CHAPTER 10

MANAGING INPUTS FOR PEAK PRODUCTION

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Chapter 10

Successful soybean production requires the integration of inputs into a system that contains only those items necessary to optimize amount of a quality product or net return. Inputs such as seed, pesticides, fertilizers, labor, machinery, and fuel that are basic to any management system, plus costs associated with financing, land (rent or ownership), and irrigation where used, must all be considered and manipulated to provide the optimum opportunity for profit. The selection of a management system for a given farm or production entity must be based on local conditions such as weather, soil properties, land cost, markets, land use restrictions, and environmental constraints.

This chapter presents discussion based on crop management research results reported since the soybean monograph chapters by Johnson (1987), and Van Doren and Reicosky (1987). Our goal is to synopsize recent research on and recommendations for specific areas of soybean management to maximize production. References that present information about a particular subject are used to suggest components of a production plan for both the southern and northern United States. Such references include recently published management guides (Honeycutt, 1996; Heatherly and Hodges, 1999; Hoeft et al., 2000). Sections on cultivar selection, tillage, soil fertility, planting practices, cropping systems, and post-planting management and harvesting are included. For reader convenience, both SI and English units of measure are often presented (rounding may cause slight disagreement between values). Where only SI units are shown, an equation for conversion to English units is given. Designations for both vegetative [fully developed unifoliolate leaves (V1) to fully developed last leaf (V*n*)] and reproductive [beginning bloom (R1) to full maturity (R8)] developmental stages are used as defined by Fehr and Caviness (1977).

Soybean management often differs between the northern and southern USA. For purposes of presentation of information in this chapter, southern USA refers to the states of Alabama, Arkansas, Florida, Georgia, Louisiana, Maryland, Mississippi, North Carolina, South Carolina, Virginia, Tennessee, and Texas. The remaining soybean producing states are referred to as the northern USA (or the midwest). Most of the USA soybean production is concentrated in the northern or midwestern states; between 1995 and 2000, only 14.5 to 18% of the USA hectarage was in the southern states, while production in the northern states ranged from 85.2% to 89.9% of total USA production. Average yield in the southern USA was only 74% of the average yield for the entire USA during the same period.

10-1 CULTIVAR SELECTION

Cultivar selection is the first step to successful soybean management. New, improved cultivars are continually released to producers by both public and private soybean breeders. These cultivars are evaluated in different production environments to determine their yield potential and supplemental traits such as resistance to diseases, nematodes, and insects, and tolerance to commonly used herbicides. Producers should always consider annually released new cultivars given that genetic improvement in yield is occurring at the rate of about 30 kg ha^{-1} yr^{-1} (about 0.45 bu $acre^{-1}$ yr^{-1}) (Specht et al., 1999). Results from cultivar trials conducted by both public (Table 10-1) and private institutions should be consulted each year to determine if a new cultivar offers higher yield potential than one currently being grown by the producer. Maturity and seed cost also should be considered when selecting a cultivar. With hundreds of soybean cultivars available in the USA, selection can be based on very narrow criteria to ensure that the chosen cultivar matches as many of the requirements as possible for a particular production scheme. When selecting a cultivar for special environments, it is important to ensure that unnecessary risks are not assumed. For instance, a cultivar with genetic resistance to soybean cyst nematode (SCN; *Heterodera glycines* Ichinohe) is not necessary for maximum yield potential on the fine-textured clay soils in the lower Mississippi River alluvial flood plain because populations of SCN are not maintained in these soils (Heatherly and Young, 1991).

The choice of cultivars should be based on desired plant properties or growing conditions. However, seed of public cultivars generally are less expensive than those of private non-transgenic cultivars, which in turn are cheaper than those of most transgenic cultivars. Thus, if cultivars are determined to be equal in desired traits, the choice can be based solely on seed cost.

10-1.1 Maturity Classification

Soybean cultivars are classified by maturity group (MG). The thirteen MGs are ordinarily expressed as Roman numerals (MG 000 being the earliest and MG X being the latest) that are used for identifying the region of adaptation for soybean. In this chapter, Arabic numbers will be used to accommodate fractional MG designations. Maturity Group zones represent defined areas where a cultivar is best adapted; however, this does not imply that cultivars of a specific MG can be grown only in that particular region. Cultivars of two to three MGs are often grown successfully at a specific site within a MG zone. The MG(s) adapted to a particular area can be determined from those that are tested in each state's cultivar trial (Table 10-1).

Plant development, from germination through the onset of flowering and on to maturity, is controlled by photoperiod and temperature (Major et al., 1975). How cultivars respond to these abiotic factors determines which MG they fall into. Soybean is a short-day plant species, because floral induction in apical and axillary meristems occurs only when days are shorter than some critical length. After floral induction occurs, temperature determines the time required for the appearance of flowers. Floral induction in southern USA cultivars is delayed by long days, making these cultivars too late to be grown in the northern USA. Conversely, northern USA cultivars flower and mature too early when grown in shorter daylengths of the southern USA. Later, we discuss reasons cultivars of a particular MG might be grown outside their region of photoperiodic adaptation.

Cultivars are often arbitrarily designated as early-, mid-, or full-season (Johnson, 1987). These terms describe the relative maturity of cultivars based on the length of growing season in a given region. The early-, mid-, and full-season classification is thus location-specific, since a cultivar classified as full-season in one location would be considered early-season in a more southerly location. For instance, in east-central Nebraska, MG 2.0 cultivars are considered early-season, MG 2.5--3.0 cultivars are mid-season, and MG 3.5 cultivars are considered full-season. In the southern USA, MG 3 and 4 cultivars are considered early-season and are used in the Early Soybean Production System (ESPS; approximate 4.5-month growing season from late March/early April through mid-August), whereas cultivars in MGs 5, 6, and 7 are considered mid- to full-season and are used for plantings that encompass the previous normal-length season of 5.5 months from early May to mid-October. Thus, it is important to have a specific growing season length or period in mind when selecting cultivars for any region.

Soybean breeders assign a cultivar to a MG based on its adaptation to the conventional planting practices used in the region. The ESPS in the southern USA is an example of using cultivars outside their assigned MG region of adaptability. In this system, indeterminate cultivars in MGs 3 and 4 are planted in late March and April in the zones ordinarily assigned to MGs 5, 6, and 7. These cultivars begin blooming (R1) in May, start setting pods in late May to early June, and reach full seed (R6) in mid-July to early August. The reason for using this system and its requisite early-maturing cultivars is to avoid drought that can adversely affect the later-maturing, full-season cultivars that are normally assigned to the region. The later-maturing cultivars are in reproductive phases during July and August when conditions that favor drought stress are common. Conversely, northern growers may use late-maturing cultivars for forage production. However, in Minnesota, late cultivars (MGs 5, 6, and 7) did not reach R6 before frost when planted from early to late May, produced forage yields that were similar to those from adapted cultivars (MGs 1 and 2), and had lower forage quality because of the low percentage of grain (Sheaffer et al., 2001).

10-1.2 Stem Growth Habit

Cultivars in MGs 000 through 4 generally are classified as having indeterminate growth habit, whereas those in MGs 5 through 10 are classified as having determinate growth habit. Stem growth habit is governed primarily by a genetic locus (Dt_1/dt_1) whose contrasting genes give rise to an apical meristem that is (dt_1) or is not (Dt_1) florally induced when daylengths are shorter than a critical daylength (Bernard, 1972). In determinate (dt_1dt_1) plants, stem apices and axillary meristems on main-stem nodes are converted immediately from vegetative to floral meristems. Later near-simultaneous appearance of flowers occurs at all nodes plus the stem tip. The uppermost leaf is usually as large as the leaf below, but can be smaller if its vegetative development was arrested during its primordial stage by the floral induction process. In the southern USA, indeterminate cultivars generally produce lateral branches only at the lowermost nodes (Pattern 12 in Lersten and Carlson, 1987), while determinate cultivars produce lateral branches from nodes over the entire length of the main stem (Pattern 22 in Lersten and Carlson, 1987). Thus, plants of determinate cultivars grown in the southern USA usually have a bushier canopy than those of indeterminate cultivars. Hartung et al. (1981) found that the primary effect of the determinate gene (dt_1) in isolines with similar maturity when grown in Nebraska was a severe shortening of stem length that resulted in pod distribution being compressed into few nodes along the main stem. This resulted in more pods at the upper and lower portions of the shorter stems of the determinate isolines.

Determinate plants will usually have a distinct cluster of pods borne on a pronounced apical raceme. In contrast, Dt_1Dt_1 indeterminate plants bear apical meristems that are resistant to floral induction, whereas axillary meristems undergo floral induction, though not simultaneously. In general, the first flower appears at the V6 node, with floral appearance spreading downward and upward from there. The stem apices almost invariably remain vegetative, producing more leaves. However, as reproductive development proceeds, photosynthate is preferentially allocated to the developing pods, thus leading to ever smaller leaves at the stem apex. Eventually, apical stem growth slows and then ceases vegetative activity before floral induction and flower appearance. In optimum environments, the pod clusters on indeterminate plant stem tips may appear to be determinate, but the clustering is almost always due to short internodes at the stem tip.

Cooper (1981) suggested that lodging was a yield-reducing factor in traditional indeterminate cultivars. Subsequently, semi-dwarf (actually dt_1dt_1 determinates) cultivars adapted for northern USA latitudes have been developed and released. These cultivars achieve 80% of their main stem height by R1 and 92--93% of their final height within 1 wk after R1 (Lin and Nelson, 1988). They generally are shorter, have fewer nodes (generally half as many), have lower pod heights on the main stem, and lodge less than indeterminate types. Stem growth habit can be modified to semi-determinancy via a second genetic locus (Dt_2/dt_2). Semi-determinate ($Dt_1Dt_1Dt_2Dt_2$) plants have stem tips that are less responsive to floral induction than are determinate (dt_1dt_1__) plants, allowing more vegetaive stem growth (i.e., more nodes) because of a less abrupt conversion of the stem apex from its vegetative to reproductive state. Semi-determinate cultivars lodge less than indeterminate cultivars, but have more nodes than semi-dwarf cultivars. A highly productive semi-determinate cultivar ('NE 3001') recently was released in Nebraska (George Graef, personal communication, 2002).

Determinate cultivars have played an important role in the northern production area since the late 1970s. In high-yield environments, determinate cultivars in MGs 2 and 3 yielded better than indeterminate cultivars and yielded similar following stress that occurred during the late vegetative through reproductive phases (Elmore et al., 1987). Determinate cultivars in MGs 0 to 2 grown in Minnesota were found useful in improving lodging resistance and yield (Foley et al., 1986). Work with MG 1 and MG 2 cultivars in Ontario, Canada shows that breeding for high yield and yield stability in determinate and semi-determinate cultivars is possible (Ablett et al., 1989, 1994). Foley et al. (1986) and Cober and Tanner (1995) found that the reproductive period in indeterminate cultivars of the early MGs was longer than that of the determinate cultivars. This resulted in the suggestion that indeterminate cultivars would better adjust to the effects of short-term stresses. However, others have found that cultivars of the two types have equal-length reproductive periods (Wilcox and Frankenberger, 1987; Ablett et al., 1989), or that determinate cultivars actually have a longer reproductive period (Ablett et al., 1989; Saindon et al., 1990). Thus, the effect of length of the reproductive period on performancee of indeterminate vs. determinate cultivars in the early-maturing MGs is not clearcut.

Robinson and Wilcox (1998) found no association between determinate and indeterminate isolines for seed yield, suggesting that neither growth habit nor plant type *per se* affected seed yield. They found an absence of any interaction of determinate and indeterminate isolines with row spacings of either 0.2 m (8 in) or 0.6 m (24 in), which indicates that high-yielding lines of both determinate and indeterminate types can be identified in either row spacing. Their data indicate that genetic loci contributing to high seed yield are expressed in both plant types.

A concern among northern USA producers when growing determinate cultivars is the typically high positive correlation between plant height and distance from ground to lowest pod (Johnson, 1987). Beaver and Johnson (1981) indicate that pods that are within 10 cm (4 in) of the ground are subject to loss during harvest. Saindon et al. (1990) successfully isolated non-dwarf (tall) MG 0 determinate soybean lines adapted to Ontario, Canada. The determinate lines were shorter than their MG 0 indeterminate sister lines, but the lowest pods of the determinate cultivar were 2.5 cm (1 in) higher off the ground. The MG 0 indeterminate and determinate lines had similar lodging and similar seed quality, but the determinate line produced the greater yield (Cober and Tanner, 1995). In a more recent comparison of indeterminate cultivars and tall determinate lines, height-to-lowest pod was greater in the determinate line. Height of plants of the two types was similar, but lodging of the determinate lines was greater and yield was lower (Cober et al., 2000). This work supports the possibility of developing early-maturing determinate genotypes with acceptable height-to-lowest pod. In a survey of Kentucky producers, average combine cutting height was 10.7 cm (4.2 in) above the ground (Grabau and Pfeiffer, 1990). This resulted in an average yield loss of about 1.4% with a range of 0 to 3.8%. Seventy percent of the fields in the survey had stubble heights of between 7.5 and 12.5 cm (3 to 4.9 in) following harvest. Iowa work reported by Hoeft et al. (2000) indicates yield losses of 5.4, 9.4, and 12.2% for cutting heights of 8.9, 12.7, and 16.5 cm (3.5, 5.0, and 6.5 in), respectively. It is obvious from these two cases that even small increases in height-to-lowest pod are important.

Determinate and indeterminate cultivars are known to have similar grain protein contents, and grain protein content increases from the lowest to the highest nodes (Escalante and Wilcox, 1993). It appears that the normal negative correlation between seed yield and grain protein is true for indeterminate but not necessarily for determinate lines (Wilcox and Zhang, 1997). Thus, determinancy may be needed to develop cultivars with both high yield and high grain protein. Thomison et al. (1990) reported that seed of determinate isolines compared to indeterminate isolines were more susceptible to infection by *Phomopsis longicolla* Hobbs, and germination of seed from the determinate isolines was also lower. They concluded that seed of early-maturing determinate cultivars may be more susceptible to this disease than are seed from early-maturing indeterminate cultivars if weather conditions during seed development and after maturation are conducive to its development.

Generally, cultivars in MGs 5 through 9 are grown in the southern USA. These determinate cultivars have a more uniform podset up the stalk, and generally branch more profusely up the stem than do indeterminate cultivars. Contrary to previous information (Fehr and Caviness, 1977; Johnson, 1987), determinate cultivars in the southern USA generally increase considerably in height after flowering begins. There are three or more unextended internodes and unexpanded leaves in the tissue cluster at the main stem terminal of determinate cultivars when flowering begins, and prevailing weather conditions after R1 dictate whether or not this unexpanded tissue will reach full size and increase height after R1 (L.G. Heatherly, personal communication, 2002). Appearance of lateral branches in determinate cultivars continues well after the onset of flowering; therefore, canopy development in determinate cultivars continues both vertically and laterally after beginning flowering.

Kilgore-Norquest and Sneller (2000) used near-isogenic pairs that contrasted in stem type to assess effect of stem type on performance in Arkansas environments. The indeterminate lines were taller and had greater lodging in all environments. Regression techniques determined that indeterminate growth habit is likely to confer a yield advantage over determinate growth habit in southern USA environments with limited growth and yield potential.

Panter and Allen (1989) in Tennessee reported that determinate lines had greater yield than indeterminate lines from late plantings (early to mid-June) compared to early plantings (late April to mid-May). Parvez et al. (1989) in Florida reported the opposite response; i.e., a determinate cultivar outyielded an indeterminate cultivar in mid-May plantings, while there was little difference in yield between the two in early July plantings. Ouattara and Weaver (1994), using near-isogenic lines planted in late June to early July in Alabama, found that the reproductive period for indeterminates was only 2 d (2.5%) longer than for determinates. However, indeterminates averaged 41% greater height and 21% more mainstem nodes per plant than determinates. They also found that determinate lines had better yield than indeterminate lines in a higher-yield environment, while indeterminate lines produced greater yield than determinate lines in a lower-yield environment. Kilgore-Norquest and Sneller (2000) suggested that indeterminate cultivars may be useful to fully exploit the yield potential of low-yield environments in the southern USA.

Early and late cultivars in a particular region should be managed differently because of differences in calendar days to R1. Thus, management inputs that are aligned with R1 will need to address this. For instance, guidelines for initiation of irrigation of soybean in the midsouthern USA have centered on R1. Beginning bloom or R1 for MGs 2 through 4 indeterminate cultivars used in the ESPS in the southern USA occurs sooner after planting than for MG 5 and later determinate cultivars. Thus, other criteria for irrigation initiation such as soil moisture content or tension, or cumulative soil water loss, should be used instead of the plant criterion of R1. This makes the use of irrigation scheduling models more appropriate.

10-1.3 Soil Type Effects

Soil texture affects soybean growth and development by affecting availability of water to the plant (Heatherly and Russell, 1979), and thus affects the amount of water that is in the plant to promote cell expansion and subsequent growth. On soils such as clays in the midsouthern USA that have a relatively low available water holding capacity and low hydraulic conductivity, this may result in plants that are too short at maturity when early-maturing cultivars are planted early. On soils such as deep sandy and silt loams that have a relatively high available water holding capacity, rapid growth of cultivars or cultivars with a long juvenile period may have increased lodging. Soils with fine texture, such as the clay soils in the alluvial flood plain of the Mississippi River and fine-textured, low lying soils in the northern USA, provide soil-water environments that are more favorable for seedling diseases such as *Phytophthora* spp. and *Pythium* spp. This results in unique stand establishment problems for susceptible cultivars or for early plantings such as those of the ESPS (Bowers and Russin, 1999). Also, low-lying soils that are subject to extended periods of saturation are a poor environment for those cultivars with poor tolerance of these conditions (Heatherly and Pringle, 1991). On the other hand, coarse-textured soils provide a more favorable environment for soybean cyst nematode (SCN) development (Young and Heatherly, 1990). Thus, selection of cultivars for these soils must consider resistance to SCN. The effect of soils with differing fertility and pH levels on cultivar selection is discussed later.

10-1.4 Cultivar trials

Soybean cultivars are assessed in field trials conducted each year by agronomists in the soybean-producing states and regions of the USA and Canada. These trials provide yield information for cultivars grown at multiple locations within a state, plus many other details about each cultivar. The amount of information provided varies among the states. Many of the states also provide multi-year yield averages for cultivars. Results from cultivar trials conducted in the USA and Ontario, Canada are published annually, and all are available on the worldwide web. Internet addresses and a list of information provided by each state in its cultivar trial publication are shown in Table 10-1.

10-1.5 Pest Resistance Considerations

Cultivars should be selected for a particular set of production conditions, to include resistance to or tolerance of prevalent pests. This information should be available from the originator of a cultivar, as well as from state cultivar trial results. Soybean cultivars are available that are resistant to soybean cyst nematode, root knot nematode, diseases, and insects.

The information in Table 10-2 is for the most prominent diseases that occur in the southern (Bowers and Russin, 1999) and the northern USA (Hoeft et al., 2000). According to Bowers and Russin (1999), disease development is controlled by the interaction between host plant, the pathogen, and the environment. The basis for this is genetic, and genetic resistance is, in most instances, the best for disease management strategy. However, there is no resistance to some prominent diseases in soybean; therefore, prophylactic measures must be taken against these diseases if successful culture of soybean is to occur.

Resistance to a disease refers to the ability of the host to interfere with the normal growth and/or development of the pathogen organism. Resistance does not mean that a particular disease has no effect on the host. Rather, a resistant plant may support some disease development but to a lesser degree than that exhibited by a susceptible plant. Symptoms of a particular disease on resistant plants generally are localized (affect only a small area on the plant) within the growing season and there is no additional spread of the pathogen organism within the plant. Tolerance to a disease is the ability of the host plant to perform effectively even though it exhibits the symptoms of a susceptible host plant. The performance of an infected tolerant plant is ordinarily expected to be similar to that of a plant without infection. Tolerance of a cultivar to a particular disease organism generally is not known; thus, this information is not presented in cultivar trial information. Avoidance or escape of susceptible plants from infection by a particular disease results from chance occurrences related to pattern of pest progression and environmental conditions that allow these plants to remain uninfected even in the presence of the causal organism, and management practices. For example, manipulating the planting date of a susceptible cultivar may allow it to avoid pest pressures and environmental conditions that promote the aggressive development of a particular disease. Disease resistance/tolerance should be balanced against other desirable traits of a cultivar. Resistance to disease(s) that is/are not prevalent where a cultivar will be grown is not a concern. Yield performance data reflect reaction to diseases present at test locations, and at least indirectly reflect reaction to those diseases. Realistically, the best-yielding cultivars have adequate resistance or tolerance to diseases common to the test site, or they would not have yielded well in those environments.

Soybean is attacked by numerous insect pests, but only a few pose a serious economic threat in North America (Funderburk et al., 1999). Table 10-3 provides information about the most prominent or damaging insect pests that affect soybean in the United States. The tabled information and the following narrative summarizes insect management information adapted from Higley and Boethel (1994), Higgins (1997), and Funderburk et al. (1999).

Injury from insects can occur during any soybean growth stage, but the greatest threat of economic loss occurs from infestations during reproductive development. Most insect pests of soybean are detected by scouting during periods of greatest potential loss. Soybean developmental stage and number and developmental stage of individual insect species should be documented for determination of effective control measures. Management decisions for control of insect infestations are based on predetermined economic injury level, which is the lowest population density of each pest that is likely to cause economic damage. The economic injury threshold usually changes during the growing season, and is affected by soybean developmental stage, changes in the growing season environment, and crop market value.

Significant yield losses occur when lepidopterous defoliators remove >35% of leaf area before R1, and >15 to 20% after R1. Injury from these insects can be avoided in ESPS plantings in the southern USA, which results in leaves maturing during July and early August before major infestation peaks occur (Baur et al., 2000). Dry soil limits larval weights and larval development, especially on the clay soils that are dominant in the midsouthern USA (Lambert and Heatherly, 1991, 1995). Thus, yield reduction resulting from lepidopterous defoliators is greater for irrigated than for rainfed plants. In fact, dryland producers may find that control measures for soybean plants growing under drought stress can be delayed or not applied because of retarded insect development and lower yield and profit potential from rainfed production.

Host-plant resistance (both chemically-derived and morphological) to insects has been identified for pest species in Coleoptera, Hemiptera, Homoptera, and Lepidoptera insect families (Todd et al., 1994). These are available in plant introductions and in crosses derived from them. However, few insect-resistant cultivars are currently available. Still, the potential for developing insect-resistant cultivars to fit into Integrated Pest Management systems is significant (Todd et al., 1994).

Insect-resistant cultivars have been developed (Bowers, 1990; Hartwig et al., 1990) and offer some resistance to foliage feeders. However, these cultivars are not planted for production in the southern United States because level of resistance is insufficient for effective control. There is a difference in cultivar preference among some insect species, which means that some cultivars may be defoliated sooner than others or to the exclusion of others. This information should be available from the originator of a particular cultivar. The best method for determining the need for insect control in soybean is scouting during periods of risk to determine the species and population density of insects, and selecting a curative measure based on economic injury levels.

With ESPS plantings in the southern USA, injury from bean leaf beetle [*Cerotoma trifurcata* (Forster)], three-cornered alfalfa hopper [*Tetranychus urticae* (Koch)], and stink bug [*Nezara viridula* (L.), *Acrosternum hilare* (Say), and *Euschistus servus* (Say)] infestations may be more pronounced and infestations may require more intense management than normal for conventional May or later plantings. This is because ESPS plantings are earlier than conventional plantings, and thus provide an immediate host at the time of insect emergence.

10-1.6 Nematode Considerations

The soybean cyst nematode is the most serious nematode pest of soybean in the USA (Lawrence and McLean, 1999). In areas with severe infestations, soybean production without control measures is not economically feasible. Soil texture affects movement of SCN in the soil (Young and Heatherly, 1990; Heatherly and Young, 1991) and also may affect their reproduction and development. Basically, major damage to soybean by SCN infestation occurs when the crop is grown on medium- and coarse-textured soils. Apparently, populations of SCN are not sustainable in soils series classified as clay (Heatherly and Young, 1991).

Determination of the presence, race, and density of SCN is important to prevent losses. A cultivar with resistance to a specific population of a race of SCN should not be planted year after year. Continuous planting of a cultivar could lead to the development of a different SCN race that damages the crop, making that cultivar useless for SCN control (Young, 1994).

Crop rotation is an effective tool for managing SCN (Wrather et al., 1992; Young, 1994). Nonhost crops such as corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and grain sorghum (*Sorghum bicolor* (L.) Moench) successfully reduce SCN populations. Young (1998a) determined that rotation of resistant and susceptible soybean cultivars with a nonhost crop produced greater long-term soybean yields and slowed the shift toward new SCN races in the field. It is important to determine the race of SCN in a field and the race-specificity of the resistance gene of a previously planted soybean cultivar when planning to use a new resistant cultivar in a crop rotation system for SCN management. The originator of a soybean cultivar should furnish information about the race-specific resistance of that cultivar. Cultivars with resistance to SCN are available in all MGs (Young, 1998b).

Early planting of soybean may benefit soybean production in fields that are infested with SCN. Wrather et al. (1992) showed that SCN populations were lower at harvest on early-maturing cultivars compared with those maturing later. Wang et al. (1999) determined that resistant cultivars of earlier MGs appeared to be more effective in reducing nematode numbers than were those of later MGs in several environments of 10 north central states of the USA. With susceptible cultivars, this was not the case. In contrast, Todd (1993) found only a small influence of MG on SCN reproduction in MG 3 and MG 4 cultivars grown in Kansas. Wang et al. (1999) concluded that planting susceptible cultivars of early MGs is not effective in reducing nematode population densities and resulted in lower yields than from similar later-maturing cultivars.

Nematicides can be effective in controlling SCN populations in infested fields, but their use should be based on expected yield and subsequent income, given that lessened yield loss in low-yield environments may not be sufficient to offset nematicide cost. Heatherly et al. (1992b) determined that irrigation of soybean did not affect cultivar response to infection by SCN, the capability of SCN to maintain cysts on any cultivar, or the yield-limiting effect of SCN on susceptible cultivars. Irrigation may increase yield of susceptible cultivars grown on SCN-infested fields, but often yields will be less than those from irrigated susceptible cultivars grown on non-infested fields as well as those from irrigated resistant cultivars grown on infested fields. Thus, irrigation of SCN-susceptible cultivars grown on infested fields should not be considered since irrigation efficiency (amount of yield increase unit^{-1} of applied water) will be low and subsequent yields will be unprofitable.

Root-knot nematodes (*Meloidogyne incognita*, *M. arenaria*, and *M. javanica*) and reniform nematode (*Rotylenchulus reniformis*) are significant pests of soybean grown in the southeastern USA, especially in the drought-sensitive soils of the southeastern Coastal Plain (Kinloch, 1992; Riggs, 1992). The use of resistant cultivars is the most effective tool for management of the root-knot nematode. Resistance to *M. incognita* is more prevalent in MG 6 through MG 8 cultivars than in MG 5 and earlier cultivars. Recent adoption of the use of MG 4 and earlier cultivars in the southern USA points to the need for *M. incognita* resistance in earlier-maturing cultivars. Continuous use of cultivars with resistance to *M. incognita* could lead to the prevalence of the other two species for which there is no cultivar with resistance. Management of root-knot nematode by crop rotation is complicated by the wide range of hosts for the three root-knot species. Cultivars resistant to *M. arenaria* and *M. javanica* have not been widely or adequately developed; therefore, rotation of soybean with other crops may be the only means of nematode management. Use of resistant cultivars is effective in the management of the reniform nematode. Breakdown of resistance to *R. reniformis* has not been reported. Rotation to grasses, which are poor hosts for *R. reniformis*, is an effective management tactic. Nematicides are not an economical control practice for either root-knot or reniform nematodes.

