ROW WIDTH AND PLANT POPULATION EFFECTS ON PLANT MORPHOLOGY, WEED CONTROL, AND YIELD IN TYPE II BLACK BEAN AND SMALL RED BEAN

By

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ABSTRACT

ROW WIDTH AND PLANT POPULATION EFFECTS ON PLANT MORPHOLOGY, WEED CONTROL, AND YIELD IN TYPE II BLACK BEAN AND SMALL RED BEAN

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The development of upright black and small red bean varieties gives dry bean growers opportunities to plant in narrower rows, which has been associated with yield and weed control benefits in many crops, and to use direct harvest methods with a standard combine. Field studies were conducted in 2010 and 2011 at two locations in Michigan to examine the effect of row width, population, and herbicide combination on canopy closure, weed suppression, pest management, plant architecture, and yield in two upright varieties, 'Zorro' black and 'Merlot' small red beans. In one set of studies, each variety was planted in 38- and 76-cm rows, as well as 51-cm rows at one location. Populations were 196500, 262000, and 327000 plants ha^{-1} in black bean and 148000, 196500, and 262000 plants ha^{-1} in small red bean. In a second set of studies, 'Zorro' only was planted at 262000 plants ha^{-1} in row widths of 38- and 76-cm, and six weed control strategies were examined: S-metolachlor + halosulfuron (PRE), S-metolachlor (PRE) fb. bentazon + fomesafen (POST), halosulfuron (PRE) + clethodim (+fomesafen in one site-year) (POST), imazamox + bentazon (POST), weed-free, and no weed control. Narrow rows generally increased canopy closure, enhanced weed suppression, did not increase pest pressure, increased branching and pod formation, and increased yield. Population had little effect on canopy closure, weed suppression, pest pressure or yield. Pod formation, seeds per pod, and branching decreased as population increased. All herbicide combinations suppressed weeds and increased yields compared to the untreated but varied in their control of specific weeds.

Nomenclature: Dry bean, *Phaseolus vulgaris* L.; preemergence; postemergence

DEDICATION

To John Casey Chumley, Derek Sova, Amanda Harden, Alex Lindsey, and Laura Bast. All of these are daring in their pursuit of scientific knowledge and are therefore worthy. Also to my parents, Bob and Debbie Holmes, without whom this thesis would not exist.

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CHAPTER 1

LITERATURE REVIEW

Introduction

Dry bean (*Phaseolus vulgaris* L.) is a leguminous plant grown as a short-season summer annual crop. It is divided into over a dozen market classes, each of which has a set of distinct characteristics and is marketed under a different name. Among the most widely grown market classes in the United States are black beans, small red beans, navy beans, and pinto beans. In temperate production regions, dry beans are typically planted in late spring, and the seeds are harvested after the plants have dried down in early fall. Dry beans are widely used as a human foodstuff, serving as a relatively inexpensive source of protein in many parts of the world, especially in developing countries where meat is difficult to obtain (Robertson and Frazier 1978). They are the third most important food legume in the world, with only soybean and peanut exceeding production levels of dry bean. Annual world dry bean production is estimated at 11.8 million tonnes on almost 13 million hectares (Schwartz et al. 2004). In the United States, dry bean was planted on an average of 634,000 hectares per year between 2006 and 2010, and total production was valued at 500 million to 900 million dollars annually (USDA-NASS, 2011).

Michigan is the second largest dry bean producer in the nation, with 80,000 to 100,000 hectares planted annually. Michigan is the nation's number one producer of two market classes, black beans and cranberry beans, and is the number two producer of two others, small red beans and navy beans (Michigan Bean Commission, 2011). Four dry bean growth habits, referred to as Types I, II, III, and IV, are recognized (Kelly 2001, 2010; Urwin et al. 1996). Type I are determinate bush forms, Type II upright, indeterminate short vines, Type III long-prostrate or semi-prostrate vines, and Type IV are climbing vines. Type IV varieties are rarely grown in the United States.

Dry Bean Production and Weed Control

Dry bean is a low-growing crop that is highly susceptible to competition from weeds (Burnside et al. 1998; Hekmat et al. 2008). Reported losses from weed competition have been as high as 80-85% (Blackshaw and Esau 1991). Others have reported losses ranging from 16-52% and from 40-71% when weeds were left uncontrolled (Chikoye et al. 1995; Wall 1995). The variability in yield loss was partly a function of different predominant weed species; the 16-52% loss was largely due to common ragweed (*Ambrosia artimesiifolia* L.), the 40-71% yield loss to redroot pigweed (*Amaranthus retroflexus* L.) and common lambsquarters (*Chenopodium album* L.), and the 80-85% yield loss to hairy nightshade (*Solanum sarrachoides* Sendtner). Two of the most problematic weeds in North American dry bean production are common lambsquarters and redroot pigweed (Wall 2005). Common ragweed and foxtails (*Setaria spp.*) are also considered significant weed problems in dry bean production systems (Chikoye et al. 1995; Lamey et al. 1991). Other weeds, such as nightshades (*Solanum* spp.), can affect harvest efficiency, stain beans, or cause spoilage in storage in addition to reducing yields (Blackshaw et al. 1999; Burnside et al. 1998; Quackenbush and Andersen 1984; Robertson and Frazier 1978).

Historically, many dry bean growers have relied heavily on inter-row cultivation (Arnold et al. 1993; Blackshaw et al. 2000; Burnside et al. 1998, Robertson and Frazier 1978) for weed control. Chemical weed control has relied heavily on preplant incorporated herbicides (Arnold et al. 1993; Blackshaw et al. 2000; Burnside et al. 1994; Goulden 1976; Robertson and Frazier 1978). Herbicide options available in the past were sometimes inadequate for good weed control in the absence of cultivation (Arnold et al. 1993; Blackshaw and Esau 1991). For a variety of reasons, dry beans have historically been grown in wide rows, often 71- or 76-cm. A key reason for this was that inter-row cultivation was needed for weed control and, in some systems, for hilling the beans in preparation for harvest (Blackshaw et al. 2000; Goulden 1976; Malik et. al., 1993). In addition, dry beans were grown in wide rows because growers desired to use equipment shared with other crops planted in wide rows (Redden et al. 1987; Schwartz et al. 2004). Moreover, there were concerns about increases in disease, especially white mold (*Sclerotinia sclerotiorum* (Lib.) de Bary), in narrow rows (Blackshaw et al. 2000; Saindon et al. 1995; Schwartz et al. 2004). Most traditional dry bean varieties grown in the United States prior to the last decade of the twentieth century had a prostrate vine habit (Type III) that was not amenable to direct harvest by combine (Horn et al. 2000; Kelly et al. 2009a; Schwartz et al. 2004). Thus, they were typically harvested with specialized equipment that cut the plant about 5 cm underground, pulled the cut plant, and placed the plants in a windrow, or that simply pulled the whole plant and windrowed it; the plants were allowed to dry, often for several days, and were then harvested with a combine equipped with special grates to prevent damage from rocks and soil clods (Robertson and Frazier 1978; Schwartz et al. 2004). Type I dry beans, which were widely grown in the mid-twentieth century, have also proven not to be amenable to direct harvest methods (Adams 1995).

Type I and Type III dry beans are still grown in the United States. However, beginning in the 1970s, breeders have been developing more upright Type II dry bean varieties with a growth habit similar to the natural habit of soybean (*Glycine max* L.) that are suitable for direct harvest (Hosfield et al. 2005; Kelly 1994, 2001, 2010; Mooers 1909; Welacky and Park 1987). Direct harvest is an attractive option because a single pass across the field is more efficient, because yield losses often occur in the windrow system, and because less specialized equipment is needed (Kelly 2010; Robertson and Frazier 1978; Schwartz et al. 2004). Growers using a direct harvest system are unlikely to use inter-row cultivation because it brings up rocks and creates mounds, which interfere with combine operation (Schwartz et al. 2004). Inter-row cultivation also requires more passes across the field, raising concerns about the possible erosion and compaction caused by repeated cultivation (Blackshaw et al. 2000). In addition, cultivation is no longer necessary to hill beans for pulling in a direct harvest system (Robertson and Frazier 1978; Schwartz et al. 2004). If a grower does not cultivate, this opens the possibility of growing dry beans in narrow rows since a significant inter-row area in which to cultivate is no longer needed (Blackshaw et al. 2000). An additional benefit of upright varieties is lower disease pressure due to a less dense canopy and fewer pods touching the ground (Blackshaw et al. 1999; Kelly and Adams 1987). Since the canopy structure of upright cultivars makes them less susceptible to white mold, the increased white mold danger associated with narrow rows is alleviated (Blackshaw et al. 2000; Kelly and Adams 1987; Saindon et al. 1993).

Preplant incorporated herbicide use, the other component of traditional weed management in dry bean, also involves soil disturbance and often multiple passes across the field. Moreover, the current availability of a wide range of preemergence and postemergence herbicides for dry bean in the United States has reduced the need for reliance on preplant incorporated herbicides (Sprague and Everman 2011). This suggests the need for research on the overall effectiveness of herbicide combinations, especially in light of research suggesting that herbicide combinations work better than single herbicides, even at reduced rates (Blackshaw et al. 2000).

Effects of Row Width and Population on Canopy Development

Numerous studies have shown that decreasing row width, and sometimes increasing planting population, increases canopy development and consequent light interception in dry bean (Table 1.1) and other crops (Table 1.2). The increase in canopy development may consist in the greater development of the canopy during certain parts of the season and/or in greater canopy closure at peak (Duncan 1986). Increased light interception is often associated with benefits to crop production, especially higher yields and weed suppression (Andrade et al. 2002; Norsworthy and Oliver 2001; Peters et al. 1965). In navy bean, Urwin et al. (1996) correlated several measures of canopy closure, including leaf area index and diffuse non-interception of light, with reduction in late-season weed emergence in one year of a two-year study; the effect was non-significant in another year when canopy development was more uniform.

Soybean, another leguminous crop harvested for seed, has been extensively studied with respect to canopy development. Because its growth habit is similar to that of Type II dry bean, insights derived from soybean research may prove applicable to dry bean. Harder et al. (2007), using a factorial design of three row widths and four populations, measured light levels above and below the soybean canopy at intervals through the growing season and used these values to calculate leaf area index (LAI). Row widths of 19 and 38 cm resulted in greater LAI mid-season than 76-cm rows, and the canopy reached the critical LAI that indicated 95% canopy closure 1 to 2 weeks sooner at the two narrow row widths than in the wide row width. Also, in the 19- and 38-cm rows only, the high population (445,000 seeds ha^{-1}) had a greater LAI than the low population (124,000 seeds ha^{-1}) on most measurement dates and a greater LAI than the next lowest population on two dates. Dalley et al. (2004) studied the same row widths (19-, 38-, and 76-cm) at a single population and found large differences in light interception between the 76-cm canopy and those of the narrower row widths; on one date, the 76-cm soybeans had only 18% interception while the 19-cm had 98% interception, and the 76-cm rows never completely closed the canopy while the 19- and 38-cm rows always did. On some dates, greater canopy closure was also evident in the 19-cm than in the 38-cm rows. Taylor (1980) destructively analyzed LAI at four row widths (25-, 50-, 75-, and 100-cm) at a constant population. Although he did not find significant differences in LAI among row widths, he did visually observe canopy closure twenty to sixty days earlier in 25-cm rows than in 100-cm rows; he attributed this to a more uniform distribution of leaf area. Yelverton and Coble (1991) compared photosynthetically active radiation (PAR) interception at 23- and 91- cm row widths in soybean and found that the 23-cm canopy essentially closed by ten weeks after planting while the 91-cm canopy never reached greater than 75% interception. Similarly, Légère and Schreiber (1989) found that LAI was greater through much of the season in 25-cm than in 76-cm rows. Quakenbush and Andersen (1984) also measured PAR interception in 18- and 76-cm rows and found that when 18-cm rows reached 95% interception, the 76-cm rows were only at 24% and did not catch up for about three weeks. Norsworthy and Oliver (2001) conducted a soybean population study in narrow (19-cm) rows using twelve planting populations ranging from 185,000 to 1,432,000 seeds ha^{-1}. Light interception increased by an average of 0.022% for each additional thousand seeds ha^{-1}; however, even the lowest population achieved 89% interceptance, suggesting that narrow rows may enable efficient light interception at a wide range of populations. Using a four-row-width, four-population factorial design, Weber et al. (1966) found that LAI increased both with decreasing row width and increasing population and that whole plant dry weight increased along with it, but they cautioned that after a certain point, increasing dry weight actually began to result in lower seed yields. Nelson and Renner (1989) found that the soybean canopy closed an average of 35 days sooner in 19-cm than 76-cm rows.

Some non-leguminous crops have also been shown to respond to narrow row widths with more complete canopy closure in the early part of the growing season. Dalley et al. (2004) examined 38- and 76- cm row widths at a constant population in corn (*Zea mays* L.) and found that narrow-row corn had higher light interception in the early season, though the advantage was lost by the time of tassel emergence. Alford et al. (2004) planted corn and sugarbeet (*Beta vulgaris* L.) in 38-, 56-, and 76-cm rows; both species demonstrated earlier canopy closure as measured by light interception in 38-cm rows than in 76-cm rows.

A few similar studies have also been conducted in dry bean with similar results. One of these was conducted in Alberta by Blackshaw et al. (1999); they studied Type II and III navy beans at populations of 240,000 or 480,000 ha^{-1} and row widths of 23-, 46-, and 69-cm. Photosynthetically active radiation was measured above and below the canopy several times during the season and expressed as light penetration. In all three years of the study, PAR penetration was progressively greater with increasing row width, and 69-cm rows still had 20-40% penetration at peak canopy coverage with significantly lower penetration at peak coverage in the narrower row widths. The higher population resulted in slightly lower penetration in one year, lower penetration at just one date in another year, and no significant difference in the remaining year. Blackshaw et al. (2000) also conducted a similar three-year study in Type II small red beans, growing them in 23- or 69-cm rows at populations of 200,000 or 500,000 plants ha^{-1}. They found that PAR interception was usually greater at the higher plant density for most of the growing season. Also, PAR interception was greater in narrow rows than in wide rows at many measurement dates, especially early in the season. Working in Queensland, Australia, Redden et al. (1987) conducted seven trials over three years, planting Type II navy beans at 112,500 or 337,500 plants ha^{-1} and row widths of 7.8-, 35.6-, 71.1-, and 107-cm. Their method of canopy analysis relied on visual observation of "the proportion of row width occupied by plants until rows were closed, after which visible bare ground was estimated by looking directly down over the canopy" at flowering and maturity. When row width had an effect on ground cover, increasingly narrow rows resulted in greater ground cover, but this effect did not occur at all sites. Similarly, increased population often resulted in increased ground cover, but not at all sites. The actual data from this study was not presented, only regression models of the data. In Brazil, Ziviani et al. (2009) used digital photography and computer analysis to assess canopy coverage in both Type II and Type III cultivars and found that in both types, 30- and 40-cm rows resulted in more complete coverage than 50- and 60-cm rows. They also found that at 36 days after planting, beans planted at 5 plants per meter of row did not provide as complete coverage as those planted at 10, 15, or 20 plants m^{-1} and that by 49 days, the 10 plants m^{-1} treatment was also lagging in coverage. In another Brazilian study, Vieira et al. (2010) varied within-row density of Type III dry beans between 4 and 16 plants m^{-1}, while keeping a constant row width of 50 cm. Canopy closure was estimated visually twice per year. They reported that canopy closure increased linearly with increasing within-row density at each date, although it does not appear that the separation between all treatments was significant at the later estimation dates (62 days after emergence in 2000, 79 days after emergence in 2001), and the precision of their method, "observing each plot from one end (looking down the rows) and visually estimating the proportion of soil surface visible between the rows," seems doubtful. Moreover, the range of populations used was very low. In Michigan, Xu and Pierce (1998) compared leaf area in

‘Mayflower’ navy beans in 56- and 71-cm rows and did not find a significant difference; however, their decision to destructively sample only three plants in each plot for each measurement time and the lack of an explanation regarding how they measured leaf area make this result ambiguous, particularly since greater yield was still observed in narrow rows.

At least two similar studies have also been conducted in snap bean, which, though used in a very different manner than dry bean and generally considered a horticultural crop, also belong to *Phaseolus vulgaris*, and these studies brought up aspects of canopy development and plant spacing not addressed by agronomic researchers. In Maryland, Teasdale and Frank (1983) planted snap beans in row widths of 15-, 25-, 36-, 46-, and 91- cm at a constant density of 430,000 plants ha^{-1} at two locations in five site-years. Canopy coverage was visually estimated weekly, and at one location, photon flux density was measured above and below the canopy weekly. Unlike in the dry bean experiments, canopy coverage and light penetration were treated separately and related to one another. Canopy cover usually increased and light penetration usually decreased with decreasing row width. Thus, canopy cover was inversely related to light penetration, but the relationship was not entirely linear. While it was linear between 15 and 46 cm, greater canopy coverage was required in 91-cm rows to achieve the same reduction in light penetration. This is likely because canopy coverage was being rated visually, so that only the outer surface of the canopy was taken into consideration. This suggests that lower leaves play a role in light absorption and that the canopy was thinner toward the middle of the 91-cm rows even if the same percent coverage was achieved. Teasdale and Frank also took note of the fact that in narrowing the rows, plants were increasingly equidistant from one another and were precisely equidistant at the 15-cm spacing and suggest that equidistance may have played a role in the quicker canopy development in narrow rows. Another snap bean study by Wahab et al.

(1986), conducted in Saskatchewan, suggested that yield advantages could be obtained by planting in an equidistant pattern. While not specifically addressing canopy development, the study was specifically designed to look at equidistance by comparing four row widths ranging from 20- to 125-cm at a within-row spacing of 5-cm, four square designs with equal inter- and intra- row spacings ranging from 10- to 25-cm, and four honeycombed triangle designs in which all plants were equidistant from their six nearest neighbors at distances ranging from 10- to 25-cm. This two-year experiment was conducted with an eye toward labor-intensive production in resource- and land-poor nations. Andrade et al. (2002) suggest that some of the advantage gained by means of equidistant spacing may be a result of more efficient use of water and nutrients, which would suggest that equidistant spacing improves the development of what might be termed the "below-ground canopy" - the roots - as well as the above-ground canopy. However, possibly due to the difficulty of studying roots, this possibility has been little explored in the literature.

Effects of Planting Practices and Canopy Development on Yield

The principal benefit that growers hope to derive from an increase in canopy closure is an increase in yield. If decreasing row width or increasing population results in quicker or more complete canopy closure, more light will be intercepted and thus more energy should be available to the crop to produce seeds. If the "below-ground canopy" also develops more efficiently, the crop will have more available water and nutrients, and this may also increase yield. The other main benefit of greater canopy closure is weed suppression due to reduced light below the canopy; reduced weed competition could also indirectly result in increased yield by reducing the amount of light, water, and nutrients made unavailable to the crop by weeds.

A large volume of work indicates that narrow rows result in higher yields in soybean and that planting population should be reasonably high but can safely be varied within wide limits, although population has also sometimes been varied along with row width, possibly conflating the effects of the two in certain studies. The principles behind these effects may also apply to dry beans, especially those with growth habits similar to soybean.

A number of these studies have come in the context of herbicide research, although these have tended to be somewhat ambiguous in their results. As early as 1965, Peters et al. compared soybean yield in 51- and 102-cm rows with different cultivation and herbicide program. In two of three years, 51-cm rows resulted in higher yield than 102-cm rows by 11.1 and 13.8 bu ha^{-1} but were approximately equal in the third year. They then compared drilled soybeans in 20-, 41-, 61-, 81-, and 102-cm row widths over three years, using lower populations for wider row widths. They concluded that widths of 20 to 61 cm resulted in the highest yields in good growing conditions, but the conclusion was questionable as only a few favorable results were chosen from the data, much of which was inconclusive. Nelson and Renner (1998), in evaluating the potential of several acetolactate synthase inhibitor (ALS) herbicides for weed control in soybean, used both 19- and 76-cm rows, lowering the population by over 100,000 seeds ha^{-1} in 76-cm rows, at each of two sites. Yield was greater across both sites in 19-cm rows in all treatments, though it was only significantly greater in five of the seven treatments; significant differences ranged from 300 to 800 kg ha^{-1}. Young et al. (2001), in the course of evaluating the effectiveness of glyphosate with various tank mix partners in glyphosate-resistant soybean, varied soybean row width using 19-, 38-, and 76-cm widths at three sites over three years. They intended to look at the effect of row width but in some cases also varied the planting population either between row widths, reducing the population in wider rows. In three site-years, yield was significantly greater in 19- and 38-cm rows, although in two of these years, population was varied between all row widths as well. In one site-year, 76-cm rows actually out-yielded 19-cm rows, though the authors believed that this was due to poor stand in the 19-cm rows. In an evaluation of herbicide combinations in glufosinate-resistant soybean, Norris et al. (2002) planted soybeans at a constant population of 480,000 seeds ha^{-1} in 38- and 76-cm rows at two locations over two years. Their results were more equivocal. At one location, no yield differences due to row width were observed, which the authors attributed to extremely dry conditions in the mid- and late growing season. At the other site, there were significant differences, and whether narrow row width resulted in higher yield varied by treatment and year, though the authors do not make it clear which differences were significant. Wax and Pendleton (1968) used 21-, 51-, 76-, and 102-cm rows but also reduced the planting populations with increasing row width to the point that 102-cm rows had half the population of 21-cm rows. They reported increases of soybean yield compared with the 102-cm width of 10, 18, and 20% with each decrease in width and concurrent population increase.

However, a number of other papers have offered clearer data. Légère and Schreiber (1989) reported that soybean yield was an average of 590 kg ha^{-1} higher in 25- than in 76-cm rows at a constant population of 39 plants m^{-2} and that this effect was consistent across all three years of the study. Lehman and Lambert (1960) compared 51- and 102-cm rows across four planting densities in two locations and found that at one location, the 51-cm rows had consistently higher yields across planting densities while at the other location there were not significant differences; there were no yield differences across planting densities. In an usually lengthy series of studies, Cooper (1977) carried out a six year succession of trials comparing 17-, 50-, and 75-cm rows in three populations in the first year. In 50- and 75-cm rows, there were no significant differences between populations, while in the 17-cm rows, the high population (375,000 plants ha^{-1}) was optimum and so was adopted as a standard population for the remainder of the trials. This series of trials, using many different soybean varieties, established that, assuming good weed control, a yield advantage of 10-20% was usually obtained by 17-cm rows while early maturing varieties often obtained a 30-40% advantage. Taylor (1980) conducted a three year experiment using 25-, 50-, 75-, and 100-cm row widths at a constant 160,000 plant ha^{-1} density and experienced one good growing season and two dry years. He reported that in the year with favorable growing conditions, 25-cm rows resulted in 17% greater yields than 100-cm rows with the middle row widths having intermediate yields. However, he also reported no significant differences between row widths in the two dry years, with wide-row plants outstripping narrow-row plants in leaf area, height, and pod set, allowing them to equal narrow row yield.

Several studies have treated soybean row width and population (or within-row spacing) as a factorial design, using every combination of several row widths and planting populations. An early example of this approach was a 1939 paper by R.G. Wiggans, who used five row widths ranging from 20 cm to 81 cm, paired with seven set within-row seed spacings ranging from 1 to 15 cm over a four year period. He discovered a remarkably consistent pattern of yield increasing with decreasing row width in all years. He also noted a very general trend toward higher yields at closer within-row spacings but found little of significance up to 8-cm; spacings above 8-cm began to reduce yield significantly. When Wiggans converted his combinations to plants per area, he found little benefit in increasing population beyond 650,000 plants ha^{-1} and serious yield consequences to populations below 330,000 plants ha^{-1}. Ethredge et al. (1989) compared 25-, 51-, and 76-cm rows in soybeans at 260,200, 390,400, and 520,400 plants ha^{-1}. In spite of the wide range of populations used, no significant yield differences were found among populations. Two cultivars were utilized, and the effects of row width within each cultivar were examined across populations and both years of the study; in one cultivar, the 25-cm rows outyielded the 76-cm rows by 15% with the 51-cm rows intermediate, while in the other cultivar, 25- and 51-cm rows yielded similarly and outyielded 76-cm rows by 5-7%. Kratochvil et al. (2004) used standard planting populations for full season and double-crop soybeans in Maryland (432,250 seeds ha^{-1} and 555,750 seeds ha^{-1} respectively) along with rates 40% and 20% lower and 20% higher than standard rates. They planted in 19- and 38-cm rows for three years, using four cultivars each year in two locations both single and double-cropped for a total of 48 individual cultivar-year-system comparisons. In two years, 19-cm rows averaged significantly higher yield than 38-cm rows, and while this did not extend to every comparison, in no comparison in these years did 38-cm rows yield significantly higher. In the other year, there was no significant yield difference overall between the row widths, but in only one individual comparison did 38-cm rows yield higher than 19-cm rows. In two years, the 40% reduced rates were found to reduce yields while the 20% reduced rates did not. The 20% increased rate increased yield of early maturing cultivars in one year but otherwise had similar yield to the standard rate. In the third year, under drought conditions, the standard rate and the higher rate yielded better than the reduced rates at one location but not the other. Harder et al. (2007) planted soybean in 19-, 38-, and 76-cm rows at five populations ranging from 124,000 to 445,000 plants ha^{-1}. They did this in three locations over two years in both weedy and weed-free conditions. They found no yield advantage of 445,000 over 296,000 plants ha^{-1} but did find that yield typically began to drop at 198,000 plants ha^{-1} and was always less than optimum at 124,000 plants ha^{-1}. At all populations except the lowest, 19-cm rows yielded higher than 76-cm rows in both weed control scenarios, and in all but one population-weed control combination, 38-cm rows yielded higher than 76-cm rows. In only one case did 19-cm rows yield higher than 38-cm rows.

J.K. Norsworthy has also conducted studies in soybean focusing only on the question of population. Norsworthy and Frederick (2002) noticed that the recommended seeding rate for narrow row (<76 cm) soybeans (624,000 seeds ha^{-1}) was double those for wide row soybeans (370,000 seeds ha^{-1}) in South Carolina and suspected that this was unnecessary. They drilled narrow-row soybeans of four cultivars at both recommended rates in two years and concluded that the lower population recommended for wide rows was sufficient to produce yields equal to the higher population in narrow rows. Earlier, Norsworthy and Oliver (2001) had used twelve seeding rates ranging from 185,000 to 1,482,000 seeds ha^{-1} in 19-cm rows for two years, in one of the years at two sites. They reported 988,000 seeds ha^{-1} to be the optimum seeding rate but also decided that this was not economically viable. They also found that at one site-year which experienced very good growing conditions, yield did not vary by seeding rate over the entire spectrum, suggesting a remarkable ability of narrow-row soybeans to compensate for low population under ideal conditions.

Studies in non-leguminous crops also suggest the possibility of increasing yields in narrow rows. For examples, Yonts and Smith (1997) grew sugarbeets in 35-, 56-, 76-, and 97-

cm rows and found that sugar yield was highest in the two lower row widths, and Winter (1989) compared 76- and 102-cm rows and found sugar quality to be higher in 76-cm rows regardless of population or irrigation.

However, the work of Sankula et al. (2001) in lima bean (*Phaseolus lunatus* L.), a close relative of dry bean, suggested that narrowing row widths may not always increase yield. They planted lima beans in Maryland and Delaware at a constant population of 175,000 plants ha^{-1} at two sites over two years, with the exception of one site-year in which the narrow rows were planted to 350,000 plants ha^{-1}. The two row widths used were 38-cm and 76-cm. In this study, yield was higher in narrow rows in only in one of the four site-years.

Some work has been conducted regarding similar issues in *Phaseolus vulgaris* itself, and the evidence points toward higher yield in narrow rows. However, many of these studies were conducted under irrigation, which may allow greater productivity in many years than dryland production and may reduce intraspecific competition, allowing plants to be successfully spaced more closely. Population effects seem less consistent, and Crothers and Westerman (1976) found that determinate (i.e., Type I) cultivars tended to response positively to increased population while indeterminate (i.e., Type II and III) cultivars tend have similar yield over a high population range due to their greater ability to compensate and fill in gaps, though this work was carried out in snap beans (also *Phaseolus vulgaris* L.) rather than dry beans.

Many of these studies have been conducted in Canada rather than in the United States. Park (1993) worked with dry bean in Ontario but did not specify whether the beans were irrigated or what class they belonged to, though at least some of the seven varieties used were navy beans. Both Type I and Type II varieties were planted for two years. Park used 30-, 60-, and 80-cm row widths with population adjusted up as row width decreased. (The populations stated are 50,000, 33,333, and 26,667 seeds ha^{-1}, but it seems likely that this is a misstatement and that the actual populations were ten times that since the stated populations are about 10% of those used by other studies.) Average yield increased as row width decreased (with the associated increase in population) from 2290 to 2882 to 3308 kg ha^{-1}; this trend occurred in all cultivars. Malik et al. (1989) using a factorial design, planted white beans (i.e., navy beans) of Types I, II, and III in Ontario without irrigation in 23-, 46-, and 69-cm rows combined with seeding rates of 225,000 and 375,000 seeds ha^{-1} in both weedy and weed-free conditions. While beans grown in weed-free conditions exhibited no yield differences by row width, those grown in weedy conditions exhibited significantly lower yield in 69-cm rows than in 46- or 23-cm rows. Malik et al. (1990) continued their experiment a second year and reported that in that year, yield was higher in 46- or 23-cm rows in both the weedy and weed-free plots. In their final paper, Malik et al. (1993) reported that in both years in 46-cm rows and in one year in 23-cm rows, the higher planting population resulted in 12-16% higher yields in the weedy plots but in no increase in yield in the weed-free plots. In Alberta, Blackshaw et al. (1999) also planted both upright and viny navy beans in 23-, 46-, and 69-cm rows at populations of 240,000 or 480,000 plants ha^{-1} under irrigation. This was repeated three years, and in each year, yield was 27-41% higher at the higher population, and when the high population was used, yield was increased an average of 35% in 23-cm rows compared to 69-cm rows. The narrow row widths also resulted in higher yields at the low population in one year. While beans were grown both in the presence and in the absence of hairy nightshade (*Solanum sarrachoides* Sendtn.), the effects occurred regardless of this factor except one year when row width was non-significant in the weedy treatment. These effects occurred regardless of cultivar. Blackshaw et al. (2000) also conducted a similar study in semi-upright small red beans under irrigation in Alberta over three years. They planted at row widths of 23- and 69-cm and used plant densities of 200,000 or 500,000 plants ha^{-1}. When maintained weed-free, the narrow row width had a 19% yield advantage, and the high population had a 17% advantage; the highest yields in the study were at high population and narrow rows. However, in one year high population only increased yield in wide rows. In the presence of weeds, narrow rows and high populations still increased yield except in one year when high population only increased yield in narrow rows; weedy yields were always less than optimum weed-free yields.

