4 Planting Geometries and the Efficient Use of Water and Nutrients[1]

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In nature and in the most primitive agricultural systems, seed distribution is broadcast across the landscape. Such a distribution results in nearly uniform spacial interaction of the developing phytomass. With the development of agrarian civilization has come an implement-dependent systemization of crop-planting patterns. This has brought about the planting of crops in uniform rows—from the drilling of small grains at inter-row spacings of 0.1 to 0.2 m and plant intra-row spacings of 1 to 5 cm, to the staking of horticultural and vine crops at 2- to 3-m inter-row spacings and typically 0.3- to 1-m intra-row spacings.

The implement dependence of agricultural cropping strategies has resulted in row cropping. The staple crops regarded as most suited to this approach are commonly called *row crops,* and this review will concentrate largely on how row crops interact with plant geometry, water, and nutrients to influence sustained productive capacity.

PRACTICAL AND HISTORICAL CONSIDERATIONS

The origins of particular row spacings can probably be traced back to implement development, beginning with animal-drawn implements. A mule

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or a horse (*Equus caballus*) requires about 0.92 to 1.02 m (36–40 in.) of clearance to walk between planted rows with a one-row cultivator. The average 50-kW (80 hp) American tractor can adjust its wheel centers from 1.52 to 2.24 m (60–88 in.). At 1.52 m, the tractor can straddle two 0.76-m (30-in.) rows. At 1.83 m (72 in.), it can straddle three 0.61-m (24-in.) rows. At 2.24 m, the tractor can straddle four 0.56-m (22-in.) rows. At 2.04 m (80 in.), it could straddle four 0.51-m (20-in.) rows, but generally, 0.51 m is nearly equal to the narrowest tire width available. That would restrict tractor use to planting and perhaps one early cultivation. In most cases, farmers prefer to straddle even numbers of rows leaving an inter-row below the low-hanging tractor center and allowing operations to be done on even-row multiples that usually are more compatible with row-crop harvesting equipment.

Where land is furrow irrigated, again, row spacings closer than about 0.51 m are difficult to achieve. Closer-spaced furrows would be destroyed by tire traffic or would not be large enough to carry water the length of a typical field. Conversely, furrow spacings wider than 0.92 m are difficult to manage on single-rowed beds. This is because water will not move laterally (sub-across) from the irrigated furrow more than about 0.46 m by capillarity in a typical 12- to 24-h irrigation set, even on well-aggregated loamy soils. With sandy or clayey soils, the maximum manageable width would be even less. This limit on maximum furrow spacing is reinforced by the common on-farm practice of irrigating only alternate furrows to save labor and prevent overirrigation.

Wide row spacings continue to be used more extensively in the South than perhaps in any other part of the USA. This has probably occurred for several reasons. The Southern states, for socio-economic reasons, were the last to fully embrace agricultural mechanization (Healy, 1985). The use of draft animals remained common in the South through the late 1940s and early 1950s. Consequently, cotton (*Gossypium hirsutum* L.), corn (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.] and tobacco (*Nicotiana tabacum* L.) remained in wide-row configurations well after extensive crop-breeding programs had gotten underway. Thus, these crops have been inadvertently bred for optimal response under wide-row configurations. The South's intense weed pressure also reinforced the need to cultivate late in the season, which is facilitated by wide rows.

The upsurgance of determinate soybean as a southern crop further played a role in establishing wide rows. If canopy closure occurs by flowering (a date dependent on maturity group and latitude, and usually near August, first at mid-southern latitudes), there is only a small impact of row spacing on yield (Beatty et al., 1982; Beaver and Johnson, 1981).

Also, southern states are typically dominated by ultisols with genetic and/or traffic induced hardpans. To promote rooting below these restricted layers, the use at planting of in-row subsoiling to a depth below the hardpan (as deep as 0.46 m) has become a common practice (Sojka et al., 1984b). An excessively close placement of subsoil shanks (the limit is about 0.6 m depending upon soil type, shank configuration, shank depth, and soil con-

dition) results in failure of the shanks to act independently, thus plowing up large soil masses.

Among the most complicated agricultural machinery is self-propelled harvesting equipment. Implements such as grain combines, corn pickers, cotton pickers, cotton strippers, potato diggers, and sugarbeet lifters, have been engineered to the prevailing row configurations of their intended crops, which have come about more from historical than technical considerations. They are usually of fixed configuration or at best only minimally adjustable. The adjustments, when available, are usually intended as one-time set-up adjustments and not for multiple adjustments during a single harvest or between crops in a given year. Since it is seldom economically feasible to acquire multiple fleets of farm equipment tailored to more than one canopy configuration, most farmers choose a compromise row spacing for all crops in their rotation.

INCREASING CANOPY DENSITY

The historical and practical considerations notwithstanding, there has been a longstanding interest in increasing production by covering the ground earlier in the season with foliage from more and/or closer-spaced plants and plant rows (Bryant et al., 1940; Jordan et al., 1950; Mooers, 1910; Morrow, 1890; Nelson, 1931; Painter and Leamer, 1953; Probst, 1945; Reynolds, 1926; Wiggams, 1939). The simplest components of planting geometry that can be manipulated to affect row-crop performance are inter- and intra-row plant spacing. A broad generalization of theory and historical results across species and environments is that yield increases as canopy density, fertility, and soil water availability simultaneously increase until an optimum density is achieved, beyond which higher density reduces yield due to competition, lodging, etc., regardless of further increases in fertility or water availability (Chandler, 1969; Fontes and Ohlrogge, 1972; Lehman and Lambert, 1960; Weber et al., 1966). A further theoretical production limit exists under the constraints of photosynthetic efficiency of the respective C3 or C4 pathways. Morphological expression is an additional limitation resulting from elongation of light-restricted plants as canopy densities increase, eventually predisposing the crop to lodging. Some of the advantages and disadvantages associated with wide vs. narrow row planting patterns are listed in Table 4-1.

SOYBEAN

Developmental Effects

Perhaps the most abundant literature on planting geometry effects on growth and performance is for soybean. The various agronomic considerations listed in Table 4-1 assume comparing canopy geometries at a fixed plant population. Many negative aspects of either wide or narrow rows can be

Table 4-1. Agronomic considerations for wide or narrow row spacings at a fixed population per hectare.