Fields in the southern USA are often infested with both SCN and root-knot nematodes. Cultivars with resistance to both SCN and root-knot nematodes are more common in the later maturity groups. Today, resistant cultivars are frequently the most productive ones when grown in both infested and noninfested fields (Young, 1998b). Still, producers can test this thesis by conducting an on-farm strip test of a susceptible and resistant pair of cultivars that are best adapted to their area.

10-1.7 Herbicide Resistance/Tolerance

Traditionally, herbicides were designed largely for crops rather than cultivars designed to tolerate a specific herbicide. During the past decade, advances in biotechnology coupled with plant breeding have resulted in the development of herbicide-resistant soybean cultivars. Currently, glyphosate-resistant (GR), glufosinate-resistant, and sulfonylurea-resistant soybean cultivars are available for use in soybean production systems (Reddy et al., 1999). Well over half of the USA soybean area is planted to GR soybean cultivars, with some states having more than 3/4 of their soybean area in GR soybean. Glyphosate does not seem to alter the chemical composition of harvested soybean seed (Taylor et al., 1999), and GR genotypes are equivalent in seed composition to parental lines and other soybean cultivars (Padgette et al., 1996).

Reddy et al. (1999) and Reddy (2001a) summarized the current situation pertaining to the use of GR soybean cultivars. Glyphosate has low mammalian toxicity and is considered environmentally safe. After more than two decades of use on cropland, weed resistance to glyphosate has occurred, but genetic shifts in weed populations have not yet been documented. Glyphosate is a nonselective herbicide that kills most annual and perennial grass and broadleaf weeds. Thus, there is no sequence-of-application concern as there is with herbicides that kill either grass weeds or broadleaf weeds, but not both. Control of weeds of the same species that differ in size can be attained simply by increasing the rate of glyphosate. Thus, herbicide application timing for adequate weed control is of less concern than when using non-glyphosate herbicides. Since glyphosate has no soil persistence, a glyphosate-only weed management program can be used with no concern for choice of following crops from a herbicide carryover standpoint.

Glyphosate-resistant cultivars offer the flexibility to control a broad spectrum of weeds in soybean with no concern for crop safety (Reddy, 2001a). Cost of weed control should be less, even with the higher cost for seed of most GR cultivars (Table 10-4). This could translate to increased profits if yields from GR cultivars are equal or nearly equal to those from non-GR cultivars. Use of GR cultivars should preempt the use of tillage and preemergent herbicides for weed management. Research has shown that non-glyphosate herbicides applied to continuously cropped GR soybean or soybean grown in rotation with corn do not adversely affect GR soybean (Bennett et al., 1998; Hofer et al., 1998; Nelson and Renner, 1999; Webster et al., 1999). This increases options and flexibility for weed control when GR cultivars are used. If weeds are present that are difficult to control with non-glyphosate herbicides, use of GR cultivars may result in greater profit, especially in low-yield environments where costs must be minimized. The advantages of GR cultivars should translate to a reduction in management decisions for producers related to weed control in soybean.

Early non-published Monsanto research with six pairs of iso-populations with and without the GR gene indicated that no yield suppression was associated with the GR gene (X. Delannay, personal communication, 1999). Glyphosate has no negative effect on GR cultivar growth, development, and yield (Nelson and Renner, 1999; Elmore et al., 2001a). However, comparisons in side-by-side cultivar performance trials indicated that a yield suppression may exist with GR soybean relative to non-GR soybean (Nelson et al., 1997, 1998, 1999; Oplinger et al., 1998a; Minor, 1998; H.C. Minor, personal communication, 1999; Nielsen, 2000). Yield suppressions may result from either cultivar genetic differentials or the GR gene/gene insertion process. The GR gene, CP4 EPSPS from breeding line 40-3-2 (Delannay et al., 1995), remains the source for resistance in current GR cultivars (X. Delannay, personal communication, 1999). In another study, five backcross-derived pairs of GR and non-GR soybean sister lines were compared along with three high-yielding, non-herbicide-resistant cultivars and five other herbicide-resistant cultivars. In contrast to the unpublished Monsanto report (X. Delannay, personal communication, 1999), GR sister lines yielded 5% (200 kg ha^{-1}; 3 bu acre^{-1}) less than the non-GR sister lines (Table 10-5) (Elmore et al., 2001b). High-yielding, non-herbicide-resistant cultivars included for comparison yielded 5% more than the non-GR sister lines and 10% more than the GR sister lines. The potential for a 5 to 10% yield advantage for non-GR cultivars vs. GR cultivars should be considered in the evaluation of profit opportunity of the two systems, especially in high-yield environments such as those with irrigation (Heatherly et al., 2002a). This is an area of evolving technology, and unpublished results from recently completed research indicate that the yield relationship between GR and non-GR cultivars is not clearcut in favor of either GR or non-GR cultivars.

There are disadvantages to the GR soybean weed management system. Lengthy periods of windy conditions in the spring may limit preplant spraying opportunities because of drift concerns. The GR system is most advantageous when used in a total postemergent weed management program; thus, lack of weed management with traditional residual herbicides will necessicate multiple sprayings with glyphosate. Lengthy periods of wet soil likewise may cause delays in applications of glyphosate by ground equipment, thus allowing weed competition with the crop in the early season to become yield-limiting to soybean before spraying is possible. Although timing of glyphosate application is not as critical as with non-GR postemergent herbicides, some weeds such as morningglories (*Ipomoea* spp.) are more easily killed by glyphosate when they are small. Thus, significant delays in glyphosate application result in using more expensive higher rates. The higher cost for seed of most GR cultivars increases the importance of using seeding rates that are within the optimal range.

Cultivar trials conducted by the entities listed in Table 10-1 typically include assessment of GR genotypes, usually in separate trials. Because these are separate trials, caution should be used in comparing GR and non-GR cultivar performance. The usual criteria for selection of cultivars should be used when selecting herbicide-resistant cultivars. Choice of GR and non-GR cultivars should be based on 1) previous weed pressure and success of control measures in specific fields, 2) availability and cost of herbicides, 3) availability and cost of GR cultivars, and 4) yield potential of a specific field. The herbicide resistance component of a cultivar's genetics should be viewed as a weed management option rather than a cultivar selection criteria.

10-1.8 Seed Quality and Germination

Experts in some southern states recommend the application of a foliar fungicide at beginning pod (R3) and beginning seed (R5) growth stages in seed production fields to prevent seed diseases that reduce germination quality of seed (Moore, 1996; Bowers and Russin, 1999). However, these applications may be too early if environmental conditions that favor seed decay occur near soybean maturity. Control of stink bugs is especially critical for soybean seed crops because of their association with seed injury and their serving as a vector for the transmitting of seed diseases. Results from research in the southern USA indicate that soybean grown for seed should be irrigated during reproductive development to ensure the highest germination (Heatherly, 1999b). Seed should be harvested as soon as they reach 14% moisture content to ensure the least possible damage from weathering and the least amount of seed damage during the threshing process.

Seed diseases often affect germination of seed. Seed treatment fungicides can reduce germination problems associated with these seed diseases (Table 10-6), but they are no substitute for high-quality, disease-free seed. There are two classes or types of seed treatment fungicides: contact or protectant fungicides that are active against pathogenic organisms that are present on the planted seed, and systemic fungicides that are active against pathogenic organisms that are soil- or residue-borne and that attack planted seed if conditions are conducive for disease development. It is generally a good practice to treat seed with a product that contains a combination of the two classes of fungicides when planting in cool, wet soils that provide a favorable environment for seedling disease development. Information in Table 10-6 gives common pathogens of planted soybean seed, along with the fungicides that provide control of these diseases.

Seed quality (germination, discoloration, shriveling, etc.) of harvested seed is of paramount importance in soybean production. Mayhew and Caviness (1994) grew four MG 3 and four MG 4 April-planted soybean cultivars under nonirrigated conditions in 1989 and 1990 in Arkansas. Average seed germination for MG 3 and MG 4 cultivars was 28 and 42%, respectively. Germination percentage was significantly and negatively correlated ($r = -0.72$) with infection with *Phomopsis longicolla*. They did not grow MG 5 or later cultivars in this study, so it is impossible to say that only seed of early plantings of early-maturing cultivars are susceptible to low germination. They concluded that cultivars resistant to *Phomopsis* seed decay are necessary if production of planting seed for early-planted, short-season soybean is to be viable in the southern United States. Elmore et al. (1998) reported that soybean lines resistant to *Phomopsis* seed decay can provide effective control without fungicide application. Heatherly (1993, 1996) measured significantly higher germination of seed harvested from irrigated vs. nonirrigated MG 4 and MG 5 cultivars at Stoneville, MS, but this improvement was not always sufficient to impart acceptable levels of germination. Heatherly (1996) also determined that planting MG 4 and MG 5 cultivars in May and later in the midsouthern USA and irrigating almost always ensured seed with adequate germination, although lower yields were obtained. The conclusion drawn from current knowledge is that production of seed from early-maturing cultivars in the southern USA results in a product with germinability that is unpredictable. Seed for ESPS plantings should be obtained from reputable sources whose seed production was conducted in locations with environments known to produce quality, germinable seeds. For soybean production where seed will be for uses other than planting seed, *Phomopsis* seed decay is not usually a concern. However, quality of harvested seed from early-planted, early-maturing cultivars in the southern portion of the midsouthern USA in 2001 was so adversely affected by seed decay that a large portion of the crop was significantly reduced in yield and value (Dorris, 2001). Thus, genetic resistance to seed decay is now important. In both the southern and midwestern USA, good quality seed of early-maturing cultivars is usually obtained from the northernmost region of their adaptation. This is because seed quality is greater when seed mature under the cooler temperatures of early fall rather than the hotter temperatures of late summer.

10-1.9 Specialty Cultivars

High protein soybean cultivars may become important to USA livestock producers. Unfortunately, the strong inverse relationship between seed protein and grain yield has limited progress. Correlations for this inverse relationship have typically ranged from r = -0.023 to -0.86. New developments have decreased this, suggesting the absence of physiological barriers between high seed yield and high seed protein (Wilcox and Cavins, 1995). For example, new populations derived from 'Maple Glen' show low association between seed yield and protein, with r values ranging from -0.06 to -0.21 (Cober and Voldeng, 2000). Additionally, determinate cultivars apparently are a better source of selections that combine high seed yield and high protein than are indeterminate cultivars for the northern production areas of the USA (Wilcox and Zhang, 1997). High protein MG 2 through MG 5 lines are now available that produce over 46% seed protein (dry matter basis) and more than 50% meal protein (Table 10-7). New high-yielding soybean cultivars with higher protein content are under development.

Markets are available for specialty soybean with different seed sizes. Natto is a Japanese food product made from small, mature soybean seed that are cooked and fermented. Cultivars that produce small seed also are used for sprouting. Specialty soybean cultivars that produce large seed are used as edamame or vegetable soybean, and these seed are harvested before maturity (at R6) when the seed have filled 80 to 90% of the pod width. The pods are boiled to assist shelling, and the seeds are eaten as a vegetable in a variety of ways, especially in East Asia. Other products like tofu and miso also call for mature, large soybean seed from specialty cultivars. Tofu consumption is growing rapidly in the USA (Rao et al., 2002). Cultivars used for natto and sprouts produce small seed that weigh ≤ 80 mg seed^{-1} (> 5700 seed lb^{-1}) when mature. The large seed produced by cultivars that are used for edamame, tofu, and miso weigh more than 220 mg seed^{-1} (<2000 seed lb^{-1}). For comparison, seed of conventional cultivars weigh from 120 to 180 mg seed^{-1} (3800 to 2500 seed lb^{-1}).

In addition to seed size, breeding for specific characteristics is important within each of the specialty types mentioned. Seed used for natto should be round and have easily permeable seed coats for rapid water uptake during soaking and rapid water loss after steaming. Hilum color is not critical. Total protein and oil content of seed is correlated with natto quality or desired sugar content (Geater et al., 2000), and can be used as a criterion by breeders to select for cultivars for the natto industry. Seed for tofu uses should have a clear hilum and high protein (Wang et al., 1983). It is possible to develop broadly adapted short-season natto cultivars for production in areas as far north as eastern Canada (Cober et al., 1997).

The ideal ideotype for edamame soybean includes 40 to 50 pods plant^{-1}, unblemished dark green pods that have dimensions of > 4.5 cm x 1.3 cm (1.8 x 0.5 in), 2.5 to 3 g fresh weight and 2 to 3 seeds pod^{-1}, round seeds with a clear hilum, and gray (white) pubescence (Konovsky et al., 1994; Cober et al., 1997; Nguyen, 1998). Two aspects of edamame soybean complicate breeding efforts. First, both greater number of pods plant^{-1} and greater pod weights are desired; however, these two traits are negatively correlated (Mebrahtu et al., 1991). Second, a tendency to shatter at maturity is common among edamame cultivars, and this a negative factor for seed production and breeding progress. Once harvested, however, release of seed from pods is a positive trait for vegetable soybean because consumers desire pods that open more easily.

Seed yields from specialty cultivars with both large and small seed are less than yields from cultivars with normal seed size. Cultivars with large seed yielded 82% of check cultivars, while cultivars with small seed yielded

72% of check cultivars in a 4-yr study in Nebraska. Seed weights were not affected greatly by either row spacing or seeding rate (Hoffmeister and Elmore, 1999). Seed weight can, however, be altered significantly by irrigation timing. Irrigation during flowering (R1 to R3) almost invariably increases number of seed plant^{-1}, and may result in a large number of smaller seed if irrigation is discontinued before seedfill. Inversely, not irrigating soybean during flowering and early pod development (R1 to R4) followed by adequate irrigation thereafter can increase weight of the fewer seed that are produced (Korte et al., 1983a,b; Kadhem et al., 1985a,b). Irrigation timing can thus be used as a management factor to exert control over the final weight of seed of specialty soybean cultivars developed for either the small- or large-seed markets. For production of specialty cultivars to be profitable and attractive to producers, any under-performance in yield must be offset by premiums paid for the seed.

10-2 TILLAGE

Tillage in soybean management systems is utilized to prepare a seedbed, remedy compaction, incorporate fertilizers and herbicides, and control weeds. Hoeft et al. (2000) have given definitions for common tillage terms: those definitions with modifications are used in this chapter. Clean tillage (synonymous with conventional tillage and often associated with moldboard plowing and disk harrowing) is a term used to describe a production system that uses tillage for any purpose at any time. Clean-till systems employ any implement or implements that leave less than 10% of the soil surface covered with residue. Reduced-till systems refer to those practices that leave between 10 and 30% residue on the soil surface, and are often a compromise choice between clean-till and conservation tillage systems. When used, reduced-till systems may increase dependence on both pre- and post-planting chemical weed control. Conservation tillage refers to any tillage system that maintains at least 30% of the soil surface covered with residue up to planting. The intention when using conservation tillage is to conserve soil and water, and reduce fuel, labor, and equipment inputs. Conservation tillage systems may include reduced-till, mulch-till, ecofallow, strip-till, ridge-till, and no-till.

No-till refers to a system where tillage is essentially eliminated during both the growing season and the off-season. However, some tillage is conducted in the process of creating a seed trench or strip with a coulter or disk-opener during planting (Jasa et al., 1991). Use of no-till and narrow rows places total dependence on herbicides for both pre- and post-plant weed management. A no-till system does not allow for any correction of soil surface or subsurface problems with tillage. Most soybean management systems combine components of conventional, reduced, and no-till approaches over a period of years. The rigid use of any one tillage approach can lead to production problems resulting from either too much tillage or too little tillage in situations where an appropriate tillage operation may offer the only solution to a particular problem.

In the midwestern USA, tillage systems used for soybean are varied (Jasa et al., 1991). In rotation systems involving soybean, a commonly used scheme is no-till planting. In this case, it is common for one or two disk harrowings followed by a field cultivation (shallow tillage with an implement having spring-tooth tines or sweeps) or shallow chisel plowing to be done following corn, grain sorghum, or wheat (*Triticum aestivum* L. emend. Thell.) harvest preceding the soybean crop in the rotation, with no tillage following the soybean crop. These operations in combination with no-till planting will leave at least 30% residue cover following both growing seasons, and provide the most erosion control while still allowing for some tillage of the less fragile non-soybean residue. In ridge systems, all crops are planted into ridges formed during cultivation of the previous row crop. Soil is undisturbed between harvest and planting of the next crop, and residue cover during this period is maximum. Post-plant tillage (cultivation) is used to maintain the ridges at least 15 to 20 cm (6 to 8 in) tall. In a ridge-plant system, no soil disturbance occurs prior to planting. A row cleaning device on the planter may be used to push a small amount of debris off the top of the ridge. In a ridge-till system, some tillage prior to planting may be done, but it is shallow and disturbs only the ridge tops without destroying them. This tillage may be necessary to flatten or smooth peak-shaped ridges so the planter will stay on the row, and/or remove excess residue. Ridge systems are well-suited for level or gently sloping fields (especially those having soils with poor internal drainage) and for fields that will be furrow-irrigated. The use of a ridge system will dictate that row spacing will be the same for all crops in a rotation, and that the rows be wide enough to accommodate effective post-plant cultivation. This likely will require rows that are at least 75 cm (30 in) apart.

Deep tillage (sometimes referred to as "subsoiling" or "deep ripping") refers to operations that affect soil 15 cm (6 in) or deeper (Hoeft et al., 2000). These operations are used to fracture or loosen deep soil barriers, improve rainfall infiltration, and mix residue and nutrients deep into the profile. Deep tillage can be part of a conservation tillage system if it minimally disturbs the soil surface. Shallow tillage, or secondary tillage, refers to operations that affect soil to depths up to 15 cm. These operations are used to kill weeds, incorporate herbicides and fertilizers, level soil, and prepare a smooth seedbed. Shallow tillage operations usually result in a clean-till environment (low soil surface residue) since they significantly disturb the soil surface and residue cover.

Bedding describes ridging soil so that the seedbed is raised on poorly drained soils. This concept is useful where early planting occurs on soils such as flat alluvial clays of the lower Mississippi River flood plain. If a disk hipper is used for bed forming, row spacing should be 76 cm (30 in) or wider because individual row beds cannot be effectively formed, maintained, and planted in more narrow rows. If narrow-row planting is desired on beds in these environments, a wide bed capable of supporting several rows per bed must be constructed. Recent equipment developments (Ginn et al., 1998) allow this to be done, and a management system of narrow rows planted on beds is possible.

Cultivar rankings do not vary among tillage systems (Elmore, 1987; 1990; Guy and Oplinger, 1989). Cultivar performance trials conducted in conventional tillage systems can therefore be used for selecting cultivars for conservation tillage systems, and vice versa. In addition, tillage system seldom interacts with planting date or seeding rate (Elmore, 1990; 1991). Thus, similar management practices are optimum for various tillage systems. Weed control in conservation tillage systems is now simplified because of herbicide-resistant cultivars. In fact, GR soybean cultivars are well-matched to reduced tillage systems because weed management expenses associated with their use should be no higher than when they are used with conventional tillage systems.

10-2.1 Deep Tillage

Deep tillage (DT) is conducted post-harvest in the fall and is used to disrupt the soil profile below 15 cm with implements such as "subsoilers", rippers, and chisel plows that have curved shanks or standards spaced 50 to 100 cm (20 to 40 in) apart. Operation of these implements is intended to lift and shatter the soil profile to the depth of operation. Correct operation of these implements should minimally disturb the soil surface. Heatherly (1981) measured almost identical yields among treatments in studies on Sharkey clay (very-fine, smectitic, thermic Chromic Epiaquert) where DT performed in late winter or early spring when soil was wet was compared to shallow, disk-harrow spring tillage preceding soybean planting. Popp et al. (2001) found that DT of wet clay soil in late winter or early spring in Arkansas resulted in net returns that were similar to those resulting from conventional shallow tillage. Thus, DT of wet soils was not effective in increasing net return. In some cases, DT to a depth of 40 to 45 cm in the fall following harvest is used to disrupt soil barriers and increase water held in the soil profile. Koskinen and McWhorter (1986) reported increased perennial and biennial weeds with no-tillage systems; thus, deep tillage of dry soil in the fall could be considered for suppressing problem perennial weeds such as redvine [*Brunnichia ovata* (Walt.) Shinners], which is deep-rooted. Wesley and Smith (1991) performed DT on a Tunica silty clay (clayey over loamy, smectitic, nonacid, thermic, Vertic Haplaquept) in the fall in Mississippi following soybean harvest when the soil profile was dry. They measured large, significant yield increases from soybean planted in May in years when drought occurred during the growing season, and determined that net return was greatly increased from this practice (Wesley et al., 2000). The increased production was associated with increased moisture content in the soil, presumably because of greater infiltration and storage resulting from DT. Wesley et al. (2001) concluded that fall deep tillage should be performed once every 3 yr on a Tunica silty clay. This work has been used to promote DT of all dry clay soils in the fall in the midsouthern USA.

Studies on Sharkey clay in Arkansas (Popp et al., 2001) and Mississippi (Wesley et al., 2001) showed average increases in yield of 580 kg ha^{-1} (8.6 bu acre^{-1}) and 365 kg ha^{-1} (5.4 bu acre^{-1}), respectively, and average increases in net return of \$96 and \$71 ha^{-1} (\$39 and \$29 acre^{-1}), respectively, from fall DT (Table 10-8). In the Arkansas study, yields following fall DT were significantly greater than those from conventional tillage even though drought was not severe. The Mississippi study used estimated DT costs that were \$17 to \$20 ha^{-1} (\$7 to \$8 acre^{-1}) more than those for a treatment that received only secondary tillage [$\leq$ 10 cm (4 in)]. Heatherly and Spurlock (2001) and Heatherly et al. (2002c) determined that profits from producing soybean following DT of Sharkey clay were significantly greater than those from conventional tillage only when plantings were made in April vs. May and later (Table 10-8). In their study, costs associated with DT were \$29 to \$42 ha^{-1} (\$12 to \$17 acre^{-1}) greater than those for a conventional shallow tillage system (fall tillage with a disk harrow and/or a spring-tooth harrow). In extremely dry years (yield levels < 1000 kg ha^{-1} or 15 bu acre^{-1}), or in production systems where irrigation was applied, deep tillage provided no yield or economic benefit (Heatherly et al., 2002c). On a Coastal Plain loamy sand soil in South Carolina, Frederick et al. (2001) measured a 12% yield increase from DT compared to no DT (2415 vs. 2160 kg ha^{-1}) just prior to May planting of soybean that was not irrigated (Table 10-8). They also measured a 50% yield increase when irrigation was applied following no DT compared to no DT and no irrigation (3201 kg ha^{-1} vs. 2160 kg ha^{-1}). Thus, both the Frederick et al. (2001) and Heatherly et al. (2002c) studies indicate that DT with irrigation is not necessary. In another South Carolina study using late May/early June plantings of determinate soybean following wheat on a loamy sand, DT combined with no surface tillage compared to only surface tillage prior to planting of soybean resulted in significantly greater yields in 19-cm-wide (7.5-in) but not in 76-cm-wide (30-in) rows (Frederick et al., 1998). Highest yields in the Frederick et al. (1998) study were achieved when both fall and spring deep tillage were conducted on the sandy soil.

In the northern USA, DT that is performed is done in the fall, followed by one or more secondary tillage operations in the spring. Chisel plows typically operate between 15 cm (6 in) and 30 cm (12 in) deep. Subsoilers or rippers operate at 46 cm (18 in) or deeper. The subsoiler shanks are usually spaced 50 to 100 cm (20 to 40 in) apart. They are designed to create deep slots in the soil profile in order to open a channel for water infiltration and root penetration in soils with natural hard pans. Subsoilers are also operated at less than 30 cm (12 in) deep to break up surface compaction. Rolling coulters may be placed in front of the shanks to improve performance in heavy crop residues. Descriptions and pictures of various tillage tools can be found in Hoeft et al. (2000).

Costs of tillage operations play a major role in the selection of a tillage system for soybean production. Yields of dryland soybean following deep tillage of the clay soils in Table 10-8 did not approach the high yield and net return levels obtained from irrigated plantings of soybean at this location (Heatherly and Spurlock, 1999). These yield and net return responses are marginal when measured against high fuel prices and low commodity prices. Using a \$0.184 kg^{-1} seed (\$5.00 bu$^{-1)}$ price for soybean, a 160 to 230 kg ha^{-1} (2.4 to 3.4 bu acre^{-1}) yield increase would be required to break even using the \$29 to \$42 ha^{-1} higher tillage cost associated with DT in the Heatherly et al. (2002c) studies. Thus, with low commodity prices, significant profitability from DT of these clay soils in the fall will require consistent yield increases such as those obtained in the cited studies. The use of DT on the clay soils should be based on anticipated early-April planting and expected commodity price since significant economical yield increases are not consistently achieved.

10-2.2 Preplant (Secondary) Tillage

Preplant tillage is conducted to remedy soil surface problems such as rutting that were created during harvest, to destroy weed vegetation so that the crop is planted in a clean seedbed, to disrupt restrictive layers in the soil profile that may interfere with root penetration and soil moisture extraction, and to promote soil warming prior to planting in the northernmost soybean-growing regions. The old adage that tillage is needed for seedbed preparation is not valid. Significant soybean hectarage in the USA is now planted in environments with no preplant tillage. Tillage systems for corn and soybean production in the midwestern USA were nearly identical in the late 1980's and into 1991. In 1992, dramatic changes in tillage systems for full-season soybean occurred. No-till production rose from 8.3% to 23.8% of the total production area between 1991 and 1992 (Conservation Technology Information Center, 2002). No-till corn increased from 9 to 16.8% between the same years. Since 1992, no-till soybean area has risen gradually to 33.4% in 2002, and no-till corn production has remained around 17%. Average corn area managed with conventional tillage (37%) and total corn area (25 400 000 ha or 63 000 000 acres) stayed about the same from 1989 until 2002. However, proportional area of conventional-tilled soybean declined from 42.7 to 21.1% as area increased from 17 900 000 ha (44 300 000 acre) to 24 400 000 ha (60 400 000 acre).

In the midsouthern USA, no tillage between harvest and planting of the subsequent soybean crop resulted in yields and net returns that were similar to or greater than those resulting from soybean being planted following fall or spring tillage for seedbed preparation on clay soil (Heatherly et al., 1990; Heatherly et al., 1993). Greater number of soybean *Bradyrhizobial* cells and *Bradyrhizobial* diversity have been measured in no-till compared to conventional tillage systems in Brazil (Ferreira et al., 2000).

All tillage operations affect the erosion potential of any soil used for soybean production. Moldboard plowing buries almost all residue, whereas chisel plowing loosens the soil but leaves considerable residue on the soil surface (Erbach, 1982). However, multiple passes with a chisel plow, disk harrow, or field cultivator used in conservation tillage production systems can result in residue cover being reduced to less than 5% at planting and lead to increased soil loss (Triplett and Dabney, 1999). Table 10-9 shows annual soil loss from conventional and no-till production systems with various crops in Mississippi. Similar results from field tests in Nebraska are shown in Table 10-10. These data indicate that no-till management can reduce soil loss from all crops, especially soybean. This was also the case for a corn--soybean rotation system using conservation tillage measures on a large watershed in Ohio (Edwards et al., 1993). However, use of no-till can lead to increased runoff of applied herbicides in some cropping systems (Shipitalo et al., 1997). Influence of soil management and cropping methods on water erosion for selected soybean management systems in Mississippi are given by Triplett and Dabney (1999).

