and seed integuments contain germination inhibitors that can delay the germination of seed under natural conditions (Carleton et al., 1968). Frequently, these compounds are leached by water, allowing the seed to germinate and establish after sufficient time to leach and once appropriate temperature and moisture conditions occur. Most commercial seed has these pods and husks removed to ensure more rapid and uniform seed germination. For farm-saved seed of forage species such as sainfoin, the failure to remove seed pods and husks may result in poorer germination and establishment.

Several forage seed species (e.g., switchgrass, eastern gamagrass) have a period of dormancy immediately following harvest (Madakadze et al., 2000; Rogis et al., 2004). This is a natural mechanism to prevent premature germination of seed under field conditions until exposed to a period of cold such as winter. The most common treatment to reduce or shorten this dormancy is a period of cold treatment following imbibition (stratification) with water that mimics overwintering in the soil. Some studies have found improved germination following several weeks of stratification at 5°C, or several cycles of alternating cool and warm temperature, depending on species. If needed, most commercial seed has already been scarified and should not require additional treatment. Farm-saved seed may require artificial stratification if the seed is not planted in the autumn to stratify naturally.

Various seed-priming methods have been used experimentally to increase seed germination rate (Rao et al., 1987; Artola et al., 2003a). In these cases, the seed is allowed to imbibe water and begin to germinate for several hours, but then is redried. When water is added again the seed germinates and begins seedling growth very quickly. For example, field and laboratory studies have found germination of Lehmann lovegrass seeds can be improved by various presowing seed treatments such as alternate moistening and drying, oven-drying, scarification, and prechilling on a moist substrate (Haferkamp et al., 1977). The increased germination may be due to improved seed-coat permeability or to a change in the metabolic state of the seed (Haferkamp et al., 1977). In contrast, surface-sowed primed seed of white clover, orchardgrass, and perennial ryegrass had rapid early emergence; however, unfavorable rainfall during later seedling growth resulted in lower overall emergence (Barker and Zhang, 1988). The emergence of big bluestem and switchgrass was increased 18% by seed priming treatments in greenhouse studies, but had no benefit in field studies (Beckman et al., 1993).

Conclusions—Seed Coatings and Pretreatments

The Code 512 General Criteria specify that seeding rates be calculated on a PLS basis, suggesting seeding rates of coated seed based on weight need to be adjusted upward. The literature suggests that benefits of seed coating may partially offset the lower seeding rate on a weight basis. There is also an economic consideration, because coated seed is usually more expensive to purchase, so the recommendation for a higher seeding rate to achieve constant PLS adds significantly to the cost of a seeding. Seedings with a short-term financial return (e.g., hay, grazing, or biomass) may benefit from the use of more expensive coated and pretreated seed, whereas seedings without short-term financial return such as those for conservation and wildlife may not justify the additional seed cost.

New technology is likely to improve the performance of seed coatings. New adhesives, pesticides, and products such as inert carriers, are likely to improve efficacy of seed coating. For example, polymer seed coatings are being used for corn and canola, and in the future may become cost effective for high-value forage crops such as alfalfa. Polymer coatings such as polyvinylidene chloride, ethyl cellulose, and polyvinyl acetate polymer resin have been evaluated for protecting seed from insects and diseases, and preventing water absorption while in storage (TeKrony, 2006). Most polymer coatings are very thin (1–10% of seed weight) and do not add appreciably to seed weight (TeKrony, 2006). Thickness is critical, because a coating rate of one or two layers of polyvinyl acetate polymer increased rate of seed water uptake, whereas five layers of coating slowed rate of water uptake.

SEED SOURCE AND ANALYSIS

Seed certification provides a guarantee of genetic identity and cultivar purity, as well as minimizing content of restricted and prohibited noxious weed seeds. State seed laws further add limits on seed of prohibited weeds and noxious species. Standard seed testing also includes determining germination and hard seed percentages. Hard seed does not germinate quickly because of an impervious seed coat, but might germinate once the seed coat is

August seeded birdsfoot trefoil 2 mo after planting with oat as a companion crop (cut). Credit: Jennifer MacAdam, Utah State University.

“Does seed that meets state quality standards improve establishment…?”

degraded. These criteria define the ability of seeds to germinate and develop into vigorous seedlings to hasten stand establishment. Higher-quality seed will usually be larger and have faster emergence, but seed size is not usually reported for commercial seed lots. This section addresses the two questions: Does seed that meets state quality standards improve establishment to have the planted seed become the dominant canopy type(s) with few weeds, and does it decrease the time for the planted seed to develop a usable canopy?

Most published research has documented seed-quality effects on emergence rates for stands established for production purposes such as hay, silage, or grazing. As a generalization, these factors should also have positive influences on stands where the purpose is for erosion control, wildlife, C sequestration, or biomass, although no literature was found on these latter issues.

Seed vigor comprises those properties that determine the potential for rapid, uniform emergence and development of normal seedlings under a wide range of field conditions (Baalbaki et al., 1983). It is most often tested by measuring germination of stressed seeds with the use of an accelerated aging test or a cold test. The cold test attempts to measure the combined effects of genotype, seed quality (both physical and physiological), seed or soil-borne pathogens and seed treatment. Other tests include rate of germination, rate of seedling growth, and tests of metabolic activity with the use of tetrazolium chloride, electrical conductivity, and respiration rates.

Factors most often related to seed vigor are seed size or weight (Heydecker and Coolbear, 1977), duration of seed storage, and the seed storage environment. Larger or younger seed often result in more rapid rates of establishment and early plant growth; however, rapid establishment should reduce risk of environmental outcomes, but does not always result in higher yield (TeKroney and Egli, 1991). Seed vigor can have a measurable effect on yield by way of improved stand establishment, which in turn is influenced by emergence and uniformity of overall establishment (TeKrony and Egli, 1991).

The electrical conductivity test and the accelerated aging test were the most effective predictors of field emergence for legume species, whereas the standard germination test was the best predictor of seed vigor for grasses (Wang et al., 2004). In situations such as late or low-density plantings, or in plantings where weed competition is strong, rapid establishment can improve survival and competitiveness of desired species to make a significant contribution to yield.

Differences in seed size of alfalfa did not influence the number of seedlings that emerged, but large seed was positively related to seed vigor, measured as plant biomass (Beveridge and Wilsie, 1959). This occurred because seed reserves remaining after emergence can support more rapid accumulation of leaf area and photosynthesis capacity by the seedlings. In white clover, sown at the same PLS percentage, higher-quality seed (e.g., heavier seed with faster germination) resulted in higher yield and significantly lower weed content in the year following planting (Pasumarty et al., 1996). Similarly, in a growth room study, larger seed size of birdsfoot trefoil produced larger cotyledon area of emerged seedlings and greater seedling vigor (Shibles and MacDonald, 1962).

Whereas established plants of kura clover are very persistent, seed are small and seedling establishment is slow. Selection for improved seed vigor, based on earlier work with birdsfoot trefoil (Twamley, 1974), showed seedling fresh shoot weight was a better indicator of seedling vigor than was seed size (DeHaan et al., 2001; Artola et al., 2003b). DeHaan et al. (2001) found kura clover seed size was correlated with fresh shoot biomass, and that fresh shoot biomass at 42 d after planting was the best and most practical selection criterion to improve seedling vigor.

Seed storage conditions can alter seed vigor over time (Zarnstorff et al., 1994). Low temperature (0–2°C) and low relative humidity (6%) are recommended for long-term (20 yr) viability of seed. During a 10-yr study, white clover seed stored at 2°C and 10–20% humidity actually increased in germination percentage as the hard seed percentage decreased. When temperature and humidity were both controlled, storage container (i.e., cloth bag, glass jar, or resealable plastic bag) did not affect grass-seed vigor, measured as the rate of hypocotyl elongation following germination (Lewis et al., 1998). At 4°C and 70–90% humidity, vigor of grass seed was higher after 10 yr when seed was stored in cloth bags than in glass jars or plastic bags. When neither temperature nor humidity was controlled, grass seed stored in resealable plastic bags had the highest vigor after 10 yr (Lewis et al., 1998). The authors noted that although germination was similar for grass seed stored in low-temperature environments, seed vigor was significantly less when storage humidity was higher, regardless of storage container.

Conclusion

The literature supported the Code 512 Criteria that all seed and planting materials should meet state quality standards. Noxious species cannot be planted for legal reasons. Based on the nine articles reviewed, the most important single measure of seed quality is the germination test and its date, as reported on the seed label. Although various other seed-quality characteristics can predict establishment, two useful characteristics, i.e., seed size and seed storage conditions, are not reported on seed labels. As a generalization, seed should be stored on-farm for the least possible time to minimize seed deterioration during storage; where on-farm storage is necessary seed should be stored in a cool dry location.

FERTILIZER APPLICATION

Although nutrient management implications of fertilizer and lime are discussed in detail in Chapter 5, this section considers the specific effects of fertilizer and lime on grassland establishment. The application of N and P fertilizer at establishment can improve plant emergence and seedling vigor, especially when soils have low fertility. Fertilizer application at seeding is useful irrespective of whether the purpose of a seeding is for forage production or quality, for biofuel/energy, or for conservation purposes such as C sequestration, water quality, or erosion control. The benefits are likely to be achieved more quickly and with less risk with appropriate fertilizer and lime application.

Banded fertilizer application of N and P has considerable potential to reduce environmental impact of a seeding, compared to the negative impacts that might result from a poor or failed stand (Teutsch et al., 2000). Banded fertilizer placement is only possible with coulter-type (no-till) drills, and is not possible for broadcast planters such as a cultipacker or Brillion® seeder. These nutrients, placed near the seed, but not in contact with it, increase the number of emerged plants, shorten their time to emergence, and increase effectiveness of these nutrients at low application rates (Kroth et al., 1976). Their study compared 48 combinations of N, P, and K in Missouri, and found that a fertilizer mixture of 17 kg N ha^{-1} and 15 kg P ha^{-1}, banded 2.5 cm below and 2.5 cm to the side of the seed, gave optimum establishment results for August and April seedings of reed canarygrass.

Nitrogen

Fertilizer N has variable effects on seedling emergence. Of the six articles summarized, three reported inhibited legume emergence, one found no response, and two found improved legume establishment with N fertilization (West et al., 1980; Seguin et al., 2001). In Virginia, N fertilizer reduced the stands of alfalfa, white clover, red clover, and birdsfoot trefoil, whether sown alone or in mixture with orchardgrass (Ward and Blaser, 1961), which was attributed to salt damage of the young seedlings as N rate was increased. Stands, root length, root weight and root:shoot ratio of birdsfoot trefoil and the botanical composition of orchardgrass-birdsfoot trefoil swards were not significantly influenced by 28 kg N ha^{-1} as starter fertilizer (Watson et al., 1968). In one Missouri study with three alfalfa cultivars over 3 yr, 45–95 kg N ha^{-1} decreased the establishing population to 88% of unfertilized plots, but still had a positive yield response (Peters and Stritzke, 1970). Grass establishment is usually responsive to fertilizer N (Kroth et al., 1976).

The effect of N fertilizer at seeding also depends on the extent of weed control. In Missouri, alfalfa establishment in spring with appropriate weed control, adequate rainfall, and a fertile soil (pH 6.5, 110 kg P ha^{-1} in soil) was improved with N at seeding in 2 out of the 3 yr studied (Peters and Stritzke, 1970). In the same study, but without chemical weed control, the alfalfa stand was reduced because

"…benefits are likely to be achieved more quickly and with less risk with appropriate fertilizer and lime application"

of competition from weed growth where N was used.

With sod seeding in early spring, especially with incomplete kill of existing vegetation, there are some cases where N applications can reduce seedling emergence; presumably because of the greater competition from established vegetation that can smother the emerging seedlings. In Quebec, for example, N had variable effects on sod-seeded red, white, and kura clovers depending on the extent of control of the prior sward by herbicides (Laberge et al., 2005).

Phosphorus

Four research papers were found that specifically addressed forage establishment and seedling emergence responses to P fertilizer application. In Ontario, seedling growth of alfalfa, birdsfoot trefoil, and smooth bromegrass was increased up to five times by banding 30 kg P ha^{-1} at 5 cm depth, prior to a surface seeding (Sheard, 1980). Growth and winter survival of an August seeding of reed canarygrass and the growth of an April seeding were stimulated by P in a low-fertility soil (Kroth et al., 1976). Pitman (2000) reported a linear yield response to P fertilizer up to 80 kg P ha^{-1} for tall fescue during the establishment year in Louisiana. At four locations in Ohio, significantly greater shoot and root dry weight occurred with spring-seeded alfalfa when P was banded at 27 kg P ha^{-1}, with no significant difference in the plant population (Teutsch et al., 2000). The primary mechanism of the P response for grass and legume establishment was by promotion of root growth (Teutsch et al., 2000). Preferably, P should be soil-incorporated prior to seeding because it has low solubility (Doll et al., 1959).

August seeded birdsfoot trefoil, at 2 months after planting without oat (compare with photo with oat as companion crop). Credit: Jennifer MacAdam, Utah State University.

In some specialized situations, such as the establishment of native grassland, low P may be a necessary prerequisite for the establishment of species-rich vegetation. In Europe, low soil P, < 5 mg 100 g^{-1} of dry soil, was an "indispensable prerequisite" for increasing species diversity in agricultural grasslands because P promoted the growth of the more productive and competitive species (Peeters and Janssens, 1998).

Potassium (K)

Three articles described K effects on seedling emergence; however, results were variable and showed an interaction with P. There was no effect of K on winter survival or growth of reed canarygrass from either August or April plantings (Kroth et al., 1976). Pitman (2000) found some K responses for tall fescue when seed were hand broadcast and incorporated by rotovator into a low-fertility soil of the Louisiana coastal plain, but responses were invariably better when P and K were used together. Similarly, in an earlier study with white clover at the same location, applying P and K fertilizer at seeding resulted in 12% more plants being established (Suman, 1954).

Lime

A correct soil pH is required for optimal seedling establishment, because acid soils reduce forage establishment rates, especially for alfalfa and other legumes. Soil acidity impairs the process of nodulation and reduces the ability of legumes to fix N. Soil acidity also slows seedling root growth during establishment and reduces plant availability of many essential nutrients. Early in the history of alfalfa establishment, the need to treat acidic soils with lime was well documented (Albrecht and Poirot, 1930). In general, surface-applied lime takes several weeks to change the soil pH, and lime or dolomite applications should be made and incorporated several months prior to seeding, rather than during or after any seeding operation. Establishment of tall fescue in a low-pH soil (pH 4.9–5.8) was improved by lime applications at two of three Louisiana sites (Pitman, 2000). Lime seed coating was found to be ineffective in improving legume establishment into an acid (pH = 4.7) tall fescue pasture in Illinois (Olsen and Elkins, 1977). Presumably, insufficient lime accompanied the seeding, and the authors concluded a presowing lime treatment of the soil might have had more positive results.