Similar studies were conducted several decades ago in Australia and New Zealand and came to similar conclusions. Goulden (1976), in Canterbury on New Zealand's South Island, grew Type I 'Sanilac' navy beans in 20- and 40-cm rows and within-row spacings of 4.8-, 7.1-, and 10.2-cm under irrigation. Yield was 57% greater in 20-cm rows than in 40-cm rows. In 20-cm rows, yield was greater at the 4.8- and 7.1-cm within-row spacings than in the 10.2-cm spacing, though within-row spacing had no effect on yield in 40-cm rows. In the Australian state of Queensland, Redden et al. (1987) planted one of two varieties of Type II navy bean at least once at six separate sites over three years for a total of eight site-years; some locations were irrigated while others were not. They were planted at row widths of 17.8-, 35.6-, 71.1-, and 107-cm and densities of 112,500 and 337,500 plants ha^{-1}. In all but one site-year (at which no yield response was observed), yields decreased with widening rows, especially at low population; a sometimes lesser response was observed at high population. In two site-years, there was no yield response to plant density, while at other sites yield was highest at the greater density in at least some row widths.

Few such studies have been conducted in the United States. In North Dakota, Grafton et al. (1988) planted upright navy beans and vining pinto beans in 19-, 38-, and 76-cm rows and four populations for each class (99,000 to 321,000 plants ha^{-1} for pinto bean, 148,000 to 371,000 plants ha^{-1} for navy bean) for two years at two sites. Yield decreased with increasing row width, with the decrease per 25-cm between rows being 565 kg ha^{-1} for pinto beans and 435 kg ha^{-1} for navy beans. Yield increased with increasing population for navy beans but did not do so for pintos. In the course of trying to examine the possibility of no-till or ridge-till production of dry beans, Xu and Pierce (1998), working in Michigan, used both 56- and 71-cm rows for 'Mayflower' navy beans for three years. They found yield to be 300 to 600 kg ha^{-1} higher in 56-cm rows than in 71-cm rows. Intended planting population was not specified, and final planting population was only reported in one year.

Other studies have been conducted in the United States and Canada on snap bean (also *Phaseolus vulgaris*). Teasdale and Frank (1983) planted snap beans at row widths of 15-, 25-, 36-, 46-, and 91- cm at a constant density of 430,000 plants ha^{-1} for three years at multiple sites in Maryland. All row widths produced similar yields except the 91-cm width, which yielded less than the other row widths in four of the five site-years. In Oregon, Peachey et al. (2006) planted snap beans in 19-, 38-, 75-, 114-, and 150-cm rows in two years at a constant 445,000 seeds ha^{-1}. This was a white mold trial, and when fungicide was applied, 19-cm rows produced the highest yield in one year, while no significant differences were seen among the other row widths. When fungicide was not applied that year and regardless of fungicide in the following year, 150-cm rows produced the lowest yield with no significant differences between the other widths. Every significant difference was at least 5000 kg ha^{-1}. As described in the last section, Wahab et al. (1986) planted snap beans in Saskatchewan, Canada in three spatial arrangements – rows, squares, and triangles, in order of increasing equidistance – and four spacings within each arrangement, observing higher yields in increasingly equidistant designs. Yield tended to increase with decreasing row width or plant spacing. Square and triangle designs generally had a yield advantage over traditional rows, and in one year, the triangular design had an advantage over the square design. Moore (1991), working with soybeans in Louisiana, added a little evidence to the idea that equidistant planting increases yields, finding that equidistant within-row spacing increased yields compared with non-equidistant spacing by 7% and 8% in sequential years, though neither result was significant at α=0.05.

Some dry bean studies have been conducted in Brazil, and most have had rather different results than those conducted elsewhere, but this is likely due to the warm, humid nature of Brazil's climate, which probably causes high disease pressure when plants are spaced densely, and also likely increases plant growth compared with beans in cooler climates, thereby increasing intraspecific competition. These results may have little application to relatively cool growing regions in the northern United States. The study that would seem more likely to be climatologically relevant to the northern United States was that conducted by Horn et al. (2000) in Rio Grande do Sul, the most temperate of Brazil's states. It was not clear whether the study was conducted under irrigated conditions. Upright black beans were planted in row widths of 25-, 50-, and 75-cm and paired with populations of 100,000, 200,000, 350,000, and 500,000 plants ha^{-1}. This study found no yield differences between populations but, contrary to most studies, found a linear increase in yield as row width increased from 977 kg ha^{-1} at 25 cm to

1132 kg ha^{-1} at 75-cm. In the extremely hot and humid state of Tocantins, Aidar et al. (2001) decided to conduct row width research due to the low yields being obtained in the region by growers trying to grow dry bean, a recently introduced crop in Tocantins, and to the observation that yields were highest in border rows. They used row widths of 45-, 60-, and 75- cm and within-row densities of 7-, 10-, 13-, and 16-plants m^{-1} of row and planted Type III carioca beans. It was determined that row width was the major factor controlling yield and that 60 cm was the ideal row width for Tocantins, with yield declining again at 75 cm; most growers had been using 45-cm rows. They also determined that yields were highest at about 13 plants m^{-1} of row. In Mato Grosso do Sul, also a state characterized by warm, humid weather, Arf et al. (1996) planted 'Ouro' Type III dry bean using within-row densities of 8, 12, and 16 plants m^{-1} of row and a double-row system in which rows were paired with a small space on one side of each row and a larger space on the other side. They used row widths of 20/80-, 30/80-, 20/70-, and 30/70- cm, as well as using constant row widths of 60- and 50- cm. They found that yield increased with increasing in-row density but also, surprisingly, that in no row width combination was yield significantly different from any other. Perhaps the most interesting Brazilian result was that of Ziviani et al. (2009), who compared a prostrate variety of carioca bean with an upright variety in 30-, 40-, 50-, and 60-cm rows and 5, 10, 15, and 20 plants m^{-1} of row in the tropical highland state of Goias. They were concerned that upright varieties were being unjustly rejected as low-yielding due to being grown at low densities and wide row widths and found that, indeed, the upright variety demonstrated the highest yields at 30- and 40-cm and at 20 plants m^{-1} of row while the prostrate variety yielded similarly across all treatments.

Effects of Planting Practices and Canopy Development on Weed Suppression

Given the strong evidence that narrow rows in many circumstances and high planting populations in some circumstances can improve canopy development and increase yield, it would be expected that they also improve weed suppression by allowing less light to penetrate the canopy and be utilized by emerging weeds and by making the crop more competitive for water and nutrients.

A number of studies have addressed the effect of planting practices on weed populations in soybean, so once again the information from these studies may give an indication of what to expect from dry bean. Harder et al. (2007) observed weed density and biomass following glyphosate application and in a weedy control using three row widths and four populations. They had found that 19-cm and 38-cm rows increased canopy closure compared with 76-cm rows. Weed populations were counted and weed biomass measured weekly two through five weeks following glyphosate application; 19-cm rows had lower weed density and biomass across all timings than 76-cm rows, and 38-cm rows had lower weed density and biomass than 76-cm rows in weeks three through five. Thus, narrow rows suppressed weed resurgence following herbicide application. Although high populations tended to improve canopy closure in narrow rows, weed density and biomass following glyphosate application did not respond to planting population. In the weedy control, weed density was unaffected by row width or planting population. Weed biomass was higher in the lowest population than in the highest but was otherwise unaffected by population. At the two lower populations, (124,000 and about 190,000 plants ha^{-1}), row width also had no effect on weed biomass. However, at the moderate and high populations (about 300,000 and 445,000 plants ha^{-1}), weed biomass was lower in 19-cm rows than in 38- and 76-cm rows. There was not a clear correlation between weed suppression and yield.

Wax and Pendleton (1968) planted soybeans in 10-, 20-, 30-, and 40-cm rows but greatly reduced population with increasing row width; they noted that with decreasing row width (and increasing population), grass control improved, and that biomass of some, but not all, broadleaf weeds was reduced at 10- and 20-cm compared with the wider spacings. Peters et al. (1965) planted soybeans in 20-, 41-, 61-, 81-, and 102-cm row widths and found that the three lower row widths reduced the need for cultivation for good weed control; unfortunately, the three narrower widths were also at the same high population while population was lowered for the wider widths, possibly calling into question which was the effective cause.

Nelson and Renner (1998) found that planting soybeans in 19-cm rows resulted in lower weed biomass in most herbicide combinations than planting in 76-cm rows, especially when an herbicide treatment resulted in only partial weed control. This advantage coincided with observed yield advantages in 19-cm rows in all treatments except the weed-free treatment and the most effective herbicide combination. It also agreed with their observation of faster canopy closure in 19-cm rows. Yelverton and Coble (1991) planted soybeans in 91-, 46-, and 23-cm rows in two years. Herbicides were applied and weed resurgence measured in terms of weed density. Resurgence increased linearly with increasing row width, which agrees with their observation that canopy cover was much greater in 23-cm rows than in 91-cm rows.

Some researchers have looked at the control of specific weeds as affected by row width. Légère and Schreiber (1989) intentionally sowed redroot pigweed in soybean in 25- and 76-cm rows. They observed canopy geometry to determine whether soybean and pigweed were competing and measured leaf area and biomass of both the crop and the weed. They found that pigweed was competing with soybean for light even though soybean always produced more leaf area. Pigweed was 43% of biomass and 29% of leaf area on average in 76-cm rows but biomass was reduced to 24% and leaf area to 15% in 25-cm rows. This was consistent with their findings that narrow rows increased canopy closure and yield. Young et al. (2001) examined the control of velvetleaf (*Abutilon theophrasti* Medik.), giant foxtail (*Setaria faberi* Herrm.), and common waterhemp (*Amaranthus rudis* Sauer) in 19-, 38-, and 76-cm rows in soybean using a variety of herbicide combinations in eight site-years. At some sites, within some herbicide treatments, giant foxtail control was improved in 19-cm rows compared with 76-cm rows, but control was good with most herbicide combinations, regardless of row width. However, common waterhemp control was better across all treatments and years in 19- or 38-cm rows than in 76-cm rows, and velvetleaf control was better across all treatments in 19- and 38-cm rows in four site-years. This was consistent with their reports of higher yields in 19- and 38-cm rows in some site-years. Norris et al. (2002) planted 38- and 76-cm soybean rows at a constant population and used a variety of herbicide combinations on fields with high populations of barnyardgrass (*Echinoloa crus-galli* Beauv.), hemp sesbania (*Sesbania herbacea* Mill. (McVaugh)), pitted morningglory (*Ipomoea lacunose* L.), large crabgrass (*Digitaria sanguinalis* L. (Scop.)) and sicklepod (*Senna obtusifolia* (L.) H.S. Irwin and Barneby). In all weeds and nearly all herbicide treatments, control was improved, often substantially, in 38-cm rows; in some cases, 100% control was achieved in 38-cm rows. However, there was no clear trend with regard to yield, which the authors attribute to drought and poor stand establishment.

Chandler et al. (2001) looked at weed seed return in addition to weed biomass. They planted soybean in 76- and 38-cm rows as well as in twin rows 19 cm apart with each pair 76 cm from the next. Seed return was estimated by collecting seeds on or just under the soil surface within two 400 cm^2 quadrats of each plot. While weed biomass was only reduced in the 38-cm rows, yield was higher in both the 38-cm and twin-row treatments. Weed seed return was also diminished in both 38-cm and twin row treatments.

In addition to the research that has been done in soybean, a few studies have also been conducted relating planting patterns and growth habit to weed control in dry bean. Malik et al. (1993) planted three navy bean varieties of Types I, II, and III in 69-, 46-, and 23-cm rows and populations of 250,000 or 375,000 plants ha^{-1}, though only at 250,000 for the widest row width. This research was conducted in two years in Ontario. Weed biomass was estimated by hand-harvesting six square meters of each plot several times over the growing season. The indeterminate vines (Types II and III) were found to result in less weed biomass than the Type I determinate bush variety, probably due to the fact that determinate cultivars stop growing after flowering while indeterminate cultivars, like weeds, continue growing. While weed biomass before flowering was similar across row widths, and population did not affect weed biomass, weed biomass after flowering was reduced in 23- or 46-cm rows compared with 69-cm rows; reductions in weed biomass ranged from 15-21% in both years. A negative correlation was observed between weed biomass and yield, with 1 kg ha^{-1} of weed biomass corresponding to about 0.38 kg ha^{-1} yield loss. Uncontrolled weed populations reduced yield as much as 70%. Blackshaw et al. (2000) in Alberta planted semi-upright small red beans for three years in 23- and 69-cm rows at populations of 200,000 and 500,000 plants ha^{-1}. Weed control was evaluated visually. Narrow (23-cm) rows did not improve weed control over that in wide (69-cm) rows at 200,000 plants ha^{-1} but did improve weed control at 500,000 plants ha^{-1}. In 69-cm rows, the effect of population was inconsistent, but in 23-cm rows, high population resulted in improved weed control. Thus, weed control was maximized at high population and narrow row width. This strongly correlated with observed increases in yield and also agreed with observations of improved interception of photosynthetically-active radiation in narrow rows and at high populations.

Blackshaw et al. (1999) looked specifically at the interaction between navy beans and hairy nightshade (*Solanum sarrachoides* Sendtn.) over three years. Both an upright Type II cultivar and a prostrate Type III cultivar were planted in 23-, 46-, and 69-cm rows at 240,000 and 480,000 plants ha^{-1}. There were few treatment differences in hairy nightshade biomass at three or six weeks after planting, but nine weeks after planting, biomass was reduced with decreasing row width in all three years, and the higher planting density decreased weed biomass in two of three years. Little difference was noted in weed suppression between cultivars. In all years, weedy plots had much lower yields than weed-free plots, demonstrating that hairy nightshade competition affected yield, and hairy nightshade was also found to reduce light available to the canopy. While yield increases often occurred in narrow rows in the weed-free plots, they always occurred in the weedy plots, suggesting that weed suppression caused by narrow rows may sometimes translate into yield benefits.

While Urwin et al. (1996) in Nebraska did not specifically look at planting practices, they did compare canopy closure in twenty dry bean varieties of different growth forms and relate it to late-season weed emergence. The cultivars were a mix of Types I, II, and III and of many market classes. Canopy closure was measured in terms of diffuse non-interceptance of light, leaf area index, plant canopy volume, and projected canopy cover. Plots were cultivated and kept weed-free through the last cultivation, and late emerging weeds were counted. In one unusually cool year, correlation was observed between weed emergence and many measures of canopy closure, along with a general trend toward better closure in more viny cultivars. However, the following year, growing conditions were better, making canopy closure more uniform and largely eliminating the correlation.

In addition, the Teasdale and Frank (1983) study in snap bean addressed the effect of row spacing on weed competition. They found that row widths of 15-, 25-, and 36- cm reduced weed biomass an average of 18% compared with 91-cm rows when weeds were allowed to emerge with the crop and that they had 82% less biomass than 91-cm rows when weeds were controlled for the first half of the season. This was consistent with their finding that narrow rows increased canopy closure. Yield increases were also observed in narrow rows but extended to 46-cm rows in which weed control benefits were inconsistently observed.

Disease Considerations with Regard to Planting Practices and Canopy Development

Despite the studies suggesting benefits to planting in narrow rows at moderate to high populations, concern has been expressed that planting beans more densely may increase disease pressure, especially white mold, due to reduced air flow through a thicker canopy. However, studies have shown that upright varieties are better at avoiding white mold infection (Kelly et al. 2009a; Saindon et al. 1995). Kelly et al. (2010) found that 'Santa Fe,' an upright pinto bean variety, had higher yield and lower levels of infection under intentional white mold inoculation than a traditional prostrate variety. Park (1993) in Ontario found in one year of a two year study that white mold incidence was 34% greater in 30-cm rows than in 60-cm rows and 56% greater than in 80-cm rows, although in a year of lower white mold pressure there were no significant differences between row widths. However, three Type I bush varieties and four upright vine Type II varieties were planted, and both years, the disease severity was found to be much lower, regardless of row width, in the Type II varieties for which narrow row recommendations are primarily being developed. Park, along with Saindon et al. (1995), suggested that the erect, narrow canopy allows better airflow and less plant contact with the ground than other types. White mold incidence was positively correlated with lodging in one year, suggesting that pod-soil contact is a significant factor in initial infection, and Type I beans exhibited more lodging, especially in the sense of lower branches coming into contact with the ground. Furthermore, despite the higher white mold incidence in narrow rows, yield continued to increase with decreasing row width even in Type I cultivars, suggesting that the increase in white mold infection was not economically significant. In addition to narrow rows, dense within-row spacing (and therefore high population) has also been implicated in increasing white mold. Vieira et al. (2010) in Minas Gerais state, Brazil, planted the Type III Pérola cultivar at 15, 7.5, or 5 seeds m^{-1} of row in constant 50-cm rows in one year and at 16, 12, 8 and 4 seeds m^{-1} in a second year. White mold incidence increased linearly with increasing within-row density in the first year, but fungicide application was found to be much more effective than planting at a low density. Disease severity index increased with increasing density, and yield was also reduced with increasing density. In the second year, disease severity index, disease incidence, and sclerotia weight all increased linearly with increasing within-row density, while yield was not significantly affected. However, it should be remembered that this research was conducted in Brazil and may not be applicable to the climate of the northern United States.

Saindon et al. (1993) in Alberta had more encouraging results with regard to white mold. They planted Type II navy beans, along with Type III small red beans as a viny control. In the first year, they used a factorial design with row widths of 30-, 45-, and 60-cm combined with within-row spacings of 4.0-5.0-, 5.5-6.9-, and 7.0-9.5- cm under irrigation. The following year, they dropped the 4.0-5.0-cm spacing was dropped and replaced with a 10.0-13.0- cm spacing, and the viny control was established only at 7.0-9.5-cm. Plots were intentionally inoculated with white mold, yet the disease difference between the viny control and the upright navy beans was large. In the first year, 73% of viny plants were infected, and 45.6% were killed while only 18.5% of upright plants were infected, and almost none were killed. In the second year, 45.8% of viny plants were infected and 11.2% killed while the upright plants were not infected by white mold at all. This suggests that the adoption of upright cultivars reduces white mold infection, independent of row width or population. Furthermore, row width did not affect white mold infection in upright cultivars, and within-row spacing did not affect white mold development at all. Moreover, in both years, yield increased linearly with decreasing row width in the absence of white mold and did so even in the presence of white mold in one year. Saindon et al. (1995) went on to conduct another four-year study specifically on planting density, using populations of 250,000, 350,000, 500,000, and 600,000 plants ha^{-1} in 23-cm rows. Two upright navy bean cultivars, an upright dark red kidney bean cultivar, and an upright black bean cultivar were grown in addition to a viny small red cultivar. The field was intentionally inoculated and irrigated. In this study, planting density did affect white mold infection in all but one year in which white mold was particularly severe; in general, higher planting densities led some cultivars, including upright cultivars, to develop more severe disease. However, disease severity remained low in all upright cultivars except in the year with the highest white mold pressure, and in every year, the viny cultivar had the highest rates of infection and death at every planting density. Moreover, yield of upright cultivars increased with higher planting densities in three of the four years.

In Oregon, Peachey et al. (2006) also looked at white mold infection and row width, though in snap beans rather than dry beans. White mold infestation in the field was naturally occurring. Row widths used were 19-, 38-, 75-, 114-, and 150- cm at 445,000 seeds ha^{-1}. The authors found that white mold severity decreased 3-5% for each 10 cm increase in row width in the absence of fungicide but that disease levels in the absence of fungicide were still unacceptable even at the widest row width since snap beans are grown for direct human consumption, and diseased pods are not considered acceptable. When fungicide was applied, yield was highest in 19-cm rows, but in the absence of fungicide, it was highest in either 38-cm or 75-cm rows, depending on year, suggesting that row width-aggravated white mold can cause yield losses in snap bean. However, the growth form of the snap bean cultivar used was not stated and may not resemble Type II dry beans.

While concern about row width-aggravated disease has centered on white mold, one paper by Conner et al. (2006) in Manitoba investigated the influence of growth habit and row width on bean anthracnose (*Colletotrichum lindemuthianum* (Sacc. & Magnus) Briosi & Cavara) development. Concern regarding this disease may be lower in part because sources of anthracnose resistance have been identified and have begun to be bred into new varieties. However, new varieties are not necessarily anthracnose-resistant and even those that are may not be resistant to all races (Hosfield et al. 2004; Hosfield et al. 2005; Kelly et al. 2009b). Conner et al. used four navy and two pinto bean varieties at two sites in two years; three of the six varieties were viny Type III beans, two were upright Type II, and one was a bushy Type I. In some plots seeds were intentionally infected with anthracnose while others were left uninfected. Anthracnose infection was visually assessed in the canopy twice, and percentage of pod tissue covered in lesions was assessed before harvest. Row widths of 30- and 60-cm were used. Pinto beans were shown to be more susceptible than navy beans. Neither row width nor growth habit had any consistent effect on bean anthracnose development, but 30-cm rows resulted in significantly higher yield in three of four site-years.

Effects of Planting Practices on Yield Components and Morphological Characteristics

Underlying the effects of planting patterns on canopy closure, yield, weed control, and disease must be some changes in basic morphological or physiological realities. A handful of studies have attempted to elucidate these realities. In bean crops, the components of per-plant yield are seed weight, number of seeds per pod, and number of pods per plant (Grafton et al. 1988; Lehman and Lambert 1960). Branching patterns and the relative allocation of reproductive resources between branches and the main stem may also change in response to planting patterns (Norsworthy and Shipe 2004). Three important characteristics not directly related to but potentially affecting yield are height, lodging, and maturity rate (Lee et al. 1996).

Several papers have examined these traits in soybean, a crop in which yield is determined by the same components as dry bean yield and in which basic morphology is similar. Pederson and Lauer (2004) noted that soybeans cannot usually be bred to enhance a specific yield component because yield-determining factors are largely outside the reproductive parts, and the plant tends to respond to environmental conditions by increasing and decreasing yield components proportionally to produce the same final yield.

Weber et al. (1966) planted soybeans in 13-, 25-, 51-, and 102-cm rows at populations of 64,200, 128,500, 257,000, and 516,400 plants ha^{-1}. Yield was maximized at 128,500 plants ha^{-1}, and it was found that in the higher populations, especially the highest, plants tended to be taller, to lodge more, to mature later, and to set fewer pods per plant, all of which were suggestive of intra-specific competition at high density. Row width had little effect on the characteristics that do not directly affect yield, but number of pods per plant was maximized in 25-cm rows and at 64,200 plants ha^{-1}; it was reduced with increasing population, presumably because soybeans compensate for lower populations by growing larger, enabling them to produce more seed. Number of seeds per pod was maximized in 51-cm rows and intermediate populations while seed weight was independent of row width and also maximized in intermediate populations. Ethredge et al. (1989) grew two varieties of determinate soybeans in 25-, 51-, and 76-cm rows in populations of 260,200, 390,000, and 520,400 plants ha^{-1}. In one variety, seed weight was lower in 25-cm rows, but this was apparently the result of greater seed numbers such that yield was inversely related to seed weight. Lehman and Lambert (1960) planted two varieties of soybean in 51- and 102-cm rows and four within-row spacings. They found that the number of seeds per plant declined steeply with decreasing within-row spacing and that the 102-cm rows produced more seeds per plant than the 51-cm rows. Number of seeds per pod was also greatest in 102-cm rows, and number of seeds per pod declined along with number of seeds per plant at lower within-row spacings. Seed weight was greater in 51-cm rows at one site, and at that site yield was also greater in 51-cm rows; at the other site, seed weight was greater in 102-cm rows, and yield was not significantly different between row widths, though it seems that 102-cm rows ought to have demonstrated higher yields than 51-cm at that site, having the advantage in both seed number and seed weight.

Board (1987) planted eight determinate soybean cultivars in order to compare yields and yield components and determine what yield components were most tightly correlated to yield. He found that pods per plant as well as seeds per plant were closely correlated to yield while seed size and seeds per pod were very weakly correlated. Similarly, Carpenter and Board (1997) planted soybeans in 75-cm rows at populations of 70,000, 164,000, 189,000, and 234,000 plants ha^{-1} and found that 164,000 plants ha^{-1} was the optimal population for yield. They determined that seed size and seeds per pod were not affecting yield across populations, and thus concluded that pods per plant must be the primary factor determining yield in various populations. Branch pods made up 75-87% of the yield in this study, so number of branch pods was strongly correlated to yield.

Norsworthy and Shipe (2004) were interested in the partition of seed yield between the main stem and branches in wide and narrow rows. They planted six varieties of soybean in 19- and 97-cm rows at populations of 432,000 and 272,000 seeds ha^{-1} respectively. They found that averaged over two years and the six varieties, main stem yield accounted for 69% of 19-cm yield but only 45% of 97-cm yield. In 19-cm rows, branch yield ranged from 14-57% of total yield, while in 97-cm rows it ranged from 47-74% of total yield. The authors noted that reduced branching has also been reported in high populations, which in this case were concurrent with narrow rows, but the authors assumed that reduced branching was due to narrow rows and suggested that varieties be examined for good main stem yield for narrow rows and good branch yield for wide rows. This suggests that when soybean plants have significant space between one another, they partially compensate by branching more than they would with less space. This also suggests that main stem yield is enhanced when there is less branching and that, given the tendency toward higher yields in conditions that might discourage branching, the main stem of soybean is more efficient at producing seed than are branches. This is supported by Ethredge et al. (1989), who found that main stem yield decreased with increasing row width as did overall yield. However, despite Norsworthy and Shipe's attribution of branch yield reduction to narrow rows, the Ethredge et al. study saw that branch yield was lowest at the highest population but was not consistently affected by row width. On the other hand, Lehman and Lambert (1960) did report more branches and a greater proportion of pods on branches in 102-cm rows than in 51-cm rows as well as more branches at wider within-row spacings. They also noted that seeds on branches tended to be smaller than those on the main stem.

In contrast to the large body of work in soybean, a rather limited amount of work has been done looking at the morphological responses of dry bean. Crothers and Westerman (1976) found that in two semi-upright, Type II dry bean varieties, the optimum planting population was about 300,000 plants ha^{-1} and that yields decreased at higher populations due to intraspecific competition manifesting itself in the death of older branches and the production of pods mainly on upper nodes. Consistent with this, Bennett et al. (1977) noted that when yield is reduced at overly high populations, the most sensitive yield component is number of pods per plant. They found that the causes of this were decreases in branching, racemes per node, and pods per node with increased population. They found that number of branches and pods per branch were inversely related and thus concluded that breeders ought not to focus on either element since increasing one decreases the other. Grafton et al. (1988) planted a determinate navy bean cultivar and an indeterminate Type III pinto bean cultivar in four row widths and four populations. The determinate cultivar showed yield increases with increased population while the indeterminate cultivar did not; in the determinate cultivar, pods per plant decreased with increasing population while seed weight remained constant, but number of seeds per pod increased, apparently accounting for part of the yield advantage at high population. In the indeterminate cultivar, pods per plant and seeds per pod both decreased with increasing population, eliminating the advantage that might have been expected from more plants per area, and suggesting that indeterminate cultivars are better able to compensate for low populations than indeterminate cultivars. The cause for increasing yields with decreasing row width remained obscure since no yield component appeared to vary significantly with row width.

Goulden et al. (1976) found that seed weight and number of seeds per pod were unaffected by row width in Type I navy beans. However, the two were found to be inversely related to one another. Variation in yield per plant was explained entirely by number of pods per plant, but pods per plant and yield per plant were inversely related to yield ha^{-1} as well as to plant density. The inverse relationship of yield components to one another is consistent with the finding of Adams (1967) that number of pods per plant is often inversely related to the other two components of yield. He postulated that the three components are genetically independent of one another and that the plant first initially focuses on allocating resources to pod formation, then to seed formation, then to increasing seed size. He further postulated that nutrient supply oscillates during the growing season and that if fewer resources are available during the determination of one yield component, the plant will compensate by allocating more resources to later-developing yield component. Later, Duarte and Adams (1972) noted that number of pods per plant was correlated with number of leaves since dry bean flowers form in leaf axils. They also noted that seed size correlated with leaf size and suggested that the two are genetically linked.

Horn et al. (2000) observed lodging in three row widths of Type II dry bean and found that lodging increased with wider rows and lower populations. The 25-cm rows were also found to reduce plant height compared to wider rows and to reduce the number of pods touching the ground.

Weed Control Systems in Dry Bean

While planting density or row width may affect many aspects of plant development and thereby affect weed management, changes in these factors alone will not normally result in sufficient weed control, as evidenced by the much lower yields obtained in soybean regardless of row width or population (Harder et al. 2007). Blackshaw et al. (2000) also observed that dry bean yield remained low in the absence of herbicide application regardless of row width or population. As such, some form of chemical or mechanical weed control is likely to be necessary for effective weed control.

Two studies have tried to establish a critical time of weed control in dry beans; that is, a period beginning at the time when weeds that emerge with the crop begin to impact yield and ending at the time when newly emerging weeds cease to impact yield (Burnside et al. 1998; Woolley et al. 1993). This is the period during which weeds must be controlled to avoid yield loss. Burnside et al. (1998) in Minnesota reported that yield was not affected by waiting four weeks after planting to control weeds but was affected by waiting six weeks. They reported that yield was unaffected if weed control ended at six weeks; however, it was affected if weed control ended at two weeks and was affected at one site if weed control ended at four weeks. This suggests that the critical period for weed control is four to six weeks after planting, though the authors suggest three to six weeks. Wooley et al. (1993) in Ontario planted two navy bean varieties in two years and calculated the critical period of weed control based on growth stage of the plant and either allowed weeds to grow up to a certain stage, afterward keeping the plot weed-free, or kept the plot weed-free up to a certain stage, then allowed weeds to grow. Three of the variety-years had a critical period from second trifoliate to first flower; the other variety-year had a longer period from second trifoliate to mid-flower. Arnold et al. (1993) in New Mexico assert without explanation that five to seven weeks after planting is the period in which competition from late-season weeds is most intense.

Burnside et al. (1994), working in Minnesota, demonstrated that there were numerous combinations of herbicides and mechanical control treatments available to dry bean growers that resulted in sufficient weed control. However, every treatment involved cultivation alone or cultivation plus rotary hoeing, and every herbicide combination except the two least effective involved pre-plant incorporated herbicides (clomazone, ethalfluralin, EPTC, trifluralin, and alachlor). In some treatments, all herbicides were pre-plant incorporated (PPI). Unless mechanical control was used as the sole method of control, a single cultivation was sufficient to produce effective weed control, but both cultivation and PPI herbicides involve soil disturbance and additional fuel use, and cultivation is impossible in narrow rows, so these combinations are not desirable for many modern dry bean growers. The only postemergence (POST) herbicides used by Burnside et al. were acifluorfen, bentazon, imazethapyr, sethoxydim, and an unnamed experimental herbicide, and no pre-emergence (PRE) herbicides were used. All herbicides used in this study are still registered for dry beans in the United States, except acifluorfen (Sprague and Everman 2011).

Hekmat et al. (2008) were working with dry beans in Ontario, where herbicide options for dry bean have been even more limited than for U.S. growers due to Canadian policy, having only bentazon and fomesafen available as POST herbicides. As such, they experimented with combining bentazon with imazamox and examined crop safety in a variety of market classes, which they thought would be acceptable due to evidence that bentazon can act as a safener for imadizolinone herbicides such as imazamox and imazethapyr. This supposition was correct, as the combination was found to result in minimal, transient crop injury. Imazamox is registered for dry beans in the United States (Sprague and Everman 2011). They did not comment on this combination's effectiveness.

Wall (1995) also examined bentazon tank-mixes for control of redroot pigweed and common lambsquarters in navy bean in Manitoba. His concern was that bentazon does not always fully control these weeds; tank-mixes of bentazon and imazethapyr applied POST were found to give adequate control of both. While such mixes usually injured dry beans, they always recovered by four weeks after treatment.