Consideration	Row space result	
	Wide	Narrow
1. Planters per tool bar		
2. Passes/ha		
3. Fuel consumed/planted ha		
4. Fuel consumed/ha for in-row subsoilers		
5. Seed/ha for equal emergence		
6. Amount of banded pesticide/ha		
7. Yield loss to individual seed skips		
8. Yield loss to skipped row segments		
9. Time interval to canopy closure		
10. Inter-row shading		
11. Competition against weeds		
12. Inter-row rooting		
13. Furrow irrigation set time per unit water infiltrated	Longer	Shorter
14. Water use	Management and environment dependent	
15. Stalk size	Smaller	Larger
16. Plant height	Taller	Shorter
17. Height to lowest pod in legumes	Higher	Lower
18. Spatial dependency of nutrient and water extraction	Greater	Less
19. Yield/photoassimilate efficiency of indeterminates	Less	Greater
20. Extraction efficiency of broadcast fertilizer	Less	Greater
21. Suitability to placed fertilizer	Greater	Less
22. Performance of platform-cutter combines	Reduced	Enhanced
23. Performance of row-crop header combines	Enhanced	Reduced

mitigated in soybean to some extent by increasing or decreasing the seeding rate. For example, farmers usually note that less seed per hectare is required to obtain a given per hectare stand in wide rows. The closer proximity of seeds to one another in the row enhances the emergence potential of neighboring seeds through interaction of the zones of soil-active forces exerted by each emerging seedling (a buddy effect).

Phenological expression in soybean also seems to influence the interaction of population and environment. Determinacy (limitation of vegetative growth and setting of potential reproductive positions during a fixed limited time period) in full-season plantings largely defeats the yield-enhancement potential of more rapid canopy closure (Beaver and Johnson, 1981). As determinate soybean are planted closer to the flowering date in late-season plantings, the effect mimics the mechanism of indeterminate soybean, increasing yield with narrower rows (Beatty et al., 1982; Beaver and Johnson, 1981; Boquet et al., 1982; Caviness, 1966; Caviness and Smith, 1959; Chan et al., 1980; Williams et al., 1970). This explains why narrow rows greatly increase yields of northern-latitude, indeterminate (low maturity group. . .00-III) soybean in full-season plantings (Cooper, 1977; Costa et al., 1980; Leffel and Barber, 1961; Ryder and Beuerlein, 1979; Safo-Kantanka and Lawson, 1980; Taylor et al., 1982, Weber et al., 1966; Wilcox, 1974) but have little effect

on southern-latitude, determinate (high maturity group. . .IV-X) soybean in full-season plantings (Beatty et al., 1982; Camper and Smith, 1958; Carter and Boerma, 1979; Caviness, 1966; Caviness and Smith, 1959; Frans, 1959; Hartwig, 1954, 1957; Parker et al., 1981; Smith, 1952).

The effect of soybean intra-row plant spacing seems less important than the effect of inter-row spacing. This may result largely from the soybean's great capacity to morphologically compensate for changes in competition (Hinson and Hanson, 1962; Ramseur et al., 1984). Hartwig (1957) observed maximum yields of determinate soybean at 0.9-m inter-row spacing with 4-cm intra-row spacing of seeds. Intra-row spacings of 4 cm up to 46 cm produced nearly the same yields (Basnet et al., 1974; Donovan et al., 1963; Hoggard et al., 1978; Johnson and Harris, 1967; Lueschen and Hicks, 1977; Probst, 1945, Ramseur et al., 1984). As a result, significant skips in the row have nearly no effect on soybean yield (Caviness, 1961, 1966; Stivers and Swearingin, 1980). Increasing soybean plant densities usually result in increased plant height, height of the lowest pod, and lodging potential (Beatty et al., 1982; Beaver and Johnson, 1981; Cooper, 1971; Wilcox, 1974).

Radiation Interception

A major motivation for changing plant geometry is to improve light interception (Loomis and Williams, 1969; Mitchell, 1970; Pendleton, 1966; Shaw and Weber, 1967). Wide-row soybean culture results in a slower increase in leaf area index (LAI) than for narrow-row culture (Weber et al., 1966). Also, as seen in Fig. 4-1, radiation interception at corresponding LAI is less efficient for wide rows (Hicks et al., 1969; Taylor et al., 1982; Shibles and Weber, 1966). As a result of earlier canopy closure, a densely shaded canopy floor provides better weed control under narrow rows (Burnside et al., 1964; Burnside and Colville, 1964; Dougherty, 1969; Felton, 1976; Frans, 1959; Howe and Oliver, 1987; Kust and Smith, 1969; Peters, 1965; Peters

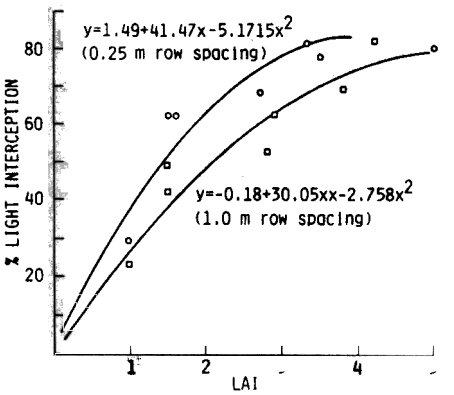

Fig. 4-1. Percentage of light interception in a soybean canopy as a function of leaf area index during canopy development. Circles are for 0.25-m row spacings; squares are for 1.0-m row spacings. From Taylor et al. (1982).

Table 4-2. Soybean response to irradiation of leveas with red (R) or far-red (FR) light. From Balatti and Montaldi (1986).

Plant property	R	FR
	0.006572a*	0.006322a
	7a	27b
	0.00891a	0.04290b
	0.00139a	0.00874b
	0.26640a	0.28090a
	28.8a	30.0a
	0.00767a	0.00842a

* Numbers in the same row followed by the same letter differ at $P = 0.05$ by the Duncan's multiple range test.

et al., 1965; Prasad et al., 1985a, b; Wax and Pendleton, 1968). The yield benefits of narrow rows can be lost entirely, however, if initial weed control is unsatisfactory, because of the inability to cultivate (Nave and Cooper, 1974; Wax et al., 1977). Several new highly effective over-the-top grass and broadleaf broad-spectrum herbicides are now available and yield loss need not result from inadequate early weed control. Management requirements, however, are more demanding when depending on these materials (Gebhardt and Minor, 1983), and economics may not be as favorable.