Sulfur (S)

In Saskatchewan, S was reported to have negligible influence on seedling emergence or survival of alfalfa, but did improve production at three trial sites (Hwang et al., 2002).

Conclusion—Fertilizer Application

We summarized 13 articles and found the most consistent improvements in grassland establishment were from applied P, with inconsistent responses for N and K, depending on interactions with species, other nutrients, and competition from unsown species. In general, the literature agrees with the Code 512 General Criteria Applicable to all Purposes, that all plant nutrients and/or soil amendments for establishment purposes should be based on a current soil test. There is sufficient local variation that application rates, methods, and dates should be obtained from local plant materials centers, land grant and research institutions, extension agencies, or agency field trials. In the specific case of grassland establishment, recommendations for fertilizer application based on soil tests should use recommendations for seeding-year stands, because mature-stand recommendations are likely to be different.

SITE AND SEEDBED PREPARATION, AND SEEDING METHOD

Seeding methods for grassland species range from high-cost, high-input methods such as conventional establishment where the site is fully cultivated into a tilled seedbed, to low-cost, low-input methods such as frost seeding or livestock seeding. Seeding methods have been thoroughly described and reviewed by several authors (Wolf et al., 1996; Cosgrove and Collins, 2003; Masters et al., 2004; Hall and Vough, 2007). This section will focus on the most common establishment methods related to the Code 512 Purposes.

Once successfully established, forages can be used to improve livestock/wildlife nutrition, reduce soil erosion, improve water quality, and eventually increase C sequestration regardless of the method used to achieve their establishment. In most cases, a variety of planting methods can be used to accomplish the primary intended Code 512 Purpose. A notable exception occurs with species that can only be vegetatively propagated because they do not produce viable seed. In specialized cases such as organic systems that preclude pesticide use, the primary intended purpose for the stand may influence which planting method would be most appropriate. In most cases, differences due to planting methods are usually short-lived and will often disappear by the second year of the stand if not sooner, assuming successful establishment of the desired species is accomplished. Our goal is to evaluate the success and the effects of seedbed preparation and establishment methods on ecosystem services during the establishment period.

The goal of full seedbed preparation using tillage, fertilizer, and lime is to create an environment that optimizes the establishment of seed or vegetative propagules. An ideal seedbed is (1) very firm below planting depth, (2) well pulverized and friable surface soil, (3) not cloddy or puddled, (4) free from competition with resident vegetation, and (5) free of weed seeds (Vallentine, 1989). This latter factor of weed-free soil can rarely be achieved in a cost-effective and practical manner; however, steps should be taken to manage weed competition (see later). This ideal seedbed will enable placement of the seed or vegetative propagules at the proper depth and in firm contact with the soil. This ensures rapid movement of water from the soil to the seed, seedling, or vegetative propagule, resulting in greater likelihood of rapid and uniform germination and early seedling growth that leads to successful stand establishment (Bartholomew, 2005).

Deviations from a tilled and prepared seedbed still need to meet the basic requirement of the seed or vegetative propagules being placed in good contact with the soil at the proper depth

“The goal… is to create an environment that optimizes the establishment of seed”

“Use of annual companion crops...is a common and successful practice”

for establishment (Bartholomew, 2005). Poor soil contact can result from cloddy or loose soil and usually results in uneven emergence, slow seed germination, or seedling desiccation, any of which can lead to other problems such as weed competition during the early establishment phase (Hall and Vough, 2007). Thus, alternative establishment methods may require more specific management to accomplish the desired objective of achieving a useable stand, including proper fertility, planting time, weed management, and adequate moisture supply after planting. The desired outcome may be more difficult to accomplish and, therefore, the risk of failure may be higher for alternative methods, yet the effort is environmentally more favorable. So these risks need to be balanced by economic costs and needs for environmental conservation during establishment.

Establishment for Forage Production, Livestock and Wildlife Nutrition

Use of annual companion crops such as spring-seeded small grain species or annual ryegrass when establishing perennial forage species is a common and successful practice, especially across northern latitudes of the USA. Companion crops usually have only short-term negative effects on forage production and nutritive value of the harvested forage (Table 2.3). Harvesting the companion crop as forage instead of grain usually increases weed-free forage yield in the seeding year, especially at the first harvest, and particularly when compared with seedings made without a companion crop or without herbicides.

The nutritive value of the combination of companion crop and perennial forage is usually lower than the nutritive value of the perennial forage crop seeded alone, but with herbicides used for weed control. However, the forage quality of the companion crop can be adequate for many classes of livestock (Sulc et al., 1993b). Although the companion crop does compete with developing perennial forage seedlings and decreases their yield in the seeding year, it reduces the density of weeds which can be even more competitive. If the companion crop has reduced seeding rate or is harvested early for forage to minimize competition to the desirable perennial species, by the second year the perennial forage stand will produce as well as if it were seeded alone with herbicides (Sulc et al., 1993a).

Use of companion crops for perennial forage establishment is not advisable if it reduces success of the desired perennial species. For example, perennial forage species with poor seedling vigor cannot be easily established with companion crops due to excessive competition (Seguin et al., 1999; Acharya et al., 2006). Recommendations based on local research and proven experience should be followed. The popularity of companion crops has declined with the introduction of effective pre- and postemergence herbicides, however, it remains a viable practice for erosion-prone soils, for organic production, for growers who prefer to not use herbicides, or for situations in which high forage yield is needed in the seeding year.

Using a row-type drill with press wheels to firm seed into a tilled soil is generally considered to be the superior method for planting forages, even with conventional tillage practices. Several studies have demonstrated that drilling with the same seeding rate results in greater forage plant density, faster establishment, and greater seedling growth during the early establishment phase than do broadcast seeding methods, which include broadcast cultipacker seeding (Tesar et al., 1954; Brown, 1959; Hart et al., 1968; Butler et al., 2008). There was no advantage of drilling after the establishment phase (Brown, 1959; Butler et al., 2008) indicating drilling seed is not superior to broadcasting seed on prepared seedbeds beyond the establishment year. Thus, seed placement methods have little effect over the long term provided the seed was placed in good contact with the soil and resulted in an adequate density of established plants.

Past research has shown both positive and negative responses for forage establishment and early-season production when establishing forages with no-till, reduced tillage, or fully tilled seedings (Table 2.5). The studies and discussions in various reviews point out that a range of tillage methods can be used to establish forages successfully (Table 2.5), and achieve forage production for animal nutrition *if* management principles specific to each method are followed (Wolf et al., 1996; Cosgrove and Collins, 2003; Masters et al., 2004; Hall and Vough, 2007).

When using less tillage, especially when introducing new species into existing sods, controlling the existing vegetation and managing residues appropriately are extremely important to achieve acceptable stand establishment (Decker et al., 1969; Seguin, 1998). For example, Cuomo et al. (2001) concluded that suppressing existing vegetation was more important than planting method when legumes are interseeded into cool-season grass pastures. Legumes established more quickly and dominated the sward after a grass sod was killed compared with being chemically suppressed (Koch et al., 1987). With sod seeding, forage yield is usually reduced during the period the existing sod is chemically suppressed and the introduced species becomes established; however, the resultant sward, including the new species, often shows higher yield, forage quality, digestible dry matter, and dry-matter intake by animals (Olsen et al., 1981; Koch et al., 1987).

Soil Erosion and Water Quality

No research was found comparing establishment methods on soil erosion or water quality. Intuitively, full cultivation carries far greater risk of water or wind erosion, because there is a period of bare soil; however, this risk on flatter soil sites is usually considered acceptable compared to the benefits once the stand is established (Fig. 2.1). No-till establishment, especially on hill slopes, is likely to reduce the risk of erosion markedly compared to a tilled seedbed. The remnant dead vegetation and nondecomposed roots of the suppressed sod offer greater soil protection. In Wisconsin, reduced-tillage methods for establishing alfalfa in spring reduced surface water runoff volume and soil loss under rainfall simulation events (Sturgul et al., 1990). Surface residue reduced soil loss to near zero among tillage treatments, whereas no till after all surface residue had been removed resulted in water runoff and soil losses similar to moldboard plowing.

Companion crops are often touted as a means to reduce soil erosion. In Wisconsin, an oat companion crop with spring-seeded alfalfa reduced soil loss to nearly half of that found when no companion crop was used. But dead crop residue on the soil surface and conservation tillage was even more effective at reducing soil loss (Wollenhaupt et al., 1995). Therefore, they recommended using crop residue management as a more effective method than companion cropping for erosion control during alfalfa establishment. In Oregon, no-till seeding of perennial ryegrass and tall fescue combined with approx. 9000 kg ha^{-1} of straw residue on the soil surface following grass seed harvest reduced estimated soil erosion by 40 to 77% compared with conventional tillage combined with low residue cover (Steiner et al., 2006).

“No-till establishment, especially on hill slopes, is likely to reduce the risk of erosion markedly”

Biomass

For species with dual-purpose use as forage or biomass, planting methods are equally applicable for either purpose. Although biomass plantings may have harvest schedules different from forage production, this harvesting will not be affected by the establishment method. The optimum establishment methods vary between species, with seeded species such as switchgrass best established in spring by either no-till, reduced-till, or full cultivation, and vegetative species such as miscanthus best established in spring by sprigging of stolons or rhizomes into cultivated seedbeds. In general these biomass species take longer to become established, which lengthens the exposure to potential environmental degradation.

Carbon Sequestration

The effects of seeding method on C sequestration have not been addressed in the literature. Based on evidence from grain crops, any cultivation during the forage establishment process is almost certain to release large amounts of CO_2 from the soil to the atmosphere (Reicosky and Archer, 2007), or at a minimum, disrupt C sequestration that might have been occurring with the previous vegetation. In addition, there will be release of CO_2 from combustion of fossil fuels during the tillage process. Less disruptive methods such as no till will likely conserve more soil C, but data specific to forage establishment were not found. Skinner and Adler (2010) report positive C sequestration occurred during the 3 yr period it took for switchgrass to establish following a no-till planting in Pennsylvania. In that study, no net C sequestration occurred in Year 4 because the established stand was harvested for biomass.

TABLE 2.5. Summary of research on planting methods.[1]

Method	Species	Location	Summary	Purpose	Reference
Tillage	Alfalfa, meadow bromegrass	Manitoba	Year-1 yield of alfalfa and meadow bromegrass were unaffected by NT or CT seeding when canola or field pea were preceding crops; when following wheat the results were variable. With high postseeding rainfall and above-average wheat straw residue, establishment and early growth of meadow bromegrass, and to a lesser extent, alfalfa, were often reduced in NT. However, under low postseeding rainfall and average wheat straw residue levels, establishment and seedling development of both alfalfa and meadow bromegrass were enhanced in NT vs. CT seeding, probably because of greater soil water conservation. There were no treatment differences for forage yield the year after seeding.	Production	Allen and Entz (1994)
Tillage	Wheat, rye	AR	NT drilled superior to CT drilled and RT broadcast when rains were delayed; otherwise all methods were equal when timely rains promoted seedling emergence and growth in all systems.	Production	Bowman et al. (2008)
Planters	Tall fescue, hardinggrass, tall wheatgrass	TX	With CT, drilling seed resulted in greater forage yield than broadcast seeding.	Production	Butler et al. (2008)
Tillage	Annual ryegrass	LA	Annual ryegrass establishment and early-season production were less consistent with NT than CT; however, NT establishment success improved when managing warm-season grass residue prior to seeding with glyphosate or burning.	Production	Cuomo et al. (1999)
Sod seeding	Alfalfa, red clover, birdsfoot trefoil, kura clover	MN	Suppressing existing vegetation was more important than planting method when renovating cool-season grass pastures with legumes; various methods were successful for establishing legumes with adequate sod suppression.	Production	Cuomo et al. (2001)
Sod seeding	Kleingrass, Illinois bundleflower	TX	Disking or paraquat suppression of a kleingrass sod resulted in significantly higher seedling densities of interseeded Illinois bundleflower than without any sod suppression; broadcasting at twice the seeding rate resulted in equal or higher seedling densities compared with drilling seed.	Production	Dovel et al. (1990)
Companion crop	Alfalfa, oat	SD	Rank of seeding year weed-free forage yield was: Alfalfa plus oat companion for forage > alfalfa + EPTC herbicide > alfalfa alone > alfalfa plus oat companion for grain	Production	Hansen and Krueger (1973)
Planters	Tall fescue, white clover	MD	When planting tall fescue + white clover, drilling seed with a banded fertilizer produced better stands and higher forage yields than broadcast and incorporated fertilizer followed by broadcasting plus cultipacking the seedbed.	Production	Hart et al. (1968)
Companion crop	Oat, alfalfa	IA	Oat companion crop increased forage yield in seeding year and reduced weed density; however, forage quality and alfalfa densities were lower than drilled clear-seeded treatments; no yield or quality treatment differences the year after seeding	Production	Hoy et al. (2002)
Tillage · fertilizer	Alfalfa, orchardgrass, birdsfoot trefoil, timothy	WY	On soils with low pH, surface liming and NT planting resulted in less-vigorous seedlings, slower establishment, and lower seeding year yield than incorporated lime with CT seedbeds	Production	Koch and Estes (1986)

TABLE 2.5. continued.

Method	Species	Location	Summary	Purpose	Reference
Sod seeding	Alfalfa, red clover, timothy	NH	Adding legumes to grass swards can be accomplished without tillage and resulted in increased legume content, improved forage quality, and higher DM intake by dairy heifers. No differences in animal response from sod and conventional seedings. Legumes established more rapidly with sod kill (glyphosate) and dominated the sward compared with sod suppression (paraquat). Where initial fertility was low, tilling was better than sod seeding. Suppressing or killing the sod for legume establishment reduced seeding year yield but increased digestible DM 48% and CP yield 75% the year after seeding compared with unseeded controls plus N fertilizer. Sod seeding with legumes can result in N fertilizer savings and improved nutrient yield where tillage is not practical.	Production	Koch et al. (1987)
Companion crop	Alfalfa, oat	CA	Planting alfalfa with an oat companion increased first-harvest forage yield relative to alfalfa seeded alone. Alfalfa yields at subsequent cuttings the first year were reduced by oat companion crop treatments; however, alfalfa yields the following year were equal in all treatments. The oat companion reduced weed biomass in both the first and second years compared with seeding alfalfa alone.	Production	Lanini et al. (1991)
Tillage · herbicide	Alfalfa, quackgrass	NH	When seeding alfalfa into a quackgrass sod, treating with glyphosate was important for increasing alfalfa and total yields, especially when using MT. Applying glyphosate to control existing sod very near to planting time may, in some cases, lead to reduced alfalfa stand establishment and slower alfalfa seedling growth, possibly due to rapid release of allelophathic compounds from the decaying sod.	Production	Mueller-Warrant and Koch (1980)
Tillage	Ladino clover, red clover, tall fescue	IL	Successful forage stands can be obtained with NT in wheat stubble provided good NT drills are used. Planting forages in late summer in wheat stubble enhanced winter cover, presumably providing better protection from soil erosion and water runoff.	Production and erosion	Olsen et al. (1978)
Sod seeding	Alfalfa, red clover, white clover	IL	Legume establishment in grass sod may be possible without chemical sod suppression, temporary chemical suppression is usually desirable to ensure legume establishment. Legumes enhanced DM yield over the long term; alfalfa was the most productive and long-lived sod-seeded legume; red and ladino clover were well suited for short-term stands.	Production	Olsen et al. (1981)
Companion crop	Kura clover, oat	MN	Oat companion crop increased total weed-free forage yields in Year 1, but reduced kura clover yield by 46% in Year 1 and later years compared with solo seeding with herbicide; seed production only occurred with solo seeding with herbicides; solo seeding with herbicide is more reliable than oat companion crop seeding for kura clover establishment.	Production	Seguin et al. (1999)
Companion crop	Oat, barley, alfalfa	MN	Semidwarf and conventional oat and barley genotypes performed similarly as companion crops for alfalfa establishment; companion crops reduced weed biomass and increased alfalfa plant mortality during establishment but did not lower alfalfa yield at later harvests.	Production	Simmons et al. (1995)

TABLE 2.5. continued.