Arnold et al. (1993) expressed dissatisfaction with the state of weed control among New Mexico pinto bean growers, who were largely relying on PPI herbicides, and so explored imazethapyr applied PPI, PRE, or POST, sometimes in combination with other herbicides. They found that imazethapyr applied as a PRE with either metolachlor or pendimethalin was highly effective at controlling the major weeds in the study. As a POST application alone, imazethapyr did not provide good control of barnyardgrass but did control many other weeds. All treatments resulted in yields that did not differ from the weed-free, suggesting that imazethapyr suppressed weeds well overall.

Blackshaw and Esau (1991) in Alberta investigated herbicides suitable for control of hairy nightshade, redroot pigweed, and common lambsquarters in pinto beans. Fomesafen applied POST was found to be insufficient for control of these weeds, while imazethapyr applied POST provided good control, though not at reduced rates; bentazon alone applied POST was inconsistent in its control of hairy nightshade but gave fairly good control of the other weeds.

Sikkema et al. (2009) in Ontario used combinations of S-metolachlor and fomesafen applied both PPI and PRE to control a variety of weeds in black, navy, kidney, and cranberry bean. Both herbicides are currently registered for use on dry bean in the United States (Sprague and Everman 2011). They concluded that this combination is safe for all four classes but did not comment on the effectiveness of weed control.

Blackshaw et al. (2000) found ethalfluralin, applied PPI followed by bentazon or imazethapyr, to be an effective herbicide combination. In general, they concluded that combinations of herbicides, even at reduced rates, controlled weeds as well or better than the full rate of individual herbicides. They found that imazethapyr alone applied POST failed to control barnyardgrass and exhibited fairly low control of some other species but that tank-mixing it with bentazon improved control of some weeds. However, they suggested that imazamox has the potential to control weeds effectively applied alone as a POST treatment.

Aside from ringing endorsements of various imazethapyr tank mixes, very little information seems to exist on the effectiveness of available PRE or POST herbicide combinations in dry beans. However, at least six PRE herbicides and seven POST herbicides are available for dry bean in the United States (Sprague and Everman 2011), suggesting the need for additional research into which combinations are effective.

Table 1.1. Summary of studies examining row width and population in dry bean.

Author/Year	Location	Classes; Types	Widths (cm); Populations (thousand ha^{-1}) or within row densities	Results
Aidar et al. 2001	Tocantins, Brazil	Carioca; II, III	45, 60, 75; 7, 10, 13, and 16 plants m^{-1} of row	Yield optimized at 60-cm, 13 m^{-1}
Alford et al. 2004	Wyoming	Not specified; not specified	38, 56, 76; not specified	No impact of row width on yield
Arf et al. 1996	Mato Grosso do Sul, Brazil	'Ouro'; not specified	50, 60, and four split-row (20x80, 30x80, 20x70, 30x70); 8, 12, and 16 plants m^{-1} of row	No impact of row width on yield; increased yield with increasing within-row density
Blackshaw et al. 1999	Alberta	Navy; II/III	23, 46, 69; 240, 480	- Increased PAR interception with narrowing rows; incomplete canopy closure in 69-cm rows - Inconsistent increase in PAR interception at 480 ha^{-1} - Higher yields in 23- than in 69-cm rows but not always at 240 ha^{-1}; highest yields in 480 ha^{-1} - Most consistent yield increases in weedy plots - Hairy nightshade biomass reduced with narrowing rows, at 480 ha^{-1}

Table 1.1 (cont'd)

Blackshaw et al. 2000	Alberta	Small red; II	23, 69; 200, 500.	- PAR interception often higher in 23-cm, especially early; also higher in 500 ha^{-1} during much of the season - Yield optimized at 69-cm and 500 ha^{-1} - Weed control maximized at 23-cm and 500 ha^{-1}
Conner et al. 2006	Manitoba	Navy, pinto; II/III	30, 60; not specified	Higher yields in 30-cm in three of four site-years
Crothers and Westerman 1976	Idaho	Snap bean (I), Pinto (III), Small red (III)	Not specified; ranged from 107.6 to 969.7	-Increased yield with higher populations in determinate cultivars but not usually in indeterminate cultivars
Goulden 1976	Canterbury, New Zealand	Navy; I	20, 40; Within-row spacings of 4.8, 7.1, and 10.2 cm	Much higher yield in 20-cm than 40-cm; within 20-cm, yield higher in 4.8- and 7.1-cm within row spacings
Grafton et al. 1988	North Dakota	Navy, Pinto; I/II	25, 50, 75, 100; 99, 173, 247, 321	Increased yield with narrowing rows; increased yield with higher population in navy beans but not in pinto beans
Horn et al. 2000	Rio Grande do Sul, Brazil	'Pampa'; II	25, 50, 75; 100, 200, 350, 500	Yield increased with widening rows; no impact of population on yield
Malik et al. 1989, 1990, 1993	Ontario	Navy; I/II/III	23, 46, 69; 250, 375	- Generally Higher yields in 23- and 46-cm - Higher yield at 375 ha^{-1} in 23- or 46-cm rows - Weed biomass highest in 69-cm - Negative correlation between weed biomass and yield - Better weed suppression in indeterminate cultivars

Table 1.1 (cont'd)

Park 1993	Ontario	Not specified*; I/II	30 (500), 60 (333.3), 80 (266.7);	Increased yield with narrowing rows
Redden 1987	Queensland, Australia	Navy; II	8, 36, 71, 107; 112.5, 337.5	- Inconsistent canopy ground cover increase with narrowing rows; also sometimes greater ground cover at 337.5 ha^{-1} - Increased yield with narrowing rows in all but one site-year; often increased yield with increased population
Saindon et al. 1995	Alberta	Dark red kidney (I), navy (II), black (II), small red (III)	23; 250, 350, 500, 600	-Increased yield with increasing population in three of four years
Vieira et al. 2010	Minas Gerais, Brazil	Carioca; III	50; 4, 5, 7.5, 8, 15, and 16 plants m^{-1} of row	Increased canopy closure with higher within-row density
Welacky and Park 1987	Ontario	Navy; II	30 (412.4), 60 (275)	Higher yields in 60-cm
Xu and Pierce 1998	Michigan	Navy; not specified	56, 71; not stated	- Leaf area unaffected by row width - Yield higher in 56-cm
Ziviani et al. 2009	Goias, Brazil	Carioca; II/III	30, 40, 50, 60; 5, 10, 15, and 20 plants m^{-1} of row	- Canopy ground cover greater at 30- and 40-cm than at 50- and 60-cm; lower ground cover at 5 plants m^{-1} throughout the season and in 10 plants m^{-1} by mid-season - Yield optimized at 30- or 40-cm, 20 m^{-1}

Table 1.2. Summary of studies examining row width and population in crops other than dry bean.

Author/Year	Location	Crop	Widths (cm); Populations (thousand ha^{-1}) or within-row density	Results
Alford et al. 2004	Wyoming	Sugarbeet, Corn	38, 56, 76; not stated	Reached 95% light interception earlier in 38-cm than in 76-cm
Andrade et al. 2002	Buenos Aires, Argentina	Soybean	19, 30, 52, 57, 60,70; 150, 300, 350, 400, 450, 460, 520	Increased light interception and yield in narrow rows; light interception increases correlated with yield increases
Carpenter and Board 1997	Louisiana	Soybean	Not stated; 70, 164, 189, 234	- Yield reduced at 70 ha^{-1} - Pods per plant increased with decreasing population, largely on branches
Chandler et al. 2001	Ontario	Soybean	19/76 (twin row), 38, 76; 200	- Yield higher in 38-cm, twin row - Weed biomass lower in 38-cm
Cooper 1977	Illinois	Soybean	17, 50, 75; 188, 281, 375	Highest yields in 17-cm, 375 ha^{-1} combination

Table 1.2 (cont'd)

Dalley et al. 2004	Michigan	Soybean, Corn	Soy: 19, 38, 76; 422 Corn: 38, 76 77	- Soy: Much greater daily and peak light interception in 19- and 38-cm; yield sometimes greater in 19- than 38-cm - Corn: Higher early-season light interception in 38-cm
Ethredge et al. 1989	Georgia	Soybean	25, 51, 76; 260.2, 390.4, 520.4	- Increased yield with narrow rows - No yield differences between populations
Harder et al. 2007	Michigan	Soybean	19, 38, 76; 124, 190, 296, 445	- Greater LAI, earlier closure in 19- and 38-cm; greater LAI in 445 ha^{-1} than 124 or 190 ha^{-1} - Higher yields with narrowing rows; yield higher at 296 and 445 ha^{-1} - Decreased weed density and biomass with narrow rows after herbicide application; no impact of population on weeds - Weed biomass higher in 124 ha^{-1}, 38- or 76-cm

Table 1.2 (cont'd)

Kratochvil et al. 2004	Maryland	Soybean	19, 38; 259.35, 333.45, 345.8, 432.25, 444.6, 518.7, 555.75, 666.9	- Higher yields in 19-cm in five of six site-years - Yield lower in lowest two populations; occasionally higher in higher populations
Légère and Schreiber 1989	Indiana	Soybean	25, 76; 385.5	- Greater LAI in 26-cm through much of the season - Greater yield in 26-cm - Reduced percentage of pigweed in biomass and leaf area of plot in 76-cm
Lehman and Lambert 1960	Minnesota	Soybean	51, 102; 13, 26, 52, and 79 plants m^{-1} of row	Greater yield in 51-cm at one of two sites; no yield differences between within-row densities
Moore 1991	Louisiana	Soybean	97; 3/6, 26/19, 48/28 plants m^{-1} of row	Increased yield with equidistant within-row spacing
Nelson and Renner 1998	Michigan	Soybean	19 (358/371), 76 (508/469)	- Canopy closed 35 d sooner in 19-cm - Higher yields in 19-cm - Lower weed biomass following partial herbicide in 19-cm rows

Table 1.2 (cont'd)

Norris et al. 2002	Mississippi	Soybean	38, 76; 480	- Occasionally higher yields in 38-cm - Better suppression all weed species after herbicide in 38-cm
Norsworthy and Oliver 2001	Arkansas	Soybean	19; 185, 247, 371, 494, 618, 741, 865, 988, 1112, 1235,1359, 1482	- 0.022% increase in light interception per thousand plants ha^{-1}, but still 89% at 185 ha^{-1} - Little variation in yield across populations; 988 ha^{-1} optimum for yield
Norsworthy and Frederick 2002	South Carolina	Soybean	Drilled; 370, 620	No effect of population on yield
Peachey et al. 2006	Oregon	Snap bean	19, 38, 75, 114, 150; 445	- With fungicide, highest yield at 19-cm, all others similar - Without fungicide, lowest yields at 150-cm, highest at 38- or 75-cm, all other yields similar

Table 1.2 (cont'd)

Peters et al. 1965	Missouri	Soybean	20, 41, 51, 61, 81, 102 (not all in same trial); not stated	- Higher yields with narrowing rows - Less cultivation needed for adequate weed control with narrowing rows
Quakenbush and Andersen 1984	Minnesota	Soybean	18 (556), 76 (395)	95% PAR interception 3 wk earlier in 18-cm
Sankula et al. 2001	Delaware and Maryland	Lima bean	38, 76; 175, 350	Yield increase in 38-cm only in one of four site-years
Taylor 1980	Iowa	Soybean	25, 50, 75, 100; 160	- No LAI differences; earlier appearance of canopy closure with narrowing rows - Yield higher with narrowing rows in good growing conditions, not in drought
Teasdale and Frank 1983	Maryland	Snap bean	15, 25, 36, 46, 91; 430	- Increased canopy cover and decreased light penetration with narrowing rows. - Lower yield in 91-cm rows; otherwise similar across row widths - Weed biomass reduced in 15-, 25-, and 36-cm

Table 1.2 (cont'd)

Wahab et al. 1986	Saskatchewan	Snap bean	Row widths: 20 (1000), 40 (440), 80 (250), 125 (160) Square designs: 10 (1000), 15 (440), 20 (250), 25 (125) Triangle designs: 10 (1160), 15 (510), 20 (290), 25 (180)	- Increased yield with increasing equidistance. - Generally increased yield with decreasing between-plant spacing - Yield highest in triangle and square designs; one year triangle higher than square
Wax and Pendleton 1968	Illinois	Soybean	25, 51, 76, 102; not specified but decreased with increasing row width	- Increased yield with narrowing rows - Weed biomass decreased with narrowing rows
Weber et al. 1966	Iowa	Soybean	13, 25, 38, 51; 64.5, 129, 258, 516.5	- Increased LAI with narrowing rows and increasing population - Increased dry matter with increasing LAI, but decreased yield at very high dry matter
Wiggans 1939	New York	Soybean	20, 31, 41, 61, 81; Within-row spacings of 1.3, 2.5, 3.8, 5.1, 7.6, 10.2, and 15.2 cm	Increased yield with narrowing rows; slight yield increases with decreasing within-row spacings; large yield declines above 7.6 cm

Table 1.2 (cont'd)

Winter 1989	Texas	Sugarbeet	76, 102; 43, 86	Sugar quality highest in 76-cm
Yelverton and Coble 1991	North Carolina	Soybean	23, 46, 91; not stated	- Earlier and more complete PAR interception in 23- than in 91-cm - Lower weed density following herbicide in 23- than in 91-cm
Yonts and Smith 1997	Nebraska	Sugarbeet	35, 56, 76, 97; 25, 40, 65, 100, 150	Sugar yield highest in 35- and 56-cm
Young et al. 2001	Illinois	Soybean	19, 38, 76; 260, 321, 346, 420, 445, 457 (varied with row width and not all present in any site-year)	- Yield usually higher in narrower row widths; higher in one site-year at 76-cm - Suppression of several weeds enhanced following herbicide in narrow rows

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CHAPTER 2

EFFECTS OF ROW WIDTH AND PLANTING POPULATION ON CROP AND WEED DEVELOPMENT IN TYPE II VARIETIES OF BLACK BEAN AND SMALL RED BEAN

Abstract

The development of upright black and small red bean varieties gives dry bean growers the opportunity to plant in narrower rows, which has been associated with yield and weed control benefits in many crops. Field studies were conducted in 2010 and 2011 at two locations in Michigan to examine the effect of row width and population on canopy closure, weed suppression, pest management, and yield in two upright varieties, 'Zorro' black and 'Merlot' small red beans. Each variety was planted in 38- and 76-cm rows, as well as 51-cm rows at one location. Populations were 196500, 262000, and 327500 plants ha^{-1} in black bean and 148000, 196500, and 262000 plants ha^{-1} in small red bean. Canopy closure was assessed by repeatedly measuring light above and below the canopy. Emerging weeds were counted in set quadrats, and weed biomass was harvested and weighed at the end of the season. Dry bean plants were examined for disease and insect feeding during the season and for lodging and maturity shortly before harvest. Yield was obtained using direct harvest by combine. In many cases, narrow rows increased canopy closure, especially in the mid- to late-season, while population had little effect on canopy closure. Narrow rows decreased weed biomass in three of four years and occasionally decreased weed emergence; population had no effect on weed suppression. Row width and population had little effect on disease pressure. Narrow rows sometimes decreased insect feeding while population did not affect it. In some cases, narrow rows reduced lodging and increased maturity while population had little effect. Narrow rows increased yield in four of

eight site-years; population did not affect yield. Narrow rows generally improved canopy closure and thus improved weed control, yield, and other variables, while planting population had minimal effects on these variables.

Nomenclature: Dry bean, *Phaseolus vulgaris.*

Introduction

Quicker and more complete crop canopy development has beneficial effects, including increased crop yield and greater weed suppression (Andrade et al. 2002; Norsworthy and Oliver 2001; Peters et al. 1965). Narrowing row width increases canopy development in several crops, including dry bean (*Phaseolus vulgaris* L.) (Blackshaw et al. 1999; Blackshaw et al. 2000; Harder et al. 2007; Redden et al. 1987; Yelverton and Coble 2001). However, dry bean producers traditionally plant in 71- or 76-cm rows to allow for weed control and harvest preparation by inter-row cultivation (Blackshaw et al. 2000; Goulden 1976; Malik et al. 1993). Through the 1970s, most commercial dry bean varieties were prostrate and vining, known as Type III, or bushy with low branches and determinate growth, known as Type I (Adams 1995; Kelly et al. 2009; Schwartz et al. 2004). Type I and Type III dry bean varieties must be harvested using a two-pass system in which plants are first pulled and windrowed, then harvested and threshed with a specially equipped combine (Robertson and Frazier 1978; Schwartz et al. 2004). However, in the late twentieth century, breeding efforts produced commercially viable Type II dry bean varieties with an upright habit suitable for direct harvest by combine in one pass (Hosfield et al. 2004; Hosfield et al. 2005; Kelly 1994, 2001, 2010; Welacky and Park 1987). Compared with the windrow system, this method improves harvest efficiency and may reduce harvest losses (Kelly 2010; Robertson and Frazier 1978; Schwartz et al. 2004). It also eliminates the need for cultivation as a hilling method to prepare beans for harvest (Robertson and Frazier 1978; Schwartz et al. 2004). In fact, direct harvest precludes cultivation as a weed control method since it requires a level surface free of rocks and soil clods (Schwartz et al. 2004). This inability to cultivate may no longer be a serious problem in most dry bean production systems due to the availability of effective modern herbicides (Sprague and Everman 2011). If no cultivation is planned, growers have the option of growing dry beans in narrower rows than in the past (Blackshaw et al. 2000), which could lead to higher yields and better weed suppression. However, row width cannot be considered independent of planting population since changing row width while keeping population constant changes within-row plant spacing. In addition, planting at an unnecessarily high population is a cost that growers should avoid.

In soybean (*Glycine max* L.), a related crop with a similar growth habit to Type II dry beans, studies indicate that narrower row widths increase leaf area index (LAI) and photosynthetically active radiation (PAR) interception (Dalley et al. 2004; Harder et al. 2007; Weber et al. 1966), indicating an increase in canopy closure. While some studies show a canopy closure benefit at higher populations, others suggest that soybean is able to compensate over a wide range of populations (Harder et al. 2007; Norsworthy and Oliver 2001; Weber et al., 1966). Very little work has been published on canopy closure in dry bean; however, Blackshaw et al. (1999, 2000) studied PAR interception in Type II and Type III navy beans and Type II small red beans and concluded that interception was greater in narrow rows and, in some cases, at higher populations.

Increased light interception due to greater canopy closure should suppress weeds since this denies weeds below the canopy a critical resource. Malik et al. (1993) found that planting navy beans in 23- or 46-cm rows decreased weed biomass 15-21% compared with 69-cm rows, but that planting population had no impact. Blackshaw et al. (2000) evaluated weed control in small red beans at various row width and plant population combinations and found that weed control was optimized by narrow rows with high populations. Similar effects have been observed in soybean with regard to row width, including by Harder et al. (2007), who found an effect of row width but not population, Nelson and Renner (1998), whose observation of decreased weed biomass in narrow rows correlated with increased canopy closure, and Légère and Schreiber (1989), who observed decreases in both weed biomass and leaf area of redroot pigweed (*Amaranthus retroflexus* L.) in narrow rows.

Weed suppression could indirectly improve yield, but enhanced canopy development could also improve yield by increasing the amount of total light energy captured and utilized by the crop. Many studies exist in soybean showing increased yields in narrow rows, with population able to be varied within wide limits to achieve optimum yield (Harder et al. 2007; Légère and Schreiber 1989; Lehman and Lambert 1960; Norsworthy and Frederick 2002; Norsworthy and Oliver 2001; Young et al. 2001). However, Norsworthy and Oliver (2001) showed that populations can be so high that yield begins to be reduced. In dry bean, Park (1993) found that simultaneously increasing population and decreasing row width resulted in increasing yields in both Type I and Type II navy beans. Malik et al. (1993) reported that 23-cm rows resulted in yield increases in navy beans of all three types compared with 46-cm rows and 375,000 plants ha^{-1} resulting in higher yields than 225,000 plants ha^{-1}, but only in the presence of weeds. In Type II small red beans, Blackshaw et al. (2000) found a 19% yield advantage of 23-cm rows over 69-cm rows and a 17% yield advantage of 500,000 plants ha^{-1} over 200,000 plants ha^{-1}. Grafton et al. (1988) found that yield increased by 400-600 kg ha^{-1} for each 25-cm decrease in row width in Type III pinto bean and Type I navy bean; they also found that yield increased with increasing population in pinto beans, but not in navy beans.

A key reason for enhanced canopy development and its accompanying effects in narrow rows may be that narrowing row width typically results in an increasingly equidistant plant arrangement. As the distance between rows decreases, it becomes increasingly similar to the smaller distance between plants within the row, improving the ability of the crop canopy to fill in the inter-row space. Wahab et al. (1986) compared a variety of planting designs in snap bean (which is the same species as dry bean) that achieved different levels of equidistance. They found that yield was maximized with an equidistant planting design, presumably because this allows each plant to reach its full potential and minimizes gaps in the canopy. Andrade et al. (2002) suggested that part of the advantage of equidistance is found in the below-ground canopy of the roots; that is, equidistance may improve the efficiency with which water and nutrients are gathered by the roots, as well as the efficiency with which light is captured by the leaves.

Presumably, any positive effects of increasing population on canopy development and the benefits associated with it are due to the fact that dropping the population below some critical level will prevent the crop from producing enough leaves or roots to take advantage of the available resources. However, very high populations could result in intra-specific competition that causes excessive vegetative growth at the expense of seed yield (Bennett et al. 1977; Crothers and Westerman 1976).

Despite the apparent advantages of narrow rows and enhanced canopies, concern has been expressed that this would also provide an enhanced environment for disease development. Park (1993) found that under high disease pressure, white mold (*Sclerotinia sclerotiorum* (Lib.) de Bary) incidence was 34% greater in 30-cm rows than in 60-cm rows and 56% greater than in

80-cm rows, though in a year of lower white mold pressure, there were no significant differences. However, Park also found that white mold development was much lower in Type II than Type I navy beans, and despite higher white mold incidence, yield continued to increase with decreasing row width even in Type I beans. Saindon et al. (1995) and Park suggested that Type II beans are less susceptible to disease than other types due to better airflow in the canopy and fewer pods touching the ground. Saindon et al. found no effect of row width on white mold infection of Type II plants and much less severe infection on Type II plants than on Type III plants. Conner et al. (2006) found no impact of row width on the severity of anthracnose (*Colletotrichum lindemuthianum* (Sacc. & Magnus) Briosi & Cavara) in any navy or pinto bean type. In addition to disease pests, a key insect pest in dry bean is western bean cutworm, *Striacosta albicosta* (Smith), the larvae of which bore into developing bean pods and damage the seeds (Michel et al. 2010). There is no published research on the effect of dry bean row width or planting population on this insect, so there is a need for research to determine whether changing these variables can increase or decrease its severity.

Although new Type II varieties of black and small red bean are widely used and economically important in Michigan, there is a notable lack of research regarding the agronomic properties of these varieties. Most of what exists focuses on navy or pinto beans, and very little research here has been done on black beans or small red beans. In addition, most dry bean research has occurred in climates dissimilar to that of Michigan. Thus, the objectives of this study were to determine the effect of row width and planting population of Type II black and small red bean on 1) canopy closure, 2) weed biomass and emergence, 3) disease and insect damage, and 4) seed yield and gross margin.

Materials and Methods

Field studies were conducted in 2010 and 2011 at the Michigan State University Harry and Hazel Box Farm near East Lansing, Michigan and at the Michigan State University Saginaw Valley Research and Extension Center near Richville, Michigan. The soil at the East Lansing site was a Capac loam (fine-loamy, mixed, mesic, Aeric Ochraqualfs) with pH 6.6 and 4% organic matter in 2010 and pH 6.5 and 2.6% organic matter in 2011. The soil at the Richville site was a Tappan-Londo loam (fine-loamy, mixed, active, calcareous, mesic Typic Endoaquolls and fine-loamy, mixed, mesic, Aeric Glossaqualfs) with pH 7.8. Soil organic matter was 2.7% and 2.6% in 2010 and 2011, respectively. The crops prior to these studies were winter wheat (*Triticum aestivum* L.) at East Lansing and corn (*Zea mays* L.) at Richville. Field preparation consisted of either fall moldboard or chisel plow followed by one to two field cultivations in the spring. Prior to planting, 336 kg of 17-8-15 (N-P-K) fertilizer containing 1.5% manganese and 1.5% zinc was broadcast onto the soil surface and incorporated.

Two Type II (upright indeterminate vine) varieties, 'Zorro' black beans and 'Merlot' small red beans (Michigan Crop Improvement Association, Okemos, MI) were planted in 38- and 76-cm row widths at East Lansing on June 16, 2010 and June 8, 2011 and in 38-, 51-, and 76-cm row widths at Richville on June 10, 2010 and June 6, 2011. Beans were planted using a John Deere split-row planter (Deere and Company, Moline, IL) at East Lansing and two Monosem planters (Monosem Incorporated, Edwardsville, KS) at Richville. Planter settings were adjusted to attain three target populations for each variety-row width combination. Target populations were 196,500, 262,000, and 327,500 plants ha^{-1} for black beans and 148,000, 196,500, and 262,000 plants ha^{-1} for small red beans. Populations were held constant across row widths, leading to differences in within-row plant spacing for each population (Table 2.1). Each combination of row width and population was repeated with two weed control systems: a total postemergence (POST) herbicide treatment and a weed-free control. The POST treatment was applied at the V2 stage of dry bean and consisted of imazamox (Raptor, BASF Corporation, Research Triangle Park, NC) at 35 g ai ha^{-1} plus bentazon (Basagran, BASF Corporation, Research Triangle Park, NC) at 28 g ai ha^{-1} applied with 1% v/v of crop oil concentrate (Herbimax, Loveland Products Inc., Loveland, CO) and 2.8 kg ha^{-1} ammonium sulfate (Actamaster, Loveland Products Inc., Loveland, CO). The PRE treatment consisted of S-metolachlor (Dual II Magnum, Syngenta Corporation, Wilmington, DE) at 1.4 kg ai ha^{-1} plus halosulfuron (Permit, Gowan Company, Yuma, AZ) at 35 g ai ha^{-1} applied preemergence (PRE) within 24 h of planting followed by hand-weeding to maintain weed-free conditions. The POST treatment was used to assess the effect of row width and population on weed dynamics, while the weed-free treatment was used to assess the effect of row width and population on the crop, independent of weed competition. At East Lansing, clethodim (Select Max, Valent USA Corporation, Walnut Creek, CA) at 77 g ai ha^{-1} with crop oil concentrate at 1% v/v was also applied POST to all plots to relieve high grass (largely *Setaria* spp.) pressure. Herbicides were applied using a custom-built, tractor-mounted compressed-air sprayer calibrated to deliver 177 L ha^{-1} at 193 kPa using AirMix 11003 nozzles (Greenleaf Technologies, Covington, LA).

Precipitation data was obtained throughout the growing season from the Michigan Automated Weather Network (http://www.agweather.geo.msu.edu/mawn/, Michigan State University, East Lansing, MI), which maintains stations on the Michigan State University Horticulture Farm less than a mile from both field locations. In addition, automated humidity and temperature sensors (HOBO U23 Pro v2 Temperature/Relative Humidity Data Logger**,** Onset Computer Corporation, Pocasset, MA) were attached to stakes and placed beneath the canopy 8 cm above the ground in two replications of the 38- and 76-cm row widths at the high and low black bean populations. These sensors recorded readings at 1-hr intervals.

The experimental design was a randomized complete block with regard to variety, row width, and planting population. Each combination of these three factors was treated as a split plot with regard to weed control system. Each treatment was replicated four times. Plot width was 3 m, with seven, five, and four rows per plot for the 38-, 51-, and 76-cm row widths, respectively. Plot length ranged from 9.1 to 10.7 m, depending on location. After the crop fully emerged, stand counts were taken in two 3-m sections of row in each plot to determine actual emerged plant populations.

Dry bean populations. In many cases, actual early-season stand counts fell short of (or, less commonly, exceeded) the target populations (Table 2.2). However, within each row width at each site, the highest target population had the highest stand count and the lowest population in the lowest stand count. In fifty-four of the sixty site-year-class-width-population combinations, stand count was similar enough to target population to essentially maintain the proper relationship of populations among treatments; in six cases stand count was dramatically lower than target planting population, although still higher than the next lowest population within the row width. Four of these six cases occurred at Richville in 2010 and may have been the result of poor emergence in dry soil (Table 2.3). The small number of interactions between population and row width suggests that the effect of most of these variations from target population had limited impact on the results of the studies.

Crop canopy development. Measurements of canopy light interception were taken in all weed-free plots at 1-2 wk intervals from approximately 3 wk after planting (WAP) through canopy senescence. Light measurements were taken from three locations in each plot above and below the canopy using a SunScan Probe (SunScan Canopy Analysis System, Dynamax Inc., Houston, TX), a 1- x 0.013-m wand containing 64 light sensors, connected to a hand-held computer (Recon, Trimble Navigation Limited, Sunnyvale, CA). The wand was placed perpendicular to the rows above and below the canopy of the center rows. The percentage of light intercepted by the canopy was calculated by dividing the below-canopy photosynthetically active radiation (PAR) by the above-canopy PAR and averaging the three measurements from each plot. Measurements were taken around solar noon in full or nearly full sun, or under uniformly overcast conditions.

Weed emergence and biomass. Two 0.25-m^2 quadrats were established in each POST-treated plot after the herbicide application controlled most of the early-emerging weeds. These quadrats were cleared of any surviving weeds, and newly emerging weeds were counted and recorded two to three times during the growing season. Prior to harvest, above-ground weed biomass in each POST-treated plot was harvested and dry weight was recorded.

In addition to counts of emerging weeds, weed biomass samples were taken shortly before harvest. Depending on weed population, area for the biomass samples ranged from four 0.25-m^2 subsamples to a swath 1 m wide running the entire length of the plot. The species of harvested weeds was noted. The predominant weeds at Richville were common lambsquarters (*Chenopodium album* L.) and pigweed (*Amaranthus spp.*). The predominant weeds at East

Lansing were common lambsquarters, pigweed, velvetleaf (*Abutilon theophrasti* Medik.), and common ragweed (*Ambrosia artemisiifolia* L.)

Insect monitoring and feeding. Western bean cutworm (WBC) populations were monitored using milk jug pheromone traps at each location. Moths trapped were counted and removed at least once weekly, and the number caught was reported to Michigan State University entomologists maintaining a statewide trap network, which allowed the monitoring of regional WBC populations. At the R5-R6 stages of bean development, two 1-m sections of the outside rows were randomly sampled for WBC damage in all POST-treated plots. The total number of pods and number of pods with apparent WBC damage were noted in order to calculate the percentage of pods with WBC damage.

Disease monitoring. Each year, all studies were repeatedly examined for white mold (*Sclerotinia sclerotiorum (*Lib.) de Bary) infection, but no white mold infection was observed in any site-year. However, at East Lansing in both years and at Richville in 2011, a pod spot fungus (*Alternaria alternata* (Fr.) Keissl. (1912)) was noted on bean pods prior to harvest. *Alternaria* was evaluated visually on a 0-100% scale in weed-free plots and by randomly sampling 50 pods from the border rows of each of the POST-treated plots. Pods were evaluated individually on a scale of 0-3: “0” represented virtually no infection, “1” infection on less than half of the pod surface, “2” infection over the majority of the pod surface, and “3” infection of the entire pod surface or infection that resulted in significant deformation. Average pod infection was then calculated for each plot.