The quantity and pathway of radiation intercepted by the plant canopy are both affected by the canopy geometry (Holmes, 1981). This produces numerous environmental alterations including temperature distributions within the soil and canopy, foliar distribution of photosynthetically active radiation (PAR), and changes in canopy light quality.

Kasperbauer et al. (1984) demonstrated that canopy spectral composition changed in rows depending on their compass orientation, varying the exposure of the growing plant parts to far red light throughout the day and at extinction in the evening. In addition to the well-known effects of light spectral quality on flowering and shoot morphology, light-quality effects have also been demonstrated on nodulation and rooting (Balatti and Montaldi, 1983, 1986; Kasperbauer et al., 1984; Lie, 1969; Malik et al., 1982). Greater soybean rooting and nodulation (Table 4-2) have been associated with as little as 5 min of red/far-red exposure at photoperiod extinction (Balatti and Montaldi, 1983, 1986; Kasperbauer et al., 1984). Top dry weight was unaffected in these studies, and Balatti and Montaldi (1983, 1986) observed no differences in shoot N concentration or accumulation. Nearly opposite effects were observed in Lie's (1969) work with *Pisum sativum* and *Phaseolus vulgaris* which are long-day and day-neutral plants, respectively, whereas soybean is a short-day plant. These experiments suggest that environments that significantly alter light spectral composition, particularly at daylight extinction, may significantly impact root development and activity, specifically governed by each species' phytochrome adaptations. Further research is needed to determine the extent to which on-farm management of row-spacing, row-orientation, and plant population can beneficially manipulate these interactions.

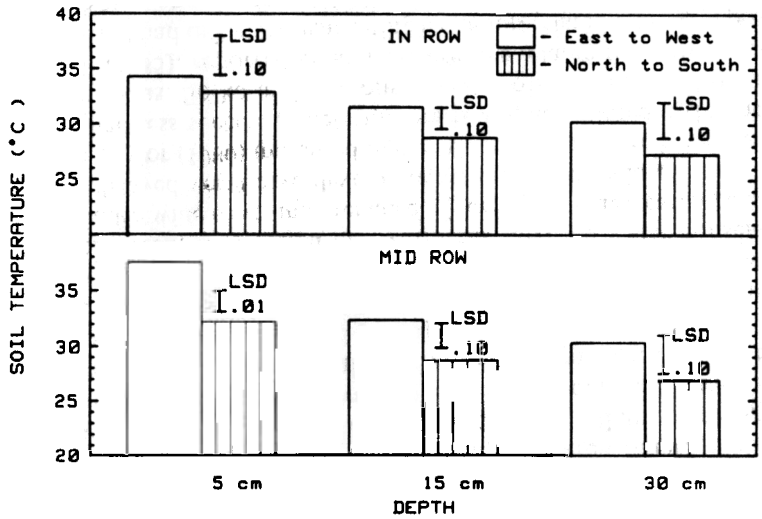

Fig. 4-2. The effect of row orientation on midday soil temperatures beneath a partially closed soybean canopy. From Hunt et al. (1985).

An interaction of soybean cultivars to *rhizobial* inoculants, row orientation and irrigation was observed by Hunt et al. (1985). They interpreted the responses as being largely soil temperature (Fig. 4-2) effects on cultivar × strain interactions. No significant differences in N concentration or accumulation occurred. In 2 of the 3 yr studied, however, irrigated North-South (N-S) oriented rows outyielded East-West (E-W) oriented rows across all strains with no consistent response in the 3rd yr. Mean soil temperatures prior to canopy closure were 3.2 °C higher for E-W oriented rows. Munevar and Wollum (1981a, b, 1982) had determined in the laboratory that for the strains later used in Hunt et al's (1985) field studies that the temperature differences between row orientations was sufficiently large to cause growth and host responses of free-living rhizobia of the magnitude and direction observed by Hunt et al. (1985). These temperature differentials were sufficient to assume an impact on root metabolism. Higher root-respiration of E-W oriented rows may have accounted for decreased yields. In addition, there may have been differences in nutrient availability related to ion activity and root absorptive capacity.

Water Use

Soybean water relations in general have been studied by a large number of researchers, but few have studied water relations as affected by planting geometry. Doss and Thurlow (1974) compared soybean performance in wide and narrow rows with high and low populations under irrigated and non-irrigated conditions. They found no influence on yield of inter- or intra-row spacing under irrigated conditions but found higher yields under low populations in the nonirrigated treatment. In earlier studies, Timmons et al. (1967)

and Peters and Johnson (1960) found the highest water-use efficiency (yield/evapotranspiration) in their narrow row treatments. Peters and Johnson (1960) determined that doubling plant population by decreasing inter-row spacing by one-half had a doubling effect on transpiration from flowering to maturity. In the study of Timmons et al. (1967), however, neither row spacing nor plant population affected evapotranspiration. Shibles et al. (1975) determined that until attainment of complete ground cover, transpiration varies in soybean canopies as a function of LAI but after complete canopy closure the aerial environment alone regulates ET.

Alessi and Power (1982) examined planting geometry effect on soybean water use from a dryland perspective. In 2 of 4 yr, they found that soybean yields were lowest, water use was highest, and for 3 of 4 yr, water-use efficiency was least for the narrowest row width they studied. Their data showed greater water use in narrow rows before flowering. In dryland situations or drought years, this early depletion caused by earlier canopy closure and increased ET (Reicosky et al., 1982b) leaves insufficient soil water for completing reproductive growth. This can reverse the usual expectation (especially for northern, indeterminate soybean) of increased yields with narrower rows, and underscores the importance of adequate water availability. Taylor (1980) found similar results. In the two driest years of a 3-yr study, there was no yield advantage for narrow rows, but a 17% increase occurred when seasonal water was adequate. In the dry years, wide-row plants grew taller, set more pods, and maintained higher leaf water potential (Ψ_L) than narrow-row plants. The amount of water conserved by wide rows in dry years, however, was evidently sufficient to maintain the early season biomass advantage, but insufficient to support an enhanced yield potential.