Method	Species	Location	Summary	Purpose	Reference
Tillage	Perennial ryegrass, tall fescue, creeping red fescue	OR	NT seeding combined with high straw residue cover reduced estimated soil erosion 40–77% compared with CT and low-residue cover seeding of cool-season grasses. NT plus high-residue cover reduced costs 60–84%.	Soil erosion	Steiner et al. (2006)
Tillage	Perennial ryegrass, tall fescue, creeping red fescue	OR	Seed yields of cool-season grasses that were NT were equal to or higher than when established with CT. High straw residue cover at seeding did not adversely affect grass seed yield	Production	Steiner et al. (2006)
Tillage	Alfalfa	WI	Year-1 alfalfa yield and quality did not vary among moldboard plow, chisel plow, and NT seedbed preparation treatments.	Production	Sturgul et al. (1990)
Tillage · companion crop	Alfalfa, oat	WI	Relative to moldboard plowing for seedbed preparation, chisel plowing reduced surface water runoff volume 23–72% and NT seeding reduced volumes 59–100%; soil loss was reduced 24–64% with chisel plow and 71–100% with NT; however, NT with all surface residue removed had the highest runoff volumes for four of five rainfall simulations, and soil losses were similar to moldboard plowing for all rainfall simulations; there was no evidence of canopy development effect on runoff volumes; however, canopy development contributed to reduced soil losses within treatments, with the greatest reduction in the moldboard plus nurse-crop treatment that, at near full canopy, reduced soil loss by 96% compared with 0% canopy cover in the same treatment.	Soil erosion	Sturgul et al. (1990)
Companion crop	Annual ryegrass, alfalfa	WI	Annual ryegrass companion crops for alfalfa establishment increased forage yield but decreased forage quality in Year 1 compared with solo-seeded alfalfa. Where conditions favored vigorous ryegrass growth, alfalfa stand establishment was reduced. Early-maturing diploid annual ryegrass cultivars were the least competitive with alfalfa establishment.	Production	Sulc and Albrecht (1996)
Companion crop	Annual ryegrass, alfalfa	WI	Rainfall quantity and distribution during the season, companion crop species and cultivar selection, seeding rate, and harvest management affect forage yield and alfalfa plant density in the year after establishment. Ryegrass was less competitive with alfalfa than oat in dry years, but the reverse was true in wet years. Early removal of the companion crop as forage reduced the competition with alfalfa.	Production	Sulc et al. (1993a)
Companion crop	Annual ryegrass, alfalfa	WI	Ryegrass–alfalfa mixtures can provide higher-quality forage than oat–alfalfa mixtures in the first harvest of Year 1, but not at subsequent harvests, especially when adequate rainfall promotes vigorous seeding year ryegrass growth.	Production	Sulc et al. (1993b)
Planters	Alfalfa, birdsfoot trefoil	MI	Banding seed on the soil surface directly over a P-fertilizer band 4 cm deep resulted in more legume seedlings and taller, more vigorous plants than were obtained with broadcast seed on similarly fertilized soil. Seedlings had to be directly over or within 2.5 cm of the fertilizer band to obtain over 60% of their P from the fertilizer during the first 2 mo of growth.	Production	Tesar et al. (1954)

TABLE 2.5. continued.

Method	Species	Location	Summary	Purpose	Reference
Frost seeding	Smooth bromegrass, orchardgrass, perennial ryegrass, reed canarygrass, timothy, red clover	WI	Frost seeding temperate forage species into aging alfalfa can increase plant diversity and forage yield while suppressing weeds; species differed in rate of establishment.	Production	Undersander et al. (2001); Casler et al. (1999)
Tillage · companion crop	Alfalfa oat	WI	Seeding alfalfa with an oat companion reduced soil loss to nearly 50% that of alfalfa sown alone, but crop residue on the soil surface with CT was more effective than a companion crop in reducing soil loss; authors concluded crop-residue management is more effective than companion cropping for erosion control during alfalfa establishment. Surface water runoff volumes were not consistently reduced by CT and were dependent on previous site conditions.	Soil erosion	Wollenhaupt et al. (1995)
Companion crop	Annual ryegrass, festulolium	WI	Annual ryegrass or festulolium can be used as companion crops for perennial forage legume establishment to enhance overall quality of harvested forage in the seeding year compared with an oat companion and will increase yield over soloseeded alfalfa; however, in years that favor aggressive ryegrass growth, legumes establish more slowly and may produce less forage even in Year 2.	Production	Wiersma et al. (1999)

[1]Abbreviations: CT, conventional tillage (usually by full cultivation); NT, No-tillage (or conservation tillage); MT, minimum tillage; RT, reduced; DM, dry matter; CP, crude protein

Specialized Methods

The review of Wolf et al. (1996) described 27 forage establishment methods. Although some were variations of the two main methods, full cultivation or no-till establishment, there are many other specialized establishment methods that have used successfully. The most common methods are described.

Sprig seeding is used for establishing plants vegetatively, usually from plant stolons, after tillage. This is most commonly used for bermudagrass (Greene et al., 1992). Stolons are harvested from an established nursery field and transported to a prepared target area. The stolons are distributed over the land surface by hand or by machine, and then buried to a shallow depth with the use of a lightweight disk at a low angle of cultivation.

Frost seeding is used to introduce species, especially legumes, into existing sods by broadcasting the seed on frozen soils and relying on the freeze–thaw cycles in late winter to achieve the necessary seed–soil contact for germination and emergence in the spring (Undersander et al., 2001; Blaser et al., 2006, 2007). This method has been used successfully by many forage producers, and has been shown to increase plant diversity and forage yield while suppressing weeds (Casler et al., 1999; Undersander et al., 2001). The freeze–thaw cycles that occur in later winter and early spring provide sufficient surface disturbance that seed have adequate soil contact for establishment.

Frost seeding can be suitable for fast-establishing species such as most legumes, but is not suitable for most grass species. The proportion of seed that actually emerges can be as low as 5–10% of seed sown, so higher seeding rates are recommended. The likelihood of successful establishment from broadcast seeding into established vegetation can be improved by minimizing the surface vegetation to allow seed–soil contact, by using livestock to tread seed into the soil, and by controlling growth of the existing vegetation with herbicides or grazing to reduce competition with the establishing seedlings for light (Blackmore, 1965; Lambert et al. 1985).

Natural reseeding is the application of knowledge about the reproductive processes within natural grasslands or managed grasslands. Naturalized annual species such as annual poa, subterranean clover and annual lespedeza are dependent on natural reseeding for their ongoing survival. In the case of short-lived perennial species, natural reseeding can be encouraged by delaying grazing or harvest until seed ripens and drops onto the soil; however, this is only relevant for long-lived seed such as those legumes that are not autotoxic, and is not recommended for grass species that tend to have short seed longevity in soil. Secondly, the canopy needs to be managed during seed germination to reduce competition as the young seedlings become established. Although it can seem attractive to generate a seed population by natural reseeding, the seed is typically of low quality, and establishes poorly in the competitive stand, so other pasture improvement mechanisms are usually preferred.

Natural reseeding was used successfully in a wheat–fallow rotation in the northern Great Plains (Carr et al., 2005) by introducing forage legumes into the rotation by no-till planting. The perennial rotation improved soil structure, improved nutrient cycling, reduced soil erosion, and improved economic and environmental sustainability of crop production. The main requirement was the production of sufficient legume seed each year to regenerate the stand the following year. Species with sufficient natural regeneration were balansa, berseem, crimson, persian, and red clovers; birdsfoot trefoil; and black and burr medics (Carr et al., 2005).

Spray seeding is a method where the seed is broadcast onto the soil surface with the use of a variety of liquid or dry carrier materials, which may include additives such as nutrients and fungicides. The resultant mixture is sprayed or broadcast over the target area. This method is most commonly used for small areas that may be too steep for mechanical cultivation, and is not widely used for field seedings; however, spray seeding followed by rolling with a cultipacker has been used successfully on flatter sites and conventionally tilled seedbeds, which allows planting of large areas in a short time.

White clover 4 mo after frost seeding in March into a tall fescue sod in Ohio. The pasture was grazed to expose bare soil for seeding, then control grazed to reduce competition. Credit: David Barker, Ohio State University.

Conclusion—Site Preparation and Planting Methods

General Criteria of Code 512 specify following recommendations for planting methods obtained from the plant materials program, land grant and research institutions, extension agencies, or agency field trials. In our summary of 28 publications we found satisfactory establishment from many methods, typically with a trade-off between cost and establishment success. Given the number of site-preparation options, the number of establishment options, the number of species and their intended purpose, the best advice on seeding method and management will come from local specialists. They know the characteristics of the local climate, soils, and adaptation of the plant species proposed to extrapolate the principles from other locations and link with the overall goals of the producer to maximize the probability of success.

The Code 512 Criteria also specify preparation of the site to provide a medium that does not restrict plant emergence. Although supported in broad terms by the literature, caution is required, because:

1. Excessive site preparation and cultivation can disrupt the structure of some soils to an extent that might impair emergence, e.g., if the soil becomes crusted following rainfall.
2. Excessive site preparation may detract from other purposes, such as erosion control, C sequestration, or cost effectiveness.
3. Cultivation can stimulate weed germination.
4. Some methods (frost seeding and no-till) do not require the same extent of site preparation as full cultivation.

The Code 512 Considerations specify that where air-quality concerns exist site preparation and planting techniques that will minimize airborne particulate matter generation and transport should be considered. The general literature supports the use of alternatives from full tillage to reduce dust and disturbance that frequently are associated with relatively bare soils. These data should be transferable to forage plantings. The Code 512 Plans and Specifications also specify site preparation, seedbed preparation, and method of planting. Given the environmental and economic costs of these steps, thorough assessment at the local level of the various options for site preparations and establishment is imperative.

CLIMATIC FACTORS AFFECTING SEEDING DATE

Seeding date is one of the most critical components of establishment success. The USA has such a wide range of environments that successful establishment may occur somewhere in almost every month of the year. The two climatic variables having the greatest influence on establishment success are temperature (Townsend and McGinnies, 1972a; Hsu et al., 1985a, 1985b; Brar et al., 1991; Kalburtji et al., 2007) and soil moisture (Roundy, 1985; Clem et al., 1993; Awan et al., 1995).

Each region has very specific periods within which planting is recommended, based largely on a high probability of adequate soil temperature and moisture (Sulc and Rhodes, 1997; Table 2.6). Typically, cool-season grasses are established in late summer in northern states or in autumn in the transition zone and lower latitudes (see Figs. 1.1 and 1.2). Legumes can also be planted at the same time, but require more time than cool-season grasses to achieve sufficient winter hardiness. Most warm-season species have higher minimum temperatures for germination and seedling growth and are planted in late spring. There was no evidence in the literature that planting date should change with the intended purpose of the resultant stand.

Soil Moisture. Rainfall subsequent to planting may have more influence on establishment success than moisture conditions at the time of planting (Bell et al., 2005). Barker et al. (1988) analyzed 14 establishment studies and found time to emergence was most closely correlated with rainfall occurring the week immediately after seeding. Cumulative rainfall during the 2 wk after seeding was poorly correlated with time to emergence, and cumulative rainfall during the month after seeding was unrelated to emergence. Germination percentages of crested wheatgrass, intermediate wheatgrass, smooth bromegrass, and Russian wildrye

> "...thorough assessment at the local level of the various options for site preparations and establishment is imperative."

TABLE 2.6. Summary of research on latest date for fall planting at various locations and forage species.

Species	Location	Date	Reference
Alfalfa	Southern Saskatchewan	1 November	Kilcher (1961)
Alfalfa	Northern Wisconsin	1 August	Undersander et al. (1991)
Alfalfa	Southern Wisconsin	Mid-August	Undersander et al. (1991)
Alfalfa	Northern Michigan	1 August	Tesar (1983)
Alfalfa	Southern Michigan	Mid-August	Tesar (1983)
Alfalfa	North Dakota	1 August	Undersander et al. (1991)
Alfalfa	Minnesota	1 August	Undersander et al. (1991)
Alfalfa	Northern New York	Early August	Cherney and Hansen (2011)
Alfalfa	Southern New York	Mid-August	Cherney and Hansen (2011)
Alfalfa	Pennsylvania	1 August	Hall (1995)
Alfalfa	Central Pennsylvania	Mid-August	Terrill (1961)
Alfalfa	Southern Pennsylvania	1 September	Terrill (1961)
Alfalfa	Maryland	10 September	Hofmann and Decker (1971)
Alfalfa	North Carolina	Mid-September	Mueller and Chamblee (1984)
Alfalfa	Central California	Mid-September	Marble and Peterson (1981)
Birdsfoot trefoil	New York	Late July	Cherney and Hansen (2011)
Birdsfoot trefoil	Pennsylvania	1 August	Hall (1995)
Creeping foxtail	Wisconsin	Mid-August	Undersander and Greub (2007)
Crested wheatgrass	Southern Saskatchewan	1 November	Kilcher (1961)
Crested wheatgrass	Montana	28 September	White and Currie (1980)
Green needlegrass	Southern Saskatchewan	1 November	Kilcher (1961)
Intermediate wheatgrass	Southern Saskatchewan	1 November	Kilcher (1961)
Intermediate wheatgrass	Montana	28 September	White and Currie (1980)
Orchardgrass	Wisconsin	Mid-August	Undersander and Greub (2007)
Orchardgrass	Pennsylvania	Mid-August	Hall (1995)
Perennial ryegrass	Wisconsin	Mid-August	Undersander and Greub (2007)
Perennial grasses	Northern New York	Mid-August	Cherney and Hansen (2011)
Perennial grasses	Southern New York	Late August	Cherney and Hansen (2011)
Perennial ryegrass	Pennsylvania	Late August	Hall (1995)
Red clover	Pennsylvania	1 August	Hall (1995)
Reed canarygrass	New York	Late July	Cherney and Hansen (2011)
Reed canarygrass	Pennsylvania	1 August	Hall (1995)
Reed canarygrass	Wisconsin	Mid-August	Undersander and Greub (2007)
Russian wildrye	Southern Saskatchewan	1 November	Kilcher (1961)
Russian wildrye	Montana	12 September	White and Currie (1980)
Smooth bromegrass	Wisconsin	Early August	Undersander and Greub (2007)
Tall fescue	Wisconsin	Mid-August	Undersander and Greub (2007)
Timothy	Wisconsin	Early September	Undersander and Greub (2007)
Thickspike wheatgrass	Southern Saskatchewan	15 September	Kilcher (1961)

were decreased and time to germination was delayed by 1–2 wk as soil moisture decreased from field capacity to permanent wilting point (McGinnies, 1960).