Maturity, lodging, and yield. At East Lansing only, bean plants failed to senesce evenly, and many plots contained green plants at harvest. Immediately before harvest, all plots were visually evaluated for maturity on a scale of 0-100 with "0" representing no observable yellowing and "100" representing all plants fully senesced. At East Lansing in 2011, maturity was also evaluated about a month before harvest.

Immediately prior to harvest, all plots were visually evaluated for lodging. The evaluation system was a 0-5 scale in which "0" indicated no lodging, and "5" indicated that all plants were prostrate. A preharvest desiccation treatment of glyphosate (Roundup PowerMax, Monsanto Company, Saint Louis, MO) at 0.84 kg ae/ha was applied to all plots at both locations in 2011. Dry bean plots were direct harvested with a small plot combine (Massey-Ferguson 8XP, AGCO, Duluth, GA) with a 1.5-m header. The center two, three, and five rows were harvested in the 76-, 51-, and 38-cm row width plots, respectively. Dry bean yield was adjusted to 18% moisture. Harvest dates were September 6 at Richville and September 29 at East Lansing in 2010 and October 6 at Richville and October 18 at East Lansing in 2011.

Economic analysis. Gross margins were calculated at grower-received prices of \$0.66, \$0.88, and \$1.10 kg^{-1} for black beans and \$0.66, \$0.99, and \$1.21 kg^{-1} for small red beans paired with dealer seed prices of \$0.77 and \$1.25 kg^{-1} for black beans and \$0.77 and \$1.43 kg^{-1} for small red beans (USDA-AMS 2011). The low and high prices were approximately the lowest and highest prices occurring in Michigan during the last five years, while the middle grower-received prices were those currently being contracted by Michigan growers (Varner 2012 pers. corr.). Gross margin was calculated using the formula:

$$Gross\ margin = (Y \times P_{grower}) - ((SR*P_{dealer}) + P_{herbicide})$$

Where Y was yield, P_{grower} was the bean price received by growers, SR was the seeding rate, P_{dealer} was the seed price paid by growers, and $P_{herbicide}$ was the cost of the POST herbicide treatment (Local herbicide prices 2011). Costs other than seed and weed control were not considered. There is no cost associated with changing row widths unless a new planter is purchased in order to plant at the desired row width.

Statistical analysis. Data were subjected to ANOVA using PROC MIXED in SAS 9.2 (SAS Institute Inc., Cary, NC), and treatment means were compared using Fisher's protected LSD at the $\alpha \leq 0.05$ level of significance. Some data were log or square root transformed for analysis, but all data are presented untransformed. Data were combined over population, row width, and herbicide when no significant interactions were present. Data could not be combined across years due to significant interactions in almost all cases. A regression analysis relating yield to observed final dry bean population was performed in SigmaPlot 12 (Systat Software Inc., Chicago, IL), but no model with a significance level above R^2=0.06 could be generated.

Results and Discussion

Growing conditions. Rainfall from June through September in 2010 was lower than the 30-yr average at both locations (Table 2.3). At East Lansing, above-average rainfall in June and near-average rainfall in July and September allowed dry bean plants to develop normally despite a dry August. At Richville, rainfall was well below average in every month, and much of the June rainfall came prior to planting; by the beginning of September, most bean plants had senesced, rendering September rainfall irrelevant. Only 11 cm of rain fell at Richville between planting and harvest, resulting in stunted crop plants and little weed growth.

In 2011, rainfall from June through September was slightly above the 30-yr average at East Lansing, while at Richville it was once again below the 30-yr average. At East Lansing, rainfall was slightly to moderately below average in three months, but in late July a single weather system brought 16 cm of rain over a three-day period, making that month's total dramatically above average and supplying ample water for pod formation, especially with moderate rainfall continuing through September. At Richville, rainfall was again below average in every month, but all rainfall in June occurred after planting, and monthly totals were higher than those of the previous year in July and August. Rainfall was sufficient for normal plant development, and pod filling continued into September.

Crop canopy development. Dry bean canopy development progressed similarly in three of the four site-years; at Richville in 2010 under drought conditions (Table 2.3), canopy development was slower and was less complete at its peak. In 2010, canopy closure (as measured by percent interception of photosynthetically active radiation) was generally greater in small red bean than in black bean at every measurement time at both sites. In 2011, canopy closure at East Lansing was greater in small red bean from 3-6 weeks after plantings (WAP), while at Richville, canopy closure was greater in small red bean from 3-4 WAP and again from 9-12 WAP.

Row width effects on canopy development. In seven of eight site-year-class combinations, narrow rows improved canopy closure during a portion of the growing season; the sole exception occurred at Richville in 2010 in black bean.

At East Lansing in 2010, black bean canopy closure was much greater in 38-cm rows than in 76-cm rows from 5 to 10 WAP, with difference ranging from 9 to 21 percentage points (Figure 1). Peak canopy closure occurred 8 WAP in 38-cm rows at 94%, while in 76-cm rows, canopy closure peaked a week later at 77%. At East Lansing in 2011, 76-cm rows actually provided a canopy closure advantage at 6 WAP; however, from 8-12 WAP, canopy closure was again greater in 38-cm rows than in 76-cm rows (Figure 2a). Peak canopy closure was 96% in 38-cm rows and only 92% in 76-cm rows. At Richville in 2011, black bean canopy closure showed no clear trend with regard to row width from 3-9 WAP; however, from 10-11 WAP, canopy closure was greater in 38- or 51-cm rows than in 76-cm rows by 5-9%, and at 12 WAP, closure in 38-cm rows was still greater than in 76-cm rows (Figure 3a). Canopy closure peaked at 83% in 38-cm rows, 80% in 51-cm rows, and 75% in 76-cm rows.

Differences in small red bean canopy closure between 38- and 76-cm rows were generally not as great as the differences between wide and narrow rows for black beans. However, at East Lansing in 2010, canopy closure was significantly greater in 38-cm rows than in 76-cm rows at 5, 6, and 10 WAP (Figure 4a). At East Lansing in 2011, canopy closure was greater in 38-cm rows than in 76-cm rows by 1-3% from 8-12 WAP, although this difference was only significant at 10 WAP (Figure 5a). At Richville in 2011, canopy closure at 5 WAP was greater in 76-cm rows than in either 38- and 51-cm rows; however, at 9 WAP, canopy closure was greater in 38-cm rows than in 51- or 76-cm rows, and at 10 and 12 WAP, canopy closure was still greater in 38-cm rows than in 76-cm rows (Figure 6a).

At Richville in 2010, black bean canopy closure was higher in 38-cm rows than in 51- or 76-cm rows at 3 WAP; however, after 4 WAP, canopy closure was not different between 38-cm rows and other row widths (Figure 7a). Peak canopy closure was only 60%. In small red bean, the effect of row width on canopy closure showed no clear trend at any time during the growing season, and canopy closure peaked between 65 and 70% (Figure 8a).

Early in the growing season when canopy closure was less than 50% and plants were in the vegetative or early flowering stages, canopy closure was sometimes erratic and was occasionally greater in wide rows, possibly due to the closer within-row spacing at a given population in wide rows. However, except under serious drought conditions (at Richville in 2010), canopy closure was improved by narrow rows as canopy closure exceeded 50% in mid- to late-season, which corresponds to full flowering and pod filling; this is likely the time when dry beans can benefit the most from increased light interception. This agrees with the results of Blackshaw et al. (1999) and Ziviani et al. (2009) who found that canopy closure in navy and carioca bean increased with decreasing row width. However, Blackshaw et al. (2000) reported earlier development of the small red bean canopy in narrow rows, while these studies found most of the canopy closure benefit to occur in mid- to late-season. Peak canopy closure was higher in narrow rows in three site-year-class combinations. The effect of greater canopy closure in narrow rows tended to be more pronounced in black beans than in small red beans, probably due to the larger size of individual small red bean plants.

Planting population effects on canopy development. The effect of planting population on canopy closure was less pronounced than that of row width. In seven of the eight site-year-class combinations, the high population resulted in greater canopy closure than the low and/or medium populations in at least one circumstance, but these effects were rarely large, and were never consistent across a large portion of the growing season.

At East Lansing in 2010, there was a population interaction with row width with regard to black bean canopy closure, with the effect of population differing between 38- and 76-cm rows. In 38-cm rows, canopy closure was greater at 327,500 seeds ha^{-1} than at 196,500 seeds ha^{-1} at 6 WAP (Figure 9a). However, in 76-cm rows, canopy closure was greater at 196,500 seeds ha^{-1}

than at 327,500 seeds ha^{-1} at 6 WAP, and from 9-10 WAP, canopy closure at both 196,500 and 262,000 seeds ha^{-1} was greater than at 327,500 seeds ha^{-1} (Figure 9b). At East Lansing in 2011, planting population had little effect on black bean canopy closure, with the 195,500 and 262,000 seeds ha^{-1} populations occasionally lagging slightly behind the 327,500 seeds ha^{-1} population (Figure 2b). At Richville in 2010, black bean canopy closure at 3 and 7 WAP was greater at 327,500 seeds ha^{-1} than at 196,500 seeds ha^{-1} (Figure 7b). No other differences were observed. At Richville in 2011, black bean canopy closure at 3 WAP was greater at 327,500 seeds ha^{-1} than at 262,000 seeds ha^{-1}, after which population did not affect canopy closure (Figure 3b).

In small red bean, canopy closure tended to lag at the lowest population of 148,000 seeds ha^{-1}. At East Lansing in 2010, this population lagged behind canopy closure of the 196,500 and 262,000 seeds ha^{-1} planting populations from 5-6 WAP; differences ranged from 13-18% (Figure 4b). At East Lansing in 2011, canopy closure at 148,000 seeds ha^{-1} was lower than at the two higher populations at 3, 4, and 6 WAP (Figure 5b). At Richville in 2010, closure at 148,000 seeds ha^{-1} lagged behind 262,000 seeds ha^{-1} only at 3 WAP (Figure 8b). At Richville in 2011, closure at 148,000 seeds ha^{-1} was lower than at 262,000 seeds ha^{-1} only at 3-4 WAP (Figure 6b).

Canopy closure tended to increase with increasing population when there was an effect of population, but this effect occurred mainly in the early season and was neither consistent nor clearly of practical significance. The low population in small red beans (148,000 seeds ha^{-1})

lagged in canopy closure enough to be of some concern; otherwise, dry beans had the ability to compensate for a wide range of populations, intercepting more light per plant at lower populations. Although Blackshaw et al. (2000), reported an in light interception at high small red bean population, this may be due to that study's use of a much higher population range, with their high population being 500,000 seeds ha^{-1}.

Weed suppression. Weed pressure was greater at both sites in 2011 than in 2010, with aboveground weed biomass in the weediest treatments being over 400 kg ha^{-1} at both sites compared with 123 kg ha^{-1} at East Lansing in 2010 and only 78 kg ha^{-1} at Richville in 2010. At East Lansing in 2010, black bean plots had about 3.5 times more weed biomass than small red bean plots, but class did not have a significant effect on weed biomass at Richville or in 2011.

Weed biomass. In six of the eight class-site-year combinations, narrow rows reduced weed biomass, with both exceptions being at Richville in 2010 (Table 2.4).

At East Lansing in 2010, weed suppression in black beans was greatly enhanced in narrow rows; weed biomass was 81% lower in 38-cm rows than in 76-cm rows. Weed suppression in small red beans was also strongly enhanced in narrow rows, being reduced by 75% in 38-cm rows compared with 76-cm rows. These results corresponded with increases in canopy closure in 38-cm rows during much of the growing season. At East Lansing in 2011, weed suppression in black beans was again enhanced by narrow rows; in 38-cm rows, weed biomass was 61% lower than in 76-cm rows. Again, this corresponded to greater canopy closure in 38-cm rows over much of the growing season. In small red beans, there was a row width interaction with planting population with regard to weed biomass (Table 2.5). Weed biomass differences at 148,000 and 196,500 seeds ha^{-1} were non-significant, but at 262,000 seeds ha^{-1}, weed biomass was 81% lower in 38-cm rows than in 76-cm rows. This corresponded to a small increase in canopy closure in narrow rows.

At Richville in 2011, the effect of row width on weed biomass in black beans was non-significant at a significance level of $\alpha \leq 0.05$; however, this seems to have been largely due to excessive variance, and at a significance level of $\alpha \leq 0.1$, weed suppression improved with narrowing rows. Weed biomass averaged 430 kg ha^{-1} in 76-cm rows, which was significantly greater than the 181 kg ha^{-1} in 38-cm rows, with 51-cm rows intermediate at 302 kg ha^{-1} (Table 2.4). This corresponded with the late season improvement in canopy closure with narrower rows. In small red bean, 38-cm rows improved weed suppression relative to both 51-cm and 76-cm rows by 76% and 71%, respectively. This corresponded to the late-season canopy closure advantage in 38-cm rows over 76-cm rows and the early- to mid- season lag in canopy closure in 51-cm rows.

At Richville in 2010, row width had no effect on weed biomass in either class. This corresponded to the presence of only small and erratic early-season differences in canopy closure (Table 2.4).

Although planting population impacted canopy closure at some measurement dates, planting population did not affect weed biomass in any site-year-class combination (Table 2.6). This was similar to the findings of Malik et al. (1993) that dry bean population did not alter weed biomass. Blackshaw et al. (1999, 2000) found that weed biomass was reduced at high dry bean populations, but their higher populations were much higher than the high populations used in these studies.

Weed emergence. Weeds that emerged following the postemergence (POST) herbicide application tended to stay small and suppressed beneath the crop canopy for the duration of the growing season, so it seems unlikely that these weeds significantly affected yield. As such, weed biomass is a more relevant measure of the actual weed control benefit derived from optimum row width than weed emergence. However, late-emerging weeds could still produce seed late in the year after crop removal.

At East Lansing in 2010, weed emergence following the POST application was very low, consisted largely of annual grass, and virtually ended by early July. At Richville in 2010, no more than two emerging weeds were observed in any plot at any counting time. Neither row width nor planting population significantly impacted weed emergence at either site in 2010.

At East Lansing in 2011, weed emergence was much higher, and when surviving weeds that had emerged since the POST application were counted in September, narrow rows reduced either overall weed emergence or survival of emerged weeds in black beans. In 76-cm rows, there were 346,000 recently emerged weeds ha^{-1}, while in 38-cm rows, there were only 48,000 recently emerged weeds ha^{-1}. This was consistent with the increase in canopy closure observed over much of the season in 38-cm rows. Row width did not significantly affect weed emergence in small red bean.

At Richville in 2011, weed emergence was again low but was much higher than in 2010. Across both classes, 76-cm rows reduced weed emergence compared with 51-cm rows with 38-cm rows intermediate. Weed emergence averaged 68,000 weeds ha^{-1} in 51-cm rows compared with 31,000 weeds ha^{-1} in 76-cm rows and 46,000 weeds ha^{-1} in 38-cm rows. This is consistent with the early season advantage of 76-cm rows and disadvantage in 51-cm rows observed in this study rather than with the late-season canopy closure that apparently affected overall weed biomass.

Planting population was never found to affect weed emergence in any site-year-class combination.

Summary. Narrow rows enhance the crop's ability to suppress weeds under normal conditions by improving canopy closure. The increased mid- to late-season canopy closure often observed in narrow rows would be expected to result in increased weed suppression, and this did occur; weed biomass was lower in narrow rows in every case when narrow rows resulted in increased canopy closure. The exception occurred when narrow rows did not result in an increase in mid- to late-season canopy closure due to drought. Weed emergence following the POST application was less influenced by row width than was weed biomass, but when it was influenced, it appeared to respond to early- to mid-season canopy closure enhancement. Although planting population had sporadic impacts on canopy closure, these impacts were too small to significantly affect weed suppression; in no case did planting population have any significant impact on weed biomass or emergence.

Disease development and humidity.

White mold. The chief disease on which concern has focused with regard to narrow rows in dry beans is white mold; frequent scouting was undertaken for this disease during every site-year, but none was ever observed.

Alternaria infection. However, in three of the four site-years, *Alternaria* pod spot infection occurred; infection levels were similar in all three of these site-years. Virtually no infection was observed at Richville in 2010, presumably due to inadequate moisture for disease development, so disease was not evaluated for this site-year. In every site-year in which *Alternaria* was evaluated, infection was much more severe in small red beans than in black beans, with average disease scores (on a 0-4 scale) ranging from 1.2-1.6 in black beans and 2.0-2.4 in small red beans and average disease ratings (on a 0-100% scale) ranging from 28-39% in black beans and 70-75% in small red beans. While most *Alternaria* infection occurred on the surface of the pods, moderately to severely infected pods often contained shrunken or aborted beans, and some beans in severely infected pods showed visible signs of infection, so *Alternaria* did appear to be having at least a small impact on yield and on bean quality.

Although *Alternaria* development began late in the season as pods began to fill, at which time canopy closure tended to be more complete in narrow rows, *Alternaria* infection was not exacerbated by narrow rows in any site-year. Planting population also did not have a large or consistent effect on *Alternaria* severity.

Humidity. Because white mold and some other diseases benefit from moist conditions in the canopy, an increase in humidity within the canopy in a given treatment may indicate a potential disease risk in that treatment even if no disease exacerbation was observed in these studies. In the early season prior to extensive canopy development and very late season after the beginning of senescence, there was very little difference between the treatments, so average humidity during the period of significant canopy development was used to determine whether there were differences between treatments. Average humidity was similar at East Lansing in 2010 (85%) and at Richville in 2011(89%); it was higher at East Lansing in 2011 (94%) and much lower at Richville in 2010 (75%). In two of the four site-years, humidity was lower in wide rows at high populations than in narrow rows or than in wide rows with low population (Table 2.7).

At East Lansing in both 2010 and 2011, average humidity between July 25 and September 1 was 6-9 percentage points less in 76-cm rows at 327,000 seeds ha^{-1} than at other treatments. At Richville in both 2010 and 2011, humidity did not differ among row widths or populations.

These data suggest that narrow rows may have the potential to increase humidity compared with wide rows, but the reason wide-row humidity was only lower at high population is not obvious, and the increase in humidity in narrow rows was inconsistent between sites. However, the possibility that these 6-9% increases in average humidity in narrow rows may sometimes be biologically significant, potentially creating a disease-enhancing environment, cannot be ruled out. In fact, an increase in humidity may be the underlying reason for the higher levels of white mold observed in narrow rows by Park (1993) and Peachey et al. (2006). According to Hagedorn and Inglis (1986), *Alternaria alternata* may also cause a destructive leaf spot disease in dry beans in cool, wet conditions; it is possible that if this occurs, narrow rows could increase disease development, but no such increase was observed for *Alternaria* as a pod rot. It was somewhat surprising not to observe higher humidity at higher populations, especially in light of the finding of Saindon et al. (1995) and Vieira et al (2010) that white mold infection increases with plant density.

Insect feeding. One insect pest affecting dry bean in Michigan is western bean cutworm. Number of male WBC moths trapped varied by site and year. At East Lansing in 2010, 421 moths were caught in the two traps; similarly 412 moths were caught in 2011. At Richville, trap catch was 226 and 118 moths in 2010 and 2011 respectively. Peak WBC flight occurred during the week of July 18 in 2010; it occurred a week later in 2011 during the week of July 24. Bean leaf beetle (*Cerotoma trifurcata* Forster) was also present, but the presence of boring in pods was considered diagnostic of western bean cutworm. Due to the superficial nature of bean leaf beetle feeding on pods, only suspected western bean cutworm feeding was evaluated. Suspected western bean cutworm (WBC) feeding varied between site-years. In 2010, 2.5% of pods at East Lansing were damaged by WBC, while at Richville 1.5% of pods were damaged. In 2011, 3.3% of pods at East Lansing were damaged by WBC, while at Richville, feeding was higher than at other site-years but differed by class, with 5.2% of black bean pods being damaged compared with 8.2% of small red bean pods. In four of eight site-year-class combinations, WBC feeding was reduced in narrow rows within at least one population (see Table 2.8 for main effect and Tables 2.9 and 2.10 for interactions). Planting population had no significant main effect on WBC feeding in any site-year (Table 2.11).

At East Lansing in 2010, there was an interaction between row width and planting population with regard to WBC damage in black bean (Table 2.9) at 327,500 seeds ha^{-1}, WBC damage was higher in 76-cm rows than in 38-cm rows, while row width was non-significant at lower populations. There was also an interaction with regard to WBC damage in black bean at Richville in 2011 (Table 2.10); within 196,500 and 262,000 seeds ha^{-1}, WBC damage was greater in 76-cm rows than in 38-cm rows with 51-cm rows intermediate; at 327,000 seeds ha^{-1}, row width was not significant. In 38-cm rows, WBC damage was higher at 327,000 seeds ha^{-1} than at either of the lower populations; in the other row widths, planting populations had no effect.

At East Lansing in 2011, WBC damage was greater in 76-cm rows than in 38-cm rows across both classes and all populations. In 76-cm rows, 4.2% of pods were damaged while in 38-cm rows, only 2.4% were damaged.

At Richville in 2010, WBC feeding was very low, and neither row width nor population had a significant effect on WBC damage in either class. Except at East Lansing in 2011, neither row width nor planting population affected WBC feeding in small red bean.

In every site-year except Richville in 2010, which experienced low insect pressure, narrow rows reduced WBC damage in black bean in at least some populations, and this effect also occurred in one site-year in small red bean; narrow rows never increased WBC damage. In each case of reduced WBC damage, canopy closure was increased in narrow rows during at least part of the WBC active period from mid-July to mid-August. Moreover, in wide rows, there was typically a gap between rows for much, if not all, of the WBC active period whereas the gap was smaller or non-existent in narrow rows. If WBC moths prefer a more open canopy for easier flight or typically enter the canopy from the side rather from above, this may explain the apparent reduction of WBC damage in narrow rows. The effect may be less pronounced in small red beans because of their more sprawling growth habit and less distinct rows. It is also possible that those plots that demonstrated reduced WBC feeding had higher below-canopy humidity, which could encourage the development of fungal pathogens that infect WBC larvae (Sprague et al. 2010). The effect of planting population was erratic and conflicting, and the reason for the observed effects is not clear. This appears to be the first study that has related row width and planting population to insect damage in dry bean.

Lodging. Lodging was always at least 80% greater in small red bean than in black bean in every site-year based on a 0-5 scale. In four of the eight site-year-class combinations, narrow rows reduced lodging (Table 2.12) while planting population had very little effect on lodging (Table 2.13).

At East Lansing in 2010, neither row width nor population significantly affected lodging in either class. At Richville in 2010, almost no lodging was observed in black bean, and treatments did not significantly differ; however, in small red bean, 38-cm rows reduced lodging compared with both 51-cm and 76-cm rows. Planting population never affected lodging in 2010.

At East Lansing in 2011, row width again did not have a significant effect on lodging in black bean. In small red bean, lodging was again lower in 38-cm rows than in 76-cm rows, averaging 3.25 in 38-cm rows and 4.2 in 76-cm rows. Planting population did not significantly impact lodging in either class. At Richville in 2011, black bean lodging was reduced in both 38- and 51-cm rows compared with 76-cm rows. Planting population did not affect lodging. In small red bean, lodging was also reduced in both 38- and 51-cm rows compared with 76-cm rows. Lodging was also reduced at medium population compared with low population, with medium population intermediate; this was the only significant effect of population on lodging.

In half of the site-year-class combinations, 38-cm rows reduced lodging compared with 76-cm rows, and in half of the cases that included 51-cm rows, these also reduced lodging compared with 76-cm rows; one of the exceptions to both effects was a case in which virtually no lodging was observed, and 76-cm rows never produced an advantage with regard to lodging. Significant differences ranged from 0.41 to 0.95 on the 0-5 scale. This advantage of narrow rows with regard to lodging may be attributed to the mutual support of intertwining rows, which presumably prevents individual plants from leaning into the inter-row space. It confirms the observation of Horn et al. (2000) that lodging increases with increasing row width. Planting population had no clear effect on lodging, with lodging being minimized at medium population in the one case in which a significant effect was detected.

Maturity. At East Lansing, but not at Richville, beans failed to mature at an even rate across the field. In 2010, maturity was rated once 1 wk prior to harvest; in 2011, it was rated twice, 7 wk and 2 wk prior to harvest. Black beans generally matured more quickly than small red beans. In three of four site-classes, plants growing in narrow rows were more mature shortly before harvest in at least one herbicide treatment, while 7 wk before harvest, plants growing in wide rows were more mature in both classes (Table 2.14). Neither planting population (Table 2.15) nor herbicide treatment affected maturity.

At East Lansing in 2010, black bean maturity 1 wk prior to harvest was greater in 38-cm rows than in 76-cm rows. In small red bean, treatments did not significantly differ from one another.

In 2011, black bean maturity 2 wk prior to harvest was again greater in 38-cm rows than in 76-cm rows. In small red bean in the weed-free treatments only, average maturity was greater in 38-cm rows than in 76-cm rows (Table 2.16). At 7 wk prior to harvest in 2011, maturity in both classes was greater in 76-cm rows than in 38-cm rows.

As dry beans began to mature, maturation was initially more rapid in 76-cm rows, but as physiological maturity approached, maturation became more rapid in 38-cm rows, to the point that 38-cm treatments caught up to or passed 76-cm treatments in maturity.

Dry bean yield. Crop yield was similar at East Lansing in 2010 and Richville in 2011, both of which were moderately dry site-years. At East Lansing in 2010, black bean yield averaged 3003 kg ha^{-1}, while small red bean yield averaged 2519 kg ha^{-1}. At Richville in 2011, black bean yield averaged 2893 kg ha^{-1} while small red bean yield averaged 2461 kg ha^{-1}. At East Lansing in 2011, abundant rainfall led to higher yields, with black bean averaging 4198 kg ha^{-1} and small red bean averaging 3080 kg ha^{-1}. In all three of these site-years, black bean yield was significantly higher than small red bean yield. At Richville in 2010, dry conditions led to extremely low yields that were similar between classes: 1694 kg ha^{-1} in black bean and 1683 kg ha^{-1} in small red bean. Herbicide treatment did not interact with row width or planting population, so yields were combined across herbicide treatments.

In four of the eight site-year-class combinations, yield was higher in narrow rows than in wide rows (Table 2.17). At East Lansing in 2010 and 2011, black bean yield was 17% and 15% higher in 38-cm rows than in 76-cm rows. Small red bean yield was also 18% higher in 38-cm rows than in 76-cm rows in 2011. In each of these cases, the increase in yield corresponded with both a mid- to late-season increase in canopy closure and an overall decrease in weed pressure in 38-cm rows. At East Lansing in 2011, in both classes, yield was 7-11% higher in weed-free treatments than in POST treatments. At Richville in 2011, small red bean yield was 11% higher in 38-cm rows and 9% higher in 51-cm rows than in 76-cm rows. In 38-cm rows, canopy closure was significantly greater than in 76-cm rows during late-season, and canopy closure in 51-cm rows was often not statistically different from that in 38-cm rows. However, 51-cm rows never resulted in a clear advantage in canopy closure over 76-cm rows, and 38-cm rows reduced weed biomass relative to both 51- and 76-cm rows, so the reason for the increase in yield in 51-cm rows compared with 76-cm rows is obscure; it may be that the canopy closure advantages in 51-cm rows compared with 76-cm rows are real even if non-significant or that the advantage was due to more efficient development of the root system.

At East Lansing in 2010, small red bean yield was not different between treatments despite a significant increase in mid- to late-season canopy closure in 38-cm rows (Tables 2.17, 18). At Richville in 2011, black bean yield also was not affected by row width or population despite a late season canopy closure advantage in 38-cm rows and several other narrow row advantages. However, this may have been due to the erratic differences in canopy closure observed in the early- to mid-season.

At Richville in 2010, black bean yield was marginally higher ($\alpha \leq 0.1$) in 76-cm rows than in 51-cm or 38-cm rows, while in small red bean, yield was higher in 38- and 76-cm rows than in 51-cm rows at medium population in weed-free treatments only. Black bean yield was also 9% higher in POST than in weed-free across all row widths and populations. Small red bean yield was 12% higher at 196,500 seeds ha^{-1} than at 262,500 seeds ha^{-1} across all combinations of row width and herbicide. These unusual results were presumably the result of drought-induced randomness in which yield was determined more by small differences in soil moisture than by the factors studied.

Planting population never had a significant overall effect on yield in black bean (Table 2.18). In small red bean at Richville in 2010 under drought conditions, small red bean yield was higher at medium population than at high populations, while at East Lansing in 2011, yield was higher at high population than at low population. In the other two site-years, planting population did not affect small red bean yield.

In four of the eight site-year-class combinations, yield was higher in 38-cm rows than in 76-cm rows (Table 2.17). In the only one of these four combinations that included 51-cm rows, yield was higher in 51-cm rows than in 76-cm rows. Two of the four exceptions occurred at Richville in 2010 when drought resulted in low yields and seemingly arbitrary differences between treatments. In all but one of these cases (the yield increase in 51-cm rows), the yield advantage of narrow rows is readily explained by advantages in canopy closure in narrow rows, possibly augmented by other observed benefits of narrow rows such as weed suppression and reduced insect feeding. It is also possible that some of the yield benefit of narrow rows resulted from undocumented improvements in root system efficiency. In no site-year-class combination did wide rows increase yield at the $\alpha \leq 0.05$ level, and only in one class at Richville in 2010 did wide rows have any positive effect on yield. This trend toward higher yield in narrow rows confirms the findings of Blackshaw et al. (1999, 2000), Redden (1987), and Malik et al. (1993) that yield is often, though not always, higher in narrow rows; Grafton et al. (1988) and Goulden (1976) found even more consistent yield advantages in narrow rows.

Only under drought conditions at Richville in 2010 did population affect yield, and this effect was not consistent between classes or row widths. This contrasted with the findings of Blackshaw et al. (1999, 2000) that increasing population increases yield; however, Blackshaw et al. much higher population ranges and used irrigation. Other studies (Malik et al. 1993, Goulden 1976, Redden et al. 1987) reported a more sporadic positive effect of increased population. However, planting population had virtually no effect on yield in these studies.

In one site-year, weed-free yield was higher than POST yield in both classes, which was likely the result of reduced weed competition; only in one class at Richville in 2010 did POST treatments have higher yields than weed-free treatments.

Economic Returns. In each of the four site-year-class combinations in which yield increased in 38-cm rows and in the one case in which yield increased in 51-cm rows compared with 76-cm rows, economic return also increased (Table 2.19). Under drought conditions at Richville in 2010 in small red beans, high population (262,000 seeds ha^{-1}) reduced economic returns compared with the 196,500 or 148,000 seeds ha^{-1} planting populations (Table 2.20); in this case, the high population also reduced yield compared with the low population. Otherwise, planting population did not significantly affect economic returns (Table 2.21). Neither seed price paid by the grower (the dealer price) nor bean price received by the grower (the grower price) affected which differences were significant within the range of prices that occurred from September 2007 to February 2012. Dealer prices ranged from \$0.77-\$1.25 kg^{-1} in black bean and \$0.77-1.43 kg^{-1} in small red bean. Grower prices ranged from \$0.66-1.10 kg^{-1} in black bean and from \$0.66-\$1.21 kg^{-1} in small red bean (USDA-AMS 2011).