Soybean residue needs special consideration when preparing soil for subsequent crops (Erbach, 1982). First, residue levels following soybean may be sufficient to meet requirements to reduce erosion for highly erodible land, but any fall or spring tillage and even the planting operation will easily destroy the residue because of its fragileness (Erbach, 1982). Both soybean and corn produce a 1:1 ratio of residue to grain. Since soybean yields about 33% as much grain as corn, it follows that soybean residue is only about 33% that of corn. Second, soybean residue degrades quickly because of its high N content. These two factors--a small amount of residue following soybean and the fragileness of that residue--may lead to increased soil erosion following a soybean crop. Erosion following soybean is about 50% greater than that from areas where corn is grown when the same tillage system is used (Fig. 1). Use of conservation tillage in a soybean production system thus becomes an important consideration. No-till systems may be the only ones that consistently leave at least 20% residue cover following soybean (Erbach, 1982; Dickey et al., 1986). Use of production systems with a tillage rotation on a given field will allow some tillage to control problem weeds, bury shallow-germinating weed seeds, and incorporate P and K fertilizers (Johnson, 1987).

Any tillage practice may leave the soil prone to erosion and result in some degree of soil moisture loss. These moisture losses could reach the equivalent of 1.5 cm (0.6 in) of rainfall per tillage operation and affect soybean stand in droughty soil environments (Paul Jasa, personal communication, 2001). Thus, on well-drained, coarse-textured, or drought-prone soils, conservation tillage systems often result in greater yield than do clean-till systems (Dick et al., 1991). On moderately- to poorly-drained, fine-textured soils, the opposite is often true. If soil moisture is excessive to the point where denitrification, nitrogen leaching, or plant diseases increase, yield probably will decrease with conservation tillage systems (Hoeft et al., 2000). Thus, it is advisable to avoid using no-till systems on poorly drained soils. Conservation tillage systems seldom show a benefit when soils are not subject to early-season moisture-deficit stress (Hoeft et al., 2000). Cool soil temperatures can result in variable stands, and slower crop development compared to clean-till systems.

Yiridoe et al. (2000) found that net returns from a corn--soybean rotation grown using conventional tillage and reduced tillage systems on clay soils in Ontario, Canada were similar. No-till systems generated lower net returns compared with conventional and reduced tillage systems because of lower yields and higher no-till machinery-related costs. They also found that tillage systems that use a common set of machinery for different crops in rotation production systems resulted in a savings on annual average machinery costs. The tillage system that results in the highest yields and/or the lowest management risk likely will result in the most profit (Hoeft et al., 2000). For example, soybean in pivot-irrigated conventional tillage and ridge till systems in Nebraska have similar costs of materials, services, and field operations (Roger Selley, personal communication, 2001). Yield and risk are the important deciding factors. On the other hand, costs of rain-dependent, conventional tillage systems are about 8% less than those for no-till systems because labor and machinery savings in no-till systems do not offset increased costs for herbicides, sprayers, and planters. These factors should be considered when selecting a tillage system.

Soybean yields on well-drained soils are often similar regardless of tillage system (Bharati et al., 1986; Elmore, 1987, 1990, 1991). However, many factors such as poor drainage, poor weed control, soybean following soybean, herbicide injury, nematodes, and diseases have been reported to reduce yields of soybean grown without preplant tillage relative to yields of soybean grown with preplant tillage (Burnside et al., 1980; Webber et al., 1987; Edwards et al., 1988; Vasilas et al., 1988). In some situations, soybean yields with no tillage are less than yields with tillage for unknown reasons (Guy and Oplinger, 1989; Philbrook and Oplinger, 1989). Van Doren and Reicosky (1987) have a detailed section on the effects of soil type and tillage on soybean yields.

Secondary tillage conducted near planting time in the midsouthern USA can delay planting of soybean on clay soils. On these poorly-drained clay soils, that delay frequently becomes extended to weeks because of inconveniently-timed spring rains, and results in reduced yield and net return (Heatherly, 1999a). A stale seedbed planting system (Heatherly and Elmore, 1983; Heatherly, 1999c) has been adopted on a large hectarage of the alluvial soils of the lower Mississippi River Valley that are normally saturated or nearly saturated in the spring. The stale seedbed is described as "a seedbed that has received no seedbed preparation tillage just prior to planting. It may or may not have been tilled since harvest of the preceding crop. Any tillage conducted in the fall, winter, or early spring will have occurred sufficiently ahead of intended planting time to allow the seedbed to settle or become stale. A crop is planted in the unprepared seedbed, and weeds present before or at planting are killed with herbicides" (Heatherly, 1999c). The stale seedbed planting system does not preclude tillage; rather, it is a minimum or reduced tillage concept where tillage is relegated to those times that will not result in delayed planting.

Weed seedlings that emerge after harvest of the preceding crop or since the last tillage operation must be dead or killed at planting in a stale seedbed (Elmore and Heatherly, 1988; Bruff and Shaw, 1992a,b; Heatherly et al., 1994; Lanie et al., 1994a; Hydrick and Shaw, 1995). This can be accomplished with a preplant, foliar-applied herbicide and the crop can be planted into the stale seedbed with the dead weed residue remaining on the soil surface. If existing weeds are not killed at planting, yields (Heatherly et al., 1994; Lanie et al., 1994a; Hydrick and Shaw, 1995) and net returns (Heatherly et al., 1994) are reduced. The use rate of burndown herbicides is critical for achieving complete weed kill (Lanie et al., 1993; Hydrick and Shaw, 1994; Lanie et al., 1994a) and subsequent maximum yield potential (Lanie et al., 1993). Herbicides with either soil activity or soil and foliar activity can be applied at or after planting to manage weeds postemergence in the stale seedbed planting system (Heatherly et al.,1992a; Lanie et al., 1994b). Use of pre- and postemergent herbicides in addition to a preplant foliar-applied herbicide results in increased yield (Heatherly et al., 1993; Hydrick and Shaw, 1995) and net return (Heatherly et al., 1993) when highly competitive weeds appear after crop emergence. The effectiveness of pre- and postemergent herbicides following application of preplant, foliar-applied herbicides in stale seedbed soybean plantings depends on the rate of burndown herbicide used and weed size at burndown application (Lanie et al., 1993). If existing weeds are not killed with burndown herbicides at planting, then application of pre- and postemergent herbicides will not be effective (Oliver et al., 1993) in this system.

Annually generated state budgets can be consulted for guidance in choosing among the various tillage management systems for soybean. An example of such budgets for soybean enterprises in the southern USA (Mississippi) can be obtained from Spurlock (2002). An example of such budgets for soybean enterprises in the northern USA (Nebraska) can be obtained from Selley et al. (2001). These budgets provide cost information for equipment, fuel consumption, and labor for various implements and different sized tractors used in the various tillage systems.

10-2.3 Postplant Tillage

Rotary hoeing is effective as a weed management tool when used shortly after soybean emergence. It is especially effective in controlling small-seeded broadleaf weeds that germinate < 5 cm (2 in) from the soil surface, but is relatively ineffective on large-seeded weeds that germinate deeper in the soil, on no-till fields, and on fields with > 20 to 30% residue cover (Gunsolus, 1990). Stand loss of up to 10% during the operation may not lower yields if initial stands are as intended (Gunsolus, 1990). Rotary hoes also improve soybean emergence from crusted soils. Both rotary hoeing and interrow cultivation are best performed on dry soils with weather conditions appropriate for rapid desiccation of disrupted weeds.

There is general agreement that interrow cultivation after soybean emergence is needed only for weed management. Interrow cultivation can contribute to excessive soil loss in conventional tillage cropping systems (Edwards et al., 1993). Soybean plantings in the USA are made in rows ranging in width from about 20 to 102 cm (8 to 40 in). Post-plant tillage for soybean planted in wide rows (> 50 cm or 20 in) may involve one to three passes with a row crop cultivator as needed for weed control. The ability to use postplant cultivation for weed management is one of the few reasons to plant soybean in wide rows. Postplant cultivation is most cost-effective when herbicides are applied on a narrow band over the row.

Banded herbicide application combined with interrow cultivation in wide rows can be used to effectively manage weeds (Buhler et al., 1992; Poston et al., 1992; Heatherly et al., 2001a,b), reduce weed control costs (Buhler et al., 1997; Heatherly et al., 2001a,b), and reduce amount of herbicide introduced into the environment (Poston et al., 1992; Swanton et al., 1998). Use of combinations of preemergent (PRE) and postemergent (POST) herbicides with POST cultivation is common in wide-row production systems in the midsouthern USA (Heatherly and Elmore, 1991; Poston et al., 1992; Heatherly et al., 1993; Oliver et al., 1993; Heatherly et al., 1994; Hydrick and Shaw, 1995; Askew et al., 1998). Herbicides banded over the crop row and cultivation of interrow areas can provide complementary weed control (Griffin et al., 1993; Newson and Shaw, 1996), and may result in lower weed management costs than for broadcast applications of herbicides (Krausz et al., 1995; Heatherly et al, 2001a) in any row spacing. Interrow cultivation alone will not control weeds over time, and will result in lower yield and net returns (Buhler et al., 1997) than when supplemented with herbicide weed control. Narrow-row systems preclude POST cultivation normally used in wide rows (Newsom and Shaw, 1996; Buhler et al., 1997; Hooker et al., 1997; Swanton et al., 1998). In narrow-row soybean plantings, effective weed management systems almost exclusively involve herbicides (Oliver et al., 1993; Johnson et al., 1997; Johnson et al., 1998a). This can lead to improved weed control in narrow-row systems that result in greater yield and net returns compared with wide-row systems (Mickelson and Renner, 1997; Swanton et al., 1998;

Heatherly et al., 2001a,b). However, increased net returns are dependent on both economical weed management for, and increased yield from, narrow-row systems. Both of these requirements may not occur, and if not, can lead to lower net returns. The use of narrow rows and post-emergence weed management with herbicides has replaced between-row cultivation on a large portion of USA soybean plantings.

10-3 SOIL FERTILITY

10-3.1 Nitrogen

From 25 to 75% of N in mature soybean plants is from symbiotic N_2 fixation by *Bradyrhizobia japonicum*; the remaining is from soil N supply (Varco, 1999). Physiological analysis of energy requirements indicates that N assimilation via N_2 fixation requires more photosynthate than does NO_3 uptake and reduction. Still, both sources of N are essential for maximum yield. High soil NO_3 inhibits symbiotic fixation. Considerable conflicting research surrounds the question of soybean responses to both preplant and post-plant N fertilizer application.

Soybean grown on most soils does not respond to preplant N fertilization (Johnson, 1987; Varco, 1999; Hoeft et al., 2000). The exceptions cited by Johnson (1987) were applications made to soils that were somewhat poorly drained, were low in organic matter, and/or were strongly acid. Ferguson et al. (2000) summarized work from Nebraska that showed positive responses to preplant N applications about half the time, but determined that it was not possible to predict soybean response to N fertilizer based on soil properties. The situations with positive responses often either had very low residual N, low N mineralization capability, or soil pH so low that it inhibited nodulation and N_2 fixation. In these cases, 56 to 112 kg N ha^{-1} (50 to 100 lb N $acre^{-1}$) increased yields. Kansas scientists found that soybean planted into large amounts of wheat residue responded to 11 to 22 kg N ha^{-1} (10 to 20 lb N $acre^{-1}$) of starter N because inorganic N is temporarily immobilized by soil microorganisms decomposing the straw. They also found that soybean planted on recently leveled soils may respond to 33 to 45 kg N ha^{-1} (30 to 40 lb N $acre^{-1}$) because of low soil N (Whitney, 1997).

Soybean N uptake reaches a maximum rate of up to 4.5 kg N ha^{-1} day^{-1} (4 lb N $acre^{-1}$ day^{-1}) between the R3 and full pod (R4) growth stages. Because of this, several researchers have attempted to increase yields by applying N during late vegetative and early reproductive growth stages. Conflicting results are reported; however, most show no positive response. Nevertheless, a recent report from Kansas found that N applications at R3 significantly increased yields and net returns at six of eight irrigated sites (Wesley et al., 1998). Generally, rates of 22 and 45 kg N ha^{-1} (20 and 40 lb N $acre^{-1}$) provided similar increases when compared to a 0 N rate. Responsive soils generally had low organic matter, low soil profile N, and were relatively high-yielding (>3700 kg ha^{-1} or >55 bu $acre^{-1}$). These Kansas scientists concluded that applications of additional N during reproductive development should be considered for irrigated soybean with high yield potential. This small amount of N could be applied through a center pivot irrigation system, but Ferguson et al. (2000) suggests that it be considered on an experimental basis until more consistently positive results are reported. In most cases, N fertilization of soybean is an unnecessary expenditure on non-problem soils (Varco, 1999; Hoeft et al., 2000). In addition, adding starter N fertilizers to soybean delays or impedes nodulation, and thus can reduce N_2 fixation.

10-3.2 Lime and Soil pH

Liming is an important prerequisite for profitable soybean production on acid soils (Johnson, 1987). Soil pH values of 6 to 6.5 are suitable to optimize yield and performance in corn--soybean rotations. Slightly higher pH values of 6.5 to 7 are needed if alfalfa (*Medicago sativa* L.) or clover (*Trifolium* spp. L.) are included in the rotation (Hoeft et al., 2000). Liming acid soils to achieve these pH levels improves the ability of a plant to take up nutrients, reduces concentrations of potentially toxic elements such as H, Al, and Mn, increases the availability of Ca, Mg, and Mo, and improves N_2 fixation by *B. japonicum* (Mengel et al., 1987). Fig. 2 graphically shows the importance of pH maintenance for optimum availability of essential nutrients. In addition, liming acid soils enhances microbial breakdown of crop residues.

Lime sources vary in their neutralizing capability and fineness of grind. These factors, plus the soil pH and the depth to which neutralization is necessary, dictate the amount of lime required. Variation in soil pH occurs naturally among and within soil series. It is possible to improve soil pH and more accurately predict lime requirements on a site-specific basis with site-specific lime applications based on spatial variability. This may improve soybean yields on a whole-field basis as well (Pierce and Warncke, 2000).

Alkaline soils present problems for soybean production. Availability of Fe, Mn, Cu, B, Zn, and P all decrease with increasing pH (Fig. 2). Iron chlorosis is common on calcareous soils with a high pH. Damaging effects from using some soil-applied herbicides (e.g., metribuzin) and carryover of triazine herbicides is more likely on alkaline soils, and can result in loss of plants in an emerging stand. Because lowering soil pH is not practical for soybean production, management practices for alkaline soils include using tolerant cultivars and increasing seeding rates to about 40 m^{-1} (12 ft^{-1}) of row length to ensure plant adjacency since soybean (even intolerant cultivars) tolerates alkaline soils better with close intrarow spacing (Ferguson et al., 2000). This precludes using narrow rows (<50 cm or <20 in) since seeding rates would exceed 775 000 seed ha^{-1} (314 000 $acre^{-1}$) and be prohibitively expensive. In the most difficult situations, iron chelate applied with the seed at planting may improve soybean performance (Penas and Wiese, 1989; Ferguson et al., 2000).

10-3.3 Phosphorus and Potassium

Soybean is less responsive to P applications than are corn, wheat, alfalfa, and clover (*Trifolium spp.* L.) (Ferguson et al., 2000; Hoeft et al., 2000). Although soybean P_2O_5 requirements are considerably less than those of either N or K (Table 10-11), all three are equally important for plant growth and productivity. Soil test P levels of 22.5 to 45 kg P ha^{-1} (20 to 40 lb P $acre^{-1}$) are considered adequate for maximum yield (Varco, 1999). Broadcast application of P fertilizer is better than banded application at planting unless P values are low. Soybean grown in rotation with well-fertilized crops such as corn and wheat requires minimal fertilizer P to optimize yields (Varco, 1999). Phosphorus deficiency symptoms are most obvious on small plants; young plants need higher P content in tissues than do older plants. This is accentuated by the fact that P is less available for uptake in cool soils typical of early-season growing conditions. Over 90% of the alluvial and coastal plain soils in the midsouthern USA are in the medium to high P category, and thus require no P fertilizer for optimum soybean yield (Varco, 1999).

Soybean requires large amounts of K (Table 10-11). In contrast to P, nearly all northern soils except sands (K readily leaches from sandy soils) have substantial amounts of K within the rooting zone (Hoeft et al., 2000). Only a small portion of the K in soils is available for plant growth, yet K is rarely required in northern states like Nebraska. In contrast to P, seedling demands for K are relatively small. Potassium deficiencies generally appear between late flowering and early seedfill. Over 85% of the alluvial and coastal plain soils in the midsouthern USA test in the medium to high category, and require no K fertilizer for optimum soybean yield (Varco, 1999).

Recommendations in the midsouthern USA for the addition of P and K to soils are based on soil test values (Varco, 1999). Recommended P and K additions based on soil test categories used by the Louisiana State University (Funderburg, 1996) and Mississippi State University (Varco, 1999) Soil Testing Laboratories are shown in Table 10-12. The recommended rate of P at the medium soil test level is essentially a maintenance fertilization rate with a low probability of a yield response. The underlying philosophy in the K categorization is that greater soil test K levels are required with increasing cation exchange capacity (Foth and Ellis, 1997).

Two philosophical approaches to P and K fertilization are followed in the soybean production area of the northern states (Frank, 2000; Sander and Penas, 2000). The more western states in the North (Kansas, Nebraska, and South Dakota) use a deficiency correction approach (Whitney, 1997; Ferguson et al., 2000), whereas the eastern states use a modified crop removal or maintenance approach (Hoeft et al., 2000; Vitosh et al., 2001). In the deficiency correction approach, both P and K are applied for crops on soils where yield increases are expected. This approach requires accurate soil testing and analysis. In the crop-removal or maintenance approach, nutrient removal amounts of the previous crops are replaced once the nutrient levels of the soils are increased to a specific maintenance range. Once a maintenance level is achieved, soil sampling may or may not be necessary with this approach. The two approaches result in different P applicaton rates on soils with the same P levels. For example, P application in Nebraska is not triggered until the soil test level is ≤ 10 ppm P (Bray-1) using the deficiency correction approach. In states where the crop removal/maintenance approach is used, fertilizer recommendations are equal to crop removal on soils testing 15 to 30 ppm (Bray-1 P). For soils testing < 15 ppm, additional P is recommended to build soil levels. Reduced P rates are suggested for soils > 30 ppm P. Soils in the eastern and southeastern USA as well as some in Wisconsin and Minnesota do not have the capacity to quickly release K to rapidly growing plants. In those areas, K recommendations are inversely correlated with cation exchange capacity (CEC) of the soil (Vitosh et al., 2001). Soils in the western states are relatively unweathered and release K almost as rapidly as plants need it.

Band application of P is more efficient than broadcast application if soil P values are low. However, bands at least 2.5 cm (1 in) from the seed are necessary to prevent seedling injury. A broadcast-incorporated application of K before planting is efficient. In conservation tillage and no-till systems, nutrient application should occur with some amount of tillage to incorporate the relatively immobile P and K. Since approaches to soil testing vary with soils and states, P and K recommendations provided by soil testing laboratories in the state or region where the crop will be grown should be followed.

10-3.4 Secondary/Micro Nutrients

Micronutrient deficiencies are the exception rather than the rule in soybean producing areas of the United States. In many cases, simply maintaining a proper pH level prevents many problems. Two perspectives exist on the use of secondary (Ca, Mg, and S) and micronutrients (Cu, Fe, Mn. Mo, Zn). The first is preventative application, and the second is deficiency correction. There is often a narrow range between deficiency and toxicity; thus, application techniques and rates are critical. Hoeft et al. (2000) has suggested seven practices in dealing with micronutrients. 1) Know deficiency symptoms and then watch for them in the first 1 to 2 mo after emergence. 2) Observe for deficiency symptoms on more sensitive crops to provide advanced warning of problems that may develop on soybean (Table 10-13). 3) Know those soil situations where deficiencies are likely to develop (Table 10-13). 4) Test soils for micronutrients, but use more reliable plant analyses to determine if adequate nutrients are being supplied to the crop. 5) Avoid crop injury by applying the proper form of a micronutrient in the proper place. 6) Control soil pH by liming acid soil. 7) Consult experts and reputable testing laboratories for recommendations after determining a problem does indeed exist.

10-4 PLANTING PRACTICES

10-4.1 Planting Date

Soybean tolerates a relatively wide range of planting dates in both the northern and southern soybean regions of the USA. Optimum planting dates for most of the northern states range from early to mid-May. This was the previous paradigm for soybean planting date in the southern region, but has been replaced by earlier planting from late March through late April in the midsouthern USA. Planting date affects the size of plant attained before floral induction. Yields in most cases decline rapidly with June and later planting in both the north and south.

In some regions of the northern USA, indeterminate soybean cultivars planted earlier and later than the recommended planting date range of 1 May to mid-June often are shorter and have fewer nodes (Beaver and Johnson, 1981; Wilcox and Frankenberger, 1987; Hoeft et al., 2000). Determinate cultivars planted from mid-May through mid-June often have similar or greater height and number of nodes as those planted earlier. Beaver and Johnson (1981) determined that node numbers of indeterminate cultivars steadily declined as planting date was delayed from mid-May through early July, whereas node numbers of determinate cultivars remained fairly constant over this range of planting dates. Planting dates of 10 to 20 May are considered optimum for achieving adequate vegetative growth and maximum yield potential.

Planting after 1 June generally results in lower yields due to a reduction in size of plants. Research in Ohio with both determinate and indeterminate cultivars determined that yield declines about 22 kg ha^{-1} (0.33 bu acre^{-1}) day^{-1} of planting date delay after the first of May (Beuerlein, 1988). In an Illinois study, seed yields of indeterminate cultivars declined linearly and averaged 33% as date of planting was delayed from early May to early July. Seed yields of determinate cultivars did not begin to decline appreciably until planting dates were delayed past early June. In plantings after early June, they declined at a greater rate than did yields of indeterminate cultivars (Beaver and Johnson, 1981). Determinate cultivars in both Nebraska and Indiana differed in response to planting date compared to indeterminate cultivars (Wilcox and Frankenberger, 1987; Elmore, 1990). Determinate cultivar yields were best with late May to early June planting, while indeterminate cultivar yields were best with early to late May planting. However, seeding rates and cultivar growth habit are often confounded in many northern USA studies (Elmore, 1990) because earlier work showed that determinate cultivars should be planted at higher rates than indeterminate cultivars (Cooper, 1981). More recent work has shown this is not necessary (see Section 10-4.3). Protein levels generally increase with delayed planting, but these increases do not compensate for the associated reductions in oil content and yield (Helms et al., 1990). Along with yield reductions, delayed planting can reduce severity of brown stem rot [*Phialophora gregata* (Allington and S.W. Chamberlain) W. Gams] (Grau et al., 1994) and sudden death syndrome [*Fusarium solani* (Mort.) Sacc. f. sp. *glycines*] in susceptible cultivars.

In the northern USA, planting the latest adapted cultivars early in the growing season followed by planting early- to mid-season adapted cultivars during mid-May through early June has some merit. Planting early-maturing cultivars early (before 1 May) could result in flowering in late May/early June and subsequent short stature, and the occurrrence of critical reproductive stages during the moisture-deficit periods of July and August. Planting late-adapted cultivars at the above-mentioned very early planting dates avoids these potential problems. Mid-season adapted cultivars are advised for later planting dates, including doublecrop systems. These cultivars will grow taller and have more nodes than will shorter-season cultivars when planted late, and will have less risk of late-season frost injury compared with full-season cultivars. Frost injury to soybean after beginning maturity (R7) will not reduce yield, but frost before this stage can reduce yield and seed quality. This is important since half of the potential seed dry matter accumulation in soybean occurs after R6.5 [pod cavites filled (Whiting et al., 1988)].

In traditional northern corn--soybean rotation systems, producers usually plant corn before planting soybean in order to realize maximum yield from corn. However, this may result in not having adequate rainfall or soil moisture to sustain soybean podfill during August. In addition, an early fall frost can reduce late-planted soybean yields. Since it appears that soybean yield is relatively stable over a wide range of planting dates, some producers are planting soybean before corn to alleviate machinery management constraints. Information from March- or April-planted soybean in the northern USA is limited, but available data indicate that yields from April-planted soybean can be about 1000 kg ha^{-1} (15 bu acre^{-1}) greater than those from June plantings (Paul Jasa, personal communication, 2001). These data are from trials planted in no-till seedbeds and using a seed-applied fungicide. Seed germination and growth were slower with the early plantings. In preliminary studies in Illinois, yields from early-April soybean plantings have been about 17% less than those from late-April plantings (E.D. Nafziger, personal communication, 2002).

Concerns with early (March and April) plantings in the northern USA include early-season frost injury and insect feeding. Frost injury to newly emerged plants with unfolding cotyledonary leaves in early plantings can significantly reduce stands (E.D. Nafziger, personal communication, 2002). There is some evidence that soybean in the early vegetative stages of growth is more tolerant of frost than at later growth stages. If the terminal growing point of soybean is killed, regrowth can occur from the cotyledonary node or the lower nodes if the lateral buds were not injured. Regrowth from the cotyledonary nodes results in an abnormal plant with two equally dominant stems. The effect of this abnormal plant on later development, lodging and stem breakage, and yield is not well-documented. Soybean stands from plantings made before mid-May in the northern USA attract adult bean leaf beetles and offer an ideal environment for egg laying. Even though mid-May and later planting may minimize the initial colonization by beetles (Hunt et al., 1994), the insect often migrates into these later-planted fields from surrounding areas that were planted earlier. Soybean cultivars are not resistant to bean leaf beetle feeding.

In the midsouthern USA, the ESPS is the new paradigm for soybean production (Bowers, 1995; Boquet, 1998; Heatherly, 1999a; Heatherly and Spurlock, 1999). The ESPS may utilize both indeterminate (MG 2 through 4) and determinate (MG 5) cultivars (Heatherly and Spurlock, 1999; Bowers et al., 2000). This system replaces the conventional soybean production system (CSPS) which includes May and June planting of later-maturing cultivars. Choice of row spacing in the ESPS depends on whether indeterminate or determinate cultivars are used (Heatherly and Bowers, 1998; Bowers et al., 2000; Heatherly et al., 2002b). Indeterminate cultivars should be planted in narrow (< 50 cm or 20 in) rows, while determinate cultivars can be planted in either wide or narrow rows. The purpose of using this earlier planting system is to avoid much of the drought stress that is associated with the high temperatures and moisture deficits that result from decreasing rainfall and increasing evaporative demand in July, August, and September, as verified by long-term weather records for Stoneville, MS and Sikeston, MO (Table 10-14). Increasing drought stress during the growing season is detrimental especially to yield of MG V and later soybean cultivars that are planted in May and later because they are setting pods and filling seed during this period. Use of the ESPS also lowers production risks (Boquet, 1998). A detailed outline of this system has been presented by Heatherly and Bowers (1998) and Heatherly (1999a).