Planting during periods of high soil moisture may result in soil compaction by heavy equipment or damage to soil structure from cultivation when the soil is too wet. The sensitivity of germination and early growth to low soil moisture varies with location and establishment method. Broadcast planting methods (such as frost seeding) are more sensitive to variable temperature and precipitation than methods that insert seed into the soil.

Soil moisture for germination and establishment can be more easily controlled in irrigated systems. In semi-arid regions where summer precipitation is inconsistent, the soil should be irrigated prior to fall seeding, leaving sufficient time for a final cultivation before planting to reduce weeds and for sufficient seedling growth before frost. Where flood irrigation is used, fields must be leveled to prevent high or low spots where seedling establishment could fail because of drought or flooding stress. Where sprinkler irrigation is available, the surface soil can be kept moist during germination and establishment by short, frequent irrigations. For a high-value cash crop such as alfalfa hay that will be flood-irrigated for regrowth, use of a sprinkler irrigation system for establishment may be justified. Other considerations for establishment of alfalfa under irrigation can be found in Summers and Putnam (2008).

Seed germination rate is the first critical step to successful establishment. Germination usually occurs near the soil surface, and studies show that measured moisture of the upper 10 or 15 cm of the soil are poor predictors of establishment success. In contrast, Awan et al. (1995) measured moisture of just the surface soil using a novel method and found those measurements could be used to predict germination success.

Temperature. Among 10 perennial legumes, alfalfa germinated readily at day/night temperatures that ranged from 8/2°C to 24/18°C (Hill and Luck, 1991). In contrast, birdsfoot trefoil and red, white, kura, and strawberry clovers germinated readily at the three higher temperatures and had depressed germination at 12/6 or 8/2°C. Crownvetch, cicer milkvetch, and sericea lespedeza germinated and developed above 20°C. Rate of seedling growth for a species had a response to temperature that was similar to the response of germination (Hill and Luck, 1991). The optimum germination and emergence temperature for six vetch species was between 18°C and 23°C, whereas the optimum temperature for root growth of these species was slightly higher, between 20°C and 25°C (Mosjidis and Zhang, 1995). Root growth is critical to ensure water and nutrient uptake.

Planting of cool-season forages in spring in many locations is more sensitive to excessive soil moisture than to cool temperatures. However, the establishment of warm-season grasses is slowed by low soil temperatures. Although stratification improved germination of the warm-season perennial grasses big bluestem, caucasian bluestem, indiangrass, and switchgrass (Hsu et al., 1985a, 1985b), rates of warm-season grass development in the field were more rapid for later planting dates (Hsu and Nelson, 1986b). The optimal planting dates in Missouri for these grasses fell between late April and mid-May, when soil temperature was warmer than 10°C, but before soil moisture was depleted (Hsu and Nelson, 1986a).

Eastern gamagrass has a high level of seed dormancy that can be improved by natural stratification. Seed planted in Iowa in either mid-August or late October experienced natural winter stratification and had higher germination in spring than seed planted in spring or summer (Gibson et al., 2005). But this was not found in all cases (Aberle et al., 2003). Dallisgrass germination was improved by flooding and high defoliation intensity of the competing plants which reduced evapotranspiration and created gaps in the canopy that increased the red:far-red light ratio that stimulates growth and significantly improved establishment (Cornaglia et al., 2009). Mosjidis (1990) found that the germination percentage of eight genotypes of sericea lespedeza, a warm-season legume, increased linearly by 20% for every 3°C as day/night temperatures increased from 18/14°C to 30/26°C; the optimum temperature for germination was between 20°C and 30°C (Qiu et al., 1995).

Planting cool-season grasses and legumes in late summer or early autumn is advantageous because it allows an annual crop to be harvested before planting, and because warmer, drier conditions mean that weed and disease

“Seed germination rate is the first critical step to successful establishment.”

pressures are generally lower than in early spring. It is recommended that cool-season species be planted early enough for 6 wk of shoot and root development and adequate carbohydrate storage to occur before the first killing frost (Cosgrove and Collins, 2003). In Minnesota, seedlings of the legumes alfalfa, red clover, sweetclover, and alsike clover could not develop adequate winter hardiness until they had developed about seven to nine trifoliate leaves (Arakeri and Schmid, 1949).

Hall (1995) and Undersander and Greub (2007) reviewed the literature on recommended late summer/early autumn planting dates for alfalfa. In Pennsylvania, Hall (1995) seeded alfalfa, birdsfoot trefoil, red clover, orchardgrass, perennial ryegrass, and reed canarygrass in spring and found seeding-year yield decreased linearly with each day of delay after the recommended seeding date. In Wisconsin, Undersander and Greub (2007) evaluated late-autumn seeding dates for orchardgrass, smooth bromegrass, timothy, reed canarygrass, perennial ryegrass, and tall fescue. Based on germination in autumn and establishment in early spring the dormant seeding failed four times out of five, and is not recommended. However, in the dry upper Great Plains, with 370 mm average annual rainfall, 1 November seedings were consistently more successful than May seedings for alfalfa, crested wheatgrass, green needlegrass, intermediate wheatgrass, and Russian wildrye (Kilcher, 1961).

A cultipacker-type seed drill used for a spring seeding in Ohio. Seed is dropped between the front and back rollers, which are offset slightly so the back roller covers the seed. Credit: Mark Sulc, The Ohio State University.

Fall plantings of alfalfa, crested wheatgrass, smooth bromegrass, and slender wheatgrass survived winter in the northern Great Plains if they reached the three-leaf stage before the ground froze (White and Horner, 1943). Planting by 1 September was recommended if there was moisture in the soil, because germination was slowed at later dates as soil temperatures decreased. Under dryland conditions in Montana, mid- to late-September plantings resulted in good establishment of crested wheatgrass, intermediate wheatgrass and Russian wildrye (White and Currie, 1980). These species survived planting as late as mid-October if they produced two leaves before the soil froze (White, 1984). These small seedlings grew significantly more the following year than did dormant-seeded plants that germinated in spring. Seedlings with three or more leaves at the beginning of spring could be grazed by midsummer of the following year, and produced more herbage dry matter by autumn than seedlings with fewer leaves in spring.

Ries and Svejcar (1991) tied the successful establishment of crested wheatgrass and blue grama to their development of adventitious (i.e., nodal) roots into subsoil water. The cross-sectional area of xylem in adventitious roots was several times that of seminal roots, indicating adventitious roots were needed to transport sufficient water to support continuing leaf expansion. By the time adventitious roots were 8–10 cm long, four–six leaves had developed on the main axis and tillering had begun.

The usefulness of tillering as a measure of grass seedling establishment was confirmed in a study of prairiegrass, grazing bromegrass, and orchardgrass that showed seedlings did not survive winter unless they had begun to tiller before ceasing growth in autumn (Sanderson et al., 2002). Undersander and Greub (2007) also identified tillering following fall planting was the factor best correlated with yield in the following spring.

Some nonleguminous forbs, often annuals, have high forage quality and have potential for use in grassland systems. Turnip planted in late July in West Virginia produced the greatest top and root dry matter that autumn compared to earlier or later plantings (Jung and Shaffer, 1995). In contrast, mid-September seedings of chicory and plantain developed two fully expanded leaves, but were not developed sufficiently to overwinter in Pennsylvania (Sanderson and Elwinger, 2000).

The average worldwide air temperature has increased by about 1°C over the last century (Easterling et al., 1997) and grassland establishment has likely been affected. A long-term study in northeast Colorado determined that annual net primary production of buffalograss, the dominant native grass of the shortgrass prairie, decreased with increase in minimum air temperature, whereas that of both native and exotic forb species increased (Alward et al., 1999). In Florida, studies of the direct effect of increased temperature and CO_2 concentration demonstrated that rate of photosynthesis and resulting rates of establishment and initial plant growth increased with higher CO_2 concentrations (Fritschi et al., 1999). Rhizoma peanut benefited more from higher CO_2 concentrations than did bahiagrass, but temperature increase benefited biomass production of bahiagrass more than rhizoma peanut (Fritschi et al., 1999). For the future these responses to global change need to be researched, including any environmental impact that might occur during establishment.

Conclusion—Planting Date

The Code 512 General Criteria specify recommendations for planting dates obtained from the plant materials program, land grant and research institutions, extension agencies, or agency field trials. These principles are well established for most geographic areas and focus on temperature and water as primary factors. However, rather than basing seeding time or method on the current temperature and moisture conditions, the literature indicates planting should be timed to precede a sufficient period of favorable temperature and rainfall.

No studies were found describing fall seeding and dormant seeding effects on soil erosion or ecosystem services. But based on other data with cover crops it is presumed that with little ground cover and small plants there would be environmental risks associated with these seeding methods. Timing seeding to ensure tillers can develop should help reduce the areas bare of ground cover, and having a better-developed adventitious root system should improve the capacity of the seedlings to stabilize the upper layers of soil. These topics need more research on the environmental risks of having minimal ground cover over winter. This also applies to plantings of annual forbs and expectations of additional risks due to climate change.

RATES OF SEEDING

Seeding rate is one of the most important variables determining the success of a new seeding. Seeding rate can be measured as either the weight of seed per unit area, or the number of seeds per unit area. The conversion between these two measures is the specific seed weight (i.e., g seed^{-1}), and this conversion varies among species, cultivars, and even seed lots. Seeding rates should be based on the delivery of PLS per unit area, and thus also needs to account for hard seed, the percent germination of the seed being planted, and the presence of inert materials such as impurities and seed coatings. To evaluate the criteria and purposes of the standard we summarized 25 articles that evaluated the effect of seeding rate on grassland establishment, forage and biomass production, and forage nutritive value (Table 2.7). No study was found that related seeding rate uniquely to ecosystem purposes such as soil erosion, water quality, C sequestration, or wildlife.

Recommended seeding rates vary by species, location and intended use of the stand. The recommended rates are usually not a specific value, but a defined range of number of seed to apply per unit area. Recommended seeding rates have been determined over the years from research and experience in the field (Table 2.7). Recommended rates tend to be higher for broadcast than drilled stands to offset poorer seed–soil contact and are lower in drier climates. Drier climates typically have less seed and seedling mortality due to diseases, and higher seeding rates can decrease stand productivity because of excessive intraspecies competition for water. Lower rates are also usually recommended for conservation plantings where ground cover and not forage production may be the primary objective.

“Seeding rates should be based on the delivery of PLS per unit area”

TABLE 2.7. Summary of research on seeding rates of forages.[1]

Species	Seed rates tested	Optimum or recommended seeding rate	Other notes	Location	Reference
Annual and companion crops					
Triticale	50, 75, 100 kg ha^{-1}	100 kg ha^{-1}	Optimal rate was 75 kg ha^{-1} for grain	Alabama	Bishnoi (1980)
Wheat, winter rye	50, 75, 100 kg ha^{-1}	75–100 kg ha^{-1}	Optimal rate was 50 kg ha^{-1} for grain	Alabama	Bishnoi (1980)
Wheat, triticale	100–400 seed m^{-2}	300–400 seed m^{-2}	Oversown with red clover by frost seeding; seeding rates impacted red clover dry matter within specific harvest periods, but the impact diminished with time and had no effect on seasonal forage total or subsequent spring yield of red clover	Iowa	Blaser et al. (2007)
Triticale, companion to alfalfa	198–594 seed m^{-2}	374 PLS m^{-2}	Quadratic grain yield response, maximum profit at 374 seeds m^{-2}. Increasing triticale seeding rate had no effect on alfalfa density and yield.	Iowa	Gibson et al. (2008)
Turnip	1.7–5.0 kg ha^{-1}	Not stated	Seeding-rate effects were significant for yield of tops and roots only 10% and 5% of the time, respectively. This was not expected, but may have been because of seeding in rows.	Pennsylvania	Jung and Shaffer (1993)
Sudangrass, sorghum · sudangrass	13.5–54 kg ha^{-1}	Not stated	Plant density and total seasonal forage yield increased as seeding rate increased to the highest rate, especially at the narrow row spacing. Increasing seeding rate reduced crude protein and increased lignin content for the first harvest of the three-cut system, but there was no seeding-rate effect on forage quality of subsequent cuttings.	Wisconsin	Koller and Scholl (1968)
Oat, companion crop to alfalfa	0–36 kg ha^{-1}	18 kg ha^{-1}	Oat companion crop at 9 kg ha^{-1} dramatically increased forage yield compared with no oat companion, and yield increases at higher oat seeding rates were small. Highest forage yields were predicted to occur at oat seeding rates of 24–27 kg ha^{-1}; however, oat at 18 kg ha^{-1} was considered best for optimizing yields, reducing weeds, and not affecting alfalfa yield the year after seeding (oat always reduced alfalfa yield in Year 1).	California	Lanini et al. (1991)
Barley, oat, triticale with undersown berseem clover	30–240 plants m^{-2}	60–90 plants m^{-2}	Cut-1 total yield increased and clover content decreased with increasing cereal density. Berseem clover regrowth (cut 2) was lowest for intercrops with the highest cereal density and increased linearly as cereal density decreased. Effect of cereal density on total seasonal yield was inconsistent across years, but seeding cereals to achieve plant density of 60–90 plants m^{-2} (25–40% of full recommended rate) usually improved forage quality without reducing total season yield of cereal–berseem clover intercrops.	Alberta	Ross et al. (2004)

TABLE 2.7. continued.