Conclusions. At Richville in 2010, drought conditions were so extreme that virtually every data set behaved differently than those from most or all of the other site-years. If this site-year is discounted, narrow rows provided an advantage in the majority of site-year-class combinations analyzed in six different variables: canopy closure, weed biomass, western bean cutworm feeding, lodging, pre-harvest maturity, and yield. Weed density and emergence were only rarely affected by row width, but when they were affected, narrow rows again provided an advantage. Narrow rows appear to provide significant advantages under favorable environmental conditions. The only variable in which wide rows offered a possible advantage was humidity; within the high population, humidity was higher in narrow rows in half of the site-years observed, and high humidity could be conducive to disease development. However, no increase in disease development was observed in narrow rows.

Since two of the four site-year-class combinations in which 51-cm rows were observed were at Richville in 2010, it is difficult to draw conclusions about whether 51-cm rows function more similarly to 38-cm rows or 76-cm rows, or are intermediate. With regard to yield, 51-cm rows appear to provide the same advantages as 38-cm rows. No clear conclusions could be drawn regarding the effect of 51-cm rows on lodging. With regard to canopy closure, 51-cm rows varied from intermediate between 38-cm and 76-cm rows to similar to 38-cm rows, to lower than either row width in the early season. With regard to weed suppression, 51-cm rows were either intermediate between 38- and 76-cm rows or resulted in equally poor weed suppression as 76-cm rows.

Planting population had virtually no effect on any variable except canopy closure, in which high and medium populations occasionally resulted in higher canopy closure than low populations, especially in small red beans.

Because 38-cm rows clearly confer advantages with regard to canopy closure, weed suppression, lodging, and yield in many cases with few disadvantages relative to 76-cm rows, and because the effect of 51-cm rows is less consistent, 38-cm rows appears to be the optimum row width among those studied for Type II black and small red bean. Since planting at the high population confers little or no advantage over the medium population, and the low populations sometimes resulted in a lag in canopy closure, the medium populations should be the target populations for growers of Type II black and small red beans regardless of row width.

Table 2.1. Target within-row plant spacings for Type II black and small red beans planted in three row widths and at three planting populations.

	Target black bean population ha^{-1}			Target small red bean population ha^{-1}		
Row width	196,500	262,000	327,500	148,000	196,500	262,000
		cm			cm	
38 cm	13	10	8	18	13	10
51 cm	10	8	6	13	10	8
76 cm	7	5	4	9	7	5

Table 2.2. Early season stand counts in 38- and 76-cm rows at East Lansing and 38-, 51-, and 76-cm rows at Richville compared with target planting populations.

	East Lansing				Richville					
Target planting	2010		2011		2010			2011		
Populations (seeds ha^{-1})	38 cm	76 cm	38 cm	76 cm	38 cm	51 cm	76 cm	38-cm	51-cm	76-cm
Black beans	plants ha^{-1}				plants ha^{-1}					
196,500	197,500	175,500	187,500	168,000	174,000	163,000	165,500	183,000	183,000	131,000*
262,000	252,000	246,000	222,500	226,000	226,000	210,000	196,500*	233,500	246,000	218,500
327,500	313,500	305,000	286,500	263,000	327,500	274,000	253,000*	295,000	300,000	228,500*
Small red beans										
148,000	149,500	162,000	141,000	139,500	141,000	131,000	138,500	142,000	148,000	135,000
196,500	211,000	207,500	175,500	173,000	187,500	148,000*	179,000	175,500	186,500	165,500
262,000	289,000	267,000	246,000	236,000	233,500	153,000*	222,000	238,500	221,000	205,000

* Stand count was at or below the next lowest target population.

Table 2.3. Monthly and 30-yr average precipitation at the Harry and Hazel Box Farm in East Lansing, MI and the Saginaw Valley Research and Extension Center in Richville, MI in 2010 and 2011[a].

	East Lansing			Richville		
Month	2010	2011	30-yr avg.	2010	2011	30-yr avg.[c]
	cm			cm		
June	10.6 (4.1)[b]	4.4	8.4	6.9 (2.8)[b]	3.8	9.3
July	6.4	17.8	8.2	2.3	3.4	7.6
August	3.4	6.4	8.3	3.2	7.6	8.0
September	9.2	6.7	9.3	2.9[d]	5.8	10.7
Total	29.6	35.3	34.2	15.3	20.6	35.6

[a] Michigan Automated Weather Network, http://www.agweather.geo.msu.edu/mawn/, Michigan State University, East Lansing, MI

[b] Precipitation data in parentheses is from the time of planting.

[c] 30-yr average for Caro, MI; none was available for Richville

[d] Does not include September rainfall after harvest

Table 2.4. Main effect of row width on weed biomass in black and small red bean plots at East Lansing and Richville in 2010 and 2011[a].

	East Lansing			Richville			
	2010		2011	2010		2011	
Row width	Black	Small red	Black	Black	Small red	Black	Small red
	kg ha^{-1}						
38 cm	24 b	9 b	174 b	102 a	33 a	181 b	111 b
51 cm	-	-	-	50 a	56 a	302 ab	470 a
76 cm	130 a	36 a	422 a	57 a	21 a	430 a	385 a
Mean	77	22	298	70	37	304	322

[a] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq 0.05$ level of significance.

Table 2.5. Interaction of row width and planting population with regard to weed biomass in small red bean at East Lansing in 2011[a].

	Planting population (plants ha^{-1})		
Row width	148,000	196,000	262,000
		kg ha^{-1}	
38 cm	344 ab	406 ab	107 b
76 cm	397 ab	308 ab	562 a

[a] Means throughout the table that have the same lower-case letter are statistically similar to one another at the $\alpha \leq 0.05$ level of significance.

Table 2.6. Main effect of planting population on weed biomass in black and small red bean plots at East Lansing and Richville in 2010 and 2011[a].

	East Lansing			Richville			
Planting	2010		2011	2010		2011	
population[b]	Black	Small red	Black	Black	Small red	Black	Small red
				kg ha^{-1}			
Low	62 a	27 a	378 a	49 a	29 a	235 a	423 a
Medium	75 a	23 a	213 a	55 a	42 a	218 a	355 a
High	93 a	35 a	347 a	104 a	39 a	324 a	188 a

[a] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq$ 0.05 level of significance.
[b] In black bean, Low = 196,500 seeds ha^{-1}, Medium = 262,000 seeds ha^{-1}, and High = 327,500 seeds ha^{-1}; in small red bean, Low = 148,000 seeds ha^{-1}, Medium = 196,500 seeds ha^{-1}, and High = 262,000 seeds ha^{-1}.

Table 2.7. Effects of row width and planting population on average humidity under the black bean canopy during the period in which the canopy was well-developed at East Lansing and Richville in 2010 and 2011[a].

		East Lansing		Richville	
Planting population (seeds ha^{-1})	Row width	2010	2011	2010	2011
		------------------------ humidity (%) ------------------------			
196,500	76 cm	85.3 a	94.8 a	74.5 a	86.9 a
196,500	38 cm	85.7 a	95.1 a	74.8 a	88.3 a
327,500	76 cm	79.3 b	89.1 b	74.3 a	88.7 a
327,500	38 cm	87.9 a	96.0 a	75.2 a	87.2 a

[a] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq$ 0.05 level of significance.

Table 2.8. Main effect of row width on western bean cutworm damage in black and small red bean in at East Lansing and Richville in 2010 and 2011[a].

	East Lansing		Richville	
Row width	2010 (Small red only)	2011 (Both classes)	2010 (Both classes)	2011 (Small red only)[b]
	—— % of pods damaged ——			
38 cm	2.3 a	2.4 b	2.4 a	4.5 b
51 cm	-	-	1.4 a	5.1 ab
76 cm	2.7 a	4.2 a	1.7 a	6.0 b

[a] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq$ 0.05 level of significance.
[b] Significance level of $\alpha \leq 0.1$

Table 2.9. Interaction of row width and population with regard to western bean cutworm damage in black bean at East Lansing in 2010[a].

	Planting population (seeds ha^{-1})		
Row width	196,500	262,000	327,500
	% of pods damaged		
38 cm	3.9 ab	1.4 bc	0.1 c
76 cm	1.1 bc	2.7 abc	5.9 a

[a] Means throughout the table that have the same lower-case letter are statistically similar to one another at the $\alpha \leq 0.05$ level of significance.

Table 2.10. Interaction of row width and planting population with regard to western bean cutworm damage in black bean at Richville in 2011[a].

	Planting population (seeds ha^{-1})		
Row width	196,500	262,000	327,500
	% of pods damaged		
38 cm	3.6 c	3.6 c	6.4 ab
51 cm	4.4 bc	5.2 abc	5.7 ab
76 cm	6.4 ab	6.7 a	4.9 abc

[a] Means throughout the table that have the same lower-case letter are statistically similar to one another at the $\alpha \leq 0.05$ level of significance.

Table 2.11. Main effect of planting population on western bean cutworm damage by planting population in black and small red bean at East Lansing and Richville in 2010 and 2011[a].

	East Lansing		Richville	
Planting population[b]	2010 (Small red only)	2011 (Both classes)	2010 (Both classes)	2011 (Small red only)
	% of pods damaged			
Low	3.6 a	3.0 a	1.7 a	4.8 a
Medium	1.7 a	3.7 a	2.4 a	5.2 a
High	2.2 a	3.0 a	1.4 a	5.7 a

[a] Means within each column that have the same letter are statistically similar to one another at the $\alpha \leq 0.05$ level of significance.
[b] In black bean, Low = 196,500 seeds ha^{-1}, Medium = 262,000 seeds ha^{-1}, and High = 327,500 seeds ha^{-1}; in small red bean, Low = 148,000 seeds ha^{-1}, Medium = 196,500 seeds ha^{-1}, and High = 262,000 seeds ha^{-1}.

Table 2.12. Main effect of row width on lodging in black and small red bean at East Lansing and Richville in 2010 and 2011[a].

	East Lansing				Richville			
	2010		2011		2010		2011	
Row width	Black	Small red	Black	Small red	Black	Small red	Black	Small red
	0-5 scale							
38 cm	0.38 a	3.92 a	2.12 a	3.25 b	0 a	0.62 b	1.83 b	2.83 b
51 cm	-	-	-	-	0 a	1.17 a	1.83 b	2.96 b
76 cm	0.71 a	4.00 a	1.77 a	4.21 a	0.21 a	1.29 a	2.5 a	3.44 a
Mean	0.54	3.96	1.94	3.73	0.07	1.03	2.05	3.08

[a] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq 0.05$ level of significance.

Table 2.13. Main effect of planting population on lodging in black and small red bean at East Lansing and Richville in 2010 and 2011[a].

	East Lansing				Richville			
	2010		2011		2010		2011	
Population[b]	Black	Small red	Black	Small red	Black	Small red	Black	Small red
	0-5 scale							
Low	0.56 a	3.75 a	1.97 a	4.0 a	0 a	1.00 a	1.81 a	3.25 a
Medium	0.56 a	3.94 a	1.81 a	3.62 a	0 a	1.08 a	1.94 a	3.04 ab
High	0.50 a	4.19 a	2.06 a	3.56 a	0.21 a	1.00 a	2.42 a	2.93 b

[a] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq 0.05$ level of significance.

[b] In black bean, Low = 196,500 seeds ha^{-1}, Medium = 262,000 seeds ha^{-1}, and High = 327,500 seeds ha^{-1}; in small red bean, Low = 148,000 seeds ha^{-1}, Medium = 196,500 seeds ha^{-1}, and High = 262,000 seeds ha^{-1}.

Table 2.14. Main effect of row width on maturity in black and small red bean at East Lansing in 2010 and 2011[a].

	2010		2011		
	Late-season rating		Mid-season rating		Late-season rating
Row width	Black	Small red	Black	Small red	Black
	%				
38 cm	88.0 a	78.5 a	30.1 b	16.6 b	92.0 a
76 cm	72.2 b	75.8 a	46.9 a	22.5 a	81.6 b
Mean	80.1	77.2	38.5	19.6	86.8

[a] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq$ 0.05 level of significance.

Table 2.15. Main effect of planting population on maturity in black and small red bean at East Lansing in 2010 and 2011[a].

	2010		2011		
	Late-season rating		Mid-season rating		Late-season rating
Planting populations[b]	Black	Small red	Black	Small red	Black
	%				
Low	79.2 a	73.1 a	41.1 a	20.4 a	88.4 a
Medium	81.7 a	79.1 a	38.5 a	19.3 a	86.4 a
High	79.4 a	79.3 a	35.9 a	19.6 a	85.6 a

[a] Means within each column that have the same letter are statistically similar to one another at the $\alpha \leq 0.05$ level of significance.
[b] In black bean, Low = 196,500 seeds ha^{-1}, Medium = 262,000 seeds ha^{-1}, and High = 327,500 seeds ha^{-1}; in small red bean, Low = 148,000 seeds ha^{-1}, Medium = 196,500 seeds ha^{-1}, and High = 262,000 seeds ha^{-1}.

Table 2.16. Interaction of row width and planting population with regard to late-season maturity in small red bean at East Lansing in 2011[a].

	Planting population (seeds ha^{-1})		
Row width	148,000	196,500	262,000
	%		
38 cm	60.2 ab	57.8 ab	64.5 a
76 cm	59.4 ab	55.2 ab	50.9 b

[a] Means throughout the table that have the same lower-case letter are statistically similar to one another at the $\alpha \leq 0.05$ level of significance.

Table 2.17. Main effect of row width on yield of black bean and small red bean at East Lansing and Richville in 2010 and 2011[a].

	East Lansing				Richville			
	2010		2011		2010		2011	
Row width	Black	Small red	Black	Small red	Black[b]	Small red	Black	Small red
	kg ha^{-1}							
38 cm	3257 a	2553 a	4494 a	3329 a	1488 b	1612 a	3040 a	2592 a
51 cm	-	-	-	-	1553 b	1674 a	2924 a	2550 a
76 cm	2785 b	2486 a	3903 b	2830 b	1814 a	1797 a	2896 a	2339 b
Mean	3021	2520	4198	3080	1618	1694	2953	2494

[a] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq$ 0.05 level of significance unless otherwise noted.
[b] Significance level of $\alpha \leq 0.1$

Table 2.18. Main effect of planting population on yield of black and small red bean at East Lansing and Richville in 2010 and 2011[a].

	East Lansing				Richville			
	2010		2011		2010		2011	
Planting population[a]	Black	Small red	Black	Small red[b]	Black	Small red	Black	Small red
	kg ha^{-1}							
Low	3020 a	2425 a	4232 a	2958 b	1674 a	1694 ab	2915 a	2427 a
Medium	3138 a	2554 a	4103 a	3059 ab	1656 a	1774 a	2984 a	2523 a
High	2902 a	2577 a	4258 a	3222 a	1751 a	1582 b	2956 a	2619 a

[a] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq$ 0.05 level of significance unless otherwise noted.
[b] Significance level of $\alpha \leq 0.1$

Table 2.19. Main effect of row width on economic return of black and small red bean at East Lansing and Richville in 2010 and 2011[a].

	East Lansing				Richville		
	2010		2011		2010		2011
Row width	Black	Small red	Black	Small red	Black[c]	Small red	Black
	\$ ha^{-1} [b]						
38 cm	1110 a	626 a	1552 a	1278 a	526 a	643 a	1015 a
51 cm	-	-	-	-	546 ab	592 a	971 a
76 cm	941 b	609 a	1341 b	1079 b	591 b	615 a	960 a
Mean	1026	618	1446	1178	554	617	982

[a] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq$ 0.05 level of significance unless otherwise noted.
[b] Assumes black bean dealer price of \$1.25 kg^{-1} and grower price of \$0.88 kg^{-1}, small red bean dealer price of \$1.43 kg^{-1} and grower price of \$0.99 kg^{-1} (USDA-AMS 2011, Varner 2012) and June 2011 herbicide prices for POST treatment (Local herbicide prices 2011)
[c] Significance level of $\alpha \leq 0.1$

Table 2.20. Interaction of row width and planting population with regard to economic return in small red bean at Richville in 2011[a].

	Planting population (seeds ha^{-1})		
Row width	148,000 seeds ha^{-1}	196,500 seeds ha^{-1}	262,000 seeds ha^{-1}
	$ ha^{-1}[b]		
38 cm	940 abcd	1007 ab	1003 abc
51 cm	901 cd	982 abcd	1014 a
76 cm	910 bcd	782 e	888 de

[a] Means throughout the table that have the same lower-case letter are statistically similar to one another at the $\alpha \leq 0.05$ level of significance.
[b] Assumes small red bean dealer price of \$1.43 kg^{-1} and grower price of \$0.99 kg^{-1} (USDA-AMS 2011, Varner 2012) and June 2011 herbicide prices for POST treatment (Local herbicide prices 2011)

Table 2.21. Main effect of planting population on economic return of black and small red bean at East Lansing and Richville in 2010 and 2011[a, b].

	East Lansing				Richville		
	2010		2011		2010		2011
Planting population[b]	Black	Small red	Black	Small red	Black	Small red	Black
	$ ha^{-1}[c]						
Low	1030 a	599 a	1463 a	1137 a	553 a	630 a	967 a
Medium	1067 a	628 a	1413 a	1171 a	541 a	656 a	998 a
High	979 a	625 a	1463 a	1228 a	569 a	564 a	980 a

[a] Means within each column that the same letter are statistically similar to one another one another at the $\alpha \leq 0.05$ level of significance.
[b] In black bean, Low = 196,500 seeds ha^{-1}, Medium = 262,000 seeds ha^{-1}, and High = 327,500 seeds ha^{-1}; in small red bean, Low = 148,000 seeds ha^{-1}, Medium = 196,500 seeds ha^{-1}, and High = 262,000 seeds ha^{-1}.
[c] Assumes black bean dealer price of \$1.25 kg^{-1} and grower price of \$0.88 kg^{-1}, small red bean dealer price of \$1.43 kg^{-1} and grower price of \$0.99 kg^{-1} (USDA-AMS 2011, Varner 2012) and June 2011 herbicide prices for POST treatment (Local herbicide prices 2011)

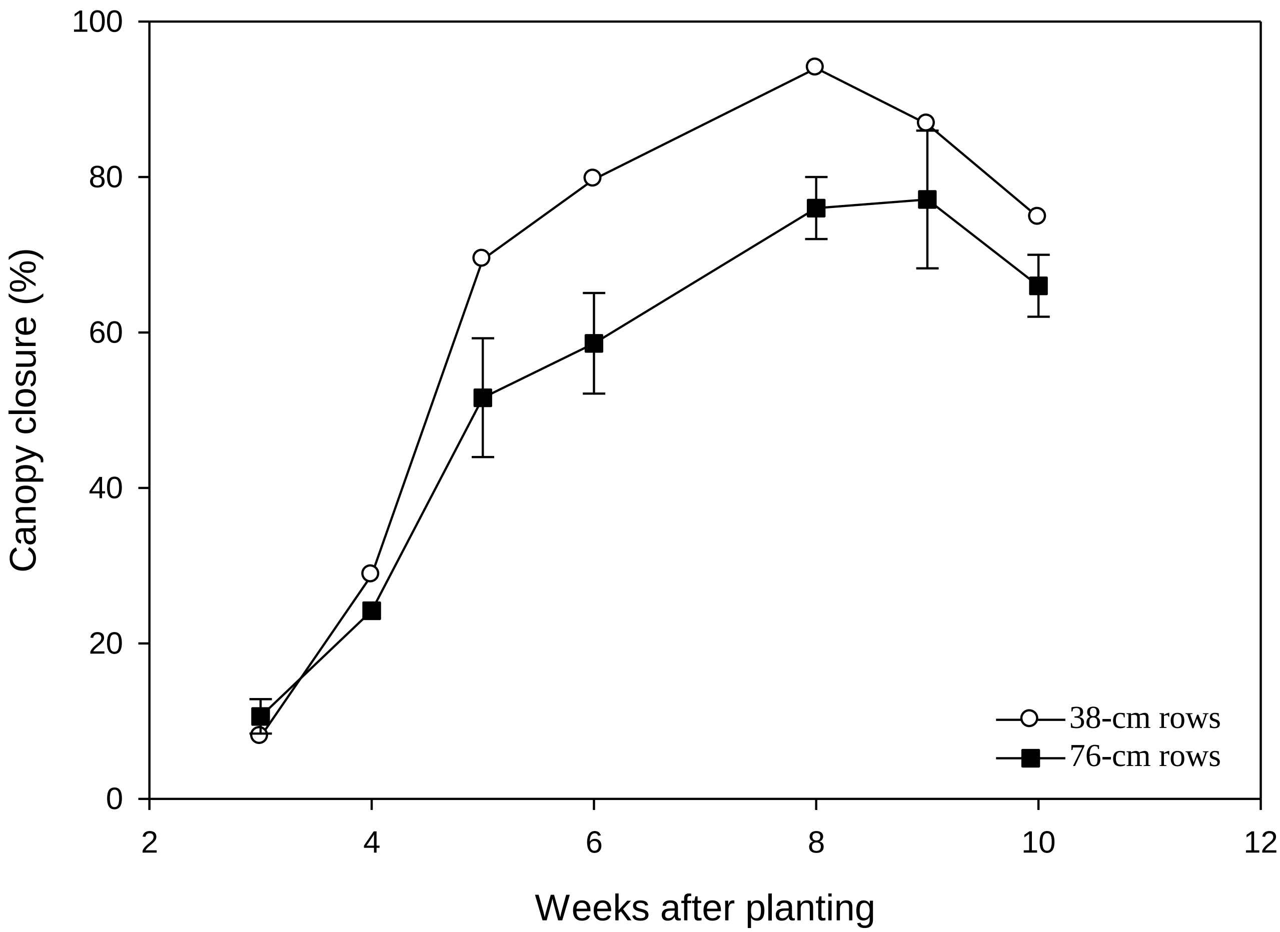

Figure 1. Main effect of row width on canopy closure for black beans planted at East Lansing, MI in 2010. Vertical bars represent Fisher's protected LSD at the $\alpha \leq 0.05$ level of significance.

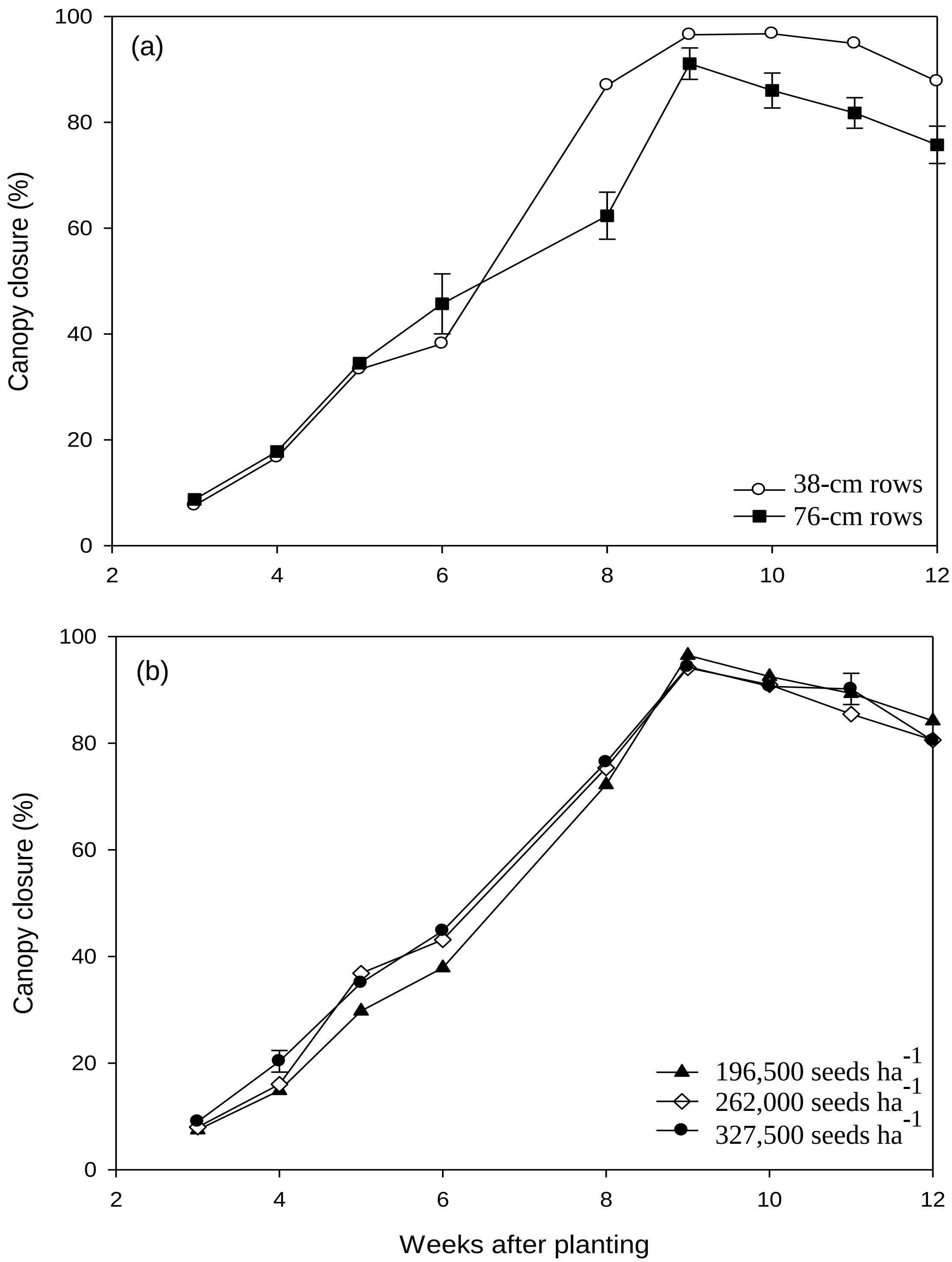

Figure 2. Main effects of (a) row width and (b) planting population on canopy closure for black beans at East Lansing, MI in 2011. Vertical bars represent Fisher's protected LSD at the $\alpha \leq 0.05$ level of significance.

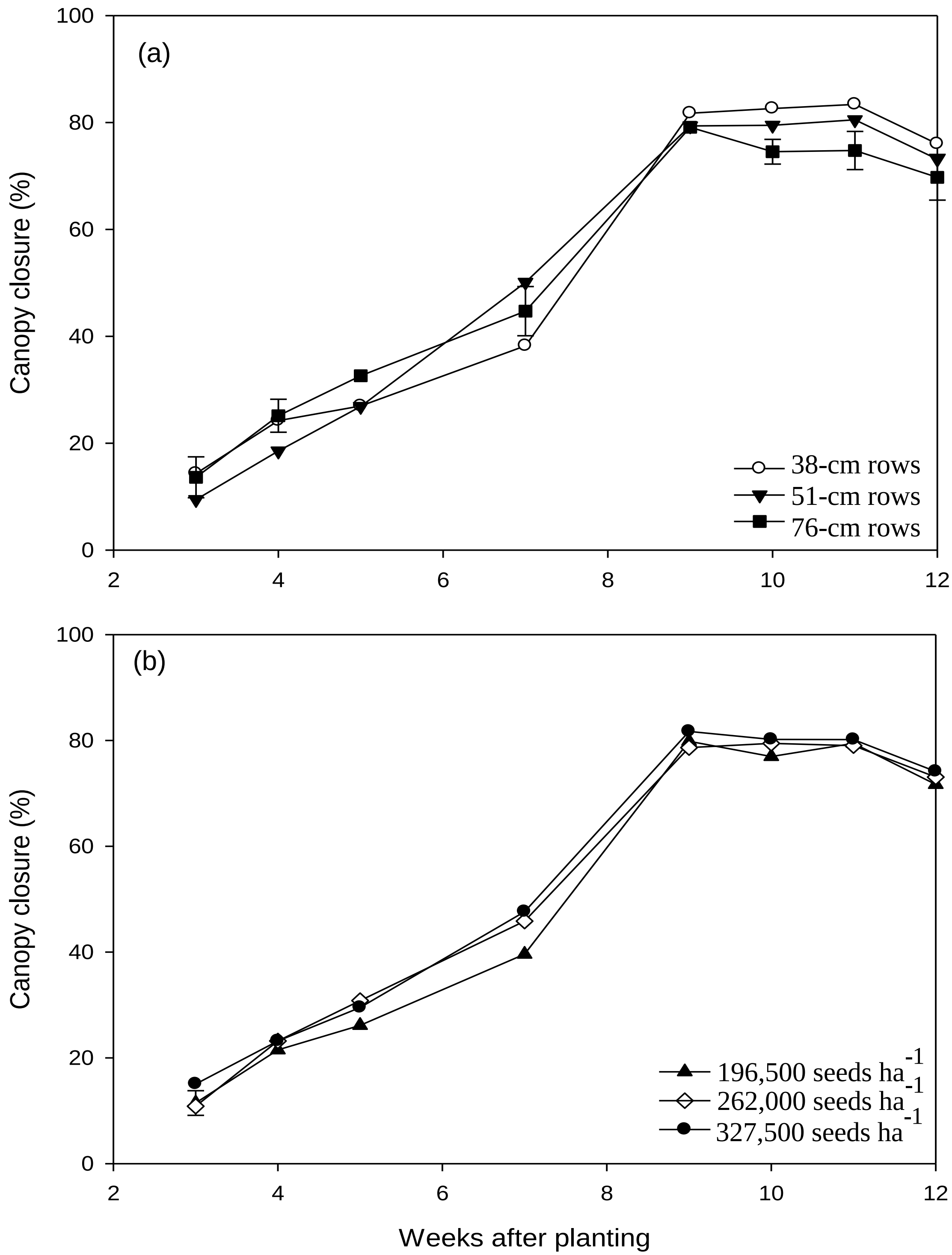

Figure 3. Main effects of (a) row width and (b) planting population on canopy closure for black beans at Richville, MI in 2011. Vertical bars represent Fisher's protected LSD at the $\alpha \leq 0.05$ level of significance.