The data in Table 10-15 show nonirrigated (NI) and irrigated (I) soybean yields from research at Stoneville, MS for the 1979 through 1990 period. These data show that planting cultivars in MGs 5, 6, and 7 in May and June and not irrigating was a high risk enterprise during this period. In many years, NI yields were below 1345 kg ha^{-1} (20 bu acre^{-1}) and only infrequently exceeded 1680 kg ha^{-1} (25 bu acre^{-1}). There was usually large response to irrigation in dry years, but even this large response to irrigation resulted in only modest yields [2850--3150 kg ha^{-1} (mid-40's bu acre^{-1})] of I soybean. Irrigated yields of May-planted soybean ranged from 2000 kg ha^{-1} (29.7 bu acre^{-1}) to 3650 kg ha^{-1} (54.3 bu acre^{-1}), but the frequency of I yields exceeding 3365 kg ha^{-1} (50 bu acre^{-1}) was low. Bowers (1995) conducted 3 years (1986-1988) of NI studies at two northeast Texas locations (Blossom and Hooks--Table 10-16). Two facts are obvious from this report: 1) early-maturing cultivars planted in April yielded more than later-maturing cultivars planted in May, and 2) early-maturing cultivars planted in May yielded as much as or more than later-maturing cultivars planted in May. Heatherly and Spurlock (1999) conducted NI and I studies at Stoneville on Sharkey clay in 1992 and 1994 through 1997 (Table 10-17). The following conclusion can be drawn from those data: In most years, cultivars in MGs 4 and 5 that are planted in April and grown with or without irrigation produced greater yields and net returns compared to conventional I and NI May and later plantings.

Stink bug management in ESPS plantings in the southern portions of the midsouthern USA is as critical as for conventional plantings (Baur et al., 2000). Early planting of early-maturing cultivars results in more early-season insect predators and in a lower likelihood of economic injury from lepidopterous and coleopterous defoliators that occur late in the growing season (Baur et al., 2000). Either ESPS alone or in combination with CSPS (depending on availability of seasonal labor) in eastern Kansas offers farmers in that region a diversification strategy for greater farm net returns (Casey et al., 1998). The use of ESPS allowed the distribution of labor and machinery field time requirements over more time and resulted in greater farm income even though soybean seed costs in the ESPS were arbitrarily \$64 ha^{-1} (\$26 acre^{-1}) higher. In the more northern regions of the southern USA (Tennessee and Kentucky), or the transistion zone between southern and northern production areas, use of the ESPS may not be advantageous (Pfeiffer et al., 1995; Kane et al., 1997; Logan et al., 1998). In a Kentucky study where early-maturing cultivars (MGs 1 through 3) were planted late to simulate the planting date of soybean doublecropped with wheat, there was no alleviation of the yield penalty associated with the late planting of the usual MG 3 and MG 4 cultivars (Egli and Bruening, 2000). On the other hand, these results do indicate that early-maturing cultivars can be used in late plantings for a particular region. This shortened growing season for late plantings may mean lower management costs (fewer inputs) and lower risk since the early-maturing cultivars will be in the field for a shorter time.

10-4.2 Row Spacing

Certain tenets pertaining to row spacing for soybean have become accepted. Soybean grown in narrow rows [< 50 cm (20 in) in the southern USA and < 38 cm (15 in) in the northern USA] canopies sooner, and thus intercepts radiation that would have been expended on the soil surface in a wide-row environment. Soybean grown in narrow rows uses more soil water or depletes soil water more rapidly during vegetative development (Taylor, 1980; Van Doren and Reicosky, 1987). This enhanced early-season water use is usually beneficial; however, it may be detrimental in rainfed environments where stored soil water from early-season rainfall is not sufficient to compensate for low rainfall during reproductive development. Soybean grown in narrow rows results in less weed presence than when grown in wide row systems due to suppression of weed seed germination in soil surfaces shaded by a closed canopy. Soybean grown in narrow rows precludes postemergent cultivation in most cases, thus requiring weed management by herbicides. This may lead to greater weed management expense in narrow- vs. wide-row soybean.

In the northern soybean growing region of North America, soybean grown in narrow rows generally outyields soybean grown in wide rows (Devlin et al., 1995; Mickelson and Renner, 1997; Elmore, 1998; Swanton et al., 1998; Nelson and Renner, 1999). Reasons for this narrow-row advantage may be related to better weed control in narrow rows (Mickelson and Renner, 1997; Nelson and Renner, 1999), drought-free growing seasons (Devlin et al., 1995), and less weed resurgence following early-season weed management in narrow rows (Yelverton and Coble, 1991).

When the only factor limiting productivity is light, equidistant plant spacings result in maximum crop yields (Johnson, 1987). Many recent research reports from northern states like Illinois, Iowa, Indiana, Minnesota, Missouri, and Ohio indicate that soybean grown in rows 25 cm (10 in) or less in width have greater yields relative to wider rows, which is similar to what Johnson (1987) reported. However, there is an increasing amount of research from western (Kansas and Nebraska) and northern (Michigan and Wisconsin) states that indicates that soybean in wider rows (> 50 cm or 20 in) may yield more than those in rows that are 25 cm (10 in) or less in width [Devlin et al., 1995 (Kansas); Graterol et al., 1996 (Nebraska); Elmore, 1998 (Nebraska); Nelson and Renner, 1999 (Michigan); Bertram and Oplinger, 2000 (Wisconsin)]. These reports of low yields from narrow rows are often related to situations with poor early-season growing conditions or poor environments. Kansas data showed that yields were greater in 20-cm-(8-in-) wide rows than in 76-cm- (30-in-) wide rows in "high yield" environments, with the reverse occurring in "low yield" environments (Devlin et al., 1995). They classified "high yield" environments as those that produced yields greater than about 3400 kg ha^{-1} (50 bu acre^{-1}) and "low yield" environments as those that produced yields less than about 2700 kg ha^{-1} (40 bu acre^{-1}). A report from Michigan showed that soybean in 19-cm- (7.5-in-) wide rows with good weed control from either hand weeding or glyphosate yielded the same as soybean in 76-cm- (30-in-) wide rows (Nelson and Renner, 1999). Narrow rows provided better weed control with all other herbicides tested, and thus yields were better in narrow rows than in wide rows in non-glyphosate treatments. Even with early season stress that limits yield responses in narrow rows, canopy closure rates are faster with narrow rows than with wide rows. For doublecropped soybean in the northern USA which are planted from early to late June, Beuerlein (2001b) states that narrow rows (18 cm or 7 in) are required for maximum yield. Indeterminate and determinate cultivars often respond the same to row width if early-season stress is absent.

Sclerotinia stem rot [*Sclerotinia sclerotiorum* (Lib.) de Bary] is a greater problem in narrow rows because of canopy microclimate and more interrow shading in narrow rows (25 to 38 cm or 10 to 15 in) vs. wide rows (76 cm or 30 in) (Grau and Radke, 1984). However, narrow rows (17 vs. 76 cm or 7 vs. 30 in) do not appear to affect brown stem rot [*Phialophora gregata* (Allington and D.W. Chamberlain) W. Gams] severity (Grau et al., 1994). If a drill is used to plant narrow rows, seeding rates should be increased by 10 to 15% to improve plant emergence and subsequent stands. Also, avoid using large seed (< 5300 seed kg^{-1} or < 2400 seed lb^{-1}) in drills since they may be damaged by the seed-metering device (Beuerlein, 1995).

Soybean production using row widths of < 25 cm (10 in) is giving way to production in mid-width row spacings of 38 to 50 cm (15 to 20 in) in the major northern soybean producing states. Studies that have included a mid-range of row widths often show that soybean yields are optimized in row spacings of 38 to 50 cm (15 to 20 in) (Elmore, 1998; Bertram and Oplinger, 2000), which is consistent with Johnson (1987). Bullock et al. (1998) found that yields of an indeterminate cultivar were increased as row widths were reduced from 114 (45 in) and 76 cm (30 in) to 38 cm (15 in) as a result of increased pods plant^{-1}, plant height, and harvest index. They suggested that these responses were due to the beneficial effects of narrow rows prior to the main grain fill period, which is similar to results reported by Duncan (1986). In contrast, Singer (2001) found no differences in yield, pods plant^{-1}, branches, or harvest index between 18- to 20-cm- (7- to 8-in-) wide rows and 76-cm- (30-in-) wide rows at relatively high yield levels. In a series of narrow-row, no-till, multi-state studies, soybean grown in rows spaced 18 to 25 cm (7 to 10 in) apart yielded more than soybean grown in rows spaced 76 to 91 cm (30 to 36 in) apart at 6 of 21 sites. At one site, soybean in wide rows outyielded soybean in narrow rows (Oplinger et al., 1998b). Narrow rows yielded the same as intermediate rows (37 to 56 cm or 15 to 22 in).

Reasons for planting soybean in mid-width row spacings (38 to 50 cm or 15 to 20 in) in the northern states are given by Hoeft et al. (2000). They are: 1) white mold is becoming more of a problem with drilled soybean; 2) the higher cost for seed of transgenic cultivars makes the typically higher seeding rates required for drilled plantings less attractive; 3) producers are recognizing that row widths typical for grain drills (17 to 25 cm or 7 to 10 in) are not necessary to maximize yield; 4) some corn and sugar beet (*Beta vulgaris* L.) producers are shifting to mid-width row spacings which means that a single planter can be used for all crops; and 5) variability in seed-to-seed distance is greater the narrower the row spacing (drill seed-metering imprecision), which makes achieving true equidistant plant spacing difficult.

In the southern USA, recent results indicate that use of narrow rows (50 cm or 20 in) in ESPS plantings results in taller plants and better weed control in both nonirrigated and irrigated environments (Heatherly et al., 2002b). Others have reported varying degrees of enhanced weed control in narrow rows vs. wide rows (Mickelson and Renner, 1997; Nelson and Renner, 1999). However, costs for weed management in narrow rows is greater. Choice of row width for MG 5 cultivars in ESPS plantings that are not irrigated appears arbitrary, but MG 4 cultivars in nonirrigated ESPS plantings have done best in narrow rows. In irrigated environments, both MG 4 and MG 5 cultivars have higher yields and greater net returns when grown in narrow rows. Bowers et al. (2000) determined that yields of MG 3 and MG 4 indeterminate cultivars grown in narrow rows were greater than yields from wide rows at 50% of the sites in a regional study (Arkansas, Louisiana, and Texas). However, both narrow- and wide-row treatments were kept weed-free in these studies, with no comparison of the costs for this factor. The economic value of the yield advantage of narrow over wide rows might have been nil if the additional revenue was offset by greater weed control costs in narrow- vs. wide-row systems.

In the southern USA, conventional plantings (May and later) of soybean grown in narrow rows (≤ 50 cm or 20 in wide) generally produce higher yields than soybean grown in wide rows (Heatherly, 1988; Ethredge et al., 1989; Boquet, 1990; Oriade et al., 1997). However, the yield advantage of narrow rows is inconsistent over years and relatively small without irrigation (Heatherly, 1988). Thus, choice of row spacing should not be based solely on the presumption that narrow-row soybean systems will yield more than wide-row systems. A yield advantage for narrow rows should be measured against the economics of each system. Use of narrow-row systems is important when the ESPS is used because indeterminate cultivars planted in this system have only upright branching from the lower stem and are short-statured. Thus, they will not form a canopy in wide rows. In doublecropped systems (May and June planting of soybean) in the southern USA, soybean grown in narrow rows results in greater yields (Frederick et al., 1998; Ball et al., 2000). Wide-row systems should be used only where special circumstances are present, such as rotations with crops such as cotton where wide rows are considered necessary, or the need to replace broadcast herbicide applications with banded applications in conjunction with use of mechanical weed control. If a wide-row system of production is used in the southern USA, determinate cultivars should be used because of their bushier canopy structure which is more likely to result in a closed canopy (Heatherly et al., 2001b).

The preponderance of research results indicates that soybean in all regions of the USA should be grown in intermediate or narrow-row systems [50 cm (20 in) or less row width]. The review and results given by Bullock et al. (1998) support the hypothesis that yield increases from growing soybean in narrow vs. wide rows result from more vigorous early-season growth and development that occurs before about R5. Soybean grown in narrow-row production systems enhances weed management by forming a quicker canopy, and produces a higher net return.

10-4.3 Seeding Rate/Plant Density

Results over the years from numerous seeding rate experiments across the northern USA soybean production area have shown the same thing: seeding from 300,000 to 370,000 viable seeds ha^{-1} (120,000 to 150,000 seed acre^{-1}) optimizes yield in wide rows when conventional tillage and indeterminate cultivars are used. Fig. 3 shows data from one of these studies. Seeding rates in this range result in 250,000 mature, harvestable plants ha^{-1} (100,000 acre^{-1}) if normal plant losses during emergence and the remaining growing season occur. Soybean responses to seeding rates are the same in both rainfed and irrigated systems, and low- and high-yield environments. Plants in fields with low population densities are often short, thick-stemmed, heavily branched at the lower nodes, and will have more pods close to the ground. Weed control is more difficult because of an incomplete canopy. Plants in productive fields resulting from seeding rates above 370 000 seed ha^{-1} (150 000 acre^{-1}) and following good emergence are tall, spindly, and more susceptible to lodging. Lodging disrupts the canopy structure, and if it occurs at R3, will limit pod set, seed development, and thus yield, as well as reduce harvest efficiency. Determinate cultivars generally follow the same response as indeterminate cultivars to seeding rates. However, higher seeding rates for the ordinarily short determinate cultivars will result in taller plants and pods higher off the ground, which often improves harvest efficiency.

The general recommendation of planting 300,000 to 370,000 viable seed ha^{-1} (120 000 to 150 000 acre^{-1}) is based on wide-row, conventional tillage systems. Special circumstances that may involve tillage system, planting date, and row spacing will require modification of this recommendation to achieve the desirable goal of 250,000 plants ha^{-1} (100,000 plants acre^{-1}) at harvest, and these are given in Table 10-18. For example, fewer seedlings survive when no-till or minimum-till planting systems are used. Studies conducted over several northern states have shown that seeding rates of around 550,000 seed ha^{-1} (225,000 seed acre^{-1}) may be necessary to achieve maximum yields from no-till environments (Oplinger et al., 1998b). Yields increased 111 kg ha^{-1} for every 100,000 increase in planted seed ha^{-1} (1.65 bu acre^{-1} for every 40,000 seed acre^{-1}).

In the southern USA, the preponderance of research results and information indicate that a population of 200,000 to 300,000 plants ha^{-1} (80,000 to 120,000 plants acre^{-1}) provides optimum yield opportunity. Information in Table 10-19 can be used to determine the seeding rate to achieve a desired plant population in selected row spacings, as well as cost associated with the different seeding rates for cultivars differing in seed size and price. A website calculator is available to determine this information (Anonymous, 2002). Soil moisture conditions and seed germination quality should be determined in order to select a seeding rate that will likely produce these populations.

Seeding rates should be based on seed per unit area rather than on weight per unit area. Seed of cultivars grown under optimum conditions differ greatly in size, and this is under genetic control. The size of any seed lot typically is stamped on the originator's bag. Generally, seed sizes range from 5300 to 7950 seed kg^{-1} (2400 to 3600 seed lb^{-1}), but sizes of common cultivars and specialty cultivars can be outside this range. This variation in seed size requires that planters are calibrated to accommodate this variation when different cultivars are used. This is easily accomplished by counting the number of seed dropped over a 6-m (20-ft) distance and then referring to Table 10-19 to estimate seeding rate. Using the same planter settings for a 7950 seed kg^{-1} (3600 seed lb^{-1}) cultivar as for a 5300 seed kg^{-1} (2400 seed lb^{-1}) cultivar results in overseeding, a population density that is too high, and extra expense since cost of both cultivars is based on weight. From Table 10-19, this unnecessary extra cost for overseeding of the small-seeded cultivar at a rate of 296,000 seed ha^{-1} (120,000 seed $acre^{-1}$) will be about \$20.80 ha^{-1} (\$8.32 $acre^{-1}$) when using the \$25 cost for a bag of seed.

10-4.4 Inoculation With *Bradyrhizobia japonicum*

The relationship between *Bradyrhizobia spp.* bacteria and plants is unique to legumes. When infected by *B. japonicum*, the soybean and the bacteria form special structures called nodules. The plant provides carbohydrates and mineral nutrients to the bacteria which in turn provides N to the host soybean plant. This relationship is symbiotic (beneficial to both). The *B. japonicum* organism that "infects" soybean is not native to the USA and acts in symbiosis only with soybean.

Soybean can obtain up to 75% of its N requirements from the air when N-fixing *B. japonicum* bacteria are present in the soil, have infected the roots of soybean, and functioning nodules are present on those roots. Establishing *B. japonicum* (inoculation) in a field where soybean has never been grown is necessary to ensure N_2 fixation. There is inconsistency in results from inoculation of fields with a previous history of soybean culture. For example, *B. japonicum* numbers were similar among treatments in a long-term crop rotation and tillage study even though some plots had not had soybean for more than 5 yr (Triplett et al., 1993). The currently established *B. japonicum* strains were introduced early in the last century and are typically less efficient at N_2 fixation than modern strains. Unfortunately, modern strains often do not compete well with established strains and may not overwinter (Jim Beuerlein, personal communication, 2001). In these cases, reinoculation with modern strains may increase yields even in fields with a recent history of soybean culture. Nguyen (1998) states that edamame (vegetable) soybean seed should be inoculated with *B. japonicum* strain CB1809.

Aggressive new strains of *B. japonicum* from public and commercial laboratories are introduced periodically and incorporated into inoculant products. Commercial firms typically rotate strains or use a blend of strains in their products. Products currently available are dry peat- and clay-based products for planter box treatment, liquid products for planter box and in-furrow treatment, and granular products for in-furrow treatment. Two cautions are important when in-furrow products are used: 1) they are not economical for drilled plantings, and 2) they must be placed within 13 mm (0.5 in.) of soybean seed (Jim Beuerlein, personal communication, 2001). The first caution may be ignored when new labels are approved to allow a lower inoculant rate per linear row length of drilled plantings.

Most inoculant products contain more than 2 x 10^9 *B. japonicum* cells gm^{-1} and deliver more than the previously recommended minimum of 10^5 cells $seed^{-1}$. However, Hume and Blair (1992) found that increasing *B. japonicum* cells to 10^6 bacterial cells $seed^{-1}$ increased soybean yields. Not all products they tested provided that many cells. New products that may improve nodule development in cool soils early in the growing season are being evaluated (Beuerlein, 1999). Also, new seed treatment processes may make pre-inoculated seed a viable option for producers.

Early-season soil temperature differences apparently are responsible for differences in *B. japonicum* inoculation recommendations in the northern USA. Inoculation resulted in yield increases of 8.6% with an associated

13% reduction in cost of production in several northern states (Mich., Minn., S. Dak., and Wis.), whereas inoculated soybean in warmer, more southern states (Ill., Ind., Ohio) in the study performed the same as uninoculated controls (Oplinger et al., 1998b). Inoculation of previously inoculated fields in Nebraska has not improved soybean yields. Other data from Ohio indicate that responses to inoculation are frequent and profitable (Beuerlein, 2001a).

Glyphosate inhibits the enzyme 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) and thus blocks aromatic amino acid synthesis. While GR soybean cultivars contain resistant EPSPS, *B. japonicum* does not contain a resistant enzyme. Thus, glyphosate applied to GR soybean may interfere with the symbiotic relationship (King et al., 2001). In greenhouse and growth chamber studies, early applications of glyphosate generally delayed N_2 fixation and decreased biomass and N accumulation. However, plants had recovered by 40 d after emergence. In growth chamber studies, N_2 fixation was more sensitive to water deficits in GR plants treated with glyphosate.

Conditions that may justify *B. japonicum* inoculation of soybean, and author recommendations for its use are given in Table 10-20. Inoculation failures are infrequent but do occur, especially on soils that never have had well-nodulated soybean. Most failures are probably due to heat- or desiccation-induced killing of *B. japonicum* prior to, during, or following the inoculation process, or an incompatible inoculant--seed fungicide treatment. Post-plant inoculant applications should not be considered in failure cases. If an inoculation failure is discovered early in the growing season (< 30 days after planting), apply N fertilizer. A "rule of thumb" can be used to determine the amount of N to apply to overcome an inoculation failure. First, assume that 25% of the N contained in harvested soybean seed comes from the soil; inversely, 75% comes from N_2 fixation in a well-nodulated crop. If the goal is to harvest 3350 kg ha^{-1} (50 bu acre^{-1}) of seed, then about 160 kg N ha^{-1} or about 140 lb N acre^{-1} (projected yield x 0.0625 N in seed) will be required to offset the lack of N_2 fixation.

10-4.5 Fungicide Treatment of Seed

Fungicide treatment of seed can help control seedling damping off and seed rot problems caused by fungi. Several materials are available for commercial and/or on-farm use (Table 10-6). *Pythium spp.*, *Phytophthora sojae*, *Rhizoctonia spp.*, and *Fusarium spp.* are the most common pathogens associated with reduced soybean germination and emergence and subsequent stand failures (Table 10-2). Conditions which favor responses to fungicide seed treatments are early plantings in cool, wet soils with anticipated slow seedling emergence and growth, minimum-till or no-till systems, high amounts of surface residue, deep planting, fields that have continuous or frequently-grown soybean, and fields with a previous history of seedling diseases. Soybean replanted into a failed stand situation is especially prone to fungal disease infection since the soil likely will have a high level of fungal activity. In this case, a fungicide seed treatment should be used to maximize plant stands from replanting. In cases where replanting is sufficiently later so that soils are warmer and drier, use of fungicide seed treatment is optional. Treatment of seed for ESPS plantings in the midsouthern USA is recommended since a stand failure results in the cost of replanting plus the lost benefit of early planting.

The primary benefit of fungicide seed treatment is to improve crop stands rather than to improve seed viability. Because soybean will yield well under a wide range of plant densities, yield responses to fungal seed treatments are not always observed. Oplinger et al. (1998b) found that fungicides improved plant stands 2% in 2 of 3 yr in no-till tests across several states. However, there was no yield response in five of eight Iowa trials although plant stands were increased by 20,000 ha^{-1} (8000 acre^{-1}). In trials conducted in Wisconsin, fungicides increased stands by 19% and yields by 11%. The difference between the Iowa and Wisconsin results was likely due to cooler soil temperatures and high crop residues in Wisconsin.

Three cautions are worthy of consideration when using fungicide seed treatments. First, some seed treatment fungicides are incompatible with *B. japonicum*. See Table 10-20 for ways to handle this situation. Second, feeding or selling treated seed is prohibited by federal law; therefore, treat only those seed that will be planted. Third, fungicide seed treatments will not improve the quality or viability of a seed lot. Therefore, plant high-quality seed even if a seed treatment is considered necessary.

10-5 CROPPING SYSTEMS

10-5.1 Crop Rotation

Crop rotation is a term used to describe the temporal pattern of occurrence of two or more crop species in the production history of a given field. Soybean is commonly rotated with corn, wheat, cotton, rice (*Oryza sativa* L.), or grain sorghum. The growing of soybean rotated with wheat and other small grains within a 12-month period is referred to as doublecropping or intercropping (crops grown in sequential seasons of the same year) and are discussed later. Johnson (1987) and Wesley (1999b) have presented extensive reviews of crop rotation research. A summary and update of their presentations follow.

Reasons for growing soybean in rotation rather than continuously are: 1) higher yields of one or both crops; 2) a decreased need for N fertilizer on the crop following soybean; 3) increased residue cover; 4) mitigation of pest and weed cycles; and 5) distribution of labor and machine requirements over a larger portion of the growing season. Studies cited by Johnson (1987) and Wesley (1999b) show that rotated soybean generally yields more than continuous soybean and that other crops benefit from rotations that include soybean. Ferreira et al. (2000) measured greater *Bradyrhizobia* diversity and higher rates of N_2 fixation in cropping systems where soybean was rotated with wheat or corn in Brazil.

Continuous soybean is not a common cropping practice in the northern USA. Yields of both corn and soybean are increased when planted in rotation (Table 10-21). Some evidence indicates that soybean responds more to crop rotation than does corn (Table 10-22). Perhaps the main reason for this is that soybean may be more affected by soil-borne diseases than is corn. Not all situations favor short-term rotations with soybean. For example, severity of brown stem rot increased and soybean yield and seed weight decreased as soybean frequency in rotation with corn increased (Adee et al., 1994). Soil organic carbon and N are greater with continuous corn than with a corn--soybean rotation (Omay et al., 1997). These differences were related to the amount of crop residues returned to the soil. Soil microbial biomass and potentially mineralizable N were not affected by rotation with soybean. Nevertheless, economic and agronomic incentives favor a 2-yr corn--soybean rotation in the northern states.

Crops that are rotated with soybean produce more dry matter and subsequent residue than does soybean. In an Iowa study, residue cover after planting soybean no-till following corn exceeded 50%, whereas residue cover after planting corn no-till following soybean was only 37% (Erbach, 1982). The same relative differences in after-planting residue cover following corn compared to following soybean were measured in various tilled systems as well. This increased residue resulting from rotation of soybean with other crops may lead to improved water infiltration, soil tilth, and organic matter.

Rotation of soybean with a crop that is not a host to soybean cyst nematode can be used effectively to help alleviate damage to soybean by the pest in addition to delaying or preventing buildup of new SCN races (Dabney et al., 1988). Soybean in a rotation with corn may mitigate the need for pesticides to control pests of corn such as corn rootworm (*Diabrotica* spp.). Longer crop rotation cycles between soybean crops can break pest cycles and thus require less expenditure for control of insects and diseases (Adee et al., 1994; Hoeft et al., 2000). The continuous growing of either crop maximizes the opportunities for those weed species best adapted to compete with the crop to increase. Crop rotation, on the other hand, limits the potential for establishment of weed species that are most competitive with a given crop species (Gunsolus, 1990). Rotation of corn and soybean also allows the rotation of herbicides, which may limit occurrence of resistant weed species. In New York, Katsvairo and Cox (2000) found that a soybean--corn rotation resulted in greater net returns and reduced fertilizer, herbicide, and pesticide use compared to a continuous corn system.

A full economic analysis to include the different equipment complements necessary for culture of the different crops should be used to determine economic feasibility of any cropping system. Yield response alone may not be an adequate guide for determining whether or not to adopt a rotational system using soybean. The presence or absence of irrigation plays an integral part in response of soybean to rotation in the midsouthern USA, and this should be a key factor to consider. Long-term commodity price prospects should be used to project the potential net returns of varying cropping systems that may involve rotation. Machinery costs that are crop specific increase production costs and therefore reduce net returns from rotational systems (Yiridoe et al., 2000). The decision to rotate soybean with other crops thus should be evaluated from both agronomic and economic perspectives.

In a study conducted in the midsouthern USA using systems of continuous soybean and soybean rotated with corn or grain sorghum, plus doublecrop systems of wheat--soybean alone and in rotation with corn and grain sorghum (Wesley et al. 1994, 1995), the analysis of net returns to eight cropping systems over an 8-yr period (Table 10-23) provided the following conclusions: 1) without irrigation, grain sorghum was the more desirable component crop for rotation with soybean and in rotation with a wheat--soybean doublecropping sequence; 2) with irrigation, net returns to cropping systems that included corn rotated with soybean and in rotation with a wheat--soybean doublecropping sequence were greater than those from continuous single-crop systems or the other rotations; and 3) in both nonirrigated and irrigated systems, rotated crop sequences provided greater net returns than a continuous soybean system. With the advent of the higher-yielding ESPS in the midsouthern USA, these findings need updating. In an 8-yr study at Stoneville, MS, Kurtz et al. (1993) reported yields of 1235 and 1860 kg ha^{-1} (18.4 and 27.7 bu acre^{-1}) from nonirrigated soybean that was grown continuously and in rotation with rice, respectively. Respective net returns were \$20 and \$161 ha^{-1} (\$8 and \$65 acre^{-1}). Rice yields and net returns also were increased by rotation with soybean, and 8-yr average net returns from rice--soybean rotations exceeded those from both continuous nonirrigated soybean and continuous rice. This same result from nonirrigated soybean following rice was also acheived in later work at this location (Wesley, 1999b). Where soybean was irrigated (which will be the case in a soybean/rice rotation), soybean that was cropped in a 1:1 rotation with rice produced yields and net returns that were similar to those from continuous soybean (Wesley, 1999b). Since irrigated soybean yields following rice do not appear to be enhanced by the rotation with rice, the advantages of rotating soybean with rice where both are irrigated must accrue from benefits such as enhanced rice yields and disruption of pest and weed cycles rather than a yield benefit to the soybean.