A similar response was reported by Campbell et al. (1984) for southern determinate soybean grown in a tillage study. In a year in which postflowering drought occurred, they found all treatments favoring water conservation (these included wide rows, maintenance of surface residues, early maturity groups, or delayed vegetative development) increased yields.

Although Taylor (1980) measured higher Ψ_L in wide-row soybean, other workers have had less success in determining row space-related differences in plant water status. Sojka and Parsons (1983), Sojka et al. (1984a), and Reicosky et al. (1985), reported greater differences related to cultivar than to row spacing and had difficulty delineating irrigation-related effects on plant water status. Sojka and Parsons (1983) and Sojka et al. (1984a) observed no significant row space-related differences in leaf temperature, Ψ_L, parallel leaf-diffusive resistance, vapor-pressure deficit, or leaf-air temperature differential. Reicosky et al. (1985) could not discriminate differences between Ψ_L in wide vs. narrow rows and found that Ψ_L differences between Ψ_L differences with irrigation were only significant under severe water stress.

Reicosky et al. (1982b, 1985) found a slight increase in ET of 0.15- or 0.25-m row spaced irrigated soybean compared to wider-spaced rows. They believed this increase in ET was related to the higher early season LAI and light interception of the narrow rows. They also showed a slightly greater root-length density in the narrow rows. Mason et al. (1982) and Taylor et

al. (1982) also saw increased radiation interception, LAI, shoot to root ratio, and yield in narrow rows. Mason et al. (1982) further determined that the narrow-row treatments produced 49% more roots per hectare and 52% more roots per unit leaf area at identical plant populations. Despite the different root densities, there were no consistent differences for nonirrigated treatments in Ψ_L, soil temperatures, or water use over time or depth. Reicosky et al. (1982a) determined that the relationship between ET and Ψ_L was similar for both wide and narrow rows. This relationship was much more affected by application or absence of irrigation than by row spacing. There was, nonetheless, greater hysteresis in Ψ_L-ET diurnal curves for the non-irrigated narrow rows, which they interpreted as indicating greater early season water extraction.

Nutrient Use

The importance of adequate N availability (either as applied N fertilizer or as fixed N) to the effectiveness of narrow-row soybean culture was demonstrated by Cooper and Jeffers (1984). Nitrogen uptake rate and soil N depletion can be expected to occur more rapidly under narrow-row culture of soybean because more nearly equidistant spacing results in increased density of roots (Bohm, 1977; Taylor, 1980) as shown in Fig. 4-3, particularly with the common production practice of increasing plant populations in narrow-row systems.

Although N accumulation or seed yield did not increase, Bello et al. (1980) observed higher N_2-fixation rates (acetylene reduction) for higher plant populations and narrower row spacings. Maximum nodulation and N_2 fixation had earlier been shown to depend on adequate fertilization with P, K, and Ca (deMooy and Pesek, 1966; Fellers, 1918; Heltz and Whiting, 1928; Ludecke, 1941; Poschenrieder et al., 1940; Wilson, 1917). The rates required for this effect are higher than normal commercial fertilizer-application rates. Coupled with the recognized requirement for enhanced soil fertility in denser canopies, a heretofore unrecognized need for higher soil test values for narrow-row culture of soybean may exist.

Apart from the studies of soybean N production and uptake discussed above, there have been only a limited number of examinations of the interaction of soybean planting geometry and plant water status on nutrient accumulation. Bennie et al. (1982) found that Iowa soybean grown in 1.0-m row widths, regardless of irrigation, accumulated N, P, K, Ca, Mg, Na, Cu, Zn, Mn, Fe, B, and Al at a faster rate during the linear stage of nutrient uptake (between 49 and 91 d after planting) than those grown in 0.25-m row width. Concentrations of Mn were higher in 1.0-m row plants regardless of irrigation and Fe was higher in irrigated 1.0-m row plants. Sojka et al. (1984a) observed greater soil K^+ depletion in narrow rows but also found that depletion relative to row geometry was dependent on irrigation regime (Table 4-3), with greater depletion in the irrigated treatment. Furthermore, they found greater between-row depletion of K, Ca, and Mg. This may have indicated a concentrating effect within the row or that severe leaching effects oc-