Species	Seed rates tested	Optimum or recommended seeding rate	Other notes	Location	Reference
Perennial and biennial species					
Alfalfa	4.5–17.9 kg ha^{-1}	13.5 kg ha^{-1}	Under irrigation, each increase in seed rate increased forage yield in Year 1. Under dryland, no yield differences above 13.5 kg ha^{-1} seed rate in Year 1. Year 2 yield increased up to 9 kg ha^{-1} at one location and up to 13.5 kg ha^{-1} at the two other locations. Crude protein content of forage was not affected by seed rate. Root and crown weight of alfalfa decreased as seed rates increased up to 13.5 kg ha^{-1}. At 4.5 kg ha^{-1}, alfalfa plant size the year after seeding did not sufficiently compensate to maintain yield.	South Dakota	Hansen and Krueger (1973)
Alfalfa	3–27 kg PLS ha^{-1}	17 kg ha^{-1}	Initial seedling densities were a near linear function of seeding rate, and those rankings remained consistent as stands thinned over 4 yr; plant mortality was much greater at high than low densities in Year 1; doubtful that rates above 17 kg ha^{-1} would increase useful life of the stand and provided no long-term measurable benefit; rates below 17 kg ha^{-1} had lower plant density for up to 4 yr after planting.	Missouri, Pennsylvania	Hall et al. (2004)
Alfalfa	1.1–22.4 kg ha^{-1}	7.8 kg ha^{-1}	Recommended rate of 7.8 kg ha^{-1} in Montana to obtain 30 seedlings m^{-1} of row; seeding-year yield was directly proportional to seeding rate, but yield the following year was not affected by seeding rate.	Montana	Cooper et al. (1979)
Alfalfa	10–40 kg ha^{-1}	10 kg ha^{-1}	At the lowest seeding rate, 40–52% of seeds produced established plants, decreasing to 31–44% at the highest seeding rate. Stand density declined most rapidly in the first year. By Year 4, greatest percentage plant mortality had occurred at the highest seeding rate (75–85%) compared with 49–68% mortality of original emerged plants at the low seeding rate. Seed rate affected total 3-yr yield in one of three experiments, and had little or no influence of crude protein and leaf-to-stem ratio.	Spain	Lloveras et al. (2008)
Alfalfa, under oat companion	18–36 kg ha^{-1}	No effect	Alfalfa seeding rate did not impact yield or forage composition.	California	Lanini et al. (1991)
Alfalfa and red clover, seeded into suppressed grass sod	4.4–17.6 kg ha^{-1}	17.6 kg ha^{-1}	Seeding rate effects on legume yield were dependent on location, legume species and grass competitiveness. Seeding rates of at least 17.6 kg ha^{-1} appeared to increase establishment year alfalfa and red clover yields when high levels of grass competition exist, and alfalfa may benefit more from higher seeding rates than red clover.	Minnesota	Sheaffer and Swanson (1982)

TABLE 2.7. continued.

Species	Seed rates tested	Optimum or recommended seeding rate	Other notes	Location	Reference
Red clover	0–1500 seed m^{-2}	900–1200 seeds m^{-2}	Frost seeded into winter cereals, 11–40% of red clover seed established mature plants with actual densities of 46–314 plants m^{-2}; increasing seeding rate increased DM yield but had no effect on forage quality.	Iowa	Blaser et al. (2006, 2007)
Red clover, with and without timothy or tall fescue	6–18 kg ha^{-1}	12 kg ha^{-1}	Total mixture forage yield, digestible organic matter, and crude protein content were not markedly affected by red clover seed rate; but red clover DM, DOM, and CP were increased as red clover seed rate was raised due to increases in red clover component.	Scotland	Frame et al. (1985)
Tall fescue, with red clover	6–18 kg ha^{-1}	Not stated	Tall fescue increased DM yield by 10 and 29% in Years 1 and 2, respectively, compared with red clover alone, but did not increase total forage organic matter digestibility, but decreased crude protein content. Increasing grass seed rate intensified the effects as it decreased the red clover component in the sward.	Scotland	Frame et al. (1985)
Timothy, with red clover	2–6 kg ha^{-1}	2–4 kg ha^{-1}	Timothy increased DM yield by 6.5 and 10% in Years-1 and 2, respectively, compared with red clover alone; timothy increased total forage organic matter digestibility, but decreased CP content. Increasing grass seed rate intensified the effects as it decreased the red clover component in the sward.	Scotland	Frame et al. (1985)
Perennial ryegrass	10–30 kg ha^{-1}	Not stated, no differences	All treatments sown with white clover at 3 kg ha^{-1}; grass seed rate did not affect total DM production or white clover performance.	Scotland	Frame and Boyd (1986)
Bahiagrass	5.6–50.4 kg ha^{-1}	Not stated, no long term advantage–higher rates	Increasing seeding rate increased bahiagrass emergence, tiller density (nearly linearly), and Year-2 cover, but yield advantages were small; advantages of higher rates were short lived.	Georgia, Florida	Gates and Mullahey (1997)
White clover, perennial ryegrass	10/0, 8/5, 5/10, 3/15, 0/20 kg ha^{-1} for white clover/ ryegrass	Not stated	Sowing rate had large effect on clover content in Year 1, and higher clover sowing rate gave higher production in the first year, but this effect disappeared by Year 3; there was little effect of sowing rate on crude protein content; amount of DM removed by grazing decreased as ryegrass sowing rate increased (clover content decreased) in the first year, but this effect disappeared by Year 3.	Australia	Kelly et al. (2005)

TABLE 2.7. continued.

Species	Seed rates tested	Optimum or recommended seeding rate	Other notes	Location	Reference
Big bluestem	110–440 PLS m^{-2}	110–220 PLS m^{-2}, with herbicides	Big bluestem frequency usually increased with increasing seeding rate; successful establishment occurred in three of four environments at 110 PLS m^{-2}, and in all environments at the higher seeding rates; seeding rate influenced yield in three of four environments; if pre-emergent herbicides are used, high-yielding stands of big bluestem can be established at seeding rates of 110 or 220 PLS m^{-2}.	Nebraska	Masters (1997)
Hairy vetch, with wheat	0–162 PLS m^{-2} for HV, 324 PLS m^{-2} for wheat	For high-quality seed vetch at 162 PLS m^{-2}	Forage yield decreased but crude protein content and digestibility increased with increasing vetch seeding rate, which was a function of the increasing vetch component in mixture.	Illinois	Roberts et al. (1989)
Switchgrass	Evaluated varying grid frequency levels on farmer fields	40% grid frequency	Establishment-year stand grid frequencies of 40% or greater can be considered an establishment-year stand threshold indicating successful establishment and subsequent postplanting year biomass yields for switchgrass. Establishment-year grid frequency of 25% would be adequate for conservation plantings where no harvests were planned for several years.	Nebraska, South Dakota, North Dakota	Schmer et al. (2005)
Ryegrasses, companion to alfalfa	215–645 PLS m^{-2}	215 PLS m^{-2}	Increasing ryegrass seeding rate had no effect on total mixture Year-1 yield in environments with adequate rain but decreased forage yield in dry years. Seeding-year alfalfa yield was decreased by increasing ryegrass seeding rate. The lowest ryegrass seeding rate reduced competition with alfalfa, improved forage quality in the seeding year, and reduced the changes of suppressing alfalfa stand establishment.	Wisconsin	Sulc et al. (1993a)
Smooth bromegrass, orchardgrass, perennial ryegrass, reed canarygrass, red clover	0–880 PLS m^{-2}	Orchardgrass > 220 PLS m^{-2}; timothy > 440 PLS m^{-2}; smooth bromegrass, 100–200 PLS m^{-2} most economical	Species were frost seeded into aging alfalfa stand. Forage yield increased with seeding rate at sites with the greatest initial establishment of frost-seeded species, but the response was highly variable. Generally, the fast-establishing species (i.e., perennial ryegrass, orchardgrass, and red clover) had significant responses of grass or legume dry matter contribution to increasing seeding rate, whereas the slow species (i.e., reed canarygrass, smooth bromegrass, and timothy) did not.	Wisconsin	Undersander et al. (2001)

TABLE 2.7. continued.

Species	Seed rates tested	Optimum or recommended seeding rate	Other notes	Location	Reference
Switchgrass	3.4–16.8 PLS m^{-2}	3.4 kg PLS ha^{-1}	Greater seeding rates increased seedling number, tiller number, and forage yield, but slightly decreased digestibility and crude protein of the forage. Seeding date had a greater effect than seeding rate on forage yield and quality. Highly productive switchgrass stands were obtained during the establishment year with mid-April to early-May seeding dates at rates of only 3.4 kg PLS ha^{-1} when atrazine was used for weed control.	Iowa	Vassey et al. (1985)
Big bluestem, switchgrass	107–430 PLS m^{-2}	100–200 PLS m^{-2}	When atrazine is used as pre-emergence herbicide, seeding rates greater than 200 PLS m^{-2} of switchgrass and big bluestem are not necessary for obtaining adequate stands, and lower rates may be sufficient in many years, especially for conservation plantings.	Nebraska	Vogel (1987)

[1]Abbreviations: PLS, pure live seed; DM, dry matter; CP, crude protein; DOM, digestible organic matter.

The primary goal of any seeding is to achieve a minimum plant population that will result in a productive stand or, at least, a stand able to fulfill the purpose for which it was planted. Recommended seeding rates usually exceed the minimum desired plant population, to allow a safety margin because all seed will not emerge as seedlings. Many studies demonstrate, however, that there is rarely any sustained benefit to increasing seeding rates above the documented recommended range (Table 2.7). There may be an initial yield or quality response to higher seeding rates, but this advantage is short-lived (rarely exceeding 1 yr) and cost associated with the higher seeding rate is rarely justified.

There have been a number of studies aimed at defining the best species and the optimal seeding rates for companion crops used during the establishment of perennial species (Table 2.7). Many companion crops can also be used for grain production, and research has demonstrated that seeding rates of a companion crop should be lower than when planted for grain production to avoid excessive competition, especially for light, with the weaker perennial species. In contrast, in the rare case these companion (annual) crops are planted as monocultures, the optimal seeding rate for forage production is usually higher than when it is sown for grain production because the purpose is a rapid cover of leaf mass rather than the grain (Bishnoi, 1980).

Sometimes seeding-rate recommendations are increased based on planting method or conditions. For example, a Texas study found that Illinois bundleflower broadcast into a grass sod required twice the seeding rate to achieve the same seedling density as for drilling (Dovel et al., 1990). In most cases, the better option is to use the best seeding method and management rather than attempting to overcome adverse establishment methods or conditions with increased seeding rates.

Conclusion—Rates of Seeding

The Code 512 General Criteria specify recommendations for planting rates obtained from the plant materials program, land grant and research institutions, extension agencies, or agency field trials. This section summarized 25 articles and found no benefits for seeding rates higher than those recommended by state agencies. Seed size varies among species and cultivars, and seeding rate should be adjusted to deliver seed on a PLS basis.

PLANTING DEPTH

Proper planting depth is one of the critical factors determining success of a grassland planting. Utilizing the proper depth will maximize emergence and seedling growth to allow quicker establishment. Seed of forage species are typically smaller than most grain crops and, additionally, have a large range of seed shapes and sizes, so planting equipment should be adjusted to seed at the appropriate depth. We summarized 30 articles and found no evidence that planting depth should vary depending on the eventual purpose for the seeding.

Establishment From Seed

Successful establishment is dependent upon placement of seed in a favorable environment for germination and subsequent emergence (Tables 2.8 and 2.9). The ideal planting depth depends on seed size, soil texture, soil moisture availability, time of seeding, and firmness of the seedbed. The most important consideration for determining planting depth of a given species is seed size. In general, larger seed can emerge from greater depths. There is a trade-off between increased water availability at greater soil depths, especially in arid environments, and the ability of seedlings to emerge from lower depths (Townsend, 1979). A general rule of thumb is that seed should not be planted deeper than seven times its diameter, with the optimum depth being four to seven times the diameter (Masters et al., 2004).

Even within a species, variation in seed size can affect the ideal planting depth. In Wyoming, the smaller alfalfa seed germinated and emerged better from 0.6 cm, whereas larger seeds benefit from the deeper placement (Erickson, 1946). This same study also found that alfalfa seed size was more important than planting depths between 0.6 and 1.7 cm. A common problem in arid environments is shallow and soil surface planting which causes seedlings to desiccate and die before becoming established (Cosgrove and Collins, 2003), because bare surfaces lose water more rapidly than when protected by litter (Winkel et al., 1991). However, extremely small seeds may be an exception because their emergence seems to be optimal when placed on the soil surface (Cox and Martin, 1984), and seedling vigor can be compromised by deeper plantings (Tischler and Voigt, 1983).

Planting depth should vary with soil texture (Aiken and Springer, 1995). As a general rule, small seeded species should be planted slightly deeper in sandy soils (1.2–2.5 cm) compared to loam or clay loam soils (0.6–1.2 cm). Bermudagrass is very small seeded, and its recommended planting depth is 0–1.3 cm (Taliaferro et al., 2004), with an optimal depth of 0.6 cm (Keeley and Thullen, 1989). Proper seed placement is difficult to regulate unless the seedbed is firm to prevent seeding too deep (Masters et al., 2004). Typically seed should be covered with enough soil to maintain moist conditions for germination, but not so deep that the shoot cannot reach the surface (Zhang and Maun, 1990; Roundy et al., 1993; Cosgrove and Collins, 2003). Moisture conditions at planting and the subsequent precipitation were the most important factors affecting successful establishment (Townsend, 1979).

Establishment success will also vary with the degree of soil compaction, partly because compaction improves the capillary flow of water to the seed and seedling, yet too much compaction restricts the ability of seedlings and their roots to penetrate through the soil. Soil moisture near the surface increased as compaction increased from 0 to 83 kPa (0–12 psi) and was positively related to the emergence percentage of alfalfa seed (Triplett and Tesar, 1960). Conversely, switchgrass was able to germinate and emerge from 8 cm in loose soil, but only 10% of seeds emerged when compaction was 6.9 kPa (1 psi) and no seedlings emerged with pressure of 69 kPa (10 psi) (Hudspeth and Taylor, 1961). In addition to moisture, soil compaction also affects oxygen diffusion, soil temperature, and light penetration, all of which influence germination and emergence (Hudspeth and Taylor, 1961). In some species, the red:far red ratio of light that penetrates through the soil can regulate seed dormancy; however, this has not been well documented for forage seed (Cornaglia et al., 2009).

Vegetative Establishment

Hybrid bermudagrass is typically planted as sprigs, which are vegetative propagules

> "The most important consideration for determining planting depth of a given species is seed size"

TABLE 2.8. Summary of published literature on planting depth for legume species, environment, and soil type.