Crop rotation can be used to decrease erosion potential. As shown in Table 10-9, culture of some crops results in more of an erosion hazard than others. Soils planted to soybean or cotton may have as much as 10 to 100% greater soil loss potential than do soils planted to corn or grain sorghum (Triplett and Dabney, 1999). Reasons for this are: 1) neither soybean nor cotton produce a large volume of residue that covers the soil during the off-season; and 2) soybean residue decomposes more rapidly than the stalks and leaves of non-leguminous crops. Rotation of corn and soybean with soybean planted no-till allows corn residue cover to persist into the soybean growing season, thus reducing erosion potential during the soybean growing season. Small grain straw also provides extensive, persistent cover, making a soybean--small grain doublecrop system effective in controlling soil loss. For this system to function well, the small grain straw should not be burned and soybean should be planted no-till.

10-5.2 Doublecropping

Doublecropping refers to the practice of growing two crops in one year. The potential advantages of doublecropping are: 1) increased cash flow that results from having income from two crops in one 12-month period; 2) reduced soil and water losses by having the soil covered with a plant canopy most of the year; 3) more intensive use of land, machinery, labor, and capital investments; and 4) harvesting more of the solar radiation available in a given year by deploying two crop canopies. Doublecropping is practiced in the southern portion of the soybean growing region of the USA, and the majority of the doublecropped hectarage in this region involves soybean and soft red winter wheat. Dabney et al. (1988) found that doublecropped soybean planted from early June through early July yielded significantly less than full-season soybean that was planted in early to mid-May. Wesley et al. (1994, 1995) confirmed this, and determined that a wheat--soybean doublecrop system should be used only with irrigation for profitable production on the clayey soils in the midsouthern USA. With the increased use of early planting in the ESPS and subsequent higher yields from continuous soybean in the midsouthern USA, producers should compare the economics of continuous soybean using the ESPS vs. doublecropping when determining which system to use.

Using results from dryland wheat--soybean doublecropping and continuous wheat research in Mississippi, Spurlock et al. (1997) determined that doublecropping was less profitable than continuous wheat if the soybean price is less than \$0.184 kg^{-1} (\$5 bu^{-1}) and the wheat price is greater than \$0.101 kg^{-1} (\$2.75 bu^{-1}). At a soybean price of \$0.220 kg^{-1} (\$6 bu^{-1}) and a wheat price of \$0.101 kg^{-1} (\$2.75 bu^{-1}), doublecropping was slightly more profitable. A wheat price of \$0.165 kg^{-1} (\$4.50 bu^{-1}) and a soybean price of \$0.220 kg^{-1} (\$6 bu^{-1}) is required to exceed net returns from continuous dryland soybean resulting from use of the ESPS [2350 kg ha^{-1} (35 bu acre^{-1}) yield, \$0.196 kg^{-1} (\$5.35 bu^{-1}) price] in the Mississippi Delta region.

Most farmers in the southern USA generally decide to plant wheat following soybean based on the expected price of wheat, and government programs in force at that time. The decision to plant soybean following wheat is influenced by both agronomic and economic factors. Agronomic factors include harvest date of the wheat crop (which dictates soybean planting date), soil moisture status for soybean planting and emergence, and availability of seed of desired cultivars. Economic factors that influence planting soybean following wheat are the return realized from the wheat crop, expected soybean price, and the expected yield of soybean compared to the known cost of production.

Wesley (1999a) has compiled a detailed listing of management practices for doublecropping wheat and soybean in the midsouthern USA. The following information is summarized from that publication, plus additional sources. For wheat, use shallow tillage to prepare a seedbed (number of seedbed preparation tillage trips depends on preceding crop and rutting from harvest). Plant in 15- to 25-cm-wide (6- to 10-in-wide) rows using a seeding rate of 100 to 135 kg seed ha^{-1} (90 to 120 lb acre^{-1}). Apply 22.5 to 34 kg N ha^{-1} (20 to 30 lb acre^{-1}) if wheat follows a summer grass crop or fallow. Use a fungicide seed treatment if planting on low-lying soils that are subject to submergence or prolonged saturation. If ryegrass (*Lolium multiflorum* Lam.) infestations are present after wheat emergence, make fall applications of herbicide before ryegrass reaches the five-leaf stage. Apply appropriate herbicides in late winter to control winter weeds such as wild garlic (*Allium vineale* L.), curly dock (*Rumex crispus* L.), and annual broadleaf weeds, if needed. Apply 100 to 135 kg N ha^{-1} (90 to 120 lb acre^{-1}) in late February/early March, using split applications on soils with poor internal drainage. Harvest wheat with a combine having a straw shredder/spreader. If soybean is to be planted no-till, cut wheat 15 to 30 cm (6 to 12 in) above the ground. If wheat stubble is to be burned prior to soybean planting, ensure that conditions are conducive for the complete burning of the wheat stubble. Results from previous research in the midsouthern USA indicate that burning of wheat straw is a management practice that enhances net returns if soybean is planted no-till following burning (Wesley and Cooke, 1988). Kelley and Sweeney (1998) found that burning wheat straw over a 12-yr cycle of doublecropped wheat--soybean followed by continuous full-season soybean had no long-term effect on soil properties.

Soybean cultivars selected for superior performance in conventional environments (early planting) can be expected to be among the superior cultivars in doublecrop or later-planted environments (Panter and Allen, 1989). Soybean that is doublecropped should be planted in narrow rows (<50 cm or 20 in) as soon as possible after wheat harvest. The least planting delay occurs when soybean is planted into standing or burned wheat stubble. Conventional recommendations in the midsouthern USA promote a seeding rate to achieve a final stand that is about 10% to 30% higher than that for conventional earlier plantings (Boquet, 1996; Wesley, 1999a). However, recent results from Arkansas research show that there is no irrefutable evidence to support a higher seeding rate for doublecropped later plantings (Ball et al., 2000). As shown in Table 10-19, using a higher seeding rate results in additional cost for soybean seed in doublecrop plantings. Application of a preplant non-selective herbicide to kill weeds in standing wheat stubble is recommended at time of soybean planting. Planting soybean in a prepared seedbed is recommeded if problem weeds are present or if adverse weather conditions resulted in rutting during wheat harvest. Use broadcast-applied postemergent herbicides to ensure the least cost associated with weed management. Irrigation where available will ensure maximum emergence, growth, and yield on droughty soils. Production of soybean after wheat on clayey soils in the midsouthern USA without irrigation generally is not profitable due to the effects of normal summer drought.

In the midwestern USA, doublecropping of soybean and wheat can be practiced in the more southerly portions of the region such as southern Ohio. Beuerlein (2001a) has listed management considerations for soybean following wheat in that area. Add required P and K fertilizer at time of wheat planting. Plant an early-maturing wheat cultivar to ensure early wheat harvest and the earliest possible soybean planting time of early to mid-June. Cut wheat to leave ≈30 cm (12 in) of stubble to provide mulch cover for the soybean. Wheat straw passing through the combine should be shredded; otherwise, bale and remove. Plant soybean as early as possible after wheat harvest, but no later than 10 July. If soil is quite dry at time of wheat harvest and will not be irrigated, do not plant soybean. Plant soybean no-till at 13 seed m^{-1} (4 ft^{-1}) in narrow rows (≈18 cm or 7 in), and use a mid-season maturity (MG 3.4 to MG 3.8) cultivar. Plant no-till, and kill existing weeds with a non-selective herbicide. Use GR cultivars and glyphosate for the most satisfactory and economical weed management in doublecropped soybean.

10-5.3 Intercropping

Relay intercropping has been used to extend multiple cropping further northward in the USA or to improve yields compared to those from doublecropping. In this system, soybean is planted into growing small grains, which means that both crops occupy the same area until small grain harvest. Usually, small grain rows are widened to accommodate soybean planting equipment. Thus, small grain yields may be reduced in accordance with the area lost by the widened rows of the small grain crop, or by injury to small grain plants during soybean planting (Reinbott et al., 1987). Soybean emergence and seedling growth may be adversely affected by the removal of soil moisture by the small grain crop from the soybean seeding zone (Duncan and Schapaugh, 1997). Soybean planting date should be selected with regard to the growth stage of the small grain or the anticipated small grain harvest date to ensure that soybean plants are sufficiently short to be unaffected by small grain harvest (Reinbott et al., 1987). Wallace et al. (1992) determined that the overlap between soybean planting and wheat harvest must be relatively short (2 to 3 wk in the southern USA) to prevent negative effects of relay intercropping on soybean yield.

Jacques et al. (1997) compared net returns from continuous soybean, doublecropped soybean and wheat, and relay intercropped soybean and wheat in Arkansas. Doublecropping produced a higher net return than relay intercropping, which produced a higher net return than continuous soybean. However, yields from continuous soybean were below 2000 kg/ha because of a late May planting date. Yield from soybean that was intercropped was below that from both continuous and doublecropped soybean. Duncan and Schapaugh (1997) conducted research in Kansas and concluded that supplemental irrigation must be available for soybean that is intercropped into standing wheat on soils that are droughty or that have low moisture holding capacity. They also determined that the height of wheat cultivars (determines degree of shading of emerging soybean seedlings) was instrumental in early-season soybean seedling survival until wheat harvest. Net returns from intercropping were less than returns from continuous irrigated soybean. Reinbott et al. (1987) in a Missouri study measured a 3-yr average intercropped soybean yield that was 25% less than yield from a continuous soybean treatment, but 52% greater than yield from late June/early July-planted doublecropped soybean.

Strip intercropping is a variation of intercropping. In this system, soybean is grown simultaneously with other crops such as corn or grain sorghum in contiguous alternating strips. When soybean and corn have been grown in strip intercrop systems, increased corn yields have usually been offset by reduced soybean yields from rows that bordered the corn strips (Crookston and Hill, 1979; Iragavarapu and Randall, 1996). The use of wheat as a strip crop between corn and soybean resulted in the determination by Iragavarapu and Randall (1996) that alternate three-crop strips of wheat--soybean--corn could be planted in a north-south row direction to optimize production in Minnesota. Lesoing and Francis (1999a) determined that a corn--soybean strip intercropping system in Nebraska has more potential under irrigation than under rainfed conditions. In fact, their irrigated intercropping system was economically competitive with continuous single-crop systems. Lesoing and Francis (1999b) determined that grain sorghum and soybean yields from intercropped strips in a 2-yr rotation were similar to single-crop yields in the same rotation under both rainfed and irrigation conditions.

10-5.4 Cover Crops

Growing vegetation is often used as a source of soil cover during the winter and spring seasons when summer annual crops are not present. This vegetation can consist of annual weeds or a crop planted specifically to provide cover. Where a cover crop is used, wheat or some other small grain is ideal to precede soybean. Cover crops usually are destroyed prior to planting of the summer row crop with no short-term economic gain from their use. Thus, the potential long-term benefits for integrating cereal cover crops into a soybean production system would have to arise from erosion control, increasing soil organic matter, and increasing soil productivity. Cover crops can play a role in decreasing erosion and increasing soil organic matter following soybean, since soybean typically leaves the soil more prone to wind and water erosion than either corn or grain sorghum. This is especially valued on low organic matter soils and rolling loess soils (Wilson et al., 1993). Shipitalo at al. (1997) proposed using a rye (*Secale cereale* L.) cover crop following soybean harvest in a corn--soybean rotation as an acceptable management practice for reducing total herbicide loss in runoff in the northern Appalachian region of the USA.

Cover crops are not used widely in northern USA soybean production systems. When used in conventional soybean production systems (i.e., not organic production systems), cover crops are grown between harvest and planting of row crops rather than in place of them (Hoeft et al., 2000). They typically are planted at or slightly before the fall harvest of the summer crop and are allowed to grow during the fall, winter, and early spring. Moore et al. (1994) found that soybean yields were comparable with or without cover crops in an Ontario, Canada study. Thus, net returns in their study effectively would have been reduced because of the expense incurred for seeding the cover crops. In Nebraska, a planting of winter rye following soybean harvest resulted in as much post-planting residue cover as a crop of corn (Kessavalou and Walters, 1997). Rye was destroyed in the spring by disking prior to corn planting. In 2 of 3 yr, the rye produced enough residue to limit erosion and did not affect corn yields. In the third year, rye development was delayed in the spring and corn plant density and yields were decreased, possibly because of allelopathic effects of the rye. In addition to this concern, the large immobilization of NO_3-N and fertilizer N by cover crop residues may result in N deficiency in corn unless corrected with N application. In Iowa, Karlen and Doran (1991) found that a winter cover crop resulted in a 10% lower corn yield, which they attributed to the depletion of soil nitrate levels by cover crop decomposition that was not overcome by post-emergence broadcast application of N. In the mid-Atlantic States, Lu et al. (1999) found that net returns from a 2-yr rotation of corn--wheat--soybean grown in a no-till system with and without winter cover crops were essentially identical over a 4-yr period ($233/ha vs. $238/ha). However, the no-till system without cover crops was determined to have the lowest economic risk (C.V. = 1.14 vs. 1.24; lower limit = $53/ha vs. $39/ha).

In the upper midwestern USA, there is concern about the small amount of time for cover crop growth and development when planted after harvest of the summer row crop. To address this, Johnson et al. (1998b) overseeded oat (*Avena sativa* L.) and rye as monocultures (sole crops) and mixtures into standing soybean in August. This practice allowed more dry matter production from the cover crop than was obtained from post-harvest plantings of cover crops in the fall. Oat was more advantageous than rye because it was winter-killed and thus required no herbicide treatment in the spring. Yield of soybean in the overseeded treatments was slightly below (but not statistically so) that from a continuous soybean control treatment with no winter cover crop. A rye cover crop was associated with reduced corn yields the following year, but yields of corn following oat were not affected. In Nebraska, aerial seeding of winter rye at beginning leaf drop of soybean is possible on sand and sandy loam soils; light irrigations are sometimes necessary to promote rye germination and development (Wilson et al., 1993).

Cover crops also may have a role when planted prior to soybean in a rotation. They have suppressed early-season weeds for the first 3 to 5 wk after soybean planting (Williams et al., 1998). Efficacy of other integrated weed management tactics possibly is enhanced when used in conjunction with cover crops (Williams et al., 1998). Cover crops planted in the fall and killed with herbicides before soybean planting the following spring favored soybean emergence and growth over that of weeds (Williams et al., 1998). In one year of their study, however, abnormally heavy cover crop residues (6.3 to 7.2 Mg ha^{-1} or 5 625 to 6 430 lb acre^{-1}) of both winter rye and wheat interfered with soybean seed placement and reduced soybean plant densities.

The limited use of cover crops in northern USA soybean production systems probably is due to the shorter and cooler growing season available for cover crop growth. Development in the fall and early spring is slow, and cover crops impede soil warming (Hoeft et al., 2000). In addition, cover crop residue with unfavorable spring weather is difficult to handle and makes the practice unattractive. In drier areas, allowing the cover crop to grow too long in the spring can use soil moisture that will be needed for soybean germination and emergence.

In the southern USA, cover crops have numerous benefits in row crop production, and can be used effectively in the stale seedbed system (Griffin and Dabney, 1990; Elmore et al., 1992; Heatherly et al., 1993; Reddy, 2001b). The cover crop can be killed at the appropriate time with foliar-applied herbicides (Griffin and Dabney, 1990; Elmore et al., 1992). However, using wheat or other cereals as a winter cover crop may result in lower net returns (Table 10-24; Reddy, 2001b, 2003) due to the expense incurred in establishing the small grain cover with no resulting soybean yield increase (Elmore et al., 1992; Heatherly et al., 1993), whereas doublecropping soybean and a small grain provides both soil cover and the potential for extra income. Thus, the potential long-term benefits of erosion control, increases in soil organic matter, and increases in soil productivity resulting from use of cover crops in soybean production systems provide the only advantages for their use.

Where soil protection provided by a cover crop is needed to reduce erosion potential on slopes, drainage usually is adequate for wheat to be well-adapted. Under these conditions, doublecrop soybean following wheat has been more profitable than either wheat or soybean grown as a sole crop. On a poorly drained Tunica clay, however, a wheat cover crop killed before planting did not increase soybean yield, reduced net returns, and increased the percentage winter ground cover only in years when fall tillage reduced the populations of volunteer winter annual weeds (Elmore et al., 1992).

Winter cover crops offer the potential to overcome weed problems which may be otherwise unmanageable in the winter and spring (Reddy et al., 1999). In the southern USA, using volunteer winter weeds themselves as a cover crop in a soybean production system has merit. There is no expense associated with their establishment and they can be killed in the spring with preplant, foliar-applied herbicides. Successful use of winter weeds as cover crops may depend on amount and time of fall tillage, since some of the winter annual species emerge in late summer/early fall and tillage after this time may jeopardize volunteer stands of weeds. Recently imposed label restrictions on the latest date for late winter/early spring aerial application of some preplant, foliar-applied herbicides may reduce the value of winter weeds as cover crops if they are killed too far ahead of planting soybean.

10-6 POST-PLANTING MANAGEMENT

10-6.1 Replanting Decisions

Replanting as a result of poor emergence should be considered only when plant densities are below the desired ranges given previously. A decision to replant also should be evaluated on an economic basis because of the cost of seed and replanting. Cost for replanting can be significant and minimally will include cost of seed (Table 10-19), seed treatment (if used), and planting [>\$27 ha^{-1} (\$11 acre^{-1}); Spurlock, 2000]. Also, even a small delay in planting, or in this case, a later planting date resulting from replanting, can result in much lower seed yield in some regions if weather conditions during the growing season are less favorable for development of the later planting (Gaska, 2000; Heatherly and Spurlock, 2002a).

Farmers faced with poor stands have three choices: keep the stand, replant affected areas of a field, or plant an additional row alongside each existing but poorly emerged row. In the northern USA, Vasilas et al. (1990) investigated the three options in Illinois and found that even a 66% reduction from an original stand of 16 to 19 plants m^{-1} (4.8 to 5.8 ft^{-1}) of 76-cm- (30-in-) wide rows did not justify replanting. An offset row [20 cm (8 in) to the side and parallel to each row] increased yield only in the cases where > 66% of the stand was lost in randomly placed gaps. Soybean is extremely tolerant of poor stands, assuming they are uniformly spaced. Yields from stands as low as 120,000 plants ha^{-1} (50,000 acre^{-1}) are often the same as those from higher populations. When stands are less than this level, replanting should be considered a viable option. Mid-season adapted cultivars are advised for replantings at later-than-optimum dates. These cultivars provide greater height and node numbers than shorter-season cultivars when planted late, and will have reduced risk of late-season frost injury.

Some stands may be adequate in terms of number of plants, but crusting-induced cotyledon shearing at emergence or hail or insect damage soon after emergence can greatly slow vegetative growth of surviving plants and irreparably lower their yield potential. In these cases, a determination must be made that the conditions causing plant injury can be remedied or likely will not be repeated for a replanting. It also must be determined that the yield potential of and projected net return from the replanted crop will exceed yield potential of and net return from the damaged crop. Objective assessment of these criteria is difficult. A situation that likely justifies remedying is that of a marginal stand of damaged plants. If a stand is at the lower end of an acceptable population range, but a significant number of emerged plants is damaged, then replanting is recommended.

Assessment of hail-damaged stands requires an estimation of total plants (stand count) and damaged plants (defoliation and stem breakage). Soybean plants can recover from stem damage if the stem is not severed below the cotyledonary (seed leaf) node. This is the first node on the seedling; the two fleshy, dark-green cotyledons are attached on opposite sides of this node. Buds on each side of this node can grow new branches if they are still present and undamaged. A plant that is broken below this node will not survive. Hail stones often damage stem tissue at the base of plants which may lead to stem lesions at or near the soil surface. These injuries may contribute to lodging susceptibility later in the season as the plant canopy reaches maximum size and the weight of filling pods becomes too great for the injured stem to support. Shapiro et al. (1985) provide a detailed guide for estimating soybean yield loss due to hail damage.

In general, determining plant density on an area basis is preferred. To determine if a soybean stand is adequate, a systematic sampling of plant density and adjacency should be used (Willers et al., 1999). This involves using line-intercept sampling (LIS) in a management unit [i.e., a 20- to 40-ha (50- to 100-acre) field]. The first step in using LIS is to divide the field into subunits where crop phenology and soil type are similar. Within each subunit, locations for transect lines (a string or rod that lies perpendicular to row direction) are chosen randomly. Generally, each transect line should be the width of one planter pass, with longer lines encompassing multiples of whole planter passes. Plant counts are taken on segments [typically 0.3 to 1 m (1 to 3.3 ft)] of each of the rows emanating from one side of the transect line. The shorter length sample is sufficient where stands are dense and uniform, whereas the longer length sample should be used where the stand is sparse and/or nonuniform. The length of row sampled should be the same for all rows within and among transect lines within a subunit. Use of such a system allows an objective determination of the number of plants present on an area basis after final emergence, and the uniformity of their distribution.

Key points to consider before replanting have been adapted from Martin (2001). 1) Use an objective method [such as that given by Willers et al. (1999) and described above] for assessing stand and compare the sample numbers to the values in Table 10-19 that are needed for a given population range. 2) Assess the health and vigor of plants in stands that are at the lower end of the acceptable population range. Compare estimated yield and net return from damaged stands with estimated yield from a replanted crop. This should weigh the cost of replanting and the estimated effect of later planting on yield against the cost of protecting/recovering plants in damaged stands. This also assumes that the factor(s) (such as hail, insects, or soil crusting) causing damage to the affected stand will not be repeated. Gaska (2000) provides estimated yields based on replanting dates in Wisconsin. 3) Consider replanting only if the cause of a stand failure can be determined and corrected with the replanting. 4) Determine availability of seed of preferred cultivars since replanting with substandard cultivars is discouraged.

10-6.2 Weed/Pest Management

Inputs used for weed management in soybean represent a significant cost (Heatherly et al., 1994; Buhler et al., 1997; Johnson et al., 1997), and must be managed early (PRE) or on an as-needed basis (POST). In narrow-row soybean plantings, effective weed management systems almost exclusively involve herbicides (Oliver et al., 1993; Johnson et al., 1997; Johnson et al., 1998a) because of the inability to effectively conduct interrow cultivation. However, this can lead to improved weed control in narrow-row systems and result in greater yield and net returns than from wide-row systems (Mickelson and Renner, 1997; Swanton et al., 1998). Use of combinations of PRE and POST herbicides with POST cultivation for broadleaf and grass weed control is common in wide-row soybean production systems in the midsouthern USA (Poston et al., 1992; Heatherly et al., 1993, 1994; Oliver et al., 1993; Hydrick and Shaw, 1995; Askew et al., 1998), while a weed management system that is totally dependent on herbicides is used in narrow-row systems.

A comprehensive summary of weed management for soybean grown in the southern USA is presented by Reddy et al. (1999). Comprehensive summaries of disease, insect, and nematode management for soybean grown in the southern USA are presented by Bowers and Russin (1999), Funderburk et al. (1999), and Lawrence and McLean (1999), respectively. Chapter 18 in this Monograph contains an up-to-date summary of weed management issues for the soybean producing region of the USA. Summaries of management practices for diseases and nematodes are presented in Chapters 14 and 15. Management of insect pests is addressed in Chapter 17.

10-6.3 Irrigation

It is widely thought that crops adapt to drought stress and become capable of withstanding drought. There is no evidence to support this view when it is considered on the basis of producing an economic yield. The limited adaptation that does occur only increases the plant's ability to survive during drought. This may be a valuable mechanism for a desert shrub, but it is of little value where production of a profitable seed yield from a crop such as soybean is important. The moisture status of plants is a function of soil water supply, evaporative demand of the atmosphere, and the capacity of the soil to release water. In the field, significant water deficits develop on hot sunny days even in well-watered plants. As water is transpired from the leaves, the moisture tensions that develop increase the rate of water uptake from the soil. If roots cannot absorb water rapidly enough, plant water tension increases. These tensions often become growth-limiting. See Chapter 12 of this Monograph for extensive details on the impact of water-deficit stress on soybean.

Irrigation that is properly managed or applied is important for soybean production in several areas of the USA, especially if consistent profits are expected. The lower Mississippi River alluvial flood plain and eastern Nebraska have high concentrations of irrigated soybean. Irrigated soybean yields in Nebraska have increased 40% faster than those of rainfed soybean [35.1 vs. 24.9 kg ha^{-1} yr^{-1} (0.52 vs. 0.37 bu acre^{-1} yr^{-1}); Specht et al., 1999], probably because of better management of irrigation. Inadequate water supply to soybean limits absolute crop yield and appears as an obstacle to yield improvements (Specht et al., 1999). In the midsouthern USA, irrigation of soybean is required to make a profit on a consistent basis (Heatherly, 1999b).

Because of the importance of irrigation for optimizing yield and maximizing efficient use of inputs, and because of restrictions on water use imposed by regulatory agencies in the central Great Plains, many researchers have proposed soybean irrigation-scheduling strategies to optimize productivity and/or irrigation water-use efficiency. Water use (evaporation plus transpiration, or ET) of a fully irrigated crop of full-season soybean ranges from about 47 to 61 cm (18.5 to 24 in) per growing season (Benham et al., 1998). About 75% of this is used during reproductive development (Fig. 4). Table 10-25 lists irrigation water requirements for soybean during the reproductive stages when grown in Nebraska assuming the soil water reservoir is at or near capacity to a 1.5-m (5-ft) depth at planting. This usually is the case in the eastern half of Nebraska if the soils were irrigated the previous season and if there was sufficient off-season rain to recharge the profile. Peak water use is about 0.76 cm day^{-1} (0.3 in. day^{-1}), which occurs from R2 to R3. Yield responses to factorially and serially timed irrigation during reproductive development indicate that irrigations coinciding with the pod elongation (R3 to R4) and seedfill (R5 to R6) periods are the most effective (Korte et al., 1983a,b; Kadhem et al., 1985a,b). This of course assumes that plants had adequate water up to this time, which may not be the case for soybean grown on sandy soils or during years with a dry early season. In these cases, irrigation during vegetative and early reproductive development may be necessary to ensure optimum growth and development of plants, with careful attention to avoiding irrigation-induced excessive vegetative growth which will result in lodging (Benham et al., 1998). The use of determinate or semi-determinate cultivars can mitigate the lodging problem. Irrigation initiated before or during flowering must be followed with adequate water for the remainder of the season to ensure maximum number of seed and seed weight.

Soybean does best on soils with good internal and surface drainage. Although soybean roots may reach depths of 2 m (6.5 ft), irrigation management should concentrate on the top meter (3.3 ft) of the soil profile since most roots proliferate there. Soil type, irrigation system, and system capacity are important considerations for irrigation management. Soil type determines available water holding capacity and infiltration, irrigation system determines how water is delivered and affects irrigation efficiency, and irrigation system capacity determines the amount of time required to deliver an amount of irrigation water.