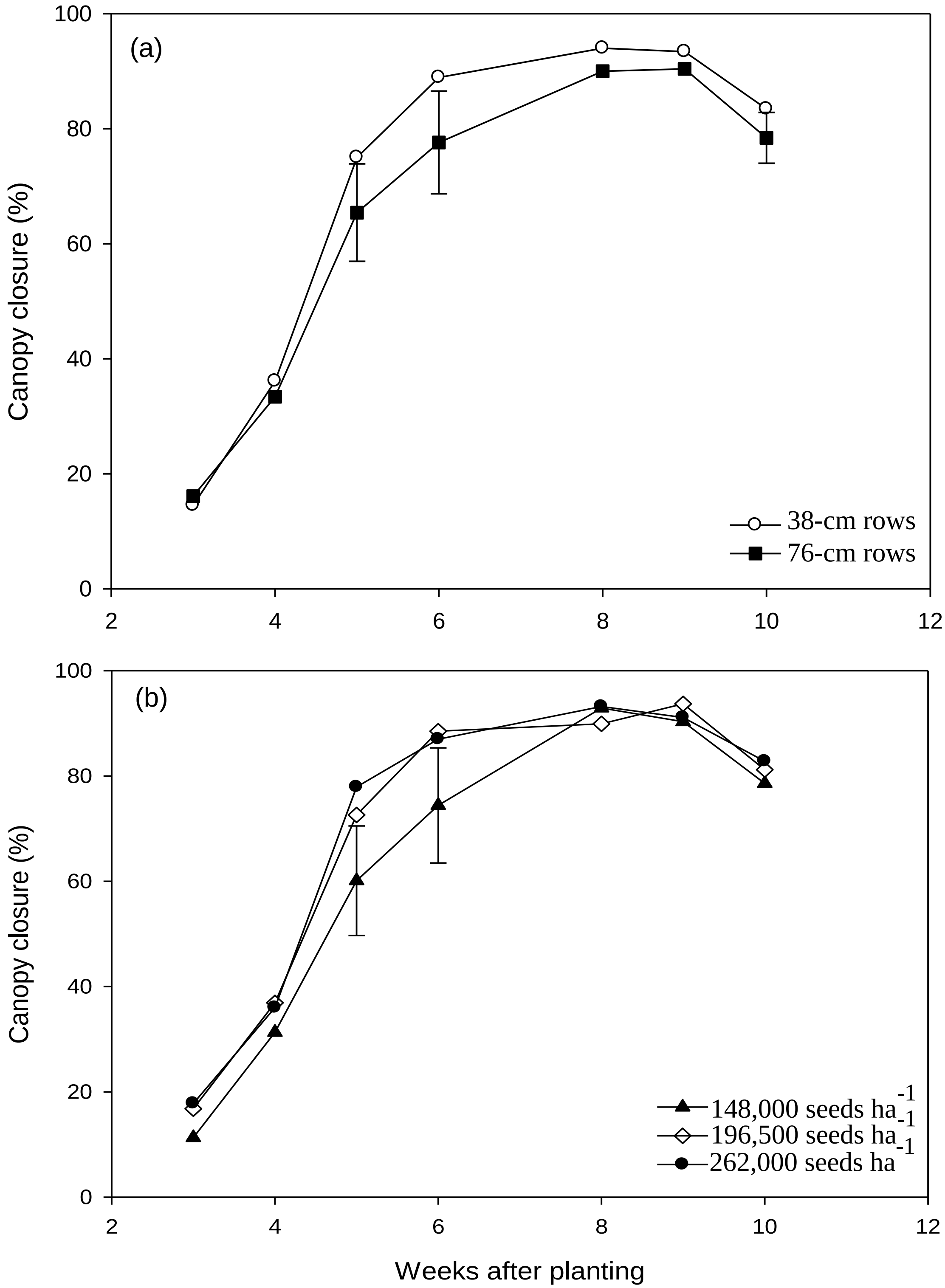

Figure 4. Main effects of (a) row width and (b) planting population on canopy closure for small red beans at East Lansing, MI in 2010. Vertical bars represent Fisher's protected LSD at the $\alpha \leq 0.05$ level of significance.

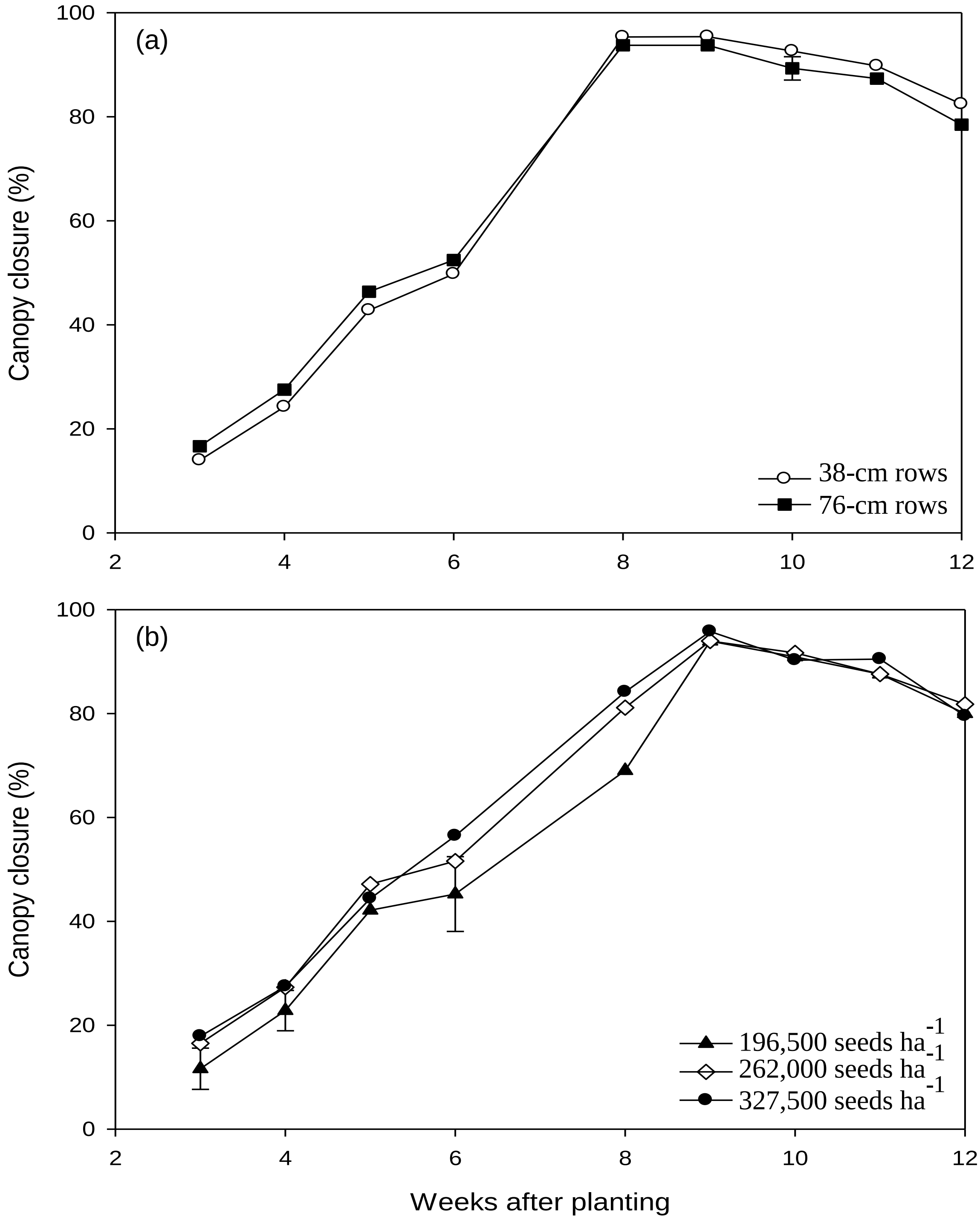

Figure 5. Main effects of (a) row width and (b) planting population on canopy closure for small red beans at East Lansing, MI in 2011. Vertical bars represent Fisher's protected LSD at the $\alpha \leq$ 0.05 level of significance.

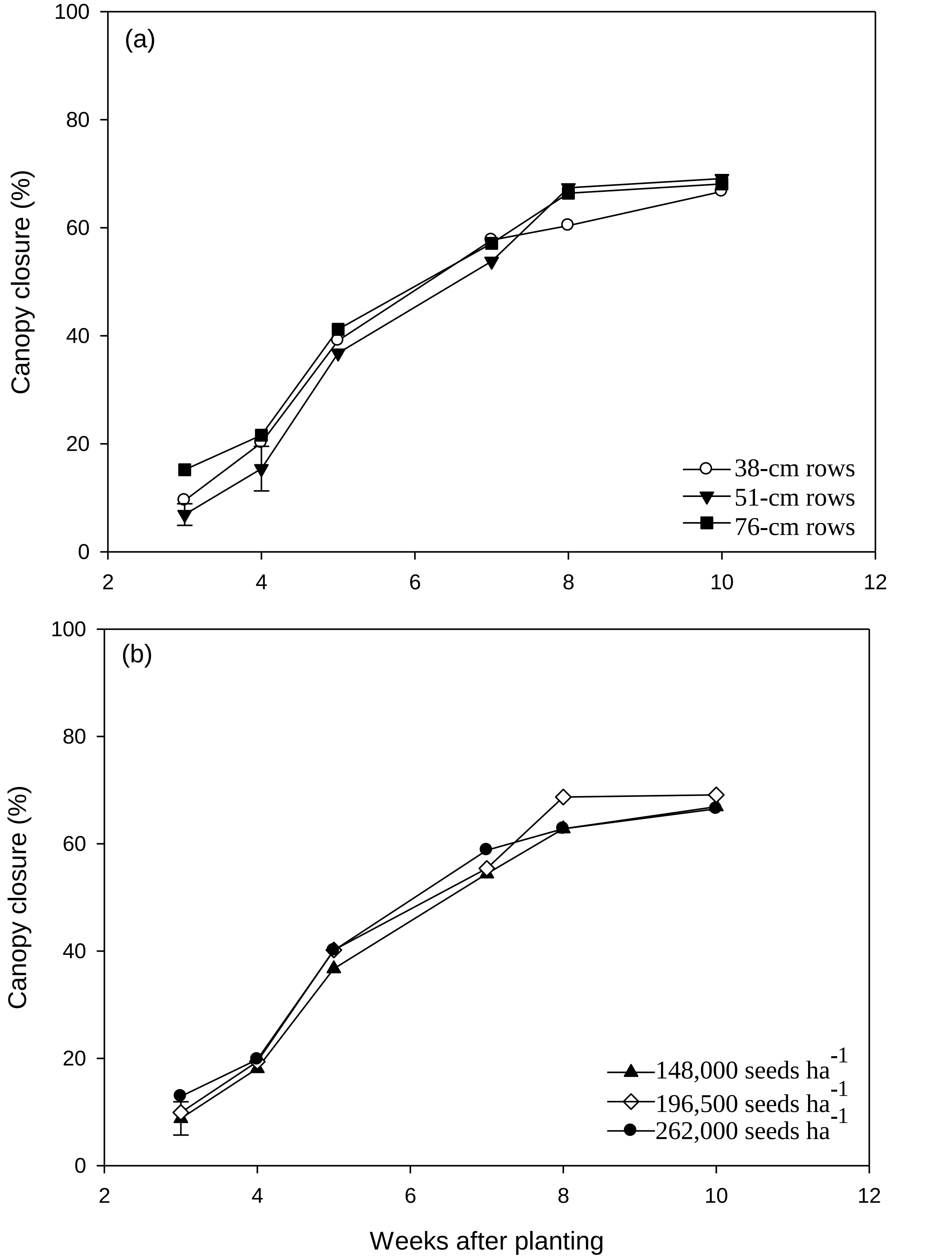

Figure 6. Main effects of (a) row width and (b) planting population on canopy closure for small red beans at Richville, MI in 2010. Vertical bars represent Fisher's protected LSD at the $\alpha \leq$ 0.05 level of significance.

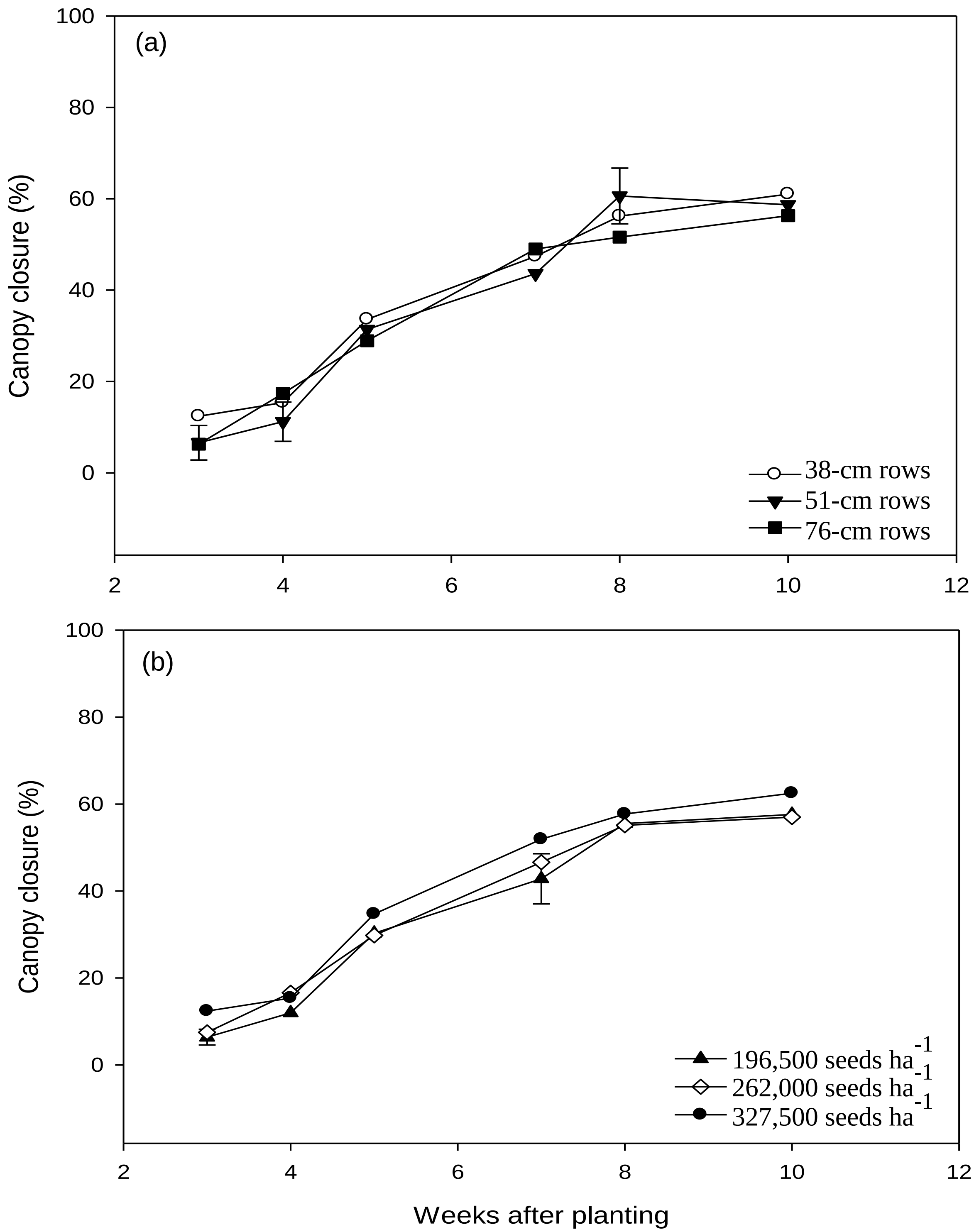

Figure 7. Main effects of (a) row width and (b) planting population on canopy closure for black beans at Richville, MI in 2010. Vertical bars represent Fisher's protected LSD at the $\alpha \leq 0.05$ level of significance.

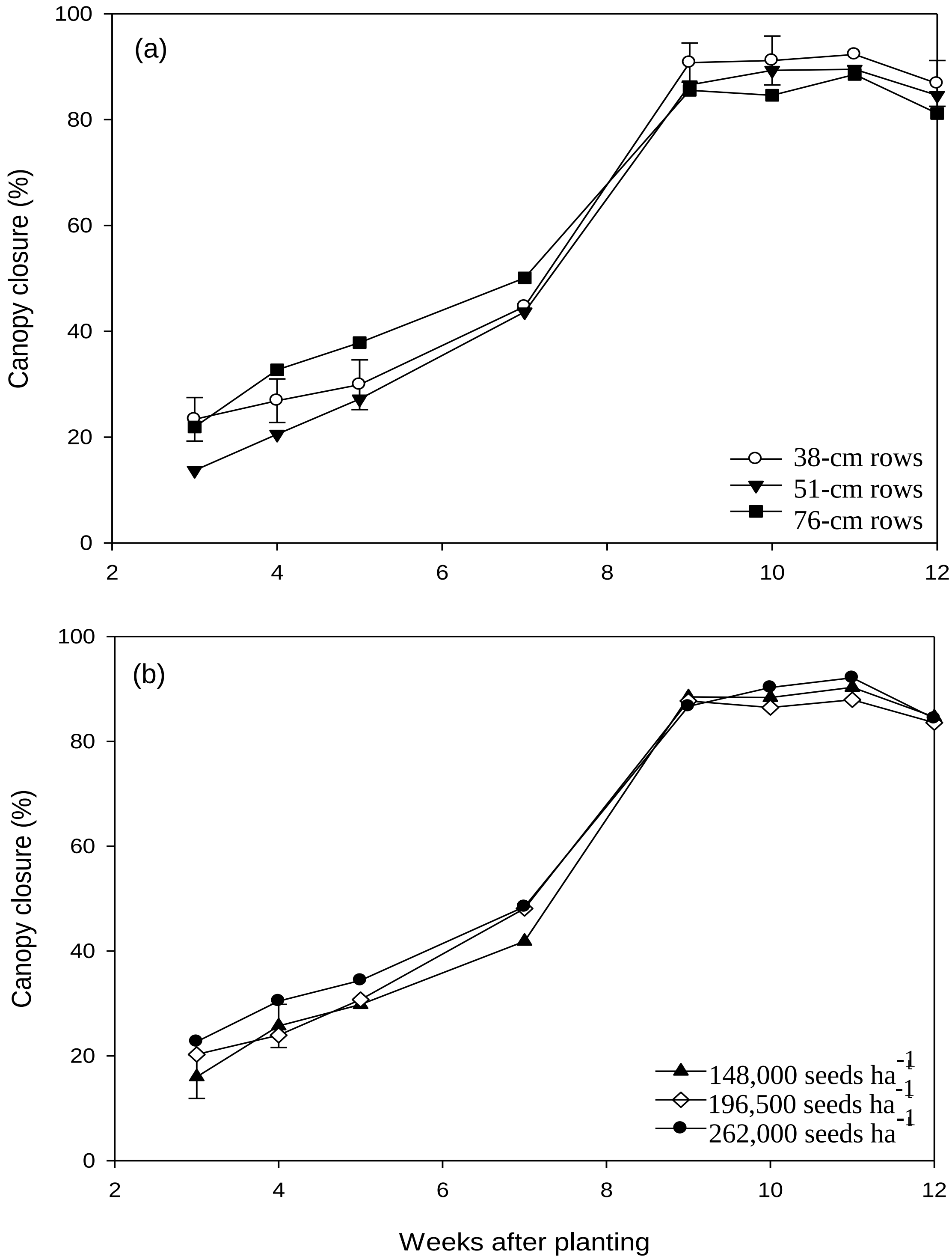

Figure 8. Main effects of (a) row width and (b) planting population on canopy closure for small red beans at Richville, MI in 2011. Vertical bars represent Fisher's protected LSD at the $\alpha \leq$ 0.05 level of significance.

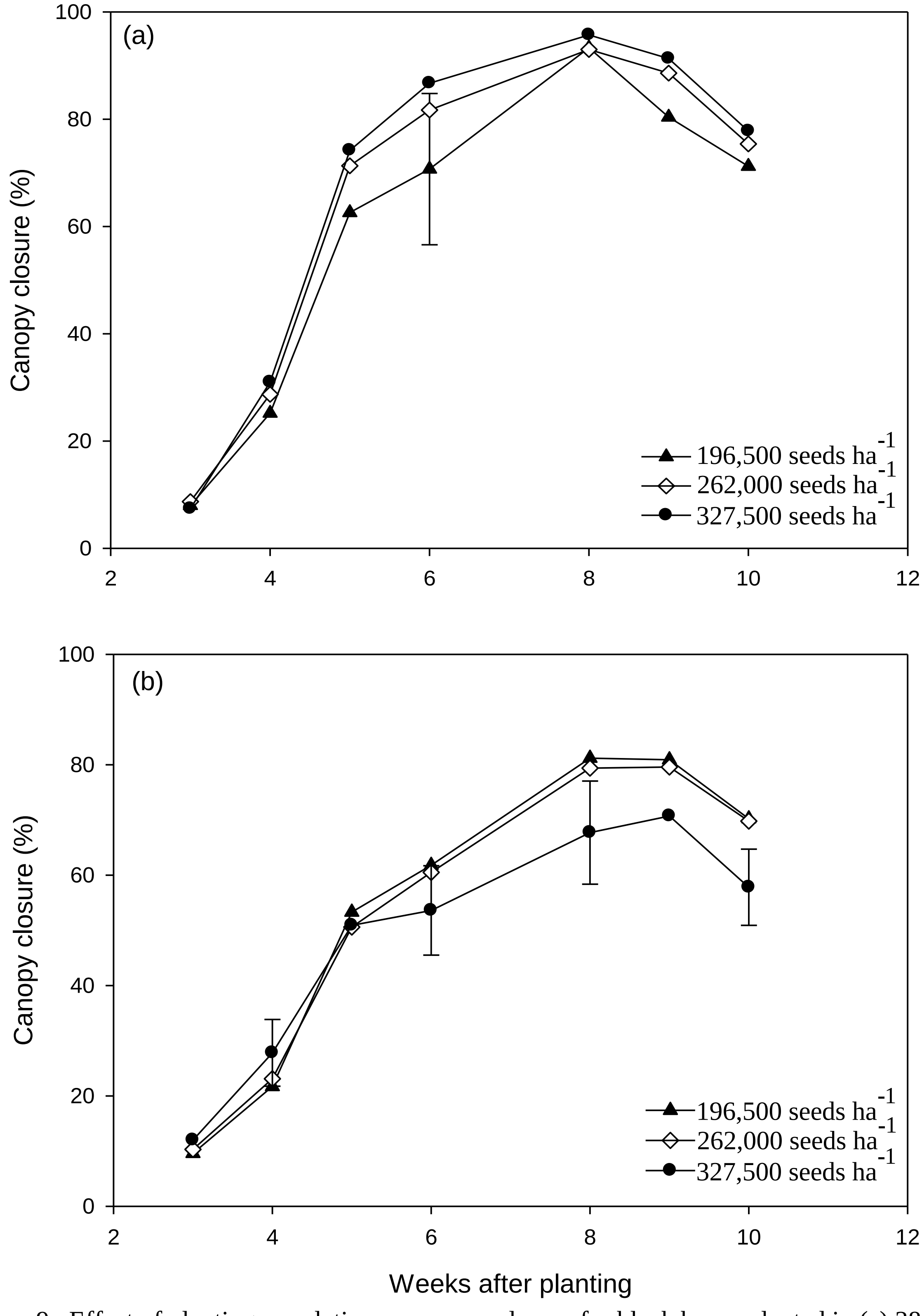

Figure 9. Effect of planting population on canopy closure for black beans planted in (a) 38- and (b) 76-cm rows at three populations at East Lansing, MI in 2010. Vertical bars represent Fisher's protected LSD at the $\alpha \leq 0.05$ level of significance.

APPENDIX

Table A2.1. Schedule of activities in the field for population-row width studies.

	2010		2011	
Event	East Lansing	Richville	East Lansing	Richville
Planting	June 16	June 10	June 8	June 6
Preemergence application	June 17	June 11	June 8	June 6
Cutworm trap establishment	June 22	June 23	June 21	June 20
Stand counts	June 28	June 23	June 21	June 20
Bean thinning	June 28	June 24	none	none
Clethodim application	July 1	none	July 12	none
First light meter reading	July 6	June 29	June 29	July 6
Postemergence application	July 6	July 1	July 5	June 30
Humidity meter placement	July 6	July 7	July 15	July 6
Emergence quadrat placed	July 12	July 13	July 13	July 6
First emergence count	July 25	July 29	July 22	July 14
Cutworm scouting	August 19	August 20	August 29	August 30
Plot length reduction	September 27	August 31	none	none
Early maturity rating	none	none	September 2	none
Glyphosate application	none	August 31	October 10	September 12
Weed harvest	September 21	September 4	September 22	September 9/10
Disease rating	September 23	none	October 4	October 6
Lodging rating	September 23	September 7	October 12	September 23
Final Maturity Rating	September 23	September 7	October 3	none
Disease pod harvest	September 23	none	October 2	October 6
Yield component harvest	September 30	September 7	October 11	September 23
Final harvest	September 29	September 7	October 18	October 6

Table A2.2. Dates of light meter readings and weed emergence counts in population-weed control studies.

Site-year	Light meter readings	Weed emergence counts
East Lansing 2010	July 6, 14, 25, 30	July 25, 30
	August 10*, 13*, 18, 27	August 10
Richville 2010	June 29	July 23, 29
	July 7, 13, 26	August 17
	August 7, 17	
East Lansing 2011	June 29	July 22
	July 8, 15, 21, 31	August 8
	August 10, 19, 26	September 20
	September 1	
Richville 2011	June 30	July 14
	July 6, 12, 25	September 2
	August 11, 16, 22, 28	

*Replications 1 and 2 only were measured on August 10, while replications 3 and 4 were measured on August 13.

LITERATURE CITED

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CHAPTER 3

WEED CONTROL IN WIDE- AND NARROW-ROW BLACK BEANS

Abstract

Dry beans are traditionally grown in wide rows with a heavy reliance on pre-plant incorporated herbicides and inter-row cultivation for weed control. Narrow rows have been shown to increase weed suppression in other crops, and preemergence and postemergence herbicides are a key component of most contemporary weed management systems, so various herbicide combinations were examined in wide and narrow rows. Field studies were conducted in 2010 and 2011 at two locations to examine the effect of row width and herbicide combination on weed suppression and yield in 'Zorro' black beans, a new upright variety. Dry beans were planted in 38- and 76-cm rows. Six weed control strategies were examined: S-metolachlor + halosulfuron (PRE), S-metolachlor (PRE) fb. bentazon + fomesafen (POST), halosulfuron (PRE) + clethodim (+ fomesafen in one site-year) (POST), imazamox + bentazon (POST), weed-free, and no weed control. Weed control and crop injury were three to four times beginning at the last POST herbicide application. In addition, weeds were counted by species in late July, and weed biomass was harvested and weighed at the end of the season. Yield was obtained by direct harvest. Narrow rows reduced weed population in two of the four site-years, reduced weed biomass in three of four site-years, and often improved control of upright broadleaf weeds. All herbicide combinations generally reduced weed populations and biomass, but control of specific weeds was variable. Crop injury was generally slight and transient. Yield was greater in narrow rows in three of four site-years. All herbicide combinations increased yield compared with the

untreated and resulted in similar yields to one another. Yield and weed suppression was maximized in narrow rows, while herbicide performance varied by year and weed spectrum

Nomenclature: Dry bean, *Phaseolus vulgaris*; preplant incorporated; preemergence; postemergence.

Introduction

Weed management in dry bean production has traditionally relied heavily on pre-plant incorporated (PPI) herbicides and between-row cultivation after beans have emerged (Arnold et al. 1993, Blackshaw et al. 2000; Burnside et al. 1994; Burnside 1998; Robertson and Frazier 1978). Traditional harvest methods involve pulling and windrowing mature plants and harvesting them in a second pass (Robertson and Frazier 1978; Schwartz 2004). However, development of new upright varieties of many dry bean classes, including black bean, has led many growers to adopt single-pass direct harvest with a typical combine (Hosfield et al. 2005; Kelly 1994, 2001, 2010; Schwartz et al. 2004). This method of harvest strongly discourages between-row cultivation due to the need for a level soil surface free of stones at harvest (Schwartz et al. 2004). However, the need for cultivation has been the primary limiting factor requiring beans to be grown in wide rows, typically 76-cm; if cultivation is not performed, row width can be narrowed (Blackshaw et al. 2000). Many studies in dry bean and other crops have shown that narrow rows can improve weed suppression, thereby at least partly offsetting the lack of cultivation (Blackshaw et al. 1999; Blackshaw 2000; Harder et al. 2007; Malik et al. 1993; Nelson and Renner 1998; Peters et al. 1965). In addition, PPI herbicides have also become less popular due to fuel and time costs and soil disturbance associated with incorporation. However, a number of preemergence (PRE) and postemergence (POST) herbicides are now available for use in dry bean in the United States, which may be able to maintain weed control in the absence of cultivation or PPI herbicides (Sprague and Everman 2011). Therefore, research is warranted to determine effective herbicide combinations for modern dry bean production and whether narrow rows can play a role in current weed management programs.

Many studies have shown that decreasing row width increases canopy development in dry bean and other crops (Blackshaw et al. 1999; Blackshaw et al. 2000; Harder et al. 2007; Redden et al. 1997; Yelverton and Coble 2001). Quicker or more complete canopy development may have beneficial effects, including weed suppression and increased yield (Andrade et al. 2002; Norsworthy and Oliver 2001; Peters et al. 1965). Malik et al. (1993) found that planting navy beans in 23- or 46-cm rows reduced weed biomass 15-21% compared with beans planted in 69-cm rows. In small red beans, Blackshaw et al. (2000) evaluated weed control at various row width and population combinations and found that control was optimized by narrow rows and high populations. Blackshaw et al. (1999) also found that peak canopy closure was increasingly close to 100% as rows were narrowed. Similar effects have been observed in soybean with regard to row width. Planting soybean in row widths of 25-cm or less has resulted in lower weed emergence, biomass and leaf area compared with 76-cm rows (Harder et al. 2007; Légère and Schreiber 1989; Nelson and Renner 1998). These observations often correlated with increased canopy closure.

In addition to improving weed suppression, growing dry beans in narrow rows could also result in higher yields. Weed suppression could indirectly result in improved yield, but enhanced canopy development could also improve yield by increasing the amount of total light energy captured and utilized by the crop. Although very little research has been published on canopy development in dry beans, abundant studies exist in soybean showing increased yields in narrow rows (Harder et al. 2007; Légère and Schreiber 1989; Lehman and Lambert 1960; Young et al. 2001). For instance, Cooper (1977) compared three row widths and determined that 17-cm rows obtained a yield advantage over wider rows ranging from 10-40%, and Ethredge (1989) analyzed the effect of row width in two soybean cultivars at many populations and found that in both cultivars, yield was greater in narrow rows. Some work has also been carried out in dry beans; Park (1993) simultaneously increased population and decreased row width and found that this resulted in increasing yields in both Type I and Type II navy bean cultivars. Malik et al. (1993) reported that 23-cm rows resulted in yield increases in three types of navy beans compared with 46-cm rows. In Type II small red beans, Blackshaw et al. (2000) found a 19% yield advantage of 23-cm rows over 69-cm rows. Grafton et al. (1988) found that yield increased an average of 565 kg ha^{-1} for each 25-cm decrease in row width in Type III pinto beans and an average of 435 kg ha^{-1} for each such decrease in Type I navy bean.

In spite of the possible weed suppression and yield increases gained by planting in narrow rows, Blackshaw et al. (2000) observed that small red bean yield remained depressed regardless of row width in the absence of chemical or mechanical weed control. Harder et al. (2007) made similar observations in soybean, obtaining low yield in the absence of weed control, regardless of row width or population. Thus, effective herbicide combinations are needed to give narrow-row dry beans an initial competitive advantage over weeds in order to maximize yield.

In 1994, Burnside et al. demonstrated that there were numerous combinations of herbicides and mechanical control treatments available to dry bean growers that resulted in sufficient weed control; however, every treatment involved cultivation or rotary hoeing, and every herbicide combination except the two least effective involved PPI herbicides. In 1993, Arnold et al. (1993) had expressed dissatisfaction with the state of weed control among New

Mexico pinto bean growers, who largely relied on PPI herbicides, and so explored imazethapyr applied PPI, PRE, or POST; they found that it was highly effective applied PRE in combination with metolachlor and pendimethalin and was generally effective at increasing yields above the untreated control in any treatment. Blackshaw and Esau (1991) in Alberta had investigated the potential of imazethapyr, bentazon, and fomesafen applied POST and found generally good results for imazethapyr but inconsistent results for bentazon and fomesafen alone. Blackshaw et al. (2000) investigated several PPI and POST herbicides and concluded that herbicide combinations were better than any one herbicide applied alone, though they indicated that imazamox may be somewhat effective alone. While these investigations suggest promise for PRE and POST herbicide combinations in dry bean, little research is available. Much of what is available focuses on imazethapyr, and none has explored the relationship of herbicide combinations to row width or investigated herbicide combinations in Type II black beans. Therefore, the objectives of this research were to investigate the combined effect of row width and herbicide combinations in the absence of both cultivation and PPI herbicides on: 1) weed control in Type II black bean, 2) Type II black bean yield, and 3) economic returns.