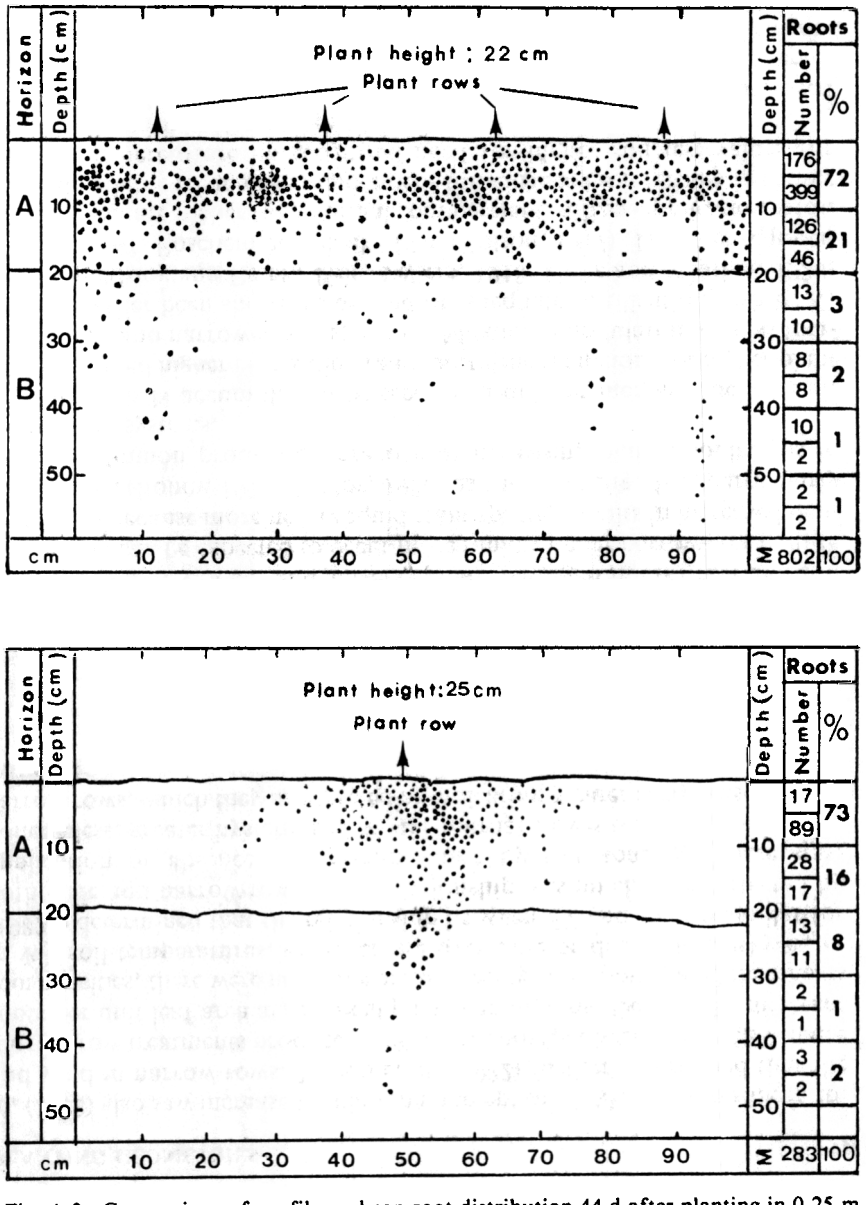

Fig. 4-3. Comparison of profile soybean root distribution 44 d after planting in 0.25-m vs. 1.00-m rows. Each dot represents approximately 5.0-mm root length on the exposed soil profile. From Bohm (1977).

curred between wide rows associated with high rainfall and sandy soils of the southeastern Coastal Plains. Mason et al. (1980) presented a detailed comprehensive summary of seasonal plant nutrient concentrations and accumulations by plant part. In their study, row spacing had little effect on plant

Table 4-3. Postharvest Mehlich I extractable K, Ca, and Mg as influenced by soybean row spacing, sampling depth, sampling position, and year. From Sojka et al. (1984).

Sampling depth	Row spacing	Sampling position	1980			1980		
			K	Ca	Mg	K	Ca	Mg
m			g/Mg					
0-0.15		M†	49	410	76	72	435	122
0-0.15		R	57	385	72	68	445	124
0-0.15		M	38	355	64	64	410	101
0-0.15		R	75	430	84	82	449	108
0.15-0.30		M	29	123	24	33	143	36
0.15-0.30		R	31	169	26	37	218	57
0.15-0.30		M	34	116	25	41	160	35
0.15-0.30		R	36	164	28	38	207	55
0.30-0.60		M	42	152	43	46	250	69
0.30-0.60		R	43	152	44	40	198	58
0.30-0.60		M	58	221	64	56	223	66
0.30-0.60		R	55	193	57	49	186	58
0.60-0.90		M	30	230	53	28	273	73
0.60-0.90		R	31	218	55	32	292	77
0.60-0.90		M	30	245	64	36	250	63
0.60-0.90		R	36	252	64	34	276	66
LSD (0.05)			10	116	15	10	77	18

† Sampling position M indicates between soybean rows while R indicates within the rows.

nutrient concentrations even though plants grown in wide rows were greener in color. Nodulation differences could not be detected. Because of greater biomass, there was greater per hectare elemental accumulation of all elements except Zn on a whole plant basis in wide rows. There were, however, higher concentrations in narrow rows of: pod wall P, stem and pod wall K, and whole plant B and Zn. Higher concentration of whole plant Mn and Fe occurred in wide rows.

CORN AND SORGHUM

The principles governing the effect of planting geometry on corn and sorghum [*Sorghum bicolor* (L.) Moench] are similar to those for soybean but are affected by the absence of the N_2-fixing process, and different root and shoot growth habits. The topic was reviewed by Duncan (1969); Dungan et al. (1958); Hinkle and Garrett (1961); Pendleton (1966); Stringfield (1962); and has been dealth with in varying degrees by other authors more recently as well (Blad, 1983; Cardwell, 1982; Waldren, 1983). In general, as population increases and row spacing decreases, water and nutrient availability plus overall management intensity must increase to optimize yields (Brown and Shroder, 1959; Grimes and Musick, 1959). Furthermore, Stringfield (1962) and Pendleton (1966) noted that these inputs must be expected to intensify even further as varieties are continually improved.

Conflicting experimental results have been accumulated related to the effects of row space and water use. Significant increases in corn and sorghum

yields have been frequently reported for narrow rows and/or increased populations with good management (Andrews and Peek, 1971; Brown et al., 1970; Camp et al., 1985; Colville and Furrer, 1964; Colville, 1966; Downey, 1971; Duncan, 1958; Hoff and Mederski, 1960; Karlen et al., 1987; Kohnke and Miles, 1951; Lang et al., 1956; Larson and Hanway, 1977; Laude et al., 1955; Lutz et al., 1971; Porter et al., 1960; Sentz, 1965; Stickler, 1964; Stivers et al., 1971; Wooley et al., 1962; Yao and Shaw, 1964a.)

Radiation Interception

As with soybean, the increased yield of narrower rows appears to be the result of more efficient interception of PAR, either by increased LAI or more uniform spatial distribution, especially early in the season. The increased yield generally results in higher water-use effiency without significantly affecting seasonal water use (Aubertin and Peters, 1961; Colville, 1968; Denmead et al., 1962; Duncan, 1972; Knipmeyer et al., 1962; Pendleton et al., 1966; Peters and Russell, 1959; Tanner, 1957; Tanner et al., 1960; Timmons et al., 1966; Yao and Shaw, 1964a, b).

Corn may be more sensitive to competition than soybean, and for that reason stand uniformity can significantly affect the success of any planting geometry. Theoretically, equidistant spacing is optimum (Aldrich et al., 1976; Shubeck and Young, 1970). The need to ensure stand uniformity increases as all other management factors become more intensive, particularly with higher populations (Duncan, 1969).