Irrigation scheduling is a means of accurately forecasting the times and amounts of water application to ensure that irrigation-mediated yield enhancement is economical. Factors that affect irrigation amount and frequency are determined by the amount of water applied by the previous irrigation (minus runoff), effective rainfall (amount that entered the soil), and estimated water use by the soybean crop since the previous irrigation and/or rain. The sensitivity of the developmental stage to water-deficit stress must also be considered. Rainfall measurements at the field site can be made easily, and well capacities or irrigation system outputs and efficiencies can be measured and/or calculated. Crop water use can be estimated by using pan evaporation numbers from the nearest weather station since actual evapotranspiration during the R1 to R6 period closely resembles pan evaporation (Reicosky and Heatherly, 1990). Estimates of water use based on pan evaporation can be combined with estimates of water supplied by irrigation and rainfall to predict the soil water deficit in the effective rooting zone.

The following guidelines for soybean irrigation management are adapted from recommendations for Nebraska by Benham et al. (1998). For coarse-textured or sandy soils with less than 12.5 cm m^{-1} (1.5 in ft^{-1}) water holding capacity, allow no more than 50% water depletion in the top 0.6 m (2 ft) of soil during flowering (R1 to R2). Allow no more than 50% depletion in the top 0.9 m (3 ft) of soil during the pod elongation to seedfill period (R3 to R6). For deep medium- and fine-textured soils (silt loams, silty clay loams, and silty clays) with more than 12.5 cm m^{-1} (1.5 in

ft^{-1}) water holding capacity, allow no more than 50% water depletion in the top 1 m (3.3 ft) of soil during the R1 to R6 period. Producers with the latter soils often use an irrigation trigger criterion of 25% during the water-deficit-stress-sensitive pod elongation (R3 to R4) and seed enlargement (R5 to R6) periods, but 50% to 60% for other periods. Paraphrasing a comment made in the prior Monograph (Van Doren and Reicosky, 1987), the sensitivity of the plant to water-deficit stress should signal when to irrigate, with the soil water status determining how much to irrigate.

Soil water levels at specified depths can be determined by soil sampling and drying, by instruments such as tensiometers, gypsum blocks, and neutron probes, or by ET estimates. Scheduling based solely on reproductive stage sensitivity or according to stage of development (Specht et al., 1989), or solely on soil and weather parameters, can be used with equal effectiveness for irrigation management of soybean. However, application amounts applied using the different methods may be different. For example, in a series of Nebraska studies (Klocke et al., 1989), irrigation initiated at growth stage R3 to R4 with soil water content not considered resulted in 40 kg ha^{-1} of seed produced per cm of irrigation water (1.52 bu $acre^{-1}$ in^{-1}). Irrigation scheduled using the 50% soil water depletion parameter resulted in 25 kg ha^{-1} of seed produced per cm of irrigation water (0.95 bu $acre^{-1}$ in^{-1}). The growth stage technique is simple but requires the soil profile over the entire potential rooting zone to be at or near field capacity at planting. This is usually the situation in eastern Nebraska and the midsouthern USA, assuming normal off-season and preplant rainfall patterns.

In the midsouthern USA, moisture deficits become more negative from April through August, as indicated from weather data collected at Stoneville, MS (Table 10-14). This leads to serious drought stress during reproductive development of soybean nearly every growing season. Since pod and seed growth, which are quite sensitive to plant water deficits, occur later in the season when soil moisture and rainfall are at the lowest seasonal levels, the potential for significant reductions in their growth and development and subsequent yield is great. Drought stress conditions can also result in greater infection of soybean roots by *Macrophomina phaseolina*, the causal organism of the yield-reducing disease charcoal rot (Kendig et al., 2000).

The advantages of irrigating soybean in the southern USA are well-documented (Reicosky and Heatherly, 1990; Heatherly, 1999b). Irrigation of soybean significantly increases yields by overcoming drought. The effectiveness of irrigation in alleviating the effects of drought on soybean in the southern USA is accepted, and is typically profitable (Heatherly, 1999b). If an irrigation system is in place, then it should be used since the fixed costs associated with the equipment exist regardless of whether or not the system is used. The question, then, is not whether to irrigate soybean for significant yield enhancement, but how to do it properly for maximum profit.

Weather data and measurements of the amount of water applied at each irrigation at Stoneville, MS, and the recent summary of irrigation research results (Heatherly, 1999b) have resulted in the following practical approach to scheduling irrigation for soybean in the midsouthern USA. Pan evaporation in the region ranges from 6.4 to 7.1 mm d^{-1} (0.25 to 0.28 in d^{-1}) during the months of June, July, and August (Boykin et al., 1995). Water use by MG V irrigated soybean that is in reproductive development during this period is about 7.7 mm d^{-1} (0.3 in d^{-1}) (Heatherly, 1986). Thus, in the absence of rain, about 7.5 cm (3 in) of water (net applied to soil) is needed about every 10 to 12 d. This is the amount typically supplied by a normal furrow or flood irrigation to cracking clay soils (Heatherly, 1999b). Therefore, furrow or flood irrigation should be planned every 10 to 12 d in the absence of rain to match the normal water deficit that occurs in the period since the last irrigation. To modify this approach, results from studies conducted in Arkansas (Tacker et al., 1997) should be used. These results show that irrigation scheduled to replace a 5 cm (2 in) soil water loss since the last irrigation resulted in significantly greater soybean yield than irrigation scheduled to replace a 7.5 cm (3 in) deficit. This simple approach results in a successful strategy for irrigating soybean in most situations, and ensures that clay soils are irrigated before noticeable cracking occurs. For sprinkler irrigation and assuming no runoff, an overhead irrigation system that applies 3 gross cm (1.2 in) should be scheduled to irrigate about every 3 to 4 d (assuming 80 to 85% efficiency).

Crusting soils with a low capacity for water infiltration, or shallow soils that have a relatively low total water holding capacity, can experience runoff if large amounts of water are applied in a short period of time. In these situations, less water must be applied at each irrigation, but irrigation should be more frequent. On a silt loam site at Stoneville, MS, runoff of irrigation water applied through an overhead system occurred when an application exceeded 2 cm ha^{-1} $event^{-1}$ or 0.8 in $acre^{-1}$ $event^{-1}$ (Heatherly et al., 1992b). Thus, frequency of irrigation on this site was greater than on sites discussed above.

In Arkansas (Tacker et al., 1994), inadequate irrigation and/or improper timing of irrigations are the major reasons for lower-than-expected soybean yield responses from irrigation. They conclude that a water-balance approach has the most potential for properly irrigating soybeans. They use two irrigation scheduling methods that are based on soil moisture accounting procedures. The Arkansas Checkbook Method uses a daily water use chart and a computation table for updating soil moisture content (Tacker, 1993). The University of Arkansas Irrigation Scheduling Program operates basically the same, but uses a computer program to perform the computations (Tacker et al., 1997). The computer program requires the emergence date, the soil moisture deficit at planting, and a predetermined allowable soil moisture deficit of 5, 7.5, or 10 cm (2, 3, or 4 in). The daily information required to use either of these methods is maximum air temperature, rainfall, and irrigation amounts.

Numerous studies in the southeastern USA have investigated yield response of determinate soybean cultivars grown continuously to both full-season irrigation (water applied as needed during both the vegetative and reproductive phases of development) vs. irrigation during reproductive development only (water applied as needed from R1 to R6). The results of these studies have been summarized by Reicosky and Heatherly (1990). The conclusions from these many studies, plus the additional information supplied by Heatherly (1999b), follow: 1) irrigation before R1 produced no appreciable yield advantage above that realized from irrigation applied only during reproductive development; and 2) irrigation efficiency, defined here as the increase in seed yield ha^{-1} cm^{-1} of water applied, was usually higher for the reproductive phase irrigation. Thus, irrigation of monoculture soybean prior to R1 appears to be of little benefit, even though atmospheric demand for water increases through R1. In some years, significant drought during vegetative development may justify irrigation prior to bloom to ensure adequate vegetative framework to support a yield response to reproductively timed irrigations. Most soil types, assuming periodic rainfall, can supply the water necessary to meet atmospheric demands and support adequate growth during the vegetative phase. Exceptions to this are those soils that have a shallow rooting depth (Griffin et al., 1985) or low available water-holding capacity, or doublecropped soybean that is planted in dry soil.

Delaying initiation of irrigation until R4 or R5 in years when rainfall is limited during early reproductive stages results in seed yields that are lower than those realized from irrigation started at or about R1 (Elmore et al., 1988; Reicosky and Heatherly, 1990). Number of pods and seeds is increased if irrigation occurs during early reproductive development, but only the weight of seeds is increased if irrigation is delayed until later stages. Where drought stress is severe but alleviated by irrigation during early reproductive development, the biggest percentage yield increase comes from increased number of seeds. If irrigation is applied only after pods are set and seeds are filling, increase in weight of individual seeds is the major contributor to increased yields. Numerous research reports support the conclusion that the major effect of drought stress on seed yield is a reduced number of seeds (Reicosky and Heatherly, 1990). Frederick et al. (2001) found that increased yield resulting from irrigation of determinate cultivars grown on a Coastal Plain soil in South Carolina came from increased branch seed yield vs. main stem seed yield.

Irrigation that is started during early reproductive development must be continued into the seedfill stage (Griffin et al., 1985; Reicosky and Heatherly, 1990; Heatherly and Spurlock, 1993) so that soil moisture is readily available through the full seed stage. This ensures that yield potential is realized, and prevents increased infestations by the charcoal rot fungus (Kendig et al., 2000). Stress that occurs during seedfill results in smaller seeds, but will not reduce the total number of seeds below the number produced by plants that are irrigated during all stages of reproductive development (Reicosky and Heatherly, 1990). Thus, the number of seeds that are set is maintained during any drought stress that occurs after seed formation (except in extremely severe drought conditions), but maximum weight of individual seeds is not realized if drought occurs during seedfill. Irrigation during the full reproductive period is required to maximize both number of seeds (established by early alleviation of drought stress) and weight of seeds (maximized by later irrigations).

There may be cases where only a limited amount of irrigation water is available, and it is not enough for full reproductive phase irrigation. It can be allocated for use during early reproductive development to establish a maximum number of seeds, or to the latter stages of reproductive development to maximize weight of seeds. However, neither of these practices produces the maximum yield that may be required to maximize net returns unless adequate rainfall is received during the times of no irrigation (Heatherly, 1983; Elmore et al., 1988; Heatherly and Spurlock, 1993). The use of limited irrigation early in the reproductive phase can be advantageous if rains are received during the latter stages of reproductive development. Late-occurring rain has the greatest effect if relatively large numbers of seed are set as a result of irrigation during early reproductive development. However, the probability of late summer (August and September) rain in the midsouthern USA is low. The use of limited irrigation during the seedfill period can be advantageous for ensuring maximum weight of seeds. In cases of limited irrigation water, irrigation during the seedfill period appears to provide the greatest probability for maximizing yield. This appears less risky than using it earlier and depending on late-season rain to enlarge seeds that were set as a result of irrigation during early reproductive development. Unfortunately, producers using surface-water rights of lower priority may have those water rights halted before that occurs. Moreover, this premise assumes that a reasonably high number of seeds were set in the absence of irrigation during early reproductive development.

Irrigation of soybean interacts with other management practices such as cultivar, planting date, and row spacing. In reality, response of cultivars to irrigation probably is related more to time of reproductive development in relation to planting date than to cultivar *per se*. Early-planted, early-maturing cultivars in the midsouthern USA sometimes require less irrigation and often produce greater irrigated yields than later-maturing cultivars planted during May and June because the irrigation period (R1 to R6) of the later-planted, later-maturing cultivars is closely aligned with the period experiencing the greatest moisture deficit (Heatherly, 1999a,b). In the midwestern USA, irrigation invariably mitigates the hastening of maturity induced by water-deficit stress. Indeed, in irrigated production, full-season cultivars recommended for rainfed culture may actually mature as much as 7 to 14 d later, which may not be the best adaptation. Lodging can result in reduced response to irrigation, especially when overhead irrigation is used and irrigation is applied before beginning bloom of determinate cultivars in the southern USA (Boquet, 1989). When both irrigation and row spacing are considered, proper irrigation is more important; i.e., much greater yield responses can be achieved with irrigation of any row spacing than can be achieved by changing row spacing in the absence of adequate water (Elmore et al., 1988; Heatherly, 1999b).

From 1980 through 1997, various experiments that have involved irrigation of soybean planted in April, May, and June were conducted at Stoneville, MS (Table 10-26). The yield data lead to several general but unmistakable conclusions. First, irrigation of soybean cultivars planted in April or early May almost always resulted in greater yields than did irrigation of the same cultivars planted later. Prior to 1992, when the earliest plantings were in early to mid-May and the late plantings were in late May to late June, more irrigations of the early plantings were required to achieve these higher yields. From 1992 to 1997, when the early plantings were in April and the late plantings were in early to late May, the earlier plantings required the same or fewer irrigations. Second, in the absence of irrigation, planting dates ranging from early May to late June (1980 through 1986) had little effect on soybean yield. April plantings of soybean that was not irrigated yielded more than later plantings (1992 through 1997). These first two conclusions lead to a third. For fields that are to be irrigated, plant at the earliest acceptable time for an individual cultivar and location to provide opportunity for the maximum seed yield response from MG 4 and MG 5 cultivars with the least irrigation.

Soybean grown on the flat alluvial flood plain of the lower Mississippi River Valley in the midsouthern USA is often irrigated using flood irrigation. The following summary regarding management of flood irrigation for soybean is condensed from information presented by Heatherly (1999b). Flood irrigation results in an inundation of a field with water amounts that result in standing water on some portion of an enclosed area. The flow rate of the water source and the size of the enclosed area being irrigated determine the time required to complete the flood. During the time of flooding, an increasingly larger area is covered with water until the entire area within the levees or borders is finally inundated. Numerous studies (Griffin et al., 1988; Scott et al., 1989; Heatherly and Pringle, 1991; Heatherly and Spurlock, 2000) have been conducted in the midsouthern USA to investigate the response of soybeans to flood irrigation. Results from these studies show the following: 1) soybean exposed to longer than 2 d of standing water was more tolerant of flooding during the vegetative period (V4) than during the reproductive period (R2); 2) the damaging effect of prolonged flooding (more than 2 d) was more severe for soybean grown on a clay vs. a silt loam soil; 3) differences exist in cultivar sensitivity to conditions resulting from flood irrigation; 4) flood irrigation duration of 3 d resulted in less than maximum yield increase from irrigation, while that of 2 d or less ensured the greatest yield increase when using flood irrigation; and 5) properly timed and managed flood irrigation resulted in yields of soybean that were comparable to those resulting from proper furrow irrigation (Heatherly and Spurlock, 2000). Thus, for highest yield response from flood irrigation, it should be managed so that all area within a set of levees or borders will have the process started and finished within 2 d. Longer flood irrigation periods will lessen the expected yield response to irrigation due to root oxygen deprivation.

Determining the need and timing of a last irrigation application to soybean is important. Irrigation that exceeds that amount necessary to maximize net return is a waste of a valuable resource, increases labor costs and fuel consumption, and may result in reduced yield if lodging occurs. Drought still may occur late in the season, but the soybean plant's ability to use added water for additional increases in seed dry matter is limited at some point by the physiological processes of the maturing plant system. On the other hand, one additional irrigation may mean optimizing yield via further increase in seed size. An optimal date for the last seasonal irrigation requires consideration of two conflicting goals: 1) supply enough root-zone water for the crop to produce maximum yield, and 2) terminate soon enough to allow for the depletion of soil profile water so that off-season precipitation storage will be maximized (Klocke et al., 1991). Field information on crop growth stage, expected water use to R7, remaining useable soil profile moisture, and probability of precipitation are factors that should be considered in determining need for a final irrigation. For the northern USA, an equation adapted from Klocke et al. (1991) for use in Nebraska may be useful: Remaining irrigation amount required = Water requirement - available water capacity (AWC) - current soil moisture status. Components for calculations are presented in Table 10-27. The principal difficulty is forecasting the calendar date when R7 will occur. Physiological maturity of a pod is achieved when dry matter accumulation ceases. Some researchers use the degree to which the pod membrane clings to the pod wall instead of the seed as a key visual criterion of physiological maturity. This normally occurs in the pod about 3 to 7 d before that pod achieves a mature pod color (R7 criterion) (James Specht, personal communication, 2002).

In the midsouthern USA, an effective surface irrigation at stage R5.5 supplied enough soil moisture to finish filling seeds of MG 5 and 6 cultivars that were planted in May. Irrigation later than R5.5 did not increase yield or net returns. Termination of irrigation at an earlier stage resulted in lower yields and net returns. Irrigation terminated during early bloom (R1 to R2), full bloom (R2 to R3), podset (R3 to R4), and full pod/beginning seedfill (R4 to R5) periods resulted in negative or only slightly positive net returns, even though yields were increased significantly above nonirrigated yields by all of these early-terminated treatments (Heatherly and Spurlock, 1993). These results point out the importance of starting irrigation at early reproductive development of soybean and continuing well into the seedfill period when using surface application methods. When irrigation is supplied by overhead systems that may apply less water per event than is applied by surface methods, the last irrigation should be later since an overhead irrigation applied at stage R5.2 to R5.5 may not provide enough water to finish filling seeds. In southeast Missouri, the recommendation is that irrigation should continue past R6 on all soils that have a coarser texture than silt loam, whereas flood irrigation can be terminated at about mid-R5 on all soils but coarse sand (Henggeler, 2002). For ESPS plantings in the midsouthern USA, indications from the extreme drought periods in the late summer of 1999 and 2000 are that surface irrigation should be continued to R6. A fully charged soil profile at R6 is needed because the R6 to R7 period occurs during the hottest, driest part of the growing season and water use is still occurring.

10-6.4 Harvesting

Physiological maturity of soybean occurs when maximum dry matter has accumulated. The easiest visual indicator of this is the presence of one normal pod on the plant that has reached the mature pod color (R7) (However, see previous section). Seed moisture at this time may range between 40 and 60%. An autumn frost before R7 can result in premature plant death, with subsequent reduced yield and green pods and seeds. Leaves of frosted plants do not drop normally and field drydown of seed is slower. Only 1% green seed are allowable for US No. 1 soybean and 2% for US No. 2 grade. Oil produced from green soybean has a green tint and requires additional refining. Thus, a frost which results in green seed may reduce market value of the seed. Seed from plants frosted within 2 wk of maturity, or seed from plants only partially frosted, may lose their green color if allowed to field dry (Hurburgh et al., 2001). Seed that has a light brown coloration will lose that coloration after a few months in storage. Protein content of frosted soybean seed is similar to that of non-frosted soybean seed; however, oil content and germination are both reduced. Germination of seed from a yellow pod (55% seed moisture content) is decreased when exposed to 8 h at -7° C, while germination of seed from brown pods (35% seed moisture content) is decreased when exposed to 8 h at -12° C (Johnson, 1987). Frost-damaged or green soybean seed can be marketed as livestock feed. For swine (*Sus* spp.), extruded frost-damaged soybean may totally replace soybean meal. For sheep (*Ovis* spp.) and cattle (*Bos* spp.), frost-damaged soybean should be limited to 14% of total dry matter intake by the animals (Loy and Holden, 1993). Because of variability in composition, frost-damaged soybean seed should be analyzed before use in formulating rations.

Purposeful desiccation prior to soybean harvest is an option in some instances, such as ESPS plantings in the midsouthern USA where an earlier open canopy allows weed resurgence. The following thoughts are presented based on discussion by Ellis et al. (1998), Heatherly (1999a), and Reddy et. al. (1999). A preharvest desiccant will be needed if weed densities are high enough to lead to increases in soybean seed moisture and damaged soybean seed, more foreign material in the seed, and/or decreased combine speed and subsequent harvest efficiency. A preharvest desiccant will not be needed if: 1) weeds present at maturity emerged late in the growing season and their size will not interfere with harvest; 2) the weeds present have not produced mature seeds that will contaminate the grain; and 3) the desiccant cannot be applied sufficiently ahead of harvest so as to ensure that the weeds are dry at harvest, or that time interval restrictions in the harvest aid label can be met. This may be the case in the high temperature, low humidity conditions common to August when the time between maturity of soybean, or 95% mature pod color, and harvest maturity may be as little as 5 to 7 d and the required interval between desiccant application and harvest is 7 to 15 d, depending on the desiccant. The budgets for ESPS soybean in Mississippi (Spurlock, 2000) do not include a desiccation input since conditions rarely justify the need for or allow the effective use of desiccants.

The maturity stage of soybean seed best for harvest is when seed moisture falls to 15% or lower (Keith and Delouche, 1999). Harvest of soybean seed production fields should commence as soon as seed moisture content reaches

14% (Moore, 1996). Susceptibility to harvest-mediated mechanical damage (i.e., cracked seed coat and split seed) occurs when seed moisture content falls below about 13% (Keith and Delouche, 1999). This lowers seed quality and may result in dockage at the delivery point or reduced germination of seed beans. Combine settings should be checked over the course of each day's harvest to allow for changes in seed moisture content that occurs from the morning through the afternoon and evening of the same day.

The harvest environment is dictated by soil conditions, weather, presence of weeds, and the condition of the seed to be harvested. Harvesting is a critical phase since the condition of the final saleable product is determined at this time. Weathering or field deterioration of seeds may be associated with harvest delays beyond the harvest maturity stage. Therefore, it is critical to commence and continue harvest whenever proper conditions are present. Highest harvest efficiency occurs when the harvesting machine travels on dry soil. This allows combine ground speed and speeds of the machine components to be matched for greatest effect.

An important consideration when choosing cultivars at the beginning of the growing season in the midsouthern USA is their maturity date in relation to optimum soil conditions for harvesting on clay soils. Harvesting efficiency is reduced on soils of this texture when they are wet because of combine wheel spinning and slipping. Fields are rutted by the harvesting machine, and remediation of these ruts requires otherwise unnecessary tillage. Rutted fields must be repaired in the fall following harvest; otherwise, their remediation the following spring may cause planting delays that result in lowered yield potential caused by the delayed planting. Thus, consideration of optimum soil conditions for harvest in this region is an important component of a soybean production system.

Seed quality can be affected by the harvesting operation. Improper combine settings can result in excessive splitting of seed and/or the failure of the machine to remove seed-contaminating foreign matter. These problems can result in lowered seed quality and dockage at the delivery point.

10-7 SUMMARY

This chapter is intended to supplement those of Johnson (1987) and Van Doren and Reicosky (1987), which centered on midwestern USA soybean production. Much of the material in those chapters is still pertinent to today's production systems that involve soybean. The information in this chapter in many cases is an addendum to information in the aforementioned chapters. Most of the information in this chapter pertains to subjects that have received considerable research attention since the previous chapters, or to information about new technologies that have emerged since the writing of the previous chapters.

In the last 15 yr, new technologies and problems have become significant contributing factors to soybean production in the USA. This chapter presents details for solving those problems as well as details of new technologies that should be considered in soybean management systems. First, glyphosate-resistant soybean is a significant new technology that affects cultivar development and selection, as well as systems of management in the USA soybean production zone. The incorporation of this new technology into current management systems is requiring a reassessment of weed management for soybean and rotational systems using soybean. Second, new paradigms regarding planting date/MG combinations are being accepted as methods of avoiding pest and weather stresses. The use of cultivars from early-maturing MGs in regions outside their perceived area of adaptation is being used as a tool to manage biotic and abiotic stresses of soybean. Third, soybean cyst nematode incursion into the midwestern/northern USA soybean producing areas has added a new dimension to management systems in this region. This has placed more emphasis on pest resistant cultivars and rotational schemes as management tools. Fourth, irrigation has become an increasingly important component in soybean management systems where summer drought conditions are prominent. The need to reduce seasonal irrigation requirement for soybean and to avoid major water-deficit periods of the growing season has placed increased emphasis on management practices that enhance drought avoidance and increase water use efficiency to produce the highest possible economic yield. Fifth, the need to lower producer risk (reduce costs, decrease management time, and stablize higher yields) in the face of stiffer global competition requires that all components of soybean management be assessed in relation to each other to ensure the most efficient combination of production variables.

Competition for soybean market share has become pronounced in the global marketplace. The producer with the most efficient and economical production system will be the most competitive. Therefore, it is paramount that proven new technology and new paradigms for soybean production be adopted quickly. This requires that new and emerging educational tools be utilized to place new and improved management concepts into the hands of the producer as quickly as possible. This chapter attempts to accomplish this through presentation of information on new soybean production/management technology and where to find it.

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Table 10-1. Internet addresses of soybean cultivar trial results for USA states and Ontario, Canada, and parameters evaluated or measured.

		Parameters measured								
State	Site address†	Yield	Protein	Oil	Lodging	Mature height	Relative maturity	Seed wt.	Disease/Herbicide reaction‡	Plant traits§
Alabama	www.aces.edu/department/cotton/soybean.html	X			X	X	X			X
Arkansas	http://www.arkansasvarietytesting.org	X			X	X	X		PRO; CHLORIDE	X
Georgia	www.griffin.peachnet.edu/swvt	X			X	X	X	X		X
Illinois	http://vt.cropsci.uiuc.edu/soybean.html	X	X	X	X	X	X		SCN; SDS; WM	X
Indiana	www.agry.purdue.edu/ext/variety.htm	X			X	X	X			
Iowa	www.agron.iastate.edu/icia/YieldTesting3.html	X	X	X	X	X	X		BSR; CHL; PRR; SCN; WM	X
Kansas	www.ksu.edu/kscpt/	X			X	X	X		SCN; PRR	
Kentucky	http://www.uky.edu/Ag/GrainCrops/varietytesting.htm	X			X	X	X		BSR; FLS; PRR; SC; SCN; SDS; VIR	
Louisiana	www.agctr.lsu.edu/Subjects/soybean	X			X	X	X			X
Maryland	www.nrsl.umd.edu/extension/crops/soybeans	X	X	X	X	X	X	X	SCN	
Michigan	www.css.msu.edu/varietytrials/	X	X	X	X	X	X		PRR; WM	
Minnesota	www.extension.umn.edu/farm/	X	X	X			X	X	BSR; CHL; PRR; SCN; WM	X
Mississippi	http://msucares.com/pubs/infobulletins/ib384.pdf	X	X	X	X	X	X	X	BB; BP; BS; CLS; DM; FLS; MET; PRR; SC; SCN; SDS; VIR	X
Missouri	www.agebb.missouri.edu/index.htm	X			X	X	X		PRR; SCN	X
New Jersey	www.rce.rutgers.edu/pubs/pdfs/e041n.pdf	X	X	X	X	X	X			
Nebraska	http://varietytest.unl.edu/soytst/2002/index.htm	X	X	X	X	X	X	X	CHL; PRR	X
N. Carolina	www.cropsci.ncsu.edu/ovt/cotton_soy/2002/toc.htm	X			X	X	X			
Ohio	http://www.oardc.ohio-state.edu/soy2002/	X	X	X	X	X	X	X	PRR; WM	
Oklahoma	http://www.agr.okstate.edu/soybeans/varietyresults2002.html	X			X	X		X		X
Ontario	www.gov.on.ca/OMAFR/english/crops/index.html	X	X	X	X	X	X	X	PRR; WM	X
Pennsylvania	www.agronomy.psu.edu/Extension/Extension.html	X			X	X	X	X		
S. Carolina	cropweb.clemson.edu/	X			X	X	X			
S. Dakota	www.sdstate.edu/~wpls/http/var/vartrial.html	X	X	X	X	X	X		SCN; CHL; PRR	
Tennessee	web.utk.edu/~taescomm/research/variety.html	X			X	X	X			X
Texas	www.tamu-commerce.edu/coas/agscience/jjh.html	X				X	X			
Virginia	www.vaes.vt.edu/tidewater/soybean/variety.html	X			X	X	X		PSS	
Wisconsin	http://soybean.agronomy.wisc.edu/soyvar.htm	X			X	X	X		BSR; PRR; WM	X

†Websites verfied on 27 Nov. 2002.