Species and cultivar (if stated)	Environment[1]	State	Soil type(s)	Planting depth Tested	Planting depth Optimum	Reference
				cm		
Alfalfa 'Vernal', 'Ranger'	G/F1	Iowa	Webster silty clay loam	1.3, 2.5, 3.8	1.3	Beveridge and Wilsie (1959)
Alfalfa 'Vernal	F2	Michigan	Conover silt loam, Hillsdale sandy loam	0, 0.6, 1.3, 2.5	1.3	Triplett and Tesar (1960)
Alfalfa 'Vernal', 'Ranger'	G/F1	Iowa	Webster silty clay loam	1.3, 2.5, 3.8	1.3	Beveridge and Wilsie (1959)
Alfalfa	G	Ohio	Miami silt loam	0, 0.6, 1.3, 2.5	0.6–1.3	Moore (1943)
Alfalfa 'Grimm'	G/F1	Minnesota	Carrington, Clinton, Clarion silt loams, Merrimac loamy sand	0, 1.3, 2.5, 5.1, 7.6	0–1.3	Murphy and Arny (1939)
Falcata alfalfa 'Baker'	F3	Colorado	Vona sandy loam	1.3, 2.5, 3.8	1.3	Townsend (1992)
Alsike clover	G	Ohio	Miami silt loam	0, 0.6, 1.3, 2.5	0.6–1.3	Moore (1943)
Arrowleaf clover 'Yuchi'	F4	Texas	Norwood fine sandy loam	0, 1.0, 2.5, 4.0	1.3	Rich et al. (1983)
Birdsfoot trefoil 'Empire' 'Viking'	G	Kansas	Unknown soil	1.3, 2.5, 3.8	1.3	Stickler and Wassom (1963)
Cicer milkvetch 'Lutana'	F3	Colorado	Nunn clay loam	1.3, 2.5, 3.8	1.3–2.5	Townsend (1979)
Crimson clover	G	Tennessee	Cumberland silt loam	0.6, 1.3, 2.5, 3.8	0.6–1.3	Moore (1943)
Striate lespedeza,	G	Tennessee	Cumberland silt loam	0.6, 1.3, 2.5	0.6–1.3	Moore (1943)
Korean lespedeza	G	Tennessee	Cumberland silt loam	0.6, 1.3, 2.5	0.6–1.3	Moore (1943)
Sericea lespedeza	G	Tennessee	Cumberland silt loam	0.6, 1.3, 2.5	0.6–1.3	Moore (1943)
Sericea lespedeza 'Serala 76'	F1	Alabama	Hiwassee sandy loam	1, 3	1.0–3.0	Qiu and Mosjidis (1993)
Red clover	G	Ohio	Miami silt loam	0, 0.6, 1.3, 2.5	0.6–1.3	Moore (1943)
Red clover	G/F1	Minnesota	Merrimac loamy sand	0, 1.3, 2.5, 5.1, 7.6	0–1.3	Murphy and Arny (1939)
Sweetclover 'Madrid'	F5	Montana	Unknown sandy loam	0, 0.6, 1.3, 2.5, 3.8, 5.1 ,6.4, 7.6	0.6–5.1	Gomm (1964)
Sweetclover	G/F1	Minnesota	Carrington, Clinton, Clarion silt loams, Merrimac loamy sand	0, 1.3, 2.5, 5.1, 7.6	0–1.3	Murphy and Arny (1939)
Sweetclover, white	G	Ohio	Miami silt loam	0, 0.6, 1.3, 2.5	0.6–1.3	Moore (1943)
Sweetclover, yellow 'Madrid'	F1	Nebraska	Sharpsburg silty clay loam	1.9, 3.8, 5.7	1.9	Haskins and Gorz (1975)
Sweetclover, yellow	G	Ohio	Miami silt loam	0, 0.6, 1.3, 2.5	0.6–2.5	Moore (1943)

TABLE 2.8. continued.

Species and cultivar (if stated)	Environment[1]	State	Soil type(s)	Planting depth		Reference
				Tested	Optimum	
				cm		
Woollypod vetch 'Lana'	G	California	Unknown sand	1.0, 5.0, 10.0, 15.0	1–15	Williams (1967)
White clover	G/F1	Minnesota	Carrington, Clinton, Clarion silt loams, Merrimac loamy sand	0, 1.3, 2.5, 5.1, 7.6	0–1.3	Murphy and Arny (1939)

G, Greenhouse; F1, Field - natural rainfall; F2, Field - irrigated at planting; F3, Field - irrigated; F4, Field - 129–256 mm irrigation at 28 d; F5, Field - 304–406 mm irrigation

comprised of tillers, rhizomes, or stolons. Research from the 1950s is still relevant and recommendations have remained unchanged. Sprigs should generally be planted 3–5 cm deep into moist soil (Taliaferro et al., 2004). Chiles et al. (1966) reported a decrease in sprig emergence as depth increased from 2.5 cm to 10 cm, with 'Greenfield', 'Midland', and 'Coastal' bermudagrass. 'Coastal' was negatively affected by planting deeper than 5.1 cm. Under dryland conditions, sprigs should be planted 5.1–6.4 cm deep; if irrigated, sprigs should be planted 3.8–5.1 cm deep (Stichler and Bade, 1996). Some newer hybrids, such as 'Jiggs' and 'Tifton 85', can also be planted using "tops" which are stolons or aboveground stems. For a "top" to take root, it must be mature, at least 6 wk old, and have six or more nodes (Stichler and Bade, 1996).

The biomass species miscanthus and giant reed are sterile and can only be established vegetatively from rhizomes or stems (Huisman and Kortleve, 1994; Decruyenaere and Holt, 2001). Most research plantings have been done by hand; however, commercial planting of rhizomes and stems can be done with the use of adaptations of existing equipment, such as potato or bulb planters.

Conclusion—Planting Depth

The General Criteria of Code 512 specify planting at a depth appropriate for the seed size or plant material while assuring uniform contact with soil. We summarized 30 articles that overwhelmingly supported the specification of planting at the proper depth to achieve the purpose of successful establishment of forage and biomass. Generally, small seeds should be planted near the soil surface and larger seeds should be planted deeper to ensure adequate coverage by the soil. A good guide is to plant seed no deeper than seven times the seed diameter.

Operation and Maintenance specifications of Code 512 recommend that the operator will inspect and calibrate equipment to ensure proper rate and depth of planting material. Recalibration will be required when changing the species, or perhaps even cultivars, because seed sizes vary.

PROTECTION OF PLANTINGS—POSTSEEDING MANAGEMENT

During the period between seedling emergence and utilization for the intended purpose, a new pasture can be mowed or grazed to reduce weed competition and water requirements, and thus enhance its establishment. Mowing or grazing reduce competition from weeds on the desirable species and allow the stand density to increase by tillering. Conversely, the risk of mowing or grazing too early is that the stand can thin from plants destroyed by the physical disturbance from mowing or 'pulling' during grazing. One anecdotal guideline is to use the "pull" test to ensure that seedling roots are sufficiently developed to withstand grazing. In this section, we discuss postseeding mowing and grazing management during establishment.

Almost all research on postseeding management has been on grasslands that are intended for livestock and/or hay production. There is little information on the postseeding management of grasslands intended for erosion control,

TABLE 2.9. Summary of published literature on planting depth for grass species, environment, and soil type.

Species (and cultivar if stated)	Environment[1]	State	Soil type(s)	Planting depth: Tested (cm)	Planting depth: Optimum (cm)	Reference
Bromegrass 'Gala'	G/F1	Pennsylvania	Hagerstown silt loam	1.0, 3.0, 6.0	1–3	Sanderson and Elwinger (2004)
Buffelgrass	G	Texas	Hildago sandy clay loam	0, 0.6, 1.2, 2.4	0.6–1.2	Mutz and Scifres (1975)
Buffelgrass	G	Texas	Clareville clay loam	0, 0.6, 1.2, 2.4	0.6–1.2	Mutz and Scifres (1975)
Buffelgrass	G	Texas	Victoria clay	0, 0.6, 1.2, 2.4	0.6	Mutz and Scifres (1975)
Eastern gamagrass 'Pete'	F1	Iowa	Canistio silty clay loam	2.5, 5.0	2.5–5.0	Aberle et al. (2003)
Kleingrass 'Selection 75'	G	Texas	Valera clay	1, 2, 4, 4, 6, 8	0–6	Tischler and Voight (1983)
Orchardgrass 'Dawn' 'Pennlate'	G/F1	Pennsylvania	Hagerstown silt loam	1.0, 3.0, 6.0	1–3	Sanderson and Elwinger (2004)
Orchardgrass	G	Ohio	Miami silt loam	0, 0.6, 1.3, 2.5	0.6–2.5	Moore (1943)
Perennial ryegrass 'Madera' 'Mongita' 'Moranda'	G/F1	Pennsylvania	Hagerstown silt loam	1.0, 3.0, 6.0	1–3	Sanderson and Elwinger (2004)
Prairiegrass (rescuegrass) 'Matua'	G/F1	Pennsylvania	Hagerstown silt loam	1.0, 3.0, 6.0	1–3	Sanderson and Elwinger (2004)
Smooth bromegrass 'Lincoln'	G	North Dakota	Lihen sandy loam	0.6, 2.6, 5.1, 7.6, 10.2	2.6	Ries and Hofmann (1995)
Reed canarygrass	G/F1	Minnesota	Carrington, Clinton, Clarion silt loams, Merrimac loamy sand	0, 1.3, 2.5, 5.1, 7.6	0–1.3	Murphy and Arny (1939)
Smooth bromegrass 'Lincoln'	F1	Nebraska	Kennebec silt loam	1.5, 3.0,4.5, 6.0	1.5	Newman and Moser (1988)
Sudangrass	G	Ohio	Miami silt loam	0, 0.6, 1.3, 2.5, 3.8, 5.1	0.6–5.1	Moore (1943)
Sudangrass	G	Tennessee	Cumberland silt loam	2.5, 5.1, 7.6, 10.2	2.5–5.1	Moore (1943)
Switchgrass 'Alamo'	G	Alabama	Unknown loamy sand	0, 0.5, 1.0, 1.5, 2, 2.5	0.5–2.5	Miller and Owsley (1994)
Switchgrass 'Alamo'	G	Alabama	Unknown clay loam	0, 0.5, 1.0, 1.5, 2, 2.5	1.0	Miller and Owsley (1994)
Switchgrass 'Blackwell'	F4	Texas	Pullman clay loam	0.6, 1.3, 3.8, 6.4	0.6–1.3	Hudspeth and Taylor (1961)
Switchgrass 'Pathfinder' 'Trailblazer'	F1	Nebraska	Kennebec silt loam	1.5, 3.0, 4.5, 6.0	1.5–3	Newman and Moser (1988)
Switchgrass–local ecotype	G	Canada	Unknown sand	0, 2, 4, 6, 8, 10, 12, 14, 16	2–8	Zhang and Maun (1990)
Tall fescue 'KY31'	G	Oklahoma	Unknown sandy loam	1.3, 2.5, 3.8, 5.1	0.6–3.8	Walker et al. (2001)

TABLE 2.9. continued.

Species (and cultivar if stated)	Environment[1]	State	Soil type(s)	Planting depth		Reference
				Tested	Optimum	
				cm		
Tef–VNS	G	Kansas	Keith silt loam	0, 0.6, 1.3, 2.5, 5	0.6–1.3	Evert et al. (2009)
Timothy	G	Ohio	Miami silt loam	0, 0.6, 1.3, 2.5	0.6–1.3	Moore (1943)
Timothy	G/F1	Minnesota	Carrington, Clinton, Clarion silt loams	0, 1.3, 2.5, 5.1, 7.6	0–1.3	Murphy and Arny (1939)
Timothy	G/F1	Minnesota	Merrimac loamy sand	0, 1.3, 2.5, 5.1, 7.6	0–1.3	Murphy and Arny (1939)

[1]G, Greenhouse; F1, Field - natural rainfall; F4, Field - 129–256 mm irrigation at 28 d.

biomass, or wildlife. These latter uses are also probably optimized by successful and rapid establishment so postseeding management is likely to be similar for all purposes. Regardless of the final use, during this part of the establishment period there is continued risk for environmental degradation.

Recommendations for postharvest management vary with factors such as seeding date, location, and seeding mixture. One detailed study on spring-seeded alfalfa in Minnesota found that under optimal conditions, seeding year yield was maximized when the initial harvest was made 60 d after spring emergence (compared with 40 d or 80 d) followed by two or three subsequent harvests (Sheaffer, 1983). The harvest schedules that resulted in the greatest total season yield varied among locations and years. In Wisconsin, an annual ryegrass companion crop harvested 60 d after spring planting (and subsequent harvests at 33-d intervals) reduced alfalfa yield and stand density compared with delaying the initial harvest until 67 d or 80 d (Sulc et al., 1993a).

Grazing during establishment to reduce competition depends on site-specific conditions. Contrary to the recommendation at that time of not grazing new stands of crested wheatgrass during the seeding year, Hull (1944) found that under ideal conditions in Idaho, moderate grazing may be practiced. Without herbicide use grazing is necessary for establishment of seedlings when seed is broadcast or no-till drilled into established stands (Barker and Dymock, 1993). Existing vegetation needs to be controlled by regular mowing or grazing to reduce competition and allow light to the establishing seedlings.

In Florida, grazing to 7.5 cm resulted in a greater contribution from joint vetch that had been broadcast into limpograss pasture, compared to grazing to 15 cm (Sollenberger et al., 1987). In a species-poor permanent grassland in Germany, forbs were broadcast seeded to increase species diversity and nutritive value (Hofmann and Isselstein, 2005). In that study, the best results were from mowing nine times before the spring seeding at weekly intervals to simulate grazing, and then every 3 wk after seeding. This carried over to the second year where the addition of forbs increased long-term yield, but the frequent cutting had a negative effect on total yield.

Conclusion—Postseeding Management

In the General Criteria, Code 512 specifies that livestock shall be excluded until the plants are well established. This is not supported by the literature as grazing can be an effective method of vegetation control during establishment. We summarized six articles that compared postseeding management treatments, and there was consensus for site- and species-specific management in the year of planting. There is evidence of benefits from some mowing and/or grazing to reduce competition from weeds or other forage plants during the establishment period that can allow increased tillering and root growth to improve establishment success. One guideline is to use the "pull" test to ensure that seedling roots are

“Options for weed control include mowing, grazing, companion crops, and chemical control.”

sufficiently developed to withstand modest grazing.

PROTECTION OF PLANTINGS—WEED MANAGEMENT

The primary benefit of weed control is to enhance the establishment of the sown species, and minimize competition from nonsown species in the resultant stand (Barker et al., 1988). Options for weed control include mowing, grazing, companion crops, and chemical control.

Most research on weed control during establishment has been for grasslands for which production is the goal. We did not find any literature comparing weed control practices during establishment for those being established for purposes such as erosion control, C sequestration, wildlife, or biomass production. Intuitively, they are probably similar to that for production. However, some options, such as herbicides, are not acceptable for establishing forages for organic production.

Mowing

Mowing for weed control in forages is generally not very effective (Miller and Strizke, 1995) because it is nonselective and may occur too late to reduce competition between weeds and the seedlings. Late mowing may remove the tops of legume seedlings forcing the young seedlings to regrow from the base. And, if late, the greater amount of residue remaining on the field may continue to shade the seedlings. However, mowing can prevent weeds from going to seed and contributing to the soil seed bank. It is sometimes the best option to suppress grassy weeds, especially when trying to establish perennial grass species in grass–legume mixtures where no herbicides are approved.