Hill planting and other techniques resulting in uneven stands have generally yielded less than uniformly spaced stands (Colville and Furrer, 1964; Mock and Heghin, 1976; Pendleton, 1966; Waldren, 1983). This is due to the corn plant's tendency toward early adjustments to any inter- or intraspecies competition for light, water, or nutrients (Donald, 1958; Duncan, 1969; Hozumi et al., 1955; Waldren, 1983; Yoda et al., 1957). The tendency of closely spaced, shaded corn plants to elongate more rapidly than sunlit ones was noted by Hozumi et al. (1955). They further noted a lower phytomass accumulation in the shaded individuals. If an individual falls too far behind its neighbor it will continue to grow, using water, nutrients, and light at the expense of its neighbors, but itself remain barren. Karlen and Sojka (1985) referred to such unsuccessful individuals as "corn weeds."

As mentioned earlier, acceptance of new practices by farmers is increased when conventional equipment can be used. The objective of more uniform crop spacing, with correspondingly more uniform LAI distribution and increased yield, can be accomplished through reducing the row spacing for a given population. However, narrow rows generally require re-tooling of planters and cultivators, and purchase of narrow-row headers in the case of corn. The latter costs can be avoided in many cases by using twin rows, which are simply a pair of closely spaced rows centered on the conventional wide spacing. Karlen and Camp (1985), and Karlen et al. (1985) showed grain yields 5 to 8% higher in twin over single-row culture at constant populations. Earlier, corn silage yields had been shown to increase in twin rows (Bryant

and Blaser, 1968; Washko and Kjelgaard, 1966). Twin rows were found to have similar cultural advantages for determinate soybean, but not to have significant yield advantages (Sojka, 1985, unpublished data).

The interactions of light intensity and quality under varying corn canopies was examined by Karlen et al. (1987) and Karlen and Kasperbauer (1988). They observed minimal difference between E-W or N-S oriented rows or variations in row configurations. Their 0.19–0.57–0.19-m twin rows yielded 5 to 10% better than 0.96-m single rows but not better than 0.76-m single rows. There were not large spectral variations due to spacing or orientation within the canopy and unlike soybean (Kasperbauer et al., 1984) physiological responses were not strongly tied to red/far-red exposure regimes. Earlier, Yao and Shaw (1964a) also failed to see significant differences in performance related to row orientation.

Water Use

The relative amount of water use between wide or narrow rows has been explained by some researchers as being dependent on the amount of surface soil water. Dry soil (stage three evaporation) resists vapor transfer and is an effective supplier of sensible heat to the wide-row plants, increasing their transpirative demand per unit leaf area (Chin Choy and Kanemasu, 1974; Chin Choy et al., 1977; Kanemasu and Arkin, 1974; McCauley et al., 1978; Yao and Shaw, 1964a). In addition, advection between wide rows can significantly increase the inter-row sensible heat balance, resulting in considerably higher ET rates (Blad, 1983; Chin Choy and Kanemasu, 1974; Hanks et al., 1971). Hanks et al. (1971) documented the significance of row advection as an energy source for sorghum ET; 21% of the dryland ET energy requirement, and 64% of the irrigated, originated from advection between 1-m rows in Akron, CO. Chin Choy and Kanemasu (1974) attributed the 10% higher ET from wide than from narrow-row sorghum to row advection early, and large-scale advection late in the season at Manhattan, KS.

In situations where the soil surface is frequently rehydrated by rain or irrigation (soil surface remains in Stage 1 or 2 evaporation), evaporation from the soil surface eliminates the source of sensible heat and ET is similar between the two canopies. Shading in the narrow-row canopy reduces the sensible heat load enough to slightly reduce ET in some instances. Under irrigation, then, one would expect increased weight of grain per unit ET (WUE) in narrow rows due to increase in grain yield resulting from significantly increased efficiency of light interception (Waldren, 1983). Forage yield may not increase, however (Cummins and Dobson, 1973). These results are contrary to the row space-related water-use patterns reported for soybean, but the contradicting results probably relate to experimental artifacts as discussed below.

Interpretation of these differences in water use between narrow and wide-row spacings is complicated by at least two factors. First, results vary depending upon climate and irrigation, and second, some experiments have been conducted using constant populations per unit ground area and others with

constant plant numbers per unit row length. In these latter experiments, there exist both row-spacing and population variables, the interaction of which has not been completely described. Timmons et al. (1966) showed optimum populations for wide-row corn in the northwestern Corn Belt to increase in years with more water available during the season. In these tests, there was no clear population effect on seasonal water use, although the use generally trended upward with increased population. Contrastingly, there are data showing significant row spacing effects at constant populations. Yao and Shaw (1964a, b) showed higher water use for wide-row corn (0.53-, 0.81-, and 1.06-m spacings) in Iowa. Olson (1971) found no differences in water use for corn grown in 1.02-m rows at 35 000 plants/ha, in 0.51-m rows at 70 000 plants/ha, or in 0.51-m rows at 45 000 plants/ha.

More data exist for sorghum. Bond et al. (1964) tested 1.01- and 0.51-m row spacings, 4.4- and 8.8-kg/ha seeding rates (populations of about 45 000 and 90 000 plants/ha), and four initial soil-moisture levels in the southern High Plains. There was no significant effect of either row spacing or seeding rate on seasonal water use. However, narrower rows and higher populations shifted water use earlier in the season. Therefore, the fact that water is the limiting factor in the climate may have equalized seasonal water use. Plaut et al. (1969) studied irrigation timing on sorghum yield and water use, using a constant within-row spacing. In 1964, the apparently wetter year, 0.45-m row spacing yielded higher than 0.70-m spacing, and also used slightly more water in two of three comparisons. In the 2nd yr, with lower ET, the yield relationship reversed, and ET values were nearly the same for both row spacings. Olson (1971) showed no significant effect of row spacing on water use of either forage or grain sorghum at a constant within-row spacing in South Dakota. However, the narrow-row spacing, which had twice the population, had numerically higher water use in all years. Chin Choy and Kanemasu (1974) reported energy balances for wide (0.92-m) and narrow (0.46-m) row sorghum at a constant 12 plants/m of row. Seasonal ET was 10% higher from the wide-row sorghum, in spite of the higher population in narrow rows.