‡BB = bacterial blight; BS = brown spot; BSR = brown stem rot; BP = bacterial pustule; CHL = chlorosis; CLS = cercospora leafspot; DM = downy mildew; FLS = frogeye leafspot; MET = metribuzin; PRR = phytophthora root rot; PRO = propanil; PSS = purple seed stain; SC = stem canker; SCN = soybean cyst nematode; SDS = sudden death syndrome; VIR = virus (SMV/BPMV); WM = white mold.

§Includes bloom/flower/pubescence/hilum/pod wall color, seed size, shatter rating, and height of lowest pod, but not necessarily all.

Table 10-2. Common pathogens that affect soybean in the northern and southern USA, indication of soybean resistance, and management/control measures. Adapted from Bowers and Russin (1999), Hartman et al. (1999), Hoeft et al. (2000), and Loren Giesler, (personal communication, 2001).

Pathogen		Cultivar	
Common name	Causal organism(s)	Resistance	Management/Control
Anthracnose	*Colletotrichum truncatum* (Schw.) Andrus & W.D. Moore	No	Plant disease-free seed, treat seed with fungicide†, apply foliar fungicide during reproductive development, plow under crop residue, rotate with non-legume crops
Bacterial blight	*Pseudomonas savastanoi* pv. *glycinea*	Yes	Do not save seed from infected fields, plant high-quality seed, clean till to destroy infected residue, rotate
Bacterial pustule	*Xanthomonas axonopodis* pv. *glycines*	Yes	Do not save seed from infected fields, plant high-quality seed, clean till to destroy infected residue, rotate
Bean pod mottle	Bean pod mottle virus	No	Transmitted by insects feeding in other legumes like alfalfa and clovers, destroy alternative broadleaf weed hosts
Brown spot	*Septoria glycines* Hemmi	No	Plant disease-free seed, rotate with non-legume crop, apply foliar fungicide during reproductive development
Brown stem rot	*Phialophora gregata*	Yes	Clean till, plant late, rotate
Cercospora leaf blight, purple seed stain	*Cercospora kikuchii* (T. Matsu. & Tomoyasu) Gardner	Yes	Plant seed of resistant cultivars, plant disease-free seed, late planting, apply foliar fungicide during reproductive development, rotate with non-legume crop
Charcoal rot	*Macrophomina phaseolina* (Tassi) Goid	No	Rotate with non-susceptible (cereals and cotton) crops, plant tolerant cultivars, avoid excessive seeding rates, minimize plant stresses, conservation tillage
Downy mildew	*Peronospora manshurica*	Yes	Plant in wide rows, clean till
Frogeye leaf spot	*Cercospora sojina* Hara	Yes	Plant seed of resistant cultivars, plant disease-free seed, rotation with non-legume crop, apply foliar fungicide during reproductive development
Fusarium root rot and seedling blight	*Fusarium solani* and *F. oxysporum*	Yes	Plant resistant cultivars, plant late, treat seed with fungicide†, plant high-quality seed, clean till
Phytophthora rot	*Phytophthora megasperma* Drechs. f. sp. *glycinea* (Hildeb.) Kuan and Erwin	Yes	Plant seed of race-resistant cultivars, treat seed with fungicide†, maintain good surface drainage, use conventional tillage
Pod and stem blight and *Phomopsis* seed decay	*Diaporthe phaseolorum* (Cke. & Ell.) Sacc. f. sp. *sojae* (Lehman) Wehm., *Phomopsis sojae* Lehman, and *Phomopsis longicolla* Hobbs	Yes	Plant disease-free seed, treat seed with fungicide†, plant early (north), apply a foliar fungicide during reproductive development, harvest promptly at maturity, plow under crop residue
Powdery mildew	*Microsphaera diffusa*	Yes	Plant resistant cultivars, apply foliar fungicides
Red crown rot	*Calonectria ilicicola* Boedijn and Reitsma	No	Delay planting, plant on coarse-textured soils, plant tolerant cultivars
Rhizoctonia root rot and stem decay (damping off)	*Rhizoctonia solani*	No	Plant late, plant high-quality seed, treat seed with fungicide†, minimize stresses, clean till
Rhizoctonia foliar blight (aerial blight)	*Rhizoctonia solani* anastomosis group (AG) 1	No	No complete control; plant tolerant cultivars, apply foliar fungicide during reproductive period, avoid excessive irrigation
Sclerotinia stem rot	*Sclerotinia sclerotiorum*	Yes	Use row spacings > 90 cm (36 in), plant late, plant sclerotia-free seed, treat seed with fungicide†, rotate, clean till
Sclerotinia blight (southern blight, white mold)	*Sclerotinia rolfsii* Sacc.	No	Rotate with nonhost crop, avoid post-plant cultivation, bury residue 15 to 25 (6 to 10 in) deep
Seed rots and seedling diseases	*Pythium*, *Phytophthora*, *Fusarium*, *Rhizoctonia*, *Sclerotinia*, and *Phomopsis* spp.	Yes	Treat seed with a fungicide†, plant disease-free seed, delay planting until soil temperatures are warm
Soybean mosaic virus	Soybean mosaic virus	Yes	Plant early, plant virus-free seed, plant seed of resistant cultivars

Table 10-2. Common pathogens that affect soybean in the northern and southern USA, indication of soybean resistance, and management/control measures. Adapted from Bowers and Russin (1999), Hartman et al. (1999), Hoeft et al. (2000), and Loren Giesler, (personal communication, 2001).

Pathogen		Cultivar	
Common name	Causal organism(s)	Resistance	Management/Control
Soybean cyst nematode	*Heterodera glycines*	Yes	Plant seed of race-resistant cultivars, control weeds, balance fertility, rotate sources of resistance and with non-host crop
Stem canker	*Diaporthe phaseolorum* var. *meridionalis* (south) and var. *caulivora* (north)	Yes	Plant seed of resistant cultivars, plant disease-free seed, rotate with other crops, plow under crop residue
Sting nematode	*Belonolaimus* spp.	No	Rotate
Sudden death syndrome	*Fusarium solani* (Mart.) Sacc. f. sp. *glycines*	No	Use resistant or moderately resistant cultivars, control soybean cyst nematode, clean till, plant early (south), plant late (north)

†See Table 10-6 for proper fungicide.

Table 10-3. Major insect pests that affect soybean in the USA, plant parts injured, and important management considerations. Adapted from Funderburk et al. (1999), Higley and Boethel (1994), and Higgins (1997).

Insect pest		Injurious insect stage:	
Common name	Scientific name	Plant parts injured	Management considerations†
Bean leaf beetle	*Cerotoma trifurcata* (Forster)	Adult: leaves, stems, blooms, pods. Larva: roots and underground stem	Infestation predominates at seedling stage and during flowering and pod-forming through seed-filling period; Adult feeding results in greatest injury; may transmit viruses; encouraged by reduced tillage systems
Beet armyworm	*Spodoptera exigua* (Hübner)	Leaf blades	Late-season infestation
Blister beetle	*Epicauta* spp.	Adult: leaves and flowers.	Mid to late summer infestation; may cause complete defoliation; scout after mowing of nearby fields
Corn earworm	*Helicoverpa zea* (Boddie)	Adults: leaf blades, pods, seed	July and August infestations associated with hot and dry conditions
Grasshopper	*Melanoplus femurrubrum* (DeGeer) *M. differentialis* (Thomas)	Nymph and adult: leaves, pods, seed in pods	Early summer through harvest infestations; Monitor field edges close to grassy areas; encouraged by reduced tillage
Green cloverworm	*Plathypena scabra* (Fabricius)	Larva: Leaf blades in upper canopy	Early to mid-season infestation
Japanese beetle	*Popillia japonica* (Newman)	Adult: leaves will be skeletonized	Full summer infestation; infrequent pest in eastern portion of midwest; manage in association with other defoliators
Lesser cornstalk borer	*Elasmopalpus lignosellus* (Zeller)	Larva: Lower stems	Late-season infestations associated with hot and dry conditions; seedling damage most injurious
Mexican bean beetle	*Epilachna varivestis* Mulsant	Adult and larva: leaf blades between veins	Early-season infestation; greater threat under moderate weather conditions of coastal areas
Potato leafhopper	*Empoasca fabae* (Harris)	Nymph and adult: Leaf blades and veins	Full summer infestation; Mainly in southern USA, but migrates north; dense leaf pubescence provides mechanical barrier
Saltmarsh caterpillar	*Estigmene acrea* (Drury)	Larva: leaves in upper canopy	Similar to woollybear caterpillar
Seed corn maggot	*Delia platura* (Meigen)	Larva: underground cotyledons	May reduce emergence from cool, wet soils with recent organic matter incorporation; delay planting after residue incorporation or use chemical seed treatments.
Soybean aphid	*Aphis glycines* (Matsumura)	Leaves	Feeding may cause stunted plants with distorted leaves; peak populations during V2 to R2; overwinters on *Rhamnus* spp. (buckthorn); no economic thresholds; late plantings possibly at greater risk.
Soybean looper	*Pseudoplusia includens* (Walker)	Larva: Leaf blades	Mid- to late-season infestation; worse in soybean--cotton regions
Stink bugs: Southern green, Green, Brown	*Nezara viridula* (L.) *Acrosternum hilare* (Say) *Euschistus servus* (Say)	Adult: pods, seeds	Mid-season infestation; most injurious damage to seed during early seed formation; treatment of field borders may be sufficient
Thistle caterpillar	*Vanessa cardui* (Linnaeus)	Larva: leaves webbed, skeletonized	Full summer infestation period; may require treatment after large migrations.
Threecornered alfalfa hopper	*Spissistilus festinus* (Say)	Nymph and adult: lower stems, petioles	Early-season infestation that may go unnoticed until lodging occurs
Two-spotted spider mite	*Tetranychus urticae* (Koch)	Larva, nymph, adult: Leaf sucking, leaf yellowing, dead lower leaves	Full summer infestation period; populations can increase rapidly during hot, rain-free periods, and may require immeidate treatment
Velvetbean caterpillar	*Anticarsia gemmatalis* Hübner	Larva: leaf blades	Late-season infestation
Wireworms	*Melanotus* spp.	Larva: seed, roots, underground stem	Spring infestation period; may reduce germination in fields with grass prior to soybean.
Woollybear caterpillar	*Spilosoma virginica* (Fabricius)	Larva: leaves in upper canopy	Rare late summer outbreaks may require treatment

†Best pest management involves identifying species, sampling to estimate numbers of each species, and consulting economic threshold values provided by Cooperative Extension Service personnel, university entomologists and specialists, and/or crop consultants.

Table 10-4. Comparisons of costs using preemergent (PRE) and/or postemergent (POST) weed management in conventional (CONV) and glyphosate-resistant (GR) soybean cultivars grown in narrow row culture (no mechanical weed management) in the southern USA using 2001 prices. Adapted from Reddy et al. (1999).

Cultivar/ weed management	Inputs	Rate	Cost
			\$ ha^{-1} (\$ acre^{-1})
CONV public/ PRE + POST	Seed†	296,000 seed ha^{-1} (120,000 acre^{-1})	19.77 (8.00)
	PRE metribuzin + chlorimuron premix	420 g a.i. ha^{-1} (0.375 lb a.i. acre^{-1})	53.97 (21.84)
	POST sethoxydim‡	210 g a.i. ha^{-1} (0.19 lb a.i. acre^{-1})	29.45 (11.92)
	POST 2,4-DB + linuron§ tankmix	224 g a.i. + 560 g a.i. ha^{-1}	33.28 (13.47)
		(0.2 lb + 0.5 lb. a.i. acre^{-1})	
	Total		136.47 (55.23)
CONV public/ POST	Seed†	296,000 seed ha^{-1} (120,000 acre^{-1})	19.77 (8.00)
	POST bentazon + acifluorfen¶ premix	840 g a.i. ha^{-1} (0.75 lb. a.i. acre^{-1})	39.29 (15.90)
	POST sethoxydim‡	210 g a.i. ha^{-1} (0.19 lb a.i. acre^{-1})	29.45 (11.92)
	POST 2,4-DB + linuron§ tankmix	224 g a.i. + 560 g a.i. ha^{-1}	33.28 (13.47)
		(0.2 lb + 0.5 lb. a.i. acre^{-1})	
	Total		121.80 (49.29)
CONV private/ PRE + POST	Seed†	296,000 seed ha^{-1} (120,000 acre^{-1})	32.62 (13.20)
	PRE metribuzin + chlorimuron premix	420 g a.i. ha^{-1} (0.375 lb a.i. acre^{-1})	53.97 (21.84)
	POST sethoxydim‡	210 g a.i. ha^{-1} (0.19 lb a.i. acre^{-1})	29.45 (11.92)
	POST 2,4-DB + linuron§ tankmix	224 g a.i. + 560 g a.i. ha^{-1}	33.28 (13.47)
		(0.2 lb + 0.5 lb. a.i. acre^{-1})	
	Total		149.32 (60.43)
CONV private/ POST	Seed†	296,000 seed ha^{-1} (120,000 acre^{-1})	32.62 (13.20)
	POST bentazon + acifluorfen¶ premix	840 g a.i. ha^{-1} (0.75 lb. a.i. acre^{-1})	39.29 (15.90)
	POST sethoxydim‡	210 g a.i. ha^{-1} (0.19 lb a.i. acre^{-1})	29.45 (11.92)
	POST 2,4-DB + linuron§ tankmix	224 g a.i. + 560 g a.i. ha^{-1}	33.28 (13.47)
		(0.2 lb + 0.5 lb. a.i. acre^{-1})	
	Total		134.64 (54.49)
GR/ POST	Seed#	296,000 seed ha^{-1} (120,000 acre^{-1})	49.42 (20.00)
	POST glyphosate	1120 g a.i. ha^{-1} (1 lb a.i. acre^{-1})	25.45 (10.30)
	POST glyphosate	1120 g a.i. ha^{-1} (1 lb a.i. acre^{-1})	25.45 (10.30)
	Total		100.32 (40.60)

†Based on planting CONV public cultivar at \$0.44 kg^{-1} seed (\$10.00 per 50 lb bag) or a CONV private cultivar at \$0.73 kg^{-1} seed (\$16.50 per 50 lb bag), both with 6.6 seed g^{-1} (3,000 seed lb^{-1}).

‡Includes herbicide at \$22.98 ha^{-1} (\$9.30 acre^{-1}) + crop oil at \$6.47 ha^{-1} (\$2.62 acre^{-1}).

§Includes herbicides at \$31.06 ha^{-1} (\$12.57 acre^{-1}) + surfactant at \$2.22 ha^{-1} (\$0.90 acre^{-1}).

¶Includes herbicides at \$36.08 ha^{-1} (\$14.60 acre^{-1}) + crop oil at \$3.21 ha^{-1} (\$1.30 acre^{-1}).

#Based on planting GR cultivar at \$1.10 kg^{-1} seed (\$25.00/50 lb. bag) with 6.6 seed g^{-1} (3,000 seed lb^{-1}).

Table 10-5. Growth, development and yield of non-glyphosate-resistant soybean sister lines (non-GR sisters) and GR sister lines averaged over Nebraska locations for 2 years. Adapted from Elmore et al. (2001b).

Sister-line groups	Plant density	R1 bloom	R7 maturity	R8 maturity	R7 plant height	R7 Lodging†	Seed weight	Yield	Grain moisture
	plants ha^{-1} (acre^{-1}) x 1000	-------days from 31 May-------			cm (in)	1-5	mg seed^{-1}	Mg ha^{-1} (bu acre^{-1})	%
Non-GR sisters	266 (108) a*	43.6 a	111.9 a	120.4 a	86 (34) b	1.6 a	147 a	3.68 (54.8) a	10.0 a
GR sisters	267 (108) a	43.7 a	112.7 a	121.7 a	88 (35) b	1.4 a	141 b	3.48 (51.9) b	10.0 a
No. locations: 1998/1999	4/4	2/4	3/4	3/1	4/4	4/4	0/3	4/4	4/4

†1 to 5 scale with 1 = erect and 5 = prostrate.

*Means followed by the same letter within a column are not significantly different at $P \leq 0.05$. Means were separated with single-degree-of-freedom comparisons.

Table 10-6. Seed-treatment fungicides for control of soybean seed and seedling diseases, type of control, and organisms controlled or suppressed by each fungicide. Adapted from Anonymous (2001), L. Geisler (personal communication, 2001), Keith and Delouche (1999), and Mueller et al. (1999).

Fungicide			
Trade name	Common name	Type†	Pathogen‡ controlled
Apron XL	Mefenoxam	S	PRR, PYT
ApronMaxx	Mefenoxam + fludioxonil	C,S	FUS, PHO§, PRR, PYT, RHI, SCL
Maxim	Fludioxonil	C	FUS, RHI, SCL
Mertect	Thiabendazole	S	FUS, RHI, SCL
Rival	Captan¶ + PCNB¶ + thiabendazole	C,S	FUS, PHO, RHI, SCL
Stiletto	Carboxin + Thiram + metalaxyl	C,S	ANT, FUS, PHO, PYT, RHI, SCL
Terraclor	PCNB¶	C	RHI
Vitavax CT	Carboxin + thiram	C,S	ANT, FUS, PHO, RHI, SCL

†C = contact (protectant); S = systemic.

‡ANT = Anthracnose; FUS = *Fusarium* spp.; PHO = *Phomopsis* spp.; PRR = *Phytophthora* root rot; PYT = *Pythium* spp. seedling rot; RHI = *Rhizoctonia solani* root rot; SCL = *Sclerotinia sclerotiorum*.

§Suppression.

¶Captan and PCNB have an adverse effect on *Bradyrhizobia japonicum* inoculant (Curley and Burton, 1975). Avoid these materials if seed is directly inoculated or use an in-furrow application of the inoculant if captan is used. Check product label for compatibility with *B. japonicum* inoculant when using any seed treatment fungicide.

Table 10-7. Summary of north central USA regional high protein soybean test, 2000. Adapted from George Graef (personal communication, 2001).

Maturity Group	No. of locations	Trait	Range among standard cultivars (checks)	Range among high protein strains
II	11	Seed protein %†	33.9 - 35.7	35.5 - 42.3
		Meal protein %	48.3 - 49.4	49.1 - 54.8
		Yield (% of checks)		70.7 - 107.0
III	9	Seed protein %	35.1 - 36.6	38.6 - 41.4
		Meal protein %	48.8 - 50.3	50.3 - 54.7
		Yield (% of checks)		82.7 - 96.9
IV	6	Seed protein %	36.4 - 37.3	40.3 - 43.4
		Meal protein %	50.4 - 50.5	53.9 - 55.8
		Yield (% of checks)		78.4 - 94.3
V	6	Seed protein %	36.5 - 36.9	38.0 - 46.7
		Meal protein %	50.1 - 51.3	51.2 - 59.0
		Yield (% of checks)		80.2 - 112.4

†Dry matter basis.

Table 10-8. Yield and net return for soybean grown in tillage studies in the southern United States.

State (reference)	Soil series/ texture	Tillage treatment†	Yield	Net return
			kg ha^{-1} (bu acre^{-1})	\$ ha^{-1} (\$ acre^{-1})
Arkansas (Popp et al., 2001)	Sharkey clay‡	Conventional	2715 (40.4)	398 (161)
		DT	3235 (48.1)	480 (194)
Mississippi (Wesley et al., 2000)	Tunica silty clay‡	Conventional	2435 (36.2)	220 (89)
		DT1	3450 (51.3)	436 (176)
		DT2	3260 (48.5)	413 (167)
		DT3	3255 (48.4)	417 (169)
		DT4	3160 (47.0)	395 (160)
		DT5	2840 (42.3)	321 (130)
Mississippi (Wesley et al., 2001)	Sharkey clay‡	Conventional	1860 (27.7)	166 (67)
		DT	2225 (33.1)	237 (96)
Mississippi (Heatherly and Spurlock, 2001)	Sharkey clay‡	Conventional	2050 (30.5)	240 (97)
		DT	2465 (36.7)	305 (123)
	Sharkey clay§	Conventional	1650 (24.6)	110 (44)
		DT	1785 (26.6)	105 (42)
Mississippi (Heatherly et al., 2002c)	Tunica‡	Conventional	2000 (29.8)	156 (63)
		DT	3165 (47.1)	370 (150)
South Carolina (Frederick et al., 2001)	Eunola loamy sand§	No-till	2160 (32.1)	NA
		DT	2415 (35.9)	NA

†Conventional = shallow tillage (≤ 10 cm) with chisel plow, disk harrow, or spring-tooth cultivator; DT = deep-tilled to 38 to 46 cm (15 to 18 in) depth; DT1 = deep-tilled annually, DT2 = deep-tilled every other year, DT3 = deep-tilled every third year, DT4 = deep-tilled every fourth year, and DT5 = deep-tilled every fifth year.

‡April-planted.

§May and later-planted (South Carolina study followed wheat harvest).

Table 10-9. Annual soil loss from plots with 5% slope in the brown loam soil region of Mississippi (Triplett and Dabney, 1999).

	Conventional tillage		No-till		
		Soil loss year^{-1}		Soil loss year^{-1}	
Crop	C Factor†	Mg ha^{-1} (ton acre^{-1})	C factor†	Mg ha^{-1} (ton acre^{-1})	Reference
Sorghum	0.04	9.4 (4.2)	0.005	1.3 (0.6)	McGregor and Mutchler (1992)
Corn (grain)	0.09	16.1 (7.2)	0.005	0.9 (0.4)	McGregor and Mutchler (1983)
Corn (silage)	0.14	25.1 (11.2)	0.003	0.7 (0.3)	McGregor and Mutchler (1983)
Soybean	0.12	47.3 (21.1)	0.006	2.7 (1.2)	McGregor (1978)
Soybean	0.10	43.9 (19.6)	0.008	3.1 (1.4)	Mutchler and Greer (1984)
Cotton	0.31	69.9 (31.2)	0.053	12.1 (5.4)	Mutchler et al. (1985)

†Factor used in the Universal Soil Loss Equation to reflect influence of soil management and cropping methods on water erosion. Kind and time of tillage, implements used, time of planting, crops planted, postemergence cultivation, crop sequence, residue cover on the soil surface, and changes in soil organic matter all affect C factor.

Table 10-10. Measured surface cover and soil loss for various tillage systems used for corn and soybean production in Nebraska. Adapted from Dickey et al. (1986).

Residue type/tillage system	Residue cover	Erosion	Erosion reduction from moldboard plow
	%	Mg ha^{-1} (ton acre^{-1})	%
		Corn residue†	
Moldboard plow, disk 2X, plant	7	17.5 (7.8)	--
Chisel plow, disk, plant	35	4.7 (2.1)	74
Disk 2X, plant	21	4.9 (2.2)	72
Rotary-till, plant	27	4.3 (1.9)	76
Till-plant	34	2.5 (1.1)	86
No-till, plant	39	1.6 (0.7)	92
		Soybean residue‡	
Moldboard plow, disk 2X, plant	2	32.0 (14.3)	--
Chisel plow, disk, plant	7	21.5 (9.6)	32
Disk, plant	8	23.8 (10.6)	26
Field cultivate, plant	18	17.0 (7.6)	46
No-till, plant	27	11.4 (5.1)	64

†Nebraska tests after tillage and planting on a silt loam soil having a 10% slope and 5 cm (2 in) water applied in 45 min.

‡Nebraska tests after tillage and planting on a silty clay loam soil having 5% slope and 5 cm (2 in) water applied in 45 min.

Table 10-11. Nutrient content of soybean with a 3400 kg ha^{-1} seed yield (50 bu acre^{-1}). Adapted from Ferguson et al. (2000).

Nutrient	Grain	Plant	Total	Grain	Plant	Total
		--------kg ha^{-1}--------			--------lb acre^{-1}--------	
Nitrogen	211	142	353	188	127	315
Phosphorus (P_2O_5)	49	34	83	44	30	74
Potassium (K_2O)	74	646	720	66	576	642
Sulfur	6	17	23	5	15	20
Zinc	0.06	0.34	0.40	0.05	0.3	0.35

Table 10-12. Soil test P and K categories used by the Mississippi State University Soil Testing Laboratory, and recommended P and K fertilization rates for soybean as recommended by Louisiana State University (Funderburg, 1996) and Mississippi State University (Varco, 1999).†

			Cation exchange capacity‡				
Soil test category	Soil test P	Recommended P rate§	<7	7 to 14	15 to 25	>25	Recommended K rate¶
			Soil test K				
			kg ha^{-1}				
Very low	0--20	39#, 58††	0--56	0--67	0--78	0--90	75#, 112††
Low	21--40	29#,††	57--123	68--157	79--179	91--202	56#,††
Medium	41--81	15#,††	124--179	158--213	180--235	203--269	28#, 56††
High	82--161	0#,††	180--314	214--376	236--415	270--471	0#,††
Very high	161+	0#,††	314+	376+	415+	471+	0#,††

†Multiply all tabled values by 0.893 to convert to lb acre^{-1}.

‡Increasing values indicate increased capacity for adsorbing cations such as K. As the CEC increases, a given amount of exchangeable K will equilibrate with less K^+ in solution. Fine-textured soils (clays) require a higher level of exchangeable K to produce the same available K^+ that coarse-textured soils (sands) do (Foth and Ellis, 1997).

§Multiply values by 2.29 to convert to P_2O_5 fertilizer rates.

¶Multiply values by 1.2 to convert to K_2O fertilizer rates.

#Recommended by Louisiana State University.

††Recommended by Mississippi State University.

Table 10-13. Likely soil conditions for secondary- and micro-nutrient deficiencies observed in soybean. Adapted from Hoeft et al. (2000), Johnson (1987), and Vitosh et al. (2001).

Nutrient	Soil conditions likely to create deficiency	Most sensitive crop	Relative ratings of soil test procedures†
Calcium	$pH < 5.0$	Alfalfa, clovers	40
Copper	High organic matter (mucks, peat soils with $pH < 5.3$); highly weathered, sandy soils	Peanut	organic soils = 20; mineral soils = 5
Iron	$pH > 7.3$; wet soils; poorly aerated soil; cool temperature	Soybean, navy bean, millet, grain sorghum	$pH > 7.5 = 30$; $pH < 7.5 = 10$
Magnesium	Acid soils; sandy soils; high K levels	Corn	40
Manganese	$pH > 7.3$ (Mn deficiency); mucks, peat soils with $pH > 5.8$; black sands and lake-bed depression soils with $pH > 6.2$); (Note: $pH < 5.2$ = Mn toxicity)	Soybean, navy bean, oats	$pH > 7.5 = 40$; $pH < 7.5 = 10$
Molybdenum	$pH < 5.0$; strongly weathered soils; soils mostly east of Miss. River with moderate to heavy rainfall	Soybean, alfalfa, peas (affects primarily nodulation and N_2 fixation)	
Zinc	Exposed subsoil; areas leveled for irrigation; peat and muck soils and mineral soils with $pH < 6.5$; soils, especially sandy, with low organic matter; high pH, very high P soils; cool, wet soils	Corn	45

†Adapted from Hoeft et al. (2000). Other relative ratings are water pH = 100; P = 85; K = 70; organic matter = 75.