Materials and Methods

Field trials were conducted in 2010 and 2011 at the Michigan State University Harry and Hazel Box Farm near East Lansing, Michigan and at the Michigan State University Saginaw Valley Research and Extension Center near Richville, Michigan. The soil at the East Lansing site was a Capac loam (fine-loamy, mixed, mesic, Aeric Ochraqualfs) with pH 6.5 and 3.3% organic matter in 2010 and pH 6.5 and 2.6% organic matter in 2011. The soil at the Richville site was a Tappan-Londo loam (fine-loamy, mixed, active, calcareous, mesic Typic Endoaquolls and fine-loamy, mixed, mesic, Aeric Glossaqualfs) with pH 7.8. Soil organic matter was 2.7% and 2.6% in 2010 and 2011, respectively. The crops prior to these studies were winter wheat (*Triticum aestivum* L.) at East Lansing and corn (*Zea mays* L.) at Richville. Field preparation consisted of either fall moldboard or chisel plow followed by one to two field cultivations in the spring. Prior to planting, 336 kg of 17-8-15 (N-P-K) fertilizer containing 1.5% manganese and 1.5% zinc was broadcast onto the soil surface and incorporated.

The variety used at both locations was 'Zorro' black bean (Michigan Crop Improvement Association, Okemos, MI), which is a Type II (upright indeterminate vine) variety. Beans were planted in 38- and 76-cm rows at a target population of 262,000 plants ha^{-1} on June 16, 2010 and June 8, 2011 at East Lansing using a John Deere split-row planter (Deere and Company, Moline, IL) and on June 10, 2010 and June 6, 2011 at Richville using a Monosem split-row planter (Monosem Incorporated, Edwardsville, KS). Six weed control systems were examined in each row width (38- and 76-cm rows), resulting in a total of twelve treatments. The different weed control systems are summarized in Table 3.1. PRE herbicide applications were made within 24 hours of planting, and POST applications were made when the majority of weeds were 5-10 cm tall. In 2010, the POST portion of the PRE fb. POST treatments were applied 4-6 d after the total POST treatment; in 2011, they were applied at the same time. Herbicides were applied using a tractor-mounted, compressed air sprayer designed to deliver 177 l ha^{-1} at 193 kPa using AirMix 11003 nozzles (Greenleaf Technologies, Covington, LA).

The experimental design was a randomized complete block with regard to herbicide treatment; each herbicide treatment was treated as a split-plot between the two row widths. Each treatment was replicated four times. Plot width was 3 m, with seven rows per plot for the 38-cm row width and 4 rows per plot for the 76-cm row width. Plot length ranged from 9.1 to 10.4 m, depending on location.

Precipitation data was obtained throughout the growing season from the Michigan Automated Weather Network (http://www.agweather.geo.msu.edu/mawn/, Michigan State University, East Lansing, MI), which maintains stations on the Michigan State University Horticulture Farm less than a mile from both field locations.

Crop injury and weed control, density, and biomass. Weed control by species and crop injury were both visually evaluated throughout the growing season on a scale of 0-99%, with 0 indicating no injury and 99 indicating that all plants were dead. Weed control is presented for the 28 d after postemergence treatment (DAT) evaluation unless otherwise noted. Evaluations were also performed at 14 and 7 DAT and at the time of POST, as well as at 45 DAT at Richville in 2010 and at 3 DAT at East Lansing in 2011. At the time of the 28 DAT evaluations, the number of weeds of each species in each plot was counted. These numbers were added to find total weed densities for each plot. Prior to harvest, above-ground weed biomass in each plot was harvested, and dry weights were recorded. Depending on weed population, area for the biomass samples ranged from four 0.25-m^2 subsamples to the entire length of the plot. The predominant weeds at Richville were common lambsquarters (*Chenopodium album* L.) and pigweed (*Amaranthus spp.*). Common lambsquarters, pigweed, velvetleaf (*Abutilon theophrasti* Medik.), common ragweed (*Ambrosia artemisiifolia* L.), eastern black nightshade (*Solanum ptycanthum* Dun.), and annual grasses, chiefly foxtail (*Setaria spp.*) were among the predominant weeds at East Lansing in 2010; in 2011, these were joined by common purslane (*Portulaca oleracea* L.).

Yield. A preharvest treatment of glyphosate (Roundup PowerMax, Monsanto Company, Saint Louis, MO) at 0.84 kg ae ha^{-1} was applied to all plots at both locations in 2011 to hasten weed and bean desiccation. Dry beans were direct harvested with a small plot combine (Massey-Ferguson 8XP, AGCO, Duluth Georgia) with a 1.5-m header**.** The middle two and four rows were harvested in the 76- and 38-cm row width plots, respectively. Dry bean yield was adjusted to 18% moisture. Harvest occurred on September 6 at Richville and September 29 at East Lansing in 2010 and on October 6 at Richville and on October 18 at East Lansing in 2011.

Economic return. Gross margins were calculated at grower-received prices of \$0.66, \$0.88, and \$1.10 kg^{-1} paired with dealer seed prices of \$0.77 and \$1.25 kg^{-1} (USDA-AMS 2011). The low and high prices were approximately the lowest and highest prices occurring in Michigan during the last five years, while the middle grower-received prices were those currently being contracted by Michigan growers (Varner 2012 pers. corr.). This calculation was performed using the formula:

$$Gross\ margin = (Y \times P_{grower}) - (C + P_{herbicide})$$

Where Y is yield, P_{grower} is the bean price received by growers, C the cost of seed, and $P_{herbicide}$ is the cost of the weed control treatment at June 2011 prices (Local herbicide costs 2011). The cost of weed control for the untreated was assumed to be \$0 ha^{-1} while the cost of weed control for the weed-free was assumed to be \$323.57 ha^{-1}. Costs other than seed and weed control were not considered. There is no cost associated with changing row widths except the upfront cost of a new planter if one is not available for the desired row width.

Data analysis. Data were subjected to ANOVA using PROC MIXED in SAS 9.2 (SAS Institute Inc., Cary, NC) and treatment means were compared using Fisher's protected LSD at the $\alpha \leq 0.05$ level of significance. Some data were log or square root transformed for analysis, but all data is presented untransformed. Data were combined over row width and weed management system when no significant interactions were present.

Results and Discussion

Growing conditions. Rainfall from June through September in 2010 was lower than the 30-yr average at both locations (Table 3.2). At East Lansing, above-average rainfall in June and near-average rainfall in July and September allowed dry bean plants to develop normally despite a dry August. At Richville, rainfall was well below average in every month, and much of the June rainfall came prior to planting; by the beginning of September, most bean plants had senesced, rendering September rainfall irrelevant. Only 11 cm of rain fell at Richville between planting and harvest, resulting in stunted crop plants and little weed growth.

In 2011, rainfall from June through September was slightly above the 30-yr average at East Lansing, while at Richville it was once again below the 30-yr average. At East Lansing, rainfall was slightly to moderately below average in three months, but in late July a single weather system brought 16 cm of rainfall over three days, making that month's total dramatically above average and supplying ample water for pod formation, especially with moderate rainfall continuing through September. At Richville, rainfall was below average in every month, but all rainfall in June occurred after planting, and monthly totals were higher than those of the previous year in July and August. Rainfall was sufficient for normal plant development, and pod filling continued into September.

Crop injury. The severity of dry bean injury from herbicide treatments differed among site-years. Crop injury never exceeded 17%, and by 14 DAT, injury symptoms nearly always disappeared (Table 3.3).

At East Lansing in 2010, crop injury was not greater than 5% in any treatment at the time of POST application, and no injury was observed afterward.

At Richville in 2010, all herbicide treatments initially caused 6-8% injury, but 7 days after the POST treatment (DAT), S-metolachlor fb. bentazon + fomesafen had 16% injury while other treatments had less than 2% injury. At 14 DAT, injury in this treatment was only 4%, and injury in other treatments had disappeared.

At Richville in 2011, all treatments containing S-metolachlor caused 7-12% injury at POST and 7 DAT while treatments not containing S-metolachlor had less than 5% injury. However, all injury symptoms were gone at 14 DAT. Similarly, at East Lansing in 2011, all treatments containing S-metolachlor had injury ranging from 10-15% at POST, while other treatments had less than 5% injury, but by 7 DAT, injury in all treatments was less than 5%, and at 14 DAT, no injury was observed.

The highest injury consistently occurred in treatments involving S-metolachlor. Treatments containing halosulfuron often resulted in minor injury, as did imazamox + bentazon, which is the same result seen by Hekmat et al. (2008). Fomesafen resulted in more pronounced injury when applied with bentazon following S-metolachlor under drought conditions at Richville in 2010 but did not injure dry bean in other site-years. At East Lansing in 2011, injury was slightly higher in 38- than in 76-cm rows, but at other site-years, row width was non-significant. In every case, injury was transient and never resulted in any obvious effects beyond 14 DAT.

Weed control by species. The effectiveness of each herbicide combination and of narrow rows for the control of each major weed observed in these studies is presented in Tables 3.4-3.9 and summarized in Table 3.9. While weed control was evaluated several times during the growing season, control data is presented from the evaluation 28 days after the POST application unless otherwise noted.

Common lambsquarters. Common lambsquarters occurred in significant numbers in every site-year and was the dominant weed at Richville in both years. Common lambsquarters population was extremely high (167,300 weeds ha^{-1}) at Richville in 2011 and relatively low at East Lansing in 2010 (8900 weeds ha^{-1}).

At East Lansing in 2010, when weed pressure was low and PRE herbicides were incorporated by rainfall, all herbicide combinations provided excellent (≥ 94%) control of common lambsquarters regardless of row width (Table 3.4). Common lambsquarters populations were reduced to <15% of the untreated in all treatments and to levels similar to that of the weed-free free in all treatments except imazamox + bentazon (POST) (data not shown).

At Richville in both years, PRE herbicides were not effectively incorporated by rainfall, and all treatments involving PRE herbicides provided only 63-73% control of common lambsquarters and failed to significantly reduce common lambsquarters populations compared with the untreated. Imazamox + bentazon (POST) was better, providing an average of 89%

control and reduced population to a level similar to the weed-free. At Richville, common lambsquarters control averaged 78% in 38-cm rows and only 70% in 76-cm rows (Table 3.5).

At East Lansing in 2011, there was an interaction between row width and herbicide treatment with regard to common lambsquarters control (Table 3.6). S-metolachlor + halosulfuron (PRE) and halosulfuron (PRE) fb. clethodim + fomesafen (POST) again provided excellent (≥ 97%) control of common lambsquarters regardless of row width. Imazamox + bentazon (POST) provided 98% control in 38-cm rows; however, in 76-cm rows, it only provided 90% control. S-metolachlor (PRE) fb. bentazon + fomesafen (POST) provided only 89% control in 38-cm rows and even lower control (80%) in 76-cm rows. The two best treatments reduced common lambsquarters population to levels similar to that of the weed free, while the other two reduced populations to 37-48% of the untreated (data not shown).

When PRE herbicides were incorporated by timely rainfall, the two treatments containing halosulfuron provided excellent control of common lambsquarters, even reducing populations to levels similar to the weed-free; however, the efficacy of the halosulfuron treatments was dramatically reduced when poorly incorporated. Imazamox + bentazon (POST) was the treatment that was most consistent over all site-years and provided the best control when PRE herbicides were poorly incorporated. S-metolachlor fb. bentazon + fomesafen provided good control when the PRE was well-incorporated but sometimes less than the halosulfuron-containing treatments, and control was greatly reduced when the PRE was not well-incorporated. Imazamox appears to be a better partner for bentazon than fomesafen for common lambsquarters control. Narrow rows often improved control of common lambsquarters when herbicide control was less than complete; however, row width did not significantly affect mid-season common lambsquarters populations.

Pigweed. Pigweed (mostly *Amaranthus retroflexus* L. and *Amaranthus powellii* S. Wats., with some *Amaranthus hybridus* L.) was present at significant numbers in all four site-years but were more numerous at Richville. Populations ranged from 7200 (East Lansing 2011) to 33,200 weeds ha^{-1} (Richville 2010.)

At East Lansing in both years and at Richville in 2011, all herbicide treatments provided excellent (≥ 97%) control of pigweed and reduced populations to levels similar to the weed-free (Table 3.4). In 38-cm rows, control averaged 99% across these three site-years, while in 76-cm rows, control was reduced to 97%.

At Richville in 2010, when PRE herbicides were poorly incorporated and drought conditions prevailed, pigweed control was substantially reduced in all treatments containing PRE applications, ranging from 74-79%. These treatments still reduced pigweed populations to 16-28% of the untreated. Imazamox + bentazon (POST) still provided excellent (94%) control and reduced pigweed population to a level similar to that of the weed-free. Overall, pigweed control averaged 75% in 38-cm rows compared with just 67% in 76-cm rows (Table 3.5), and pigweed population was higher in 76-cm rows with 11,500 weeds ha^{-1} than in 38-cm rows with 7700 weeds ha^{-1}.

All herbicide treatments effectively controlled pigweed under normal environmental conditions. When PRE herbicides were not properly incorporated and drought conditions prevailed afterward, the effectiveness of all treatments involving PRE applications was reduced, although all still provided significant control. Imazamox + bentazon provided excellent control of pigweed regardless of environmental conditions. Imazamox appears to be a better partner with bentazon than fomesafen for control of pigweed. Narrow rows improved pigweed control and reduced mid-season population compared to wide rows.

Velvetleaf. Velvetleaf (*Abutilon theophrasti* Medik.) was present only at East Lansing. In 2010, velvetleaf was present in the untreated at a density of only 2000 weeds ha^{-1} but in 2011 at a density of 17,600 weeds ha^{-1}. Populations in 2010 were too low and sporadic to reliably detect differences in weed density between treatments.

In 2010, imazamox + bentazon (POST) provided virtually total (99%) control of velvetleaf (Table 3.4). S-metolachlor (PRE) fb. bentazon + fomesafen (POST) and halosulfuron (PRE) fb. clethodim (POST) also provided excellent (94-96%) control of velvetleaf. Control with S-metolachlor + halosulfuron (PRE) at 88% was significantly lower than imazamox + bentazon but statistically similar to the other two treatments. Row width did not have a significant effect on velvetleaf control (Table 3.5).

In 2011, when velvetleaf pressure was much higher, imazamox + bentazon continued to provide excellent (97%) control, and halosulfuron fb. clethodim + fomesafen also provided excellent (92%) control, and both reduced velvetleaf populations to levels similar to that of the weed-free. However, velvetleaf control with S-metolachlor fb. bentazon + fomesafen (69%) and S-metolachlor + halosulfuron (56%) was greatly reduced, and velvetleaf populations were only reduced to 54-60% of the untreated. Velvetleaf control in 38-cm rows averaged 84% compared with just 72% in 76-cm rows.

When velvetleaf pressure was low in 2010, all herbicide treatments were reasonably effective. However, in 2011, treatments involving S-metolachlor paired either with halosulfuron or with bentazon and fomesafen were unsatisfactory. However, halosulfuron paired with fomesafen or bentazon paired with imazamox were effective for velvetleaf control. In 2011, velvetleaf control was greater in narrow rows than in wide rows.

Eastern black nightshade. Eastern black nightshade (*Solanum ptycanthum* Dun.) occurred in significant numbers only at East Lansing; density was more than ten times greater in 2011 than in 2010.

At East Lansing in 2010, S-metolachlor + halosulfuron (PRE), S-metolachlor (PRE) fb. bentazon + fomesafen (POST), and imazamox + bentazon (POST) all provided very good to excellent (88-99%) control of eastern black nightshade and reduced nightshade populations to levels similar to the weed-free regardless of row width. However, halosulfuron (PRE) fb. clethodim (POST) provided very poor (39%) control of eastern black nightshade, and nightshade density was similar to that of the untreated (Table 3.7).

At East Lansing in 2011, the three treatments that previously provided very good to excellent control of eastern black nightshade all provided virtually complete (99%) control regardless of row width (Table 3.8). Halosulfuron fb. clethodim + fomesafen provided much lower control that differed by row width, with 81% control in 38-cm rows and 72% control in 76-cm rows. Moreover, it increased eastern black nightshade population to 85,500 ha^{-1} compared with just 14,400 ha^{-1} in the untreated.

Imazamox + bentazon and the two treatments that involved S-metolachlor provided excellent control of eastern black nightshade. Halosulfuron fb. clethodim, with or without fomesafen, failed to adequately control eastern black nightshade; in fact, this treatment increased eastern black nightshade population, presumably by removing other weeds that had been suppressing eastern black nightshade. The effect of row width was not assessed due to the sporadic nature of eastern black nightshade populations.

Common ragweed. Common ragweed was present in significant numbers only at East Lansing. Population in the untreated in 2010 was 10,200 weeds ha^{-1}. In 2011, there were only 1100 weeds ha^{-1} in the untreated.

In 2010, all treatments involving a PRE application provided excellent (94-99%) control of common ragweed (Table 3.7) and reduced weed populations to levels similar to the weed-free (data not shown). Imazamox + bentazon (POST) provided lesser but still good (87%) control but did not reduce weed population compared with the untreated. Common ragweed control was significantly greater (96%) in 38-cm rows than in 76-cm rows (91%) (Table 3.9), but row width did not affect common ragweed population.

In 2011, common ragweed control was not rated due to low density (1100 ha^{-1}) in the untreated; however, common ragweed population was ten times higher in the S-metolachlor fb. bentazon + fomesafen and imazamox + bentazon treatments than in the untreated, suggesting that common ragweed was being suppressed by other weeds and was released by these treatments. While there were few common ragweed plants in the halosulfuron fb. clethodim + fomesafen treatment mid-season, the reason fomesafen was applied in this site-year was the presence of a high density of ALS-resistant common ragweed following halosulfuron application; fomesafen effectively controlled this population. Common ragweed density was more than twice as high in 76-cm rows (5200 ha^{-1}) as in 38-cm rows (2500 ha^{-1}).

Treatments containing halosulfuron or fomesafen were generally effective at controlling common ragweed, but one exception was observed in both cases; in halosulfuron, this was due to an ALS-resistant population. The Total POST provided less effective control of common ragweed in one year and appeared to provide no control in the other year; it cannot be recommended for fields with high common ragweed populations or those with ALS-resistant common ragweed. Narrow rows improved common ragweed control in 2010 and decreased common ragweed population in 2011.

Annual grass. Annual grass was present in numbers significant enough to evaluate only at East Lansing in 2011. The predominant grasses were foxtails (*Setaria faberi* Herrm., *Setaria glauca* P.Beauv. and *Setaria pumila* (Poir.) Roem. & Schult.), but many other species were also present, including large crabgrass, *Digitaria sanguinalis* (L.) Scop., and stinkgrass, *Eragrostis cilinensis* (All.) Vign. Ex Janchen, among others. Annual grass population in the untreated was 42,200 weeds ha^{-1}.

S-metolachlor (PRE) fb. bentazon + fomesafen (POST), and halosulfuron (PRE) fb. clethodim + fomesafen (POST) both provided excellent (94%) control of annual grass (Table 3.7). Control in the latter combination was slightly delayed due to the slowness (1-2 wk) of clethodim activity but was more effective at actually killing, rather than merely suppressing, annual grass than the former treatment. However, halosulfuron fb. clethodim + fomesafen demonstrated no control of stinkgrass. S-metolachlor + halosulfuron (PRE) provided good (87%) control of annual grass and resulted in populations similar to the weed-free but also in some uninjured escapes. Imazamox + bentazon provided some suppression (77%) of annual grass, but it failed to actually kill it, resulting in a 273% increase in annual grass population compared to the untreated, presumably due to release from broadleaf weed competition.

Narrow rows were generally not effective at suppressing annual grass (Table 3.9). Annual grass control averaged 90% in 38-cm rows and 86% in 76-cm rows; this was only significant at α=0.1. Row width did not affect mid-season annual grass population.

Common purslane. Common purslane (*Portulaca oleracea* L.) was present in significant numbers only at East Lansing in 2011. Common purslane population in the untreated was 92,400 weeds ha^{-1}.

S-metolachlor (PRE) fb. bentazon + fomesafen (POST) and halosulfuron (PRE) fb. clethodim + fomesafen both provided excellent (98-99%) control of common purslane (Table 3.7) and reduced populations to levels similar to the weed-free. S-metolachlor + halosulfuron (PRE) also reduced common purslane population to a level similar to the weed-free but provided somewhat less control (88%) overall because it allowed a number of uninjured escapes. Imazamox + bentazon (POST) provided good suppression (82%) of common purslane but failed to actually kill the plants, with common purslane population being virtually identical to the weed-free. Row width had no significant effect on common purslane control or population (Table 3.9).

Summary. The effect of each herbicide combination and of row width on each weed is summarized in Table 3.3.

S-metolachlor + halosulfuron was the most consistently effective treatment overall when incorporated by rainfall but was much less effective when it was not incorporated and was ineffective against a high population of velvetleaf even when incorporated.

The performance of both PRE fb. POST combinations was also significantly decreased if not well incorporated. Otherwise, S-metolachlor fb. clethodim, with or without fomesafen, provided consistently effective control of most weeds but provided virtually no control of eastern black nightshade; and fomesafen was needed to control ALS-resistant common ragweed. Halosulfuron fb. bentazon + fomesafen provided good but not excellent control of common lambsquarters and poor control of velvetleaf when velvetleaf population was high; it suppressed annual grass but did not reduce its population. It provided good to excellent control of other weeds. Imazamox + bentazon had the advantage of being little affected by environmental conditions and provided consistently excellent control of the most prominent weeds as well as providing good control of velvetleaf, a weed two other treatments controlled inadequately, along with eastern black nightshade; its disadvantages were merely fair control of common ragweed, and suppression without population reduction in annual grass and common purslane. There was no perfect herbicide combination, so the optimal combination for a given situation should be chosen based on weeds known to be present in the field and expected environmental conditions. Narrow rows can play a supplementary role in the suppression of upright broadleaf weeds but appear to be largely ineffective at suppressing annual grass and common purslane.

Mid-season weed populations. Weed populations shortly before peak canopy closure (41-44 days after planting) were much higher in 2011 than in 2010 at both sites and were slightly higher in at East Lansing than at Richville in both years. In every site-year, differences in weed population were observed among the weed control treatments and in two site-years between row widths. Weed populations by row width and herbicide combination are presented in Tables 3.10 and 3.11.

At East Lansing in 2010, all treatments with a PRE component were similar to the weed-free. Overall weed population significantly differed from the weed-free only in the imazamox + bentazon (POST) treatment, which still had 68% fewer weeds (19,950 weeds ha^{-1}) than the untreated (62,140 weeds ha^{-1}.) At East Lansing in 2011, under higher weed pressure, overall weed populations in both treatments that included halosulfuron, S-metolachlor + halosulfuron (PRE) and halosulfuron (PRE) fb. clethodim (+ fomesafen at this site-year only) (POST), were again similar to the weed-free. However, overall weed populations in imazamox + bentazon and S-metolachlor (PRE) fb. bentazon + fomesafen (POST) were similar to the untreated.

At Richville in both years, all herbicide treatments reduced overall weed population compared with the untreated. In 2010, the three treatments that included a PRE component were similar to one another and had higher weed populations than the weed-free. Imazamox + bentazon had fewer weeds and was similar to the weed-free. In 2011, all herbicide treatments were statistically similar to one another, but only the halosulfuron fb. clethodim and imazamox + bentazon treatments were statistically similar to the weed-free.

In 2010, there were fewer weeds in 38-cm rows than in 76-cm rows. At East Lansing 76-cm rows averaged 21,000 weeds ha^{-1} and 38-cm rows just 10,900 weeds ha^{-1} across all treatments. At Richville, 76-cm rows averaged 22,500 weeds ha^{-1}, while 38-cm rows averaged 16,600 weeds ha^{-1}. In 2011, under higher weed pressure, row width did not have a significant effect on overall weed population at either site.

In fourteen of sixteen cases, herbicide treatment reduced weed population compared to the untreated. However, no treatment was consistently best. At East Lansing, where weed diversity was much greater and the PRE was incorporated by rainfall, S-metolachlor + halosulfuron (PRE) was among the most effective treatments at reducing weed population in both years, while imazamox + bentazon (POST) was less effective and did not differ from the untreated in 2011. At Richville, where common lambsquarters (*Chenopodium album* L.) and redroot pigweed (*Amaranthus retroflexus* L.) dominated and the PRE applications were not effectively incorporated by rainfall, imazamox + bentazon was most effective in both years while S-metolachlor + halosulfuron allowed significantly more weeds than the weed-free.

Halosulfuron fb. clethodim was the most consistent, being among the most effective at reducing weed population in every site-year except Richville 2010, when all treatments involving PRE herbicides compared unfavorably to the weed free; however, it should be noted that in the site-year of highest weed pressure, East Lansing 2011, fomesafen was added to this treatment POST due to the failure of halosulfuron to control some broadleaf weeds, especially ALS-resistant common ragweed (*Ambrosia artemisiifolia* L.) S-metolachlor fb. bentazon + fomesafen was only among the most effective at reducing weed populations at East Lansing in 2010, and at East Lansing in 2011 it did not differ from the untreated. In 2010, when weed populations were lower overall, 38-cm rows reduced weed populations by 44% and 26% compared with 76-cm rows at East Lansing and Richville respectively, but in 2011 with higher weed populations, narrow rows failed to significantly reduce weed populations. The observed differences were large enough to suggest that under some circumstances, narrow rows can reduce weed populations, which agrees with the finding of Harder et al. (2007) that weed populations are reduced in narrow row soybean.

Final weed biomass. Weed biomass was much greater in 2011 than in 2010 at both sites, and although weeds were more numerous mid-season at East Lansing, final weed biomass was higher at Richville within each year. At East Lansing in 2010, weed biomass was much lower than in other site-years. In every site-year, most or all herbicide treatments reduced weed biomass compared with the untreated (Table 3.12), and in three of the four site-years, weed biomass was reduced in 38-cm rows compared to 76-cm rows (Table 3.13).

At East Lansing in 2010, under low weed pressure, all herbicide treatments reduced weed biomass to levels similar to the weed-free. At East Lansing in 2011, imazamox + bentazon

(POST) and halosulfuron (PRE) fb. clethodim + fomesafen (POST) again reduced weed biomass to levels similar to the weed-free despite imazamox + bentazon having failed to reduce the mid-season weed population. S-metolachlor + halosulfuron (PRE) and S-metolachlor (PRE) fb. bentazon + fomesafen (POST) reduced weed biomass compared with the untreated by 86-91% but both still had more weed biomass than the weed-free.

At Richville in both years, only imazamox + bentazon reduced weed biomass to a level similar to the weed-free. The effectiveness of the three treatments that involved PRE applications was reduced by poor PRE incorporation, but in 2010, all three were similar to one another and still reduced weed biomass by 77-82% compared to the untreated. In 2011, S-metolachlor + halosulfuron and S-metolachlor fb. bentazon + fomesafen reduced weed biomass by 48-56% compared with the untreated, but weed biomass was still much higher than in the weed-free, and halosulfuron + clethodim failed to significantly reduce weed biomass.

Weed biomass was significantly reduced in 38-cm rows compared to 76-cm rows in three of the four site years. This reduction in weed biomass was 53% at East Lansing in 2010, 30% at East Lansing in 2011, and 51% at Richville in 2011. At Richville in 2010, when the canopy never fully developed, row width did not affect weed biomass.

In fifteen of sixteen cases, herbicide treatments reduced pre-harvest weed biomass compared with the untreated. Imazamox + bentazon was the most consistent weed control treatment, reducing weed biomass to a level similar to the weed-free in every site-year. S-metolachlor + halosulfuron and S-metolachlor fb. bentazon + fomesafen resulted in weed biomass similar to the weed-free only once but always reduced it relative to the untreated. Halosulfuron fb. clethodim twice resulted in weed biomass similar to that of the weed-free but once resulted in weed biomass that did not significantly differ from the untreated, and one of the cases in which it was similar to the weed-free was the case in which fomesafen was added POST. Imazamox + bentazon was affected only minimally by environmental conditions, while the efficacy of those involving PRE herbicides was reduced in years when little rainfall followed PRE application. Treatments involving PRE applications usually performed similarly; however, halosulfuron fb. clethodim was the least consistent of the three, demonstrating that relying solely on a single PRE herbicide for broadleaf control is a poor strategy in many situations.

Narrow rows decreased weed biomass across all treatments except under drought conditions, which led to incomplete canopy closure even in narrow rows. As Blackshaw et al. (2000) noted, narrow rows cannot replace herbicides; in no case did narrow rows reduce weed biomass in the untreated to levels similar to those of the most effective herbicide treatments. However, narrow rows can play a significant supplementary role in weed control. This is similar to the finding of Teasdale and Frank (1983) that narrow-row snap bean (*Phaseolus vulgaris* L.) reduces weed biomass compared to wide rows.

Dry bean yield. Site and year had a strong influence on yield. Yield was highest at East Lansing in 2011, the only site-year with above average rainfall; yield in the weed-free averaged 4829 kg ha^{-1}. Yield was lowest at Richville in 2010 under drought conditions; yield in the weed-free averaged 2083 kg ha^{-1}. Yield was intermediate at East Lansing in 2010 and Richville in 2011 under slightly dry conditions, with weed-free yield averaging 3242 and 3082 kg ha^{-1} respectively.

Yield was increased by herbicide application in every site-year, but yield was nearly always similar across herbicide treatments, and in only one site-year did the weed-free have significantly higher yield than some of the herbicide treatments (Table 3.14). In two of the four site-years, narrow rows increased yield compared to wide rows (Table 3.15).

At East Lansing in 2011, yield was similar across all herbicide treatments. All herbicide treatments increased yield by 70-83% compared with the untreated. Weed-free yield was significantly higher than any of the herbicide treatments except the halosulfuron + clethodim (+ fomesafen at this site-year only). At Richville in both years, yield was similar across all herbicide treatments and the weed-free, and all of these resulted in higher yield than the untreated. Yield increases compared with the untreated ranged from 14-19% in 2010 and from 30-48% in 2011.

At East Lansing in 2010, yield was similar across all herbicide treatments and the weed-free in 76-cm rows and in 38-cm rows within three herbicide treatments; yields ranged from 3135 kg ha^{-1} to 3408 kg ha^{-1}. In S-metolachlor (PRE) fb. bentazon + fomesafen (POST) and the weed-free, yield within 38-cm rows was similar to that of the untreated (Table 3.16).

At East Lansing and Richville in 2011, yield was higher across all treatments in 38-cm rows than in 76-cm rows. At East Lansing in 2011, yield was 19% higher in 38-cm rows, and at Richville in 2011, it was 8% higher.

Under drought conditions at Richville in 2010, yield did not significantly differ by row width.