In a recent study, Steiner (1986) reported that in a dry year narrow rows and higher populations increased seasonal ET by 7 and 9% (Table 4–4), respectively, mostly due to increased prereproductive ET. Row direction did not affect water use or yield although the dry matter to ET ratio and light interception was higher in the narrow-row crop. In a 2nd yr of the study, there was more rain, but narrow-row ET was still higher between emergence and anthesis. Intensive observation in the 2nd yr (Steiner, 1987) indicated that net radiation was 5% higher over wide compared to narrow rows and E-W rows had 14% higher net radiation than N-S rows. Higher leaf temperatures were associated with higher populations caused by greater depletion of plant available water.

It is apparent that no single summary statement can be made to include all of the foregoing results. In general, higher populations and narrower row spacings used slightly more water in some experiments, or used water earlier in the season, thus exhausting the supply in water-limiting environments. In other experiments, the water-use effects were reversed, with more ET from

Table 4-4. Row spacing and population effects on evapotranspiration (ET), yield, and water-use efficiency (WUE) of dryland grain sorghum. From Steiner (1986).

Treatment	Seasonal ET	Vegetative ET	Grain-fill ET	ET during grain-fill	Total dry matter	Grain dry matter	Harvest index	WUE total	WUE grain
	m			%	Mg/ha			kg/m³	
1983									
Spacing, m									
0.38	0.200**	0.175**	0.025*	12**	5.92	2.03	0.34	2.96*	1.02*
0.76	0.184	0.151	0.033	18	5.92	2.13	0.36	3.22	1.16
Population									
High	0.199**	0.174**	0.025	13*	6.10*	1.64**	0.27**	3.08	0.83**
Medium	0.194	0.166	0.028	14	6.22	2.31	0.37	3.21	1.18
Low	0.183	0.149	0.033	18	5.44	2.28	0.41	2.98	1.25
SE	0.011	0.009	0.010	4.9	0.72	0.44	0.04	0.35	0.20
CV, %	5.5	5.6	35.9	33.1	12.2	21.4	11.0	11.0	18.6
1984									
Spacing									
0.38	0.266	0.187**	0.078	29*	9.52*	3.33	0.35**	3.58**	1.25
0.76	0.265	0.175	0.089	34	8.13	3.29	0.40	3.08	1.25
Population									
High	0.263	0.184	0.078	30	9.41	3.39	0.36	3.56	1.28
Medium	0.269	0.183	0.085	31	8.45	3.20	0.38	3.16	1.19
Low	0.264	0.177	0.087	33	8.61	3.34	0.39	3.26	1.27
SE	0.013	0.008	0.012	35	1.05	0.50	0.02	0.33	0.18
CV, %	5.0	4.5	14.8	11.2	11.9	15.0	6.3	10.0	14.5

*,** Significant at 0.05 and 0.01, respectively.
† Significant ($P < 0.05$) spacing × population interactions in 1983 in harvest index and grain WUE. No significant spacing × population interactions in 1984.

wide row or low population studies. In these cases, higher water use was attributed either to higher net radiation or to advection from the dry soil surface between the wide rows. Yao and Shaw (1964a, b) showed higher water use for corn in wide rows and attributed it to higher net radiation over wide rows in Ames, IA. Steiner (1987) showed net radiation to be higher over wide than over narrow-row sorghum, but had earlier reported no significant water-use difference (Steiner, 1986).

The effect of row orientation on water use has been reported for corn and sorghum. Yao and Shaw (1964a, b) showed significantly greater water use for corn in E-W oriented rows than for N-S in Ames, IA. Steiner (1986), in a sorghum study at Bushland, TX, observed slightly more water use in E-W rows in both years, though not significant at the 5% level of probability. The E-W orientation had 14% higher net radiation than the N-S orientation in 1984, a moderate year. One should keep in mind that the prevailing wind in both Iowa and Texas is largely westerly. Therefore, advection may have contributed to the results. There is apparently a difference, therefore, that can be distinguished under certain circumstances of climate, soil, and crop, but it has not yet been studied sufficiently to describe.

Narrow rows have failed to increase yields where seasonal water supply was limited and when interaction of climate with days to maturity and population was not favorable for the season (Alessi and Power, 1974; Mitchell, 1970). Some have concluded sorghum is more suited to these dryland situations because of reduced water loss rates (Brown and Schroder, 1959; Olson, 1971). For the same reason, lower populations are frequently more successful under dryland conditions since they conserve early season water (Alessi and Power, 1965; Bond et al., 1964; Termunde et al., 1963).

Nutrient Use

The impact of planting geometries on nutrient relations for corn and grain sorghum has been studied, but reported less frequently than effects on water use, light interception, and plant growth. Presumably, this has occurred because most studies showed that row width caused no significant differences in grain and/or silage protein content (Bryant and Blaser, 1968; Cummins and Dobson, 1973; Karlen and Camp, 1985; Karlen et al., 1985, 1987; Lutz and Jones, 1969; Rhoads and Stanley, Jr. 1978; Stickler, 1964; Stickler and Laude, 1960). However, a second reason may be that many of the studies were conducted using high-fertilization rates or at soil-fertility levels that were considered nonlimiting (Lutz et al., 1971; Nunez and Kamprath, 1969; Rutger and Crowder, 1967; Stanley and Rhoads, 1971, 1974; Stivers et al., 1971). Karlen and Camp (1985) saw no differences in corn leaf concentrations at anthesis of N, P, K, Ca, Mg, S, B, Cu, Mn, or Zn among row-space variables.

Determining optimum planting geometries for enhanced nutrient uptake and utilization may become more important in the future. Public concern regarding the declining quality of groundwater resources is increasing (CAST, 1985; Keeney, 1986). Many significant increases in groundwater NO_3^- are the direct result of poor N fertilizer-use efficiencies. By combining precision fertilizer placement techniques, such as the spoke-injector technique (Baker et al., 1985), with improved planting geometries, fertilizer recovery may significantly increase and potential for groundwater contamination decrease (Touchton and Sims, 1987). Twin-row planting may have nutrient recovery advantages that were not apparent in the initial yield and light interception studies. In southeastern Coastal Plain soils, in-row subsoiling often results in a concentration of plant roots directly beneath the row because of a more favorable physical rooting environment (Campbell et al., 1984). In these soils, precision placement with a spoke-injector applicator may significantly increase the efficiency of N recovery by row crops.