Table 10-14. Summary of average temperature and rainfall and pan evaporation for growing season months, Stoneville, MS, 1964 to 1993 (Boykin et al., 1995), and Sikeston, MO, 1961 to 1990 (temperature and rain) and 1985 to 1997 (pan evap.) (Owenby and Ezell, 1992; J. Henggeler, unpublished data, 1998).†

	Stoneville					Sikeston				
	Air temp.			Pan		Air temp.			Pan	
Month	Max	Min	Rain	Evap.	Diff.	Max	Min	Rain	Evap.	Diff.
	------°C------		-------------cm-------------			--------°C--------		---------------cm--------------		
Apr.	23.3	11.7	13.7	15.5	- 1.8	20.6	8.3	11.7	16.3	- 4.6
May	27.8	16.7	12.7	19.6	- 6.9	26.1	13.3	13.2	19.8	- 6.6
June	32.2	20.6	9.4	21.6	-12.2	30.6	18.3	9.4	23.1	-13.7
July	32.8	22.2	9.4	20.8	-11.4	32.8	20.6	9.6	24.1	-14.5
Aug.	32.2	21.1	5.8	18.5	-12.7	31.1	18.9	8.4	20.3	-11.9
Sept.	29.4	17.2	8.6	14.7	- 6.1	27.8	15.0	9.9	15.0	- 5.1

†Multiply temperature values by 1.8 and add 32 to convert to °F; multiply rain and evaporation values by 0.394 to convert to in.

Table 10-15. Yield of nonirrigated (NI) and irrigated (I) soybean cultivars grown in a conventional soybean production system at Stoneville, MS, 1979 to 1990. From Heatherly (1999a). Adapted from Heatherly (1983, 1988), Heatherly and Elmore (1986), Heatherly and Pringle (1991), Heatherly and Spurlock (1993), and Heatherly et al. (1994).

Year	Date of planting	Cultivar (MG)	Irrigation level			
			NI		I	
			kg ha^{-1}	bu acre^{-1}	kg ha^{-1}	bu acre^{-1}
1979	13 June	Bedford (5)	2748	40.9	2668	39.7
		Tracy (6)	3367	50.1	3373	50.2
		Bragg (7)	3165	47.1	3588	53.4
1980	8 May	Bedford	732	10.9	1996	29.7
		Tracy	1149	17.1	2809	41.8
		Bragg	1317	19.6	3555	52.9
1981	13 May	Bedford	981	14.6	2775	41.3
		Bragg	1028	15.3	3273	48.7
1982	12 May	Bedford	974	14.5	2244	33.4
		Braxton (7)	1008	15.0	2715	40.4
1984	14 May	Braxton	1357	20.2	3494	52.0
1985	2 May	Braxton	1599	23.8	2876	42.8
1986	15 May	Braxton	101	1.5	2594	38.6
1986	3 June	Sharkey (6)	376	5.6	2950	43.9
1987	11 May	Sharkey	706	10.5	2688	40.0
1988	16 May	Sharkey	2278	33.9	2675	39.8
1987	8 June	A 5980 (5)	914	13.6	2614	38.9
1987	6 May	Leflore (6)	1102	16.4	2903	43.2
1988	25 May	A 5980	2641	39.3	3649	54.3
		Leflore	2211	32.9	3084	45.9
1989	8 May	A 5980	2675	39.8	2769	41.2
		Leflore	1781	26.5	2150	32.0
1990	2 May	A 5980	1277	19.0	2977	44.3
		Leflore	1068	15.9	3326	49.5

Table 10-16. Yield of MG III through VII soybean cultivars planted in April and May at Blossom and Hooks, Texas in 1986, 1987, and 1988. Adapted from Bowers (1995).

Planting date†	Cultivar (MG)	Year		
		1986	1987	1988
		---------------------------kg ha^{-1} (bu acre^{-1})-------------------------------		
		Blossom		
Apr.	Williams 82 (3)	2956 (44.0)	2842 (42.3)	1518 (22.6)
	Crawford (4)	1720 (25.6)	1787 (26.6)	2318 (34.5)
	Forrest (5)	531 (7.9)	1176 (17.5)	2526 (37.6)
	Leflore (6)	289 (4.3)	524 (7.8)	1566 (23.3)
	Bragg (7)	215 (3.2)	356 (5.3)	1082 (16.1)
May	Williams 82	1008 (15.0)	927 (13.8)	---
	Crawford	961 (14.3)	947 (14.1)	---
	Forrest	867 (12.9)	860 (12.8)	---
	Leflore	719 (10.7)	289 (4.3)	---
	Bragg	255 (3.8)	148 (2.2)	---
		Hooks		
Apr.	Williams 82	3675 (54.7)	1612 (24.0)	2392 (35.6)
	Crawford	3238 (48.2)	2116 (31.5)	3218 (47.9)
	Forrest	2473 (36.8)	759 (11.3)	3144 (46.8)
	Leflore	2862 (42.6)	443 (6.6)	2728 (40.5)
	Bragg	1848 (27.5)	752 (11.2)	2553 (38.0)
May	Williams 82	2419 (36.0)	1693 (25.2)	---
	Crawford	2150 (32.0)	726 (10.8)	---
	Forrest	2943 (43.8)	544 (8.1)	---
	Leflore	2452 (36.5)	1068 (15.9)	---
	Bragg	1915 (28.5)	1384 (20.6)	---

†Blossom: 16 April & 15 May, 1986; 17 April & 12 May, 1987; 22 April & 6 May, 1988. Hooks: 17 April & 14 May, 1986; 15 April & 11 May, 1987; 21 April & 7 May 1988.

Table 10-17. Average seed yields and net returns from irrigated and nonirrigated April and May plantings of Maturity Group (MG) 4 and 5 soybean cultivars at Stoneville, MS, 1992 and 1994 through 1997. Adapted from Heatherly and Spurlock (1999).

		Seed yield			Net return		
		Planting date†			Planting date		
MG		Apr	May	Av.	Apr	May	Av.
		kg ha^{-1} (bu $acre^{-1}$)			\$ ha^{-1} (\$ $acre^{-1}$)		
				Irrigated			
4		3770 (56.2)	3350 (49.9)	3560 (53.0)	395 (160)	283 (114)	339 (137)
5		3890 (57.9)	3430 (51.1)	3660 (54.5)	418 (169)	301 (122)	359 (145)
	Av.	3830 (57.0)	3390 (50.5)		406 (164)	292 (118)	
				Nonirrigated			
4		2245 (33.4)	1905 (28.4)	2075 (30.9)	205 (83)	109 (44)	157 (63)
5		2630 (39.2)	2210 (32.9)	2420 (36.0)	285 (115)	186 (75)	235 (95)
	Av.	2440 (36.3)	2060 (30.7)		245 (99)	148 (60)	

†15 Apr and 27 May, 1992; 21 Apr and 13 May, 1994; 18 Apr and 9 May, 1995; 30 Apr and 15 May, 1996; 9 Apr and 12 May, 1997.

Table 10-18. Special conditions that warrant seeding rate deviation from the recommended 300,000 to 370,000 viable seed ha^{-1} (120,000 to 150,000 acre^{-1}) rate in the northern USA. Adapted from Beuerlein (1995), Hoeft et al. (2000), and Oplinger et al. (1998b).

Condition	Recommendation and reason†
Row width < 25 cm (10 in) or drill-planted	Increase seeding rate up to one-third because of imprecision of seed metering system.
Poor seedbed (cloddy, high-residue)	Increase seeding rate 10% because of poor seed-soil contact.
Early-maturing cultivar	Increase seeding rate 10% if planting seed produced in the same region.
Reduced tillage system	Increase seeding rate up to 50% because of more obstacles to germination; i.e., cool soil, poor seed-soil contact, less precise planting depth, possible drying of seed drill resulting from residue.
Planting before or after optimum date	Increase seeding rate 20% because of cooler soil (before optimum date) and shorter plants (before and after optimum date).
High-cost seed	Do not seed over 300,000 seed ha^{-1}

†Do not accumulate seeding rate increases. If more than one special condition exists, use the highest recommended increase.

Table 10-19. Number of seed per 30 cm or 1 ft of row and expense for soybean seed of varied size and cost planted at different seeding rates in five row spacings. Adapted from Heatherly et al. (1999).

		Row spacing--cm (in)					Cost per 22.7 kg (50 lb) of seed			
Seed size	Seeding rate	18 (7)	38 (15)	51 (20)	76 (30)	102 (40)	$10	$15	$20	$25
No. kg^{-1} (lb^{-1})	ha^{-1} (acre^{-1}) x 1000	------No. seed per 30 cm or 1 ft of row------					---$ per 0.4 ha (1.0 acre) cost---			
5300 (2400)	198 (80)	1.1	2.3	3.1	4.6	6.1	6.67	10.00	13.33	16.67
	247 (100)	1.3	2.9	3.8	5.7	7.7	8.33	12.50	16.67	20.83
	296 (120)	1.6	3.4	4.6	6.9	9.2	10.00	15.00	20.00	25.00
	346 (140)	1.9	4.0	5.4	8.0	10.7	11.67	17.50	23.33	29.17
	395 (160)	2.1	4.6	6.1	9.2	12.2	13.33	20.00	26.67	33.33
	445 (180)	2.4	5.2	6.9	10.3	13.8	15.00	22.50	30.00	37.50
	494 (200)	2.7	5.7	7.6	11.5	15.3	16.67	25.00	33.33	41.67
	544 (220)	2.9	6.3	8.4	12.6	16.8	18.33	27.50	36.67	45.83
5750 (2600)	198 (80)	1.1	2.3	3.1	4.6	6.1	6.15	9.23	12.31	15.38
	247 (100)	1.3	2.9	3.8	5.7	7.7	7.69	11.54	15.38	19.23
	296 (120)	1.6	3.4	4.6	6.9	9.2	9.23	13.85	18.46	23.08
	346 (140)	1.9	4.0	5.4	8.0	10.7	10.77	16.15	21.54	26.92
	395 (160)	2.1	4.6	6.1	9.2	12.2	12.31	18.46	24.62	30.77
	445 (180)	2.4	5.2	6.9	10.3	13.8	13.85	20.77	27.69	34.62
	494 (200)	2.7	5.7	7.6	11.5	15.3	15.38	23.08	30.77	38.46
	544 (220)	2.9	6.3	8.4	12.6	16.8	16.92	25.38	33.85	42.31
6150 (2800)	198 (80)	1.1	2.3	3.1	4.6	6.1	5.71	8.57	11.43	14.29
	247 (100)	1.3	2.9	3.8	5.7	7.7	7.14	10.71	14.29	17.86
	296 (120)	1.6	3.4	4.6	6.9	9.2	8.57	12.86	17.14	21.43
	346 (140)	1.9	4.0	5.4	8.0	10.7	10.00	15.00	20.00	25.00
	395 (160)	2.1	4.6	6.1	9.2	12.2	11.43	17.14	22.86	28.57
	445 (180)	2.4	5.2	6.9	10.3	13.8	12.86	19.29	25.71	32.14
	494 (200)	2.7	5.7	7.6	11.5	15.3	14.29	21.43	28.57	35.71
	544 (220)	2.9	6.3	8.4	12.6	16.8	15.71	23.57	31.43	39.29
6600 (3000)	198 (80)	1.1	2.3	3.1	4.6	6.1	5.33	8.00	10.67	13.33
	247 (100)	1.3	2.9	3.8	5.7	7.7	6.67	10.00	13.33	16.67
	296 (120)	1.6	3.4	4.6	6.9	9.2	8.00	12.00	16.00	20.00
	346 (140)	1.9	4.0	5.4	8.0	10.7	9.33	14.00	18.67	23.33
	395 (160)	2.1	4.6	6.1	9.2	12.2	10.67	16.00	21.33	26.67
	445 (180)	2.4	5.2	6.9	10.3	13.8	12.00	18.00	24.00	30.00
	494 (200)	2.7	5.7	7.6	11.5	15.3	13.33	20.00	26.67	33.33
	544 (220)	2.9	6.3	8.4	12.6	16.8	14.67	22.00	29.33	36.67
7050 (3200)	198 (80)	1.1	2.3	3.1	4.6	6.1	5.00	7.50	10.00	12.50
	247 (100)	1.3	2.9	3.8	5.7	7.7	6.25	9.38	12.50	15.63
	296 (120)	1.6	3.4	4.6	6.9	9.2	7.50	11.25	15.00	18.75
	346 (140)	1.9	4.0	5.4	8.0	10.7	8.75	13.13	17.50	21.88
	395 (160)	2.1	4.6	6.1	9.2	12.2	10.00	15.00	20.00	25.00
	445 (180)	2.4	5.2	6.9	10.3	13.8	11.25	16.88	22.50	28.13
	494 (200)	2.7	5.7	7.6	11.5	15.3	12.50	18.75	25.00	31.25
	544 (220)	2.9	6.3	8.4	12.6	16.8	13.75	20.62	27.50	34.38
7500 (3400)	198 (80)	1.1	2.3	3.1	4.6	6.1	4.71	7.06	9.41	11.76
	247 (100)	1.3	2.9	3.8	5.7	7.7	5.88	8.82	11.76	14.71
	296 (120)	1.6	3.4	4.6	6.9	9.2	7.06	10.59	14.12	17.65
	346 (140)	1.9	4.0	5.4	8.0	10.7	8.24	12.35	16.47	20.59
	395 (160)	2.1	4.6	6.1	9.2	12.2	9.41	14.12	18.82	23.53
	445 (180)	2.4	5.2	6.9	10.3	13.8	10.59	15.88	21.18	26.47
	494 (200)	2.7	5.7	7.6	11.5	15.3	11.76	17.65	23.53	29.41
	544 (220)	2.9	6.3	8.4	12.6	16.8	12.94	19.41	25.88	32.35
7950 (3600)	198 (80)	1.1	2.3	3.1	4.6	6.1	4.44	6.67	8.89	11.11
	247 (100)	1.3	2.9	3.8	5.7	7.7	5.56	8.33	11.11	13.89
	296 (120)	1.6	3.4	4.6	6.9	9.2	6.67	10.00	13.33	16.67
	346 (140)	1.9	4.0	5.4	8.0	10.7	7.78	11.67	15.56	19.44
	395 (160)	2.1	4.6	6.1	9.2	12.2	8.89	13.33	17.78	22.22
	445 (180)	2.4	5.2	6.9	10.3	13.8	10.00	15.00	20.00	25.00
	494 (200)	2.7	5.7	7.6	11.5	15.3	11.11	16.67	22.22	27.78
	544 (220)	2.9	6.3	8.4	12.6	16.8	12.22	18.33	24.44	30.56

Table 10-20. Conditions that relate to *B. japonicum* inoculation of soybean and author recommendations.

Condition	Recommendation
Fields with no soybean history or poor nodulaton history	Inoculate seed with 10^5 to 10^6 bacteria cells seed^{-1}
Fields with nodulated soybean in previous 5 yr	Inoculation not necessary except in northern states with cool soils at planting
Optimum N_2 fixation	Maintain soil pH in the 6 to 7 range
Inoculation/planting time interval	Plant seed within 4 hr of inoculation
Fungicide-treated seed	Inoculate with *B. japonicum* only after fungicide is dry
Fungicide/inoculant compatibility	Check with inoculant manufacturer; if in doubt, use in-furrow inoculation
Flooded soils or sandy soils (northern USA)	Always inoculate
Acid soils (pH < 6.0)	Add lime or add seed treatment with molybdenum
Well-nodulated soybean plant	5 to 7 nodules on primary root 2 wk after emergence, or 5 nodules cm^{-1} of tap root at flowering

Table 10-21. Corn and soybean yields when grown continuously and in rotation with each other. All data but those from NE were summarized from several sources by Hoeft et al. (2000); NE data are from an irrigated trial (Roger Selley, personal communication, 2000).

		Yield of corn following:			Yield of soybean following:		
State	Site-yr no.	Corn	Soybean	Advantage†	Soybean	Corn	Advantage†
		-------kg ha^{-1} (bu acre^{-1})-------		%	-----kg ha^{-1} (bu acre^{-1})-----		%
IL	17	9 030 (144)	10 660 (170)	18			
IN	20	10 410 (166)	11 230 (179)	8	3070 (45.7)	3420 (50.9)	11
IA	8	8 030 (128)	9 090 (145)	13	2140 (31.9)	2410 (35.8)	12
MN	20	7 650 (122)	8 530 (136)	12	2420 (36.0)	2740 (40.8)	13
NE	8	10 280 (164)	10 910 (174)	6			
NY	12	7 960 (127)	8 720 (139)	9			
WI	9	8 220 (131)	9 530 (152)	16	3510 (52.2)	3700 (55.0)	5

†Advantage to rotation.

Table 10-22. Effect of number of years on yield of corn and soybean averaged over two locations in Minnesota and one location in Wisconsin. Based on Porter et al. (1997); adapted from Hoeft et al. (2000).

Years of continuous cropping following 5 yr of other crop	Corn yield	Soybean yield
	---kg ha^{-1} (bu $acre^{-1}$)---	
1	9000 (143) a†	3260 (49) a
2	8040 (128) b	2990 (45) b
3	7900 (126) b	2840 (42) c
4	7900 (126) b	2820 (42) cd
5	7880 (126) b	2800 (42) cd
Continuous	7810 (124) b	2770 (41) d
Rotated corn/soybean	8830 (141) a	3050 (45) b

†Means in individual columns followed by the same letter are not significantly different at $P \leq 0.05$.

Table 10-23. Average crop yield and net return from eight nonirrigated and irrigated cropping systems on Tunica clay near Stoneville, MS (1984 to 1991). Adapted from Wesley et al. (1994, 1995).

Cropping system†	Crop	Nonirrigated		Irrigated	
		Yield	Net return‡	Yield	Net return§
		kg ha^{-1} (bu acre^{-1})	\$ ha^{-1} (\$ acre^{-1})	kg ha^{-1} (bu acre^{-1})	\$ ha^{-1} (\$ acre^{-1})
1	Corn	4085 (60.8)	-22 (-9) e	7850 (116.8)	195 (79) c
2	Soybean	1445 (21.5)	62 (25) cd	2760 (41.1)	131 (53) d
3	Grain sorghum	5370 (79.9)	148 (60) ab	6300 (93.8)	47 (19) e
4	Corn	3615 (53.8)	104 (42) bc	8520 (126.8)	272 (110) ab
	Soybean	2710 (40.3)		3345 (49.8)	
5	Grain sorghum	4020 (59.8)	188 (76) a	7100 (105.7)	208 (84) c
	Soybean	2955 (44.0)		3465 (51.6)	
6	Wheat/	2565 (38.2)	119 (48) abc	2950 (43.9)	304 (123) a
	Soybean	725 (10.8)		2190 (32.6)	
7	Corn	2710 (40.3)	40 (16) de	8405 (125.1)	336 (136) a
	Wheat/	2895 (43.1)		3280 (48.8)	
	Soybean	1335 (19.9)		2565 (38.2)	
8	Sorghum	3910 (58.2)	158 (64) ab	6940 (103.3)	235 (95) bc
	Wheat/	3030 (45.1)		2970 (44.2)	
	Soybean	1480 (22.0)		2505 (37.3)	

†Cropping systems were: 1 = continuous corn; 2 = continuous soybean; 3 = continuous sorghum; 4 = biennial rotation of corn--soybean; 5 = biennial rotation of sorghum--soybean; 6 = continuous wheat--soybean doublecrop; 7 = biennial rotation of corn and wheat--soybean doublecrop; 8 = biennial rotation of sorghum and wheat--soybean doublecrop.

‡Values in individual columns followed by the same letter are not significantly different at $p \leq 0.05$.

Table 10-24. Effect of preplant tillage, wheat cover crop, and planting date (PD) on average yields and net returns from irrigated 'Leflore' soybean planted in a stale seedbed at Stoneville, MS (1986 and 1987). Adapted from Heatherly (1999c).

Preplant	Planting date†			Planting date		
tillage	Early	Late	Avg.	Early	Late	Avg.
	---------------kg ha^{-1} (bu acre^{-1})----------------			-------------\$ ha^{-1} (\$ acre^{-1})-------------		
Fall disk	3225 (48)	2555 (38)	2890 (43) a‡	232 (94)	89 (36)	161 (65) b
Spring disk	3225 (48)	2620 (39)	2890 (43) a	257 (104)	121 (49)	188 (76) ab
Prepared seedbed	3360 (50)	2620 (39)	2955 (44) a	294 (119)	143 (58)	220 (89) a
None after harv.	3290 (49)	2690 (40)	2955 (44) a	267 (108)	136 (55)	203 (82) a
Fall disk + Wheat	3225 (48)	2690 (40)	2955 (44) a	163 (66)	64 (26)	114 (46) c
Avg.	3225 (48) a	2620 (39) b		242 (98) a	111 (45) b	

†Early = 6 May 1986 and 5 May 1987; Late = 16 June 1986 and 28 May 1987.

‡Average values for yield or net returns that are followed by the same letter are not significantly different at $P \leq 0.05$.

Table 10-25. Irrigation water requirements in Nebraska for soybean during reproductive growth stages when grown on deep medium- and fine-textured soils. This assumes the soil water reservoir is at or near field capacity to 1.5-m (5-ft) depth. Adapted from Benham et al. (1998).

Growth stage	Reproduction stage irrigation water requirement
	cm (in)
Full flower (R2 to R3)	7.6 (3)
Pod elongation (R3 to R4)	7.6 (3)
Seedfill (R5 to R6)	11.4 (4.5)
Total irrigation water required	26.7 (10.5)

Table 10-26. Irrigation and planting date effects on seed yield and number of irrigations (No.) for soybean grown on Sharkey clay at Stoneville, MS. Adapted from Heatherly (1999b).

		Planting	Seed yield†			
Year	Cultivar (MG)	date	I	NI	I - NI	No.
			------------------kg ha^{-1} (bu acre^{-1})--------------------			
1980	Bedford (4)	12 May	2730 (40.6)	990 (14.7)	1740 (25.9)	7
		3 June	3145 (46.8))	1155 (17.2)	1990 (29.6)	5
	Bragg (7)	12 May	3520 (52.4)	1330 (19.8)	2190 (32.6)	7
		3 June	2975 (44.3)	1515 (22.6)	1460 (21.7)	5
1981	Bedford (5)	13 May	2775 (41.3)	980 (14.6)	1795 (26.7)	3
		4 June	2375 (35.3)	1050 (15.6)	1325 (19.7)	2
	Braxton (7)	13 May	3275 (48.7)	1030 (15.3)	2245 (33.4)	4
		4 June	2935 (43.7)	1695 (25.2)	1245 (18.5)	3
1982	Bedford (5)	12 May	2245 (33.4)	975 (14.5)	1270 (18.9)	3
		28 May	1665 (24.8)	880 (13.1)	785 (11.7)	3
	Braxton	12 May	2715 (40.4)	1010 (15.0)	1705 (25.4)	4
		28 May	2345 (34.9)	1195 (17.8)	1150 (17.1)	3
1984	Braxton	14 May	3570 (53.1)	1405 (20.9)	2165 (32.2)	5
		25 June	3110 (46.3)	1580 (23.5)	1530 (22.8)	4
1985	Braxton	2 May	2955 (44.0)	1860 (27.7)	1095 (16.3)	6
		24 June	1895 (28.2)	1655 (24.6)	240 (3.6)	3
1986	Braxton	15 May	2690 (40.0)	110 (1.6)	2580 (38.4)	7
		24 June	1425 (21.2)	260 (3.9)	1165 (17.3)	4
1986	Leflore (6)	6 May	3595 (53.5)	---		7
		16 June	2735 (40.7)	---		5
1987	Leflore	5 May	2895 (43.1)	---		7
		28 May	2515 (37.4)	---		7
1992	RA 452 (4)	15 Apr	4180 (62.2)	2840 (42.3)	1340 (19.9)	2
		27 May	3035 (45.2)	2175 (32.4)	860 (12.8)	2
	A 5979 (5)	15 Apr	4315 (64.2)	3555 (52.9)	760 (11.3)	2
		27 May	2935 (43.7)	2230 (33.2)	705 (10.5)	2
1994	RA 452	21 Apr	3360 (50.0)	2645 (39.4)	715 (10.6)	4
		13 May	3245 (48.3)	2155 (32.1)	1090 (16.2)	4
	A 5979	21 Apr	3440 (51.2)	2595 (38.6)	845 (12.6)	4
		13 May	3365 (50.1)	2265 (33.7)	1100 (16.4)	4
1995	DP 3478 (4)	18 Apr	4440 (66.1)	2905 (43.2)	1535 (22.9)	3
		9 May	3620 (53.9)	2035 (30.3)	1585 (23.6)	3
	A 5979	18 April	3845 (57.2)	1740 (25.9)	2105 (31.3)	4
		9 May	3890 (57.9)	1405 (20.9)	2485 (37.0)	4
1996	DP 3478	30 Apr	3835 (57.1)	2170 (32.3)	1665 (24.8)	4
		15 May	3515 (52.3)	1950 (29.0)	1565 (23.3)	5
	Hutcheson (5)	30 April	4200 (62.5)	3035 (45.2)	1165 (17.3)	5
		15 May	4110 (61.2)	3035 (45.2)	1075 (16.0)	5
1997‡	DP 3478	9 Apr	4205 (62.6)	2015 (30.0)	2190 (32.6)	4
		12 May	4150 (61.8)	2045 (30.4)	2105 (31.4)	6
	Hutcheson	9 Apr	3620 (53.9)	2420 (36.0)	1200 (17.9)	5
		12 May	4240 (63.1)	2235 (33.3)	2005 (29.8)	7

†NI = nonirrigated; I = irrigated; I - NI = irrigated minus nonirrigated yield.

‡1997 irrigation scheduled more frequently.

Table 10-27. Components and variables for equation to determine last irrigation of soybean in Nebraska. Adapted from Klocke et al., 1991.

Component	Inputs for determining value for factor
Water requirement based on crop stage and water use to R7 stage	23, 16.5, and 9 cm (9.0, 6.5, and 3.5 in) are required from the R4, R5, and R6 stages, respectively.
Available water content (AWC)	60% x AWC x 1.2 m (3.9 ft); 60% of the AWC in the top 1.2 m (3.9 ft) of the root zone can be depleted at maturity and not reduce yield.
Current soil moisture in 1.2-m-(3.9-ft) deep root zone	Determined by gravimetric sampling, hand-feel method, crop water use scheduling method, soil moisture blocks, tensiometers, etc.

Figure captions

Fig. 10-1. Soil loss associated with moldboard plow and no-till systems with either corn or soybean residue at the University of Nebraska, Lincoln, NE. Water was applied at 63.5 mm hr^{-1}. Adapted from Dickey et al., 1986.

Fig. 10-2. Soil pH effects the availability of plant nutrients. The thicker the bar, the more of the nutrient is available. The best overall balance is between pH 6.0 and 7.0. From Hoeft et al., 2000.

Fig. 10-3. Soybean seeding rate effect in irrigated and rain-dependent environments in Nebraska. Adapted from Elmore, 1998.

Fig. 10-4. Soybean crop water use (evapotranspiration) and growth stages. Data are averages from 1987 to 2002 at Clay Center, NE. Adapted from Benham et al., 1998.