Mob Grazing

Mob grazing is stocking a high density of animals in an area for a short duration (up to 1 wk). It reduces selective grazing by livestock to some extent, and thus can be effective in the control of grass weeds and allowing sunlight to the new seedlings (Miller and Strizke, 1995). In addition, the grazed material is removed from the area and no longer shades. However, grazing must be delayed until seedling roots are well established or the seedlings can be uprooted. Often, as with mowing, the efficacy of mob-grazing is only moderate, because it is applied too late to have maximum benefit in reducing weed competition for moisture, sunlight, and nutrients, and damage to the soil from foot traffic may be significant. Further, unpalatable weeds might not be grazed and the young forage seedlings may be preferred to weed species.

Companion Crops

Companion crops such as annual ryegrass, oats, rye or triticale are sometimes seeded at reduced rates and used with spring-seeded alfalfa in northern latitudes to provide quicker ground cover, help reduce wind and water erosion, and deter weed growth during forage establishment (Kust, 1968; Schmid and Behrens, 1972; Chapko et al., 1991; Becker et al., 1998; Jefferson et al., 2005). Use of companion crops should be based on site-specific conditions such as erosion potential and forage needs during the establishment year (Hoy et al., 2002). However, shade from companion crops can also reduce alfalfa establishment and yield (Lanini et al., 1991), especially in southern latitudes where alfalfa is seeded in the fall. Hall et al. (1995) reported pre- and postemergence herbicides provided better weed control and higher forage yields than a companion crop; thus herbicides are generally replacing companion crops for weed suppression for monocultures (Brothers et al., 1994), except on organic plantings.

Chemical Weed Control

Most research on weed control in pastures has been with fully established pastures (NRCS Conservation Practice Standard, Herbaceous Weed Control, Code 315), which are not discussed in this section. Most references citing effects of chemical weed control during establishment are on monocultures, mainly for spring seedings of alfalfa and some perennial warm-season grasses. Cool-season grasses are usually seeded in fall and few herbicides are registered for use on grass–legume mixtures. Therefore, this literature synthesis and discussion of weed control options draws on the research implicit for the chemical labels in addition to refereed journal articles. Data from industry for registration is thoroughly reviewed for authenticity and should be reliable. As a caution, however, full herbicide labels change and the current label is the only reliable or legal reference for use at a specific location or on a specific crop.

The point at which grassland is legally considered established for the purpose of herbicides use for pastures is usually defined in the label by the number of leaves. For labeling purposes, a grass seedling is usually *established* when it reaches the five-leaf stage. The 2,4-D amine and esters (Agri Star 2,4-D amine 4®, Anonymous, 2008c; Agri Star 2,4-D LV4 4®, Anonymous 2008d; Agri Star 2,4-D LV6®, Anonymous, 2008e) labels state they can be used on newly seeded grasses after the five-leaf stage. Likewise, the triasulfuron label (Amber®; Anonymous, 2006a) states that it can be used on newly established pastures for broadleaf weed control 60 d after emergence, which is approximately when perennial grass seedlings reach the five-leaf stage. Ries and Svejcar (1991) also reported that seedlings are considered established when seedlings form adventitious roots, which occurred between the four- and six-leaf stage in their study.

Frequently, weed control experiments report on formulations that are no longer registered (McMurphy, 1969; Fermanian et al., 1980; Bovey and Voigt, 1983; Bovey et al., 1986; Bovey and Hussey, 1991) or formulations that do not have approval for use on seedings to be grazed (e.g., atrazine, bromoxynil, metribuzin, siduron, quinclorac, MSMA) (McMurphy, 1969; Peters and Lowance, 1970; Fermanian et al., 1980; Bovey and Voigt, 1983; Bovey et al., 1986; Bovey and Hussey, 1991). Other formulations are not labeled for the reported crop (e.g., imazethapyr, metolachlor; Griffin et al., 1988; Masters, 1997; Beran et al., 2000). In this review, care was taken to not include these experiments except for the effect of weed reduction at a certain growth stage on the establishment success.

Labels are often specific not only for the crop being treated, but for the management used, the weed problems, and the location, region, or state of the USA where it can be used. Aatrex® (atrazine; Anonymous, 2008a) is labeled only for CRP plantings and it is not approved for grazing, except for grazing sorghum–sudan grass hybrids. Quinclorac (Paramount®, Anonymous, 2008e) is labeled for grass seed production, but it is not approved for grazing. Metolachlor (Dual II Magnum®, Anonymous, 2004a) has a 30-d grazing restriction in soybeans and a 120-d grazing restriction for pod crops such as peas and cowpeas. Imazethapyr (Pursuit®, Anonymous, 2008f or Thunder®, Anonymous, 2007b) is labeled for a number of forage legumes when used only as cover crops (i.e., alfalfa, birdsfoot trefoil, crownvetch, kudzu, lespedeza, lupin, milkvetch, sainfoin, velvet bean, and vetch), and has a 30-d grazing restriction for alfalfa and clovers. Bromoxynil (Buctril®, Anonymous, 2000a) has a 30-d grazing restriction for alfalfa, but is not labeled for other perennial legumes. In all cases, the current label is the only reliable guide.

A strategy for weed management during establishment must consider herbicide residues, primarily from the previous crop, especially when legumes follow grass crops and vice versa. Herbicide labels must be read carefully and planting restrictions must be followed. Soil tillage has commonly been used to reduce injury due to residual herbicide from a previous crop (Hall and Vough, 2007). There is also some potential for a negative environmental impact resulting from herbicide use. Excessive atrazine use and potential carryover can restrict the species options on treated land; however, any effect is likely to dissipate within 2 yr.

A cultivated seed bed before and after passage of a cultipacker-type seed drill. The front roller makes a shallow channel in which seed drops from a seed box; the back roller presses the seed into the soil and gives some soil coverage. Credit: David Barker, Ohio State University.

Other herbicides with potential mammalian toxicity (e.g., paraquat) have not been reported to have pronounced effects on nontarget species; however, this herbicide is being used less frequently than in previous years (Barker and Zhang, 1988). Some notorious negative effects of long-term use of agrichemicals on the environment have resulted in more carefully regulated use of these valuable tools.

Hybrid Bermudagrass

The most effective herbicide to control small-seeded grasses and broadleaf weeds during bermudagrass establishment from sprigs is diuron (Direx®, Anonymous, 2003a), which can be applied immediately after sprigging, but before the new growth emerges. In addition, 2,4-D amine plus dicamba (Weedmaster®, Anonymous, 2008h), 2,4-D amine (Anonymous, 2008c), 2,4-D LV6 (Anonymous, 2008e), and 2,4-D acid plus dicamba acid (Outlaw®, Anonymous, 2003b) can be applied any time after sprigging to control small-seeded grasses such as crabgrass, if applied when crabgrass is germinating (within 10 d of planting), or to control emerged broadleaf weeds (Butler et al., 2006a, 2006b). Alternatively, 2,4-D amine plus picloram (Grazon P+D®; Anonymous, 2009a) can be used on hybrid bermudagrass established by sprigging after stolons reach 15 cm.

Seeded Native Warm-Season Perennial Grasses

For big bluestem, imazapic (Impose®, Anonymous, 2007a; Beran et al., 2000) can be applied prior to planting or after seedlings reach the five-leaf stage to control many annual grasses such as crabgrass, broadleaf signalgrass, fall panicum, Texas panicum, sandbur, yellow nutsedge, and seedling johnsongrass, which can be problematic weeds during establishment. Imazapic does not have a grazing restriction, but treated areas should not be cut for hay for at least 7 d after application. Big bluestem was successfully established with imazethapyr (Beran et al., 2000) and atrazine can be used on CRP plantings of big bluestem to improve establishment (Martin et al., 1982; Masters, 1995; Anonymous, 2008a). Hintz et al. (1998) reported that big bluestem could be successfully established with atrazine and corn as a companion crop, since it is labeled for corn. Areas treated with atrazine have

Alfalfa seedlings 4 mo after spring seeding in Ohio using a cultipacker-type seed drill seen in previous photo. Credit: David Barker, Ohio State University a grazing restriction; however, this is not a major factor because new plantings of big bluestem should not be grazed during the establishment year.

Big bluestem has been reported to be tolerant to metolachlor (Griffin et al., 1988; Masters, 1997); however, it is not labeled for use in pastures. Metolachlor has a 30-d grazing restriction on soybean and a 120-d grazing restriction for pod crops such as peas and beans. Therefore, if big bluestem could be established with a companion crop, then the forage restriction of the primary crop (legume) could be followed to allow establishment of the companion crop. In noncrop areas, sulfosulfuron (Outrider®; Anonymous, 2004b) controls johnsongrass, yellow nutsedge, purple nutsedge, and tall fescue when applied to newly seeded big bluestem after the three-leaf stage; however, treated areas may not be grazed because sulfosulfuron is approved for grazing only in bermudagrass and bahiagrass pastures (Outrider® supplemental label; Anonymous, 2008b). In noncrop areas or where big bluestem is grown for seed production only, quinclorac plus methylated seed oil may be applied to control several annual grasses if the treated areas are not to be grazed.

For indiangrass, imazapic (Impose®; Anonymous, 2007a) can be applied prior to planting or after seedlings reach the five-leaf stage to control many annual grasses such as crabgrass, broadleaf signalgrass, fall panicum, Texas panicum, sandbur, yellow nutsedge, and seedling johnsongrass. On established plantings, imazapic does not have a grazing restriction, but treated areas should not be cut for hay for at least 7 d after application. In noncrop areas, sulfosulfuron (Outrider®; Anonymous, 2004b) controls johnsongrass, yellow nutsedge, purple nutsedge, and tall fescue when applied to newly seeded indiangrass after the three-leaf stage. However, treated areas may not be grazed during that season since sulfosulfuron is approved only for grazing in bermudagrass and bahiagrass pastures (Outrider® supplemental label; Anonymous, 2008d).

Switchgrass is categorized into upland and lowland ecotypes, which vary in their response to herbicides and management. McMurphy (1969) reported that 1.6 kg siduron ha^{-1} controlled crabgrass with no effect on 'Caddo' upland switchgrass. However, Bovey and Hussey (1991) reported excessive injury to 'Alamo' lowland switchgrass at 2.2 kg siduron ha^{-1}. 'Pathfinder' upland switchgrass tolerated pre-emergent applications of atrazine, which greatly improved establishment (Martin et al., 1982; Vogel, 1987; Masters et al., 1996; Hintz et al., 1998). McKenna et al. (1991) reported that 'Pathfinder' upland switchgrass injury increased as the rate of atrazine increased from 1.1 to 2.2 kg ha^{-1}. Atrazine suppressed the growth of 'Pathfinder' upland switchgrass and injury was greater on a sandy loam soil compared to a silty clay loam soil (Bahler et al., 1984). Upland switchgrass could be established with atrazine with corn used as a companion crop, because it is labeled for corn (Hintz et al., 1998).

> "Switchgrass is categorized into upland and lowland ecotypes, which vary in their response to herbicides and management."

Atrazine at 1.1 kg ha^{-1} can cause excessive injury to lowland 'Alamo' switchgrass and should not be used (Bovey and Hussey, 1991), whereas upland 'Cave in Rock' switchgrass tolerated this rate. Rainfall immediately after planting may reduce atrazine activity on lowland switchgrass. In one year, rainfall occurred the day after treating with atrazine and the lowland switchgrass was killed. In the second year rainfall did not occur for 2 wk after treatment and the lowland switchgrass had only transient injury (T. J. Butler, unpublished data). Imazethapyr was a viable replacement option for atrazine when big bluestem was being established, but not for 'Trailblazer' upland switchgrass, because results were not consistent across locations (Masters et al., 1996).

In noncrop areas, sulfosulfuron (Outrider®; Anonymous, 2004b) controls johnsongrass, yellow nutsedge, purple nutsedge, and tall fescue when applied to newly seeded switchgrass after the three-leaf stage; however, treated areas may not be grazed, because sulfosulfuron is approved for grazing of only bermudagrass and bahiagrass pastures (Outrider® supplemental label; Anonymous, 2008d). In noncrop areas or switchgrass grown for seed production only, quinclorac (Paramount®, Anonymous, 2008e) plus methylated seed oil may be applied to control

“There are several herbicide options for establishing alfalfa”

seedlings of several annual grasses, if the treated areas are not to be grazed.

The quinclorac label will likely be expanded to include switchgrass grown for biofuel. Already, nicosulfuron has received a 24(c) special local need label in Tennessee to control certain annual grasses and johnsongrass after the switchgrass has reached two-leaf stage (Accent®, Anonymous, 2008b). Other states will likely be added to the 24(c) label if switchgrass is grown for biofuel and the treated areas are not grazed.

Griffin et al. (1988) reported that NA (1,8-napthalic anhydride) improved resistance of switchgrass seedlings to metolachlor; however, there has been relatively little research evaluating seed safeners to improve forage establishment (Roder et al., 1987). Based on the literature, most herbicide recommendations for establishing switchgrass are unreliable, especially for lowland ecotypes.

Introduced Warm-Season Grasses

Weed control greatly increased the success of establishment in seeded bermudagrass (Fermanian et al., 1980), weeping lovegrass (Bovey and Voigt, 1983), and buffelgrass, kleingrass, Wilman lovegrass, WW Ironmaster, and WW Spar Old World Bluestem (Bovey et al., 1986; Bovey and Hussey, 1991). But none of the herbicides evaluated has been registered or approved for grazing, so these studies are not discussed.

Cool-Season Perennial Grasses

Only a few studies of herbicide use during establishment of cool-season perennial grasses are reported in the literature. Most herbicides used for establishing small grains or warm-season perennial grasses listed above are detrimental to establishment of cool-season grasses (T. J. Butler, unpublished data). In the Southern Great Plains, successful establishment of tall fescue, tall wheatgrass, and experimental hardinggrass across multiple environments could be achieved by sequentially 1) spraying glyphosate in the spring to eliminate seed production from winter annual grasses prior to the autumn planting, b) delaying seeding (with a drill) until autumn rainfall and emergence of winter annual grasses has occurred, and c) following immediately with another application of glyphosate to control emerged weeds (Butler et al., 2008). This method is also recommended for the Pacific Northwest, but production from the fields is lost for the preceding summer (Thompson, 1970).

Legumes

Alfalfa. There are several herbicide options for establishing alfalfa (Mueller-Warrant and Koch, 1983) some of which may also be used on other legumes (listed in Table 2.10). Although herbicides can give good weed control, the response might not always increase yield or be economic (Hall et al., 1995). Treflan is generally the preferred choice among pre-emergent herbicides, because the cost is significantly lower than alternatives (Anonymous 2008g). Benefin, EPTC, and trifluralin may be incorporated prior to planting to control grass weeds primarily.