All herbicide combinations used in this study in this study consistently improved yield relative to the untreated, and none increased yield more than any other. This indicates the importance of weed control for obtaining optimum dry bean yield and also suggests that there are many good options available for weed control in dry bean. In three of the four years, all herbicide treatments resulted in yields similar to the weed-free. However, in the site-year with both the highest yields and the highest weed pressure, three of the herbicide combinations failed to provide yields similar to the weed-free. Narrow rows improved yield in two of the four site-years, with the magnitude of the yield improvement being higher at higher yield. Narrow rows were not capable of replacing herbicide applications, but they did provide a supplemental yield increase. In two site-years, yield did not increase in narrow rows; in one site-year, it actually increased in wide rows in two herbicide treatments; the reason for this was unclear. In the other site-year, drought conditions severely reduced canopy development and yield, so yield did not significantly differ by row width. This trend toward higher yield in narrow rows confirms the findings of Blackshaw et al. (1999, 2000), Redden et al. (1987), and Malik et al. (1993) that yield is often, though not always, higher in narrow rows; Grafton et al. (1988) and Goulden (1976) found even more consistent yield advantages in narrow rows.

Economic returns. In both of the site-years in which yield was higher in 38-cm rows than in 76-cm rows, gross margin was likewise higher in 38-cm rows (Table 3.17). Bean price received by the grower (grower price) did not affect the relationship among treatments within the range of prices occurring from September 2007 to February 2012 except under drought conditions at Richville in 2010 (USDA-AMS 2011). At Richville in 2010, yields was low, and all herbicide treatments resulted in similar economic returns to the untreated at the lowest grower price in the five year period (\$0.66 kg^{-1}) while at the highest grower price in the period (\$1.10 kg^{-1}), imazamox + bentazon (POST) and S-metolachlor + halosulfuron (PRE) both increased economic return compared to the untreated; at the medium grower price (\$0.88 kg^{-1}), only imazamox + bentazon increased economic return.

Weed control treatment affected economic return in every site-year. The S-metolachlor + halosulfuron (PRE) treatment was also always among those with the highest gross margins (Table 3.18). Halosulfuron (PRE) fb. clethodim (POST) was among the treatments with the highest gross margins in every site-year, including East Lansing 2011 when fomesafen was included POST. Imazamox + bentazon (POST) was among the treatments with the highest gross margins in every site-year except when a grower-received bean price of \$1.10 kg^{-1} (the highest price) was used at East Lansing in 2011. Since S-metolachlor (PRE) fb. bentazon + fomesafen (POST) was the most expensive herbicide combination but did not significantly increase yield compared to other herbicides, it was not among the treatments with the highest gross margins at East Lansing except in wide rows in 2010 (Table 3.19), although it was among them at Richville. In 2010, when weed pressure was relatively low, the weed-free treatment was not among those with the highest gross margins except in wide rows at East Lansing; however, under heavier weed pressure in 2011, the weed-free was among them. The untreated control was never among the treatments with the highest gross margins in any site-year except in narrow rows at East Lansing in 2010 and at low grower price at Richville in 2010, indicating that weed control is necessary to maximize profit in dry bean.

Conclusions. Imazamox + bentazon (POST) treatment was the most effective treatment investigated at reducing both weed biomass and populations over various environmental conditions. However, it provides weak control of annual grass and common ragweed and fails to reduce common purslane populations.

S-metolachlor often results in mild early crop injury. Halosulfuron and the Total POST treatment result in very minor early crop injury. Injury symptoms for all of these normally disappeared by 14 DAT and totally disappeared by 28 DAT. It seems likely that these injury symptoms result in little or no yield loss.

The effectiveness of all three treatments involving PRE applications is compromised when significant rainfall does not soon follow the PRE application; this was especially evident with regard to common lambsquarters control.

The S-metolachlor + halosulfuron (PRE) treatment was the most effective treatment for reducing overall weed populations when incorporated by rainfall. It consistently reduced weed biomass in various environmental conditions. It allows some annual grass and common purslane escapes but is otherwise effective at reducing the population of these weeds. However, it provides poor control of velvetleaf.

The S-metolachlor (PRE) fb. bentazon + fomesafen (POST) treatment can reduce weed biomass across various environmental conditions but only reduced weed populations in three of four site-years. It provides weaker control of common lambsquarters than the other treatments, control of common ragweed is inconsistent, and it does not reduce annual grass populations.

Halosulfuron (PRE) fb. clethodim (POST) was among the most effective treatments at reducing weed population in three of the four site-years but required the addition of fomesafen at East Lansing in 2011 to control ALS-resistant common ragweed escapes from the halosulfuron. Whether this treatment was among the best at reducing weed biomass, reduced biomass to a lesser extent than other treatments, or failed to reduce weed biomass at all depended on site-year. When fomesafen was added, it was also among the best at reducing weed biomass. POST annual grass control is excellent but is delayed due to poor PRE control and the slow action of clethodim. The addition of fomesafen is needed to control common purslane. This treatment provides no control of eastern black nightshade.

Narrow rows reduced weed population in one of two years. They reduced weed biomass in all site-years except the one in which a severe drought occurred. Narrow rows usually improve control of upright broadleaf weeds unless herbicide control is excellent but generally fail to improve control of annual grass and common purslane. Narrow-row weed suppression is not strong enough to replace herbicide application but is a significant supplement to herbicide application.

All herbicide combinations improved yield compared with the untreated and had yields that were similar to one another in all site-years. All herbicide combinations resulted in yields similar to the weed-free except at East Lansing in 2011 when only halosulfuron fb. clethodim + fomesafen did so. Narrow rows often result in an increase in yield compared to wide rows. Because 38-cm rows often result in better weed suppression and higher yield than 76-cm rows, this row width should be adopted as an effective supplement to herbicide application. However, in order to maximize weed control and yield in the absence of mechanical control, herbicide application is necessary. Imazamox + bentazon (POST) is the most consistent treatment of those investigated for overall weed suppression.

Table 3.1. Weed control systems, rates, and application timings in black beans planted in 38- and 76-cm rows.

			Dry bean growth stage at application			
			East Lansing		Richville	
Weed control system	Rate ha^{-1}	Timing	2010	2011	2010	2011
S-metolachlor[a] + halosulfuron	1.4 kg + 35 g	PRE	--	--	--	--
S-metolachlor fb.[b] fomesafen + bentazon + COC	1.4 kg fb. 0.28 kg + 0.56 kg + 1% v/v	PRE fb. POST	-- fb. V4	-- fb. V3	-- fb. V6	-- fb. V2
halosulfuron fb. clethodim + fomesafen[c] + COC	35 g fb. 77 g + 0.28 kg + 1% v/v	PRE fb. POST	-- fb. V4	-- fb. V3	-- fb. V6	-- fb. V2
imazamox + bentazon + COC + AMS	35 g + 0.56 kg + 1% v/v + 2.8 kg	POST	V2	V3	V2	V2
Weed-free[d]	--	--	--	--	--	--
Untreated	--	--	--	--	--	--

[a] S-metolachlor (Dual II Magnum, Syngenta Corporation, Wilmington, DE); halosulfuron (Permit, Gowan Company, Yuma, AZ); fomesafen (Reflex, Syngenta Corporation, Wilmington, DE); bentazon (Basagran, BASF Corporation, Research Triangle Park, NC); clethodim (Select Max, Valent U.S.A. Corporation, Walnut Creek, CA); imazamox (Raptor, BASF Corporation, Research Triangle Park, NC); crop oil concentrate (Herbimax, Loveland Products, Loveland, CO); ammonium sulfate (Actamaster, Loveland Products Inc., Loveland, CO).

[b] Abbreviations: fb., followed by; COC, crop oil concentrate; AMS, ammonium sulfate; PRE, preemergence; POST, postemergence.

[c] Fomesafen was only included in this treatment at East Lansing in 2011.

[d] Weed-free treatment consisted of s-metolachlor (1.4 kg ha^{-1}) + halosulfuron (35 g ha^{-1}) applied PRE supplemented with hand-weeding.

Table 3.2. Monthly and 30-yr average precipitation at the Harry and Hazel Box Farm in East Lansing, MI and at the Saginaw Valley Research and Extension Center in Richville, MI in 2010 and 2011[a].

	East Lansing			Richville		
Month	2010	2011	30-yr avg.	2010	2011	30-yr avg.[c]
	cm			cm		
June	10.6 (4.1)[b]	4.4	8.4	6.9 (2.8)[b]	3.8	9.3
July	6.4	17.8	8.2	2.3	3.4	7.6
August	3.4	6.4	8.3	3.2	7.6	8.0
September	9.2	6.7	9.3	2.9	5.8	10.7
Total	29.6	35.3	34.2	15.3	20.6	35.6

[a] Michigan Automated Weather Network, http://www.agweather.geo.msu.edu/mawn/, Michigan State University, East Lansing, MI

[b] Precipitation data in parenthesis is from the time of planting.

[c] 30-yr average for Caro, MI; none available for Richville

Table 3.3. Summary of the effect of herbicide treatments and of narrow rows on crop injury and control of various weed species.

Weed control treatment	Crop injury	Common lambsquarters	Pigweed	Velvetleaf[a]	Common ragweed[a]	E. black nightshade[a]	Common purslane[b]	Annual grass[b]
S-metolachlor + halosulfuron (PRE)	Very slight to moderate	Excellent if PRE well incorporated; poor to fair otherwise	Excellent if normal moisture; good in drought	Good if population is low; poor to fair if high	Excellent	Excellent	Good	Good
S-metolachlor (PRE) fb. bentazon + fomesafen (POST)	Very slight to moderate	Good to excellent if PRE well incorporated; poor to good otherwise	Excellent if normal moisture; fair to good in drought	Excellent if population is low; poor to fair if high	Fair to excellent	Excellent	Excellent	Excellent but with some escapes
halosulfuron (PRE) fb. clethodim (+ fomesafen at East Lansing in 2011) (POST)	Very slight to slight	Excellent if PRE incorporated by rainfall; poor to fair otherwise	Excellent if normal moisture; fair to good in drought	Excellent if population is low or fomesafen is included	Excellent with fomesafen, fair to excellent without it	Poor	Excellent if fomesafen is included	Excellent but delayed on most species; poor on stinkgrass
imazamox + bentazon (POST)	Very slight to slight	Good to excellent	Excellent	Excellent	Poor to good	Excellent	Fair to good	Fair but usually non-lethal
Narrow rows	Usually no effect; once slightly increased injury	Consistently improve control	Improve control and reduce density	Improve control if population is high	Sometimes improve control and reduce density	No effect on weed density	Rarely improve control	Little improvement in control

[a] Only present in significant numbers at East Lansing

[b] Only present in significant numbers at East Lansing in 2011

Table 3.4. Main effect of herbicide treatment on control of common lambsquarters, pigweed, and velvetleaf at 28 DAT at East Lansing and Richville in 2010 and 2011[a].

	Common lambsquarters		Pigweed		Velvetleaf	
Herbicide combination[b]	East Lansing 2010	Richville 2010[d]/2011	East Lansing 2010/2011, Richville 2011	Richville 2010	East Lansing 2010	East Lansing 2011
	Control (%)					
S-metolachlor + halosulfuron (PRE)	98 a	63 b	97 a	79 b	88 b	56 b
S-metolachlor (PRE) fb. bentazon + fomesafen (POST)	97 a	73 b	98 a	74 b	96 ab	69 b
halosulfuron (PRE) fb. clethodim (POST)[c]	98 a	71 b	98 a	74 b	94 ab	92 a
Imazamox+ Bentazon (POST)	94 a	89 a	99 a	94 a	99 a	97 a

[a] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq 0.05$ level.

[b] Herbicide rates, application timings, and additives are presented in Table 3.1.

[c] Treatment included fomesafen applied POST at East Lansing in 2011.

[d] Data used were from the 45 DAT evaluation.

Table 3.5. Main effect of row width on control of common lambsquarters, pigweed, and velvetleaf at 28 DAT at East Lansing and Richville in 2010 and 2011[a].

Row width	Common lambsquarters		Pigweed		Velvetleaf	
	East Lansing 2010	Richville 2010[b]/2011	East Lansing 2010/2011, Richville 2011	Richville 2010	East Lansing 2010	East Lansing 2011
	Control (%)					
38 cm	98 a	78 a	99 a	75 a	96 a	84 a
76 cm	96 a	70 b	97 b	67 b	93 a	72 b

[a] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq 0.05$ level.

[b] Data used were from the 45 DAT evaluation.

Table 3.6. Interaction of row width and herbicide combination with regard to control of common lambsquarters at 28 DAT at East Lansing in 2011[a].

Herbicide combination[b]	Row width 38 cm	Row width 76 cm
	Control (%)	
S-metolachlor + halosulfuron (PRE)	97 a	98 a
S-metolachlor (PRE) fb. bentazon + fomesafen (POST)	89 b	80 c
halosulfuron (PRE) fb. clethodim + fomesafen (POST)	99 a	98 a
Imazamox + bentazon (POST)	98 a	90 b

[a] Means throughout the table that have the same lower-case letter are statistically similar to one another at the $\alpha \leq 0.05$ level.

[b] Herbicide rates, application timings, and additives are presented in Table 3.1.

Table 3.7. Main effect of herbicide treatment on control at 28 DAT of eastern black nightshade and common ragweed at East Lansing in 2010 and of annual grass and common purslane at East Lansing in 2011[a].

Herbicide combination[b]	Eastern black nightshade: East Lansing 2010[d]	Common ragweed: East Lansing 2010	Annual grass: East Lansing 2011	Common purslane: 2011[e]
	Control (%)			
S-metolachlor + halosulfuron (PRE)	99 a	96 a	87 b	88 b
S-metolachlor (PRE) fb. bentazon + fomesafen (POST)	96 a	99 a	94 a	99 a
halosulfuron (PRE) fb. clethodim (POST)[c]	39 b	94 a	94 a	98 a
Imazamox + bentazon (POST)	88 a	87 b	77 c	82 b

[a] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq 0.05$ level.

[b] Herbicide rates, application timings, and additives are presented in Table 3.1.

[c] Treatment included fomesafen applied POST at East Lansing in 2011.

[d] Data used were from POST evaluation as eastern black nightshade was largely confined to the halosulfuron fb. clethodim plots throughout the growing season.

[e] Data used were from the 14 DAT evaluation; since common purslane is a low-growing weed, canopy closure made it difficult to evaluate at 28 DAT.

Table 3.8. Interaction of row width and herbicide treatment at 28 DAT with regard to control of eastern black nightshade at East Lansing in 2011[a].

Herbicide combination[b]	Row width: 38 cm	Row width: 76 cm
	Control (%)	
S-metolachlor + halosulfuron (PRE)	99 a	99 a
S-metolachlor (PRE) fb. bentazon + fomesafen (POST)	99 a	99 a
halosulfuron (PRE) fb. clethodim + fomesafen (POST)	81 b	72 c
Imazamox+ bentazon (POST)	99 a	99 a

[a] Means throughout the table that have the same lower-case letter are statistically similar to one another at the $\alpha \leq 0.05$ level.
[b] Herbicide rates, application timings, and additives are presented in Table 3.1.

Table 3.9. Main effect of row width on control of eastern black nightshade and common ragweed at 28 DAT at East Lansing in 2010 and of annual grass and common purslane at East Lansing in 2011[a].

Row width	Eastern black nightshade: East Lansing 2010[b]	Common ragweed: East Lansing 2010	Annual grass: East Lansing 2011[c]	Common purslane: 2011[d]
	Control (%)			
38 cm	78 a	96 a	90 a	93 a
76 cm	83 a	91 b	86 b	91 a

[a] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq$ 0.05 level.
[b] Data used were from POST evaluation as eastern black nightshade was largely confined to the halosulfuron fb. clethodim plots throughout the growing season.
[c] Significant level of $\alpha \leq 0.1$
[d] Data used were from the 14 DAT evaluation; since common purslane is a low-growing weed, canopy closure made it difficult to evaluate at 28 DAT.

Table 3.10. Main effect of row width on mid-season weed populations at East Lansing and Richville in 2010 and 2011[a].

	East Lansing		Richville	
Row width	2010	2011	2010	2011
	——— weeds m^{-2} ———		——— weeds m^{-2} ———	
38-cm	1.1 b	15.5 a	1.7 b	7.8 a
76-cm	2.1 a	14.5 a	2.3 a	8.6 a

[a] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq$ 0.05 level.

Table 3.11. Main effect of weed control system on mid-season weed populations at East Lansing and Richville in 2010 and 2011[a].

	East Lansing		Richville	
Weed control system[b]	2010	2011	2010	2011
	——— weeds m^{-2} ———		——— weeds m^{-2} ———	
S-metolachlor + halosulfuron (PRE)	0.3 c	5.2 b	1.6 b	9.2 b
S-metolachlor (PRE) fb. fomesafen + bentazon (POST)	0.2 c	16.5 ab	1.7 b	10.4 b
halosulfuron (PRE) fb. clethodim (POST)[c]	0.7 c	5.8 b	1.8 b	4.0 b
imazamox + bentazon (POST)	2.0 b	25.2 a	0.5 c	5.4 b
Weed-free	0.1 c	1.9 b	0.2 c	0.5 c
Untreated	6.3 a	22.4 a	4.5 a	20.1 a

[a] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq$ 0.05 level.

[b] Herbicide rates, application timings, and additives are presented in Table 3.1.

[c] Fomesafen applied POST was included in this treatment at East Lansing in 2011.

Table 3.12. Main effect of weed control system on end-of-season weed biomass at East Lansing and Richville in 2010 and 2011[b].

	East Lansing		Richville	
Weed control system[a]	2010	2011	2010	2011
	kg ha^{-1}		kg ha^{-1}	
S-metolachlor + halosulfuron (PRE)	0.4 b	337 b	431 b	1468 bc
S-metolachlor (PRE) fb. fomesafen + bentazon (POST)	4.9 b	212 bc	517 b	1755 b
halosulfuron (PRE) fb. clethodim (POST)[c]	2.6 b	97 cd	551 b	2306 ab
imazamox + bentazon (POST)	3.6 b	82 cd	27 c	376 cd
Weed-free	0.1 b	17 d	4.6 d	25 d
Untreated	196 a	2361 a	2375 a	3375 a

[a] Herbicide rates, application timings, and additives are presented in Table 3.1.

[b] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq 0.05$ level.

[c] Fomesafen applied POST was included in this treatment at East Lansing in 2011.

Table 3.13. Main effect of row width on end-of-season weed biomass at East Lansing and Richville in 2010 and 2011[a].

	East Lansing		Richville	
Row width	2010	2011	2010	2011
	kg ha^{-1}		kg ha^{-1}	
38-cm	22 b	427 b	595 a	1020 b
76-cm	47 a	609 a	706 a	2082 a

[a] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq 0.05$ level.

Table 3.14. Main effect of weed control system on bean yield at East Lansing in 2011 and Richville in 2010 and 2011[b].

Weed control system[a]	East Lansing	Richville	
	2011	2010	2011
	—— kg ha^{-1} ——	—— kg ha^{-1} ——	
S-metolachlor + halosulfuron (PRE)	4175 b	2129 a	2703 a
S-metolachlor (PRE) fb. fomesafen + bentazon (POST)	3953 b	2114 a	2796 a
halosulfuron (PRE) fb. clethodim (POST)[c]	4260 ab	2087 a	2732 a
imazamox + bentazon (POST)	4143 b	2166 a	3067 a
Weed-free	4828 a	2171 a	3081 a
Untreated	2333 c	1832 b	2086 b

[a] Herbicide rates, application timings, and additives are presented in Table 3.1.

[b] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq 0.05$ level.

[c] Fomesafen applied POST was included in this treatment at East Lansing in 2011.

Table 3.15. Main effect of row width on bean yield at East Lansing in 2011 and Richville in 2010 and 2011[a].

Row width	East Lansing	Richville	
	2011	2010	2011
	—— kg ha^{-1} ——	—— kg ha^{-1} ——	
38-cm	4294 a	2126 a	2857 a
76-cm	3607 b	2040 a	2634 b

[a] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq 0.05$ level.

Table 3.16. Interaction of row width and weed control system with regard to bean yield at East Lansing in 2010[b].

Weed control system[a]	Row width (cm) 38-cm	76-cm
	kg ha^{-1}	
S-metolachlor + halosulfuron (PRE)	3162 abc	3343 ab
S-metolachlor (PRE) fb. fomesafen + bentazon (POST)	2816 d	3133 abc
halosulfuron (PRE) fb. clethodim + fomesafen (POST)	3337 ab	3167 abc
imazamox + bentazon (POST)	3210 ab	3169 abc
Weed-free	3073 bcd	3406 a
Untreated	3046 bcd	2865 cd

[a] Herbicide rates, application timings, and additives are presented in Table 3.1.
[b] Means throughout the table that have the same lower-case letter are statistically similar to one another at the $\alpha \leq 0.05$ level.

Table 3.17. Main effect of row width on economic return at East Lansing in 2011 and Richville in 2010 and 2011[a].

	East Lansing	Richville	
Row width	2011	2010	2011
	\$ ha^{-1}[c]	\$ ha^{-1}[c]	
38-cm	1850 a	698 a	1235 a
76-cm	1544 b	667 a	1097 b

[a] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq$ 0.05 level.
[c] Assumes black bean dealer price of \$1.25 kg^{-1} and grower price of \$0.88 kg^{-1} (USDA-AMS 2011, Varner 2012) and herbicide and adjuvant costs as of June 2011 (Local herbicide costs 2011)

Table 3.18. Main effect of weed control system on economic return at East Lansing in 2011 and Richville in 2010 and 2011[b].

	East Lansing	Richville	
Weed control system[a]	2011	2010	2011
	—— $ ha^{-1}[d] ——	—— $ ha^{-1}[d] ——	
S-metolachlor + halosulfuron (PRE)	1812 ab	711 ab	1145 a
S-metolachlor (PRE) fb. fomesafen + bentazon (POST)	1698 b	690 ab	1182 a
halosulfuron (PRE) fb. clethodim (POST)[c]	1846 ab	708 ab	1180 a
imazamox + bentazon (POST)	1798 b	724 a	1382 a
Weed-free	2002 a	626 c	1225 a
Untreated	1022 c	637 bc	946 b

[a] Herbicide rates, application timings, and additives are presented in Table 3.1.

[b] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq 0.05$ level.

[c] Fomesafen applied POST was included in this treatment at East Lansing in 2011.

[d] Assumes black bean dealer price of \$1.25 kg^{-1} and grower price of \$0.88 kg^{-1} (USDA-AMS 2011, Varner 2012) and herbicide and adjuvant costs as of June 2011 (Local herbicide costs 2011)

Table 3.19. Interaction of row width and weed control system with regard to economic return at East Lansing in 2010[a].

Weed control system[b]	Row width (cm) 38-cm	Row width (cm) 76-cm
	$ ha^{-1}[c]	
S-metolachlor + halosulfuron (PRE)	1361 ab	1442 a
S-metolachlor (PRE) fb. fomesafen + bentazon (POST)	1191 d	1332 abc
halosulfuron (PRE) fb. clethodim + fomesafen (POST)	1469 a	1374 ab
imazamox + bentazon (POST)	1382 ab	1364 ab
Weed-free	1220 cd	1369 ab
Untreated	1340 abc	1260 bcd

[a] Means throughout the table that have the same lower-case letter are statistically similar to one another at the $\alpha \leq 0.05$ level.

[b] Herbicide rates, application timings, and additives are presented in Table 3.1.

[c] Assumes black bean dealer price of \$1.25 kg^{-1} and grower price of \$0.88 kg^{-1} (USDA-AMS 2011, Varner 2012) and herbicide and adjuvant costs as of June 2011 (Local herbicide costs 2011)

APPENDIX

Table A3.1. Schedule of activities in the field for weed control-row width studies.

Event	2010		2011	
	East Lansing	Richville	East Lansing	Richville
Planting	June 16	June 10	June 8	June 6
Preemergence application	June 17	June 11	June 8	June 6
Cutworm trap establishment	June 22	June 23	June 21	June 20
Stand counts	June 28	June 23	June 21	June 20
Bean thinning	June 28	June 24	none	none
Early postemergence application	July 8	July 1	July 5	June 30
Late postemergence application	July 12	July 7	July 5	June 30
3-day rating	none	none	July 8	None
7-day rating	July 23	July 13	July 13	July 6
14-day rating	July 27	July 21	July 21	July 14
Total weed count	July 27	July 23	July 21	July 20
28-day rating	August 10	August 6	July 25	August 8
45-day rating	none	August 23	none	none
Weed harvest	September 21	September 6	September 22	September 9
Final harvest	September 29	September 7	October 18	October 6

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CHAPTER 4

EFFECTS OF ROW WIDTH AND PLANTING POPULATION ON TYPE II BLACK BEAN AND SMALL RED BEAN ARCHITECTURE AND YIELD COMPONENTS

Abstract

The development of upright black and small red bean varieties gives dry bean growers the opportunity to plant in narrower rows, which has been associated with yield benefits in many crops. Yield differences between row widths or lack of yield differences between planting populations must be explained by a change in one or more yield components in individual plants: pods plant^{-1}, seeds pod^{-1}, or seed weight, possibly coupled with changes in plant architecture. Field studies were conducted in 2010 and 2011 at two locations in Michigan to examine the effect of row width and plant population on yield, yield components, and plant architecture in two upright varieties: 'Zorro' black and 'Merlot' small red beans. Each variety was planted in 38- and 76-cm rows, as well as 51-cm rows at one location. Populations were 196500, 262000, and 327000 plants ha^{-1} in black bean and 148000, 196500, and 262000 plants ha^{-1} in small red bean. Yield was obtained using direct harvest by combine. Plants were also hand-harvested, and on each plant, height was measured, branches and pods were counted, and pods were separated into main-stem and branch fractions and by number of seeds pod^{-1}. One hundred seeds from each plot were weighed. Narrow rows resulted in higher yields than wide rows in two of four site-years in both dry bean classes. Planting population did not influence yield. The component most sensitive to both row width and population was number of pods plant^{-1}; branch pods were more responsive than main-stem pods. Number of beans pod^{-1} was slightly higher at the low

population but rarely affected by row width. Seed weight differences between treatments were rare and small. Branching increased at lower populations and in narrow rows. Row width and population had little effect on plant height. The most sensitive yield component to both row width and population was number of pods per plant, with most of the increase occurring on branches, although number of seeds per pod also increased at low population.

Nomenclature: Dry bean, *Phaseolus vulgaris*.

Introduction

Dry bean yield is a function of plant population per area and the three components of individual plant yield: number of pods per plant, number of seeds per pod, and seed size (Adams 1967; Lehman and Lambert 1960; Grafton et al. 1988). Plant population is a function of plant spacing within and between rows and is therefore largely dependent on the planter and planter settings used by the grower. However, dry bean plants are capable of compensating for lower populations through increases in one or more of the three yield components, while extremely high plant populations may reduce yield due to intraspecific competition (Bennett et al. 1977). The objective of this study was to observe the response of the three plant-level yield components and other aspects of plant architecture to changes in population and row width.

One morphological trait that has been associated with yield in dry bean and observed to vary with plant population and row width is branching; more branching has been reported to accompany higher yield (Bennett et al. 1977). Plant height and lodging have also been observed to vary with row width or population, and both could have an indirect impact on yield, especially since low-hanging pods are associated with yield loss in direct harvest systems (Horn et al. 2000).

Little research exists regarding dry bean yield components; however, there is a great deal of published literature with regard to yield components and architecture in soybean. Since the growth habit of Type II dry bean is similar to that of soybean, and the components of yield are the same, these results may be suggestive of the behavior of Type II dry bean. Weber et al. (1966) planted soybeans in row widths ranging from 13 to 102 cm and populations ranging from 64,200 to 516,400 plants ha^{-1}. They found that yield was maximized at 128,500 plants ha^{-1} or higher populations and that with increasing population, height and lodging increased while pods per plant decreased. With regard to row width, yield and number of pods per plant were maximized in 25-cm rows, though the number of seeds per pod was maximized in 51-cm rows. The number of pods per plant was the primary factor controlling yield, and it was greatest at intermediate row widths and populations. Norsworthy and Shipe (2004) found that the main stem contributed the majority of the yield in narrow row soybean while the branches contributed the majority of the yield in wide rows. In contrast, Ethredge et al. (1989) found that main stem yield decreased in wide rows while branch yield was unaffected. They also found that branch yield decreased as population increased.

In dry beans, a few studies have touched on the subject of yield components. Crothers and Westerman (1976) found that yield decreased above 300,000 plants ha^{-1} due to decreased pod formation on lower nodes and death of branches. Bennett et al. (1977) found that the yield component that changed the most when yields were reduced at high populations was pods per plant. Grafton et al. (1988) found that in determinate Type I dry beans, yield tended to rise with population; however, indeterminate Type III pinto beans maintained similar yields over a wide range of populations due to decreases in both pods per plant and seeds per pod with increasing population. In a review paper, Adams (1967) noted that dry bean yield components were often inversely related to one another.

Few, if any, studies have been conducted comparing the development of yield and morphology across row widths and populations in Type II dry bean. Understanding how Type II dry beans compensate, or fail to compensate, for low populations and wide rows and how crowding in high populations or narrow rows affects the structure and reproductive allocation of individual plants will be useful for determining the optimum planting population for various row widths and for evaluating varieties for their potential in wide- or narrow-row systems. Therefore, the objectives of this study were to determine how row width and population in Type II black and small red bean affect: 1) the ability of plants to grow tall yet remain upright, 2) the three yield components of individual plant yield, and 3) branching patterns and 4) the allocation of yield between branches and main stem.

Materials and Methods

Field experiments were conducted in 2010 and 2011 at the Michigan State University Harry and Hazel Box Farm near East Lansing, Michigan and at the Michigan State University Saginaw Valley Research and Extension Center near Richville, Michigan. Two Type II (upright indeterminate vine) varieties were planted at both sites: ‘Zorro’ black beans and ‘Merlot’ small red beans (Michigan Crop Improvement Association, Okemos, MI). At East Lansing, both varieties were planted in 38- and 76-cm rows using a John Deere split-row planter (Deere and Company, Moline, IL) on June 16, 2010 and June 8, 2011. At Richville, both varieties were also planted in 51-cm rows; two separate Monosem planters (Monosem Incorporated, Edwardsville, KS) were used to plant the three different row widths on June 10, 2010 and June 6, 2011. Planter settings were adjusted to attain three target populations for each variety-row width combination.

Target populations were 196,500, 262,000, and 327,500 plants ha^{-1} for black bean and 148,000, 196,500, and 262,000 plants ha^{-1} for small red bean. Populations were held constant across row widths, leading to differences in within-row plant spacing for each population (Table 4.1). When the crop fully emerged, the number of bean plants in two 3-m sections of row in each plot was counted to obtain actual emerged plant populations. Actual early-season stand counts following emergence showed populations that often fell short of (or, less commonly, exceeded) the desired populations. However, within each row width at each site, the highest target population did result in the highest stand count and the lowest population in the lowest stand count (Table 4.2). The experimental design was a randomized complete block with regard to variety, row width, and planting population. Each treatment was replicated four times. All plots were maintained weed-free throughout the growing season with a preemergence (PRE) application of S-metolachlor (Dual II Magnum, Syngenta Corporation, Wilmington, DE) at 1.4 kg ai ha^{-1} plus halosulfuron (Permit, Gowan Company, Yuma, AZ) at 35 g ai ha^{-1} supplemented with hand weeding. At East Lansing, clethodim (Select Max