Optimizing planting geometries may also become more important for the development of profitable agriculture production systems. By determining optimum plant spacing and populations for individual soil types or mapping units, fertilizer, herbicide, and irrigation applications can be managed more efficiently. The use of controlled traffic patterns and/or tramlines will also increase the importance of planting geometries. Using alternative planting geometries to enhance nutrient utilization of corn and sorghum may also

become important when leguminous plants are grown in association to provide N, reduce soil erosion, recover residual fertilizer N, and supply subsoil water and nutrients to the primary crop (Blevins, 1987; Power, 1987).

Denser canopies are beneficial for soil erosion control. Greater uniformity and density of plant cover provides rainfall interception over a greater fraction of the soil surface. This reduces the velocity and hence kinetic energy of the rain drops, which in turn reduces the amount of soil dislodged at the soil surface. These effects prevent filling of macropores with soil debris from runoff and promote higher infiltration rates than under more open canopies (Mitchell, 1970; Pendleton, 1966) resulting in more efficient use of sprinkler irrigation or rainfall. A benefit of narrow rows in reducing furrow erosion has also been seen (Sojka and Brown, 1987). This resulted from shorter set times, energy dissipation by foliage intrusion, furrow lining by brace roots, fibrous root binding of aggregates at the furrow-water interface, and an increase in the infiltration of applied water.

OTHER CROPS

The topic of planting geometry has been addressed in a number of other crops. It would be beyond the scope of this chapter to review all of them in detail, but several unifying concepts and innovations are mentioned here briefly.

The twin-row concept has been adopted for use in wheat (*Triticum aestivum* L.) production in the Pacific Northwest. In this application, twin rows are coupled with banding of fertilizer between the rows (Veseth, 1987). This placement efficiently supplies nutrients to the intra-twin row soil, but "hides" nutrients from weeds in the inter-twin row area beyond the flanking pair of wheat rows. Early indications are that this practice can be used successfully with conservation tillage to limit weed growth and thereby increase the efficiency of nutrient and water use by the crop.

Row orientation has been studied in wheat with some interesting results (Erickson et al., 1979; Kirkham, 1980, 1982; Santhirasegaram and Black, 1968). Kirkham (1980) found that leaf orientation in wheat is cultivar dependent and that row orientation affected growth and light interception of winter wheat (Kirkham, 1982). During the winter, N-S rows had wide, short leaves and E-W rows had long narrow leaves. The N-S rows received more light than E-W rows, but less light, rather than more light, was associated with greater grain production. Santhirasegaram and Black (1968) determined that maximum light absorption occurred at 1200 h for E-W rows and at morning and evening for N-S rows.

Planting geometries have become a highly researched topic in peanut (*Arachis hypogaea* L.) production (Alexander, 1970; Chin Choy et al., 1977; Cook, 1980; Hauser and Buchanan, 1981; Mozingo, 1984; Mozingo and Coffelt, 1984; Schubert et al., 1983; Shelton, 1978; Stone et al., 1985). In one study, there were no differences in quality or yield for irrigated treatments for a variety of planting patterns including solid planting, skip-row plant-

ing, and twin-row planting (Schubert et al., 1983). Mozingo and Coffelt (1984) reported numerically but not statistically higher yields for twin-row planting patterns over single rows. Stone et al. (1985) found that stomatal diffusive resistance was higher in response to greater water stress in narrow-row peanuts. This suggests that peanut, like soybean, depletes more soil water in narrow rows.

Planting geometry effects on rice (*Oryza sativa* L.) yields and cultural relations were reviewed by Chandler (1969). His summary stated that newer stiff-strawed, low to medium tillering, shorter varieties performed best with close spacing at all N levels. The taller leafy tropical varieties would yield better at somewhat closer spacings if N and light were abundant. Jones and Snyder (1987a, b) confirmed this, stating that narrow-row spacings increased grain yields for both tall and semidwarf plants when drill seeded and did not affect yields of the subsequent ratooned crop.

Halterlein (1983) reviewed results for spacing of edible bean (*Phaseolus vulgaris* L.) and found that nearly all previous studies showed substantial yield benefit to increased LAI and narrow rows. He cautioned, however, that adoption of the newer configurations might be difficult due to the need to accommodate mechanical harvesters designed for wide rows.

Planting geometry of cotton was studied and reviewed briefly by Bilbro (1981) and Mohamad et al. (1982). Their work and the work they reviewed indicate that cotton is particularly sensitive to cultural practice interactions (e.g., irrigation and fertility) with season and choice of plant ideotype in determining the success of denser planting patterns. It appears that shorter statured, semideterminate, early maturing cultivars are most responsive to narrow rows and/or high populations.

CONCLUSION

For a wide range of species it appears that a greater yield advantage may exist for dense, uniformly spaced canopies than for more open canopies, provided early weed management, water availability, and fertility are adequate. This advantage is more pronounced for plants with indeterminate growth habits. Manipulation of row-spacing configurations may be the most practical means of optimizing canopy geometry. Leguminous plants may require greater than expected mineral nutrient availability to maximize nodulation and N_2 fixation in these denser, management-intensive cropping systems. Row spacing and row orientation may affect canopy light quality and soil temperatures sufficiently to alter rhizobial-host interactions and N_2 fixation of leguminous plants. The interaction of planting geometry and the nutrient relations of the soil-plant system are not well documented. Due to earlier LAI increases, early season (and often total season) ET are frequently higher in denser canopies. Wider rows of some crops may have higher ET due to sensible heat transfer from dry inter-row soil surface, although there are conflicting data on this point. Plant physiological indices of water stress frequently indicate greater stress in narrow rows or denser canopies, particularly

under nonirrigated conditions, probably due to greater early season water depletion. Soil-physical and equipment-engineering limitations may impose the ultimate practical and financial barriers to adoption of high-intensity, dense-canopy management systems.

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