Pendamethalin may be applied to the soil after alfalfa reaches the two-leaf stage; however, it must be activated by rain or irrigation to control weeds as they germinate and it does not have any postemergent activity. The herbicide 2,4-DB may be applied to very small broadleaf weeds that are actively growing once alfalfa reaches the two-leaf stage. Bromoxynil will control several broadleaf weeds after alfalfa reaches the four-leaf stage, but like 2,4-DB, bromoxynil will not control grassy weeds. Imazethapyr may be applied to alfalfa after it reaches the two-leaf stage to control both grass and broadleaf weeds that are very small, and it also provides residual weed control. Imazamox can be applied after alfalfa reaches the two-leaf stage to control certain broadleaf and primarily grassy weeds. It tends to have more grass activity than imazethapyr, but it has less residual activity. Clethodim and sethoxydim will control grassy weeds, but not broadleaf weeds. Recommended tank mixes for the simultaneous application of two herbicides (e.g., to control both grasses and broadleaf weeds) are specified in the full versions of herbicide labels.

Roundup Ready® Alfalfa. Following its initial release in 2005, Roundup Ready® (i.e., glyphosate-tolerant) alfalfa was removed from commercial sale during 2007–2010 for additional environmental testing. It was

TABLE 2.10. Herbicides labeled for alfalfa along with conventional use rates, applications timings, grazing or harvest restrictions, and other forage legumes listed on the label.

Active ingredient	Rate ha⁻¹	Timing	Harvest restriction d	Other legumes[1]
Preplant, incorporated				
Benefin	2.24 kg	Preplant, incorporated	–	C, BT
EPTC	7.0 L	Preplant, incorporated	14	C, BT, L
Trifluralin	1.17 L	Preplant, incorporated	21	
Seedling stage				
Bromoxynil	1.8 L	> Four leaf	30	
2,4-DB	4.68 L	Two–four leaf	60	RC, WC, BT
Pronamide	1.68 kg	> One leaf	25	C, CV, S
Imazethapyr	0.2–0.4 L	> Two leaf	30	C, FP,
Sethoxydim	2.3 L (annuals) 4.3 L (perennials)	Early postseeding	14	C, BT, S
Pendimethalin	2.3 L	> Two-leaf alfalfa, prior to weeds	50	
Imazamox	0.3 L	> Two leaf	20	FP, CP
Clethodim	0.6 L (annuals) 1.2 L (perennials)	Early postseeding	15	C, BT, S
Established stands (in addition to seedling stage)				
Flumioxazin	0.3 L	< 15 cm alfalfa, prior to weeds	25	
Paraquat	0.9 L	Postseeding	30	
Pendamethalin	4.7 L	< 15 cm alfalfa, prior to weeds	50	
Norflurazon	0.5–2.8 L	> 5 mo alfalfa, prior to weeds	28	
Trifluralin	2.3–4.6 L	Prior to weeds	21	
Dormant				
Paraquat	1.8 L	> 1 yr, dormant	60	
Diuron	2.8 L	> 1 yr, dormant	70	BT, RC, FP
Pronamide	2.2 kg	Dormant (< 12°C)	25	
Terbacil	1.7 kg	Dormant	–	
Metribuzin	2.3 L	> 1 yr, dormant	28	S
Hexazinone	4.7 L	> 1 yr, dormant	30	

[1]BT, birdsfoot trefoil; C, clovers not specified; CP, cowpea; CV, crownvetch; FP, field pea; L, lespedeza; RC, red clover; S, sainfoin; WC, white clover.

released from USDA regulation and became available commercially in January 2011. Glyphosate (Anonymous, 2005a) may be applied at 0.84–1.68 kg ae ha^{-1} (22–44 fl oz ac^{-1}) from the time of emergence until 5 d prior to first cutting to control many broadleaf and grass weeds, especially perennial weeds that most conventional herbicides do not control. No yield reduction of alfalfa occurred when glyphosate was applied up to 3.36 kg ae ha^{-1}, which is four times the normal rate (Steckel et al., 2007). No differences in establishment or yield were found between Roundup Ready® alfalfa treated with glyphosate and a conventional alfalfa treated with imazamox (Sheaffer et al., 2007). However, Roundup Ready® systems with glyphosate provided more consistent weed control and less injury to the alfalfa compared with the conventional system with imazamox (McCordick et al., 2008). In addition, the conventional herbicides imazamox and imazethapyr caused minor alfalfa injury and 2,4-DB and bromoxynil further decreased crop safety compared to glyphosate (Wilson and Burgener, 2009).

TABLE 2.11. Summary of purposes, criteria used for evaluation, and level of research support of NRCS Conservation Practice Standard, Forage and Biomass Planting, Code 512.

Purposes of the Practice Standard	Criteria used for assessing achievement of purpose	Support by research based on 363 scientific publications and 162 species
Improve or maintain livestock nutrition and health	· By establishing species and cultivars with greater production, and potential to increase animal intake	· Species and cultivars differ in production and quality. But increased livestock production was assumed more likely from increased stocking rate than intake per head.
	· By establishing species and cultivars with greater nutritive value (i.e., energy content, protein or mineral concentration)	· A negative relationship often occurs between production and nutritive value. Less productive species and cultivars (above) can have higher nutritive value.
	· By replacing species with low nutritive value or with high levels of toxic compounds	· Whether through complete stand replacement (e.g., full cultivation) or partial stand replacement (e.g., sod- or no-till seeding), species with greater nutritive value can be introduced into grasslands.
	· By establishing species and cultivars to provide nutrition during periods of feed deficit (e.g., extend forage production season)	· Species and cultivars that are tolerant to cold can improve early-spring and late-autumn production, and those tolerant to heat and drought can improve summer production. Major species are well characterized in the scientific literature.
	· By establishing species with wildlife benefits such as nesting habitat, cover, biodiversity, and insects	· Wildlife species vary in nutritional and habitat requirements that are not met by any single forage species. Species-rich vegetation offers more benefits to wildlife than monocultures.
Provide or increase forage supply during periods of low forage production	· By establishing species and cultivars with greater production potential	· More productive species and cultivars can be harvested for hay or silage, or for use during periods of low forage production.
	· By establishing species with higher environmental tolerance (e.g., cold, heat, drought, pH, salinity)	· Cold- and drought-tolerant species with greater forage production during feed-deficit periods can provide in situ grazing and reduce hay or silage feeding costs.
	· By establishing annual forage crops to fill predicted feed deficits for harvest or grazing	· Annual forage species can be planted into existing grassland or as cover crops in grain systems, to provide forage for in situ grazing or for hay or silage harvest.
Reduce soil erosion	· By establishing perennial species that provide year-round ground cover, and by avoiding cultivation	· Perennial grasslands have year-round soil cover with lower rates of soil loss than bare soil and can be managed for improved persistence.
	· By establishing species with improved adaptation and greater persistence	· Stand longevity of new alfalfa cultivars with multiple insect and disease resistance may be more than double that of older cultivars.
	· By using no-till methods for establishment to alleviate soil cultivation	· Sod- and no-till seeding, especially with herbicide use for vegetation control can successfully establish grasslands.
	· By establishing plants with greater ground cover that reduces the rate of surface water flow	· Plants with greater ground cover and denser vegetation have less runoff and higher water infiltration. Vegetation density is also affected by management.

Other Legumes. Arrowleaf clover was relatively tolerant to 2,4-DB, which was effective in controlling many broadleaf weeds when they are small and actively growing (Conrad and Stritzke, 1980). Both 2,4-DB and bromoxynil were safe on Korean lespedeza, and 2,4-D amine only caused minor injury and provided better ragweed control (Peters and Lowance, 1970). Currently, 2,4-DB is labeled only for alfalfa and seedling birdsfoot trefoil; however, efforts are under way to include other legume species.

TABLE 2.11. continued.

Purposes of the Practice Standard	Criteria used for assessing achievement of purpose	Support by research based on 363 scientific publications and 162 species
Improve soil and water quality	· By establishing species with vigorous root growth that ensures carbon sequestration and nutrient uptake	· In general, grasses have dense, fibrous root systems while legume root systems may include large taproots and crowns; rooting characteristics are affected by management as well as establishment practices.
	· By establishing N-fixing legumes, thus reducing the need for fertilizer N	· Legumes are relatively fast to establish, can be included in grassland mixtures, or can be no-till drilled (sod-seeded) or broadcast seeded (frost-seeded) into grass stands
	· By establishing species that ensure efficient nutrient cycling, and support active populations of soil macro- and micro-organisms	· Nutrient cycling and some soil microbial processes are impaired during establishment, but resume once the stand is established. Later on, nutrient cycling is affected significantly by forage removal as hay or silage.
	· By reducing soil erosion	· Where water quality is a critical issue, new seedings should use no-till methods or fast-establishing companion crops to avoid bare soil or reduce time of bare soil exposure.
Produce feedstock for biofuel or energy production	· By establishing species and cultivars with high biomass potential	· The most productive biofuel feedstocks (miscanthus and giant reed) can be established vegetatively with the use of stems and/or rhizomes. Switchgrass can be established from seed.
	· By establishing species and cultivars with unique characteristics for biofuel or energy production (e.g., low ash, high cellulose)	· Species differ in concentration and types of structural and nonstructural carbohydrates for biofuel purposes. Several forage species have high ash content and may be less suitable for biofuel purposes than others.

Imazethapyr improves establishment of tickclover, roundhead lespedeza, and leadplant better than imazapic, whereas crownvetch, partridgepea, purple prairie clover (Beran et al., 1999) and Illinois bundleflower (Masters et al., 1996; Beran et al., 2000) tolerated both imazapic and imazethapyr. Imazethapyr caused transient injury only to birdsfoot trefoil, cicer milkvetch, red clover, sainfoin, and yellow sweetclover, and did not reduce legume yield (Wilson, 1994). Imazapic is approved for grazing, whereas imazethapyr is approved only for alfalfa, clover, and field peas. Most forage legumes are not listed in the specimen label and there are no chemical weed control options for these crops. Interestingly, if these forage legumes were mixed at planting with alfalfa as a companion crop, then all the labeled herbicides for alfalfa establishment could be used legally, as long as the grazing restrictions were followed for alfalfa as the primary crop.

Conclusion—Weed Management

The Code 512 General Criteria specify that invasion by undesirable plants shall be controlled by cutting, using a selective herbicide, or by grazing management by manipulating livestock type, stocking rates, density, and duration of stay. Insects and diseases shall be controlled when an infestation threatens stand survival. The literature strongly supports the statement that forage establishment is greatly improved when weeds are controlled. Generally, herbicides that selectively kill the undesirable herbaceous vegetation (even with minor crop injury) speed the rate and success of establishment compared to alternative methods, but may not be the most economic strategy. One area of deficiency in the literature is the quantified benefit of herbicide use for other conservation values. Implicitly, the faster a stand can be established to shorten the duration to utilization and lesson the risks of low ground cover, the greater its conservation value will be.

A seasonal, grazing dairy herd on endophyte-free tall fescue pasture in Ohio. Credit: David Barker, Ohio State University.

CONCLUSIONS AND EMERGING ISSUES

Code 512 specifies practices for planting grasslands intended to 1) sustain livestock nutrition and health, 2) provide forage during periods of low supply, 3) reduce soil erosion, 4) improve soil and water quality, and 5) produce feedstock for bioindustrial purposes. The objective of this chapter was to evaluate the research to determine if it supports the purposes and criteria of the practices described in the Standard. We summarized 363 publications related to grassland establishment, and found a high degree of consensus between the recommended practices in the standard and the research literature (Table 2.11). Most of the basic principles are known, and local experts can fine-tune the recommendations to increase the chances for establishment success.

The literature was deficient in some areas of research. In general, past research has focused primarily on grass and legume establishment in support of livestock production, and primarily on a limited number of popular species. Specific emphasis has included total forage production (for grazing, hay, or silage), forage quality, and to a lesser extent, the seasonality of production. Some forage literature addressed other ecosystem services (e.g., erosion, wildlife, water quality, carbon sequestration, and biofuels); however, this research was mainly conducted in mature pastures and hayfields, i.e., on the desired result, and rarely considered the establishment period.

In general, establishment practices are similar for all purposes for which a stand might be used. In cases where erosion and water quality are of special concern, establishment practices that avoid full cultivation are most likely justified, but there were no studies directed at this relationship. Further, it is not known if establishment practices differ in their effect on carbon sequestration; however, species selection and their postestablishment management can greatly influence the net carbon balance of a grassland system. This was very evident in the number of species evaluated in that several 'minor' species may be the best for delivery of priority environmental of ecosystem services with adequate, but not optimum production value (Table 2.11).

Researchers have a daunting task to describe interactions for all grassland species (162 in this chapter), in all topographies, for all climate zones within the USA, and for all the purposes for which these species can be used. To this extent, grassland establishment cannot be completely supported in all respects by research, and practitioners will be forced to extrapolate establishment guidelines to individual fields, producers, and purposes. In this respect, Code 512 is valid to recommend input from local plant materials programs, land grant and research institutions, extension agencies, or agency field trials. Even so, there is a need for modeling approaches to allow more effective transfer of technology and cost–benefit relationships to assist in decision making on species and establishment practices at the local level.

The scientific literature includes relatively little information on establishment failures, yet it is common knowledge that several systems tried did not work and were not published. One publication (Bartholomew, 2005) estimated that 7–55% of the cases resulted in failures of forage reseedings, and recommends this cost be included in economic analyses. We have incomplete information on factors contributing to establishment failure, something that likely varies from location to location because of soil and climate, with amount of management input. If unsuccessful approaches were studied the scientists could learn and perhaps use the information to alter practices to overcome the problems, but without some basic information everyone begins with no information. This is especially critical because the variety of purposes emerging will demand data and recommendations on a greater variety of species than currently used for production.

Several emerging issues are likely to affect future forage establishment practices:

1. Roundup Ready® technology has been introduced to alfalfa, but the effect this technology might have on establishment practices is yet unknown. Emerging technologies take time to conduct the research to be published, and then the publication process may take an additional year or more.
2. The organic forage-based livestock industry has been growing at a steady rate in the USA (approx. 18% yr^{-1}). The restriction on the use of agrichemicals and genetically modified plant species within these systems intensify the need for research on successful establishment practices for pastures and hayfields. Many organic plantings were established with conventional methods and transitioned into organic production, but new forage seedings will require establishment using organic principles including the use of seed grown organically.
3. New technologies (e.g., polymer seed coats, new rhizobium strains) are being developed that will improve seed longevity in storage, and improve establishment success.
4. New cultivars are continually being developed in most species used for production with faster and more uniform emergence characteristics.
5. Seed quality is being recognized as an important factor, and more specialized methods for production and storage are being developed.
6. New equipment for seeding to assure good soil–seed contact and improved pesticides will continue to be evaluated.
7. Hayfields and pastures will continue to occupy the most erosive land sites and global change and ecosystem expectations and regulations will gain emphasis.
8. More emphasis is needed on establishing principles of potential biofuel crops and those species that will improve grasslands for environmental and ecosystem services.
9. There is a strong need for modeling research to strengthen the interrelationships among principles to allow decision makers to evaluate species and establishment methods to most effectively meet the broader goals of the landowner.
10. There will be a greater need for monitoring to insure the practice implemented is working and will be successful. This will need to be linked with landowner education and enhanced ability to have adaptive management to steer the practice to success.

“Several emerging issues are likely to affect future forage establishment practices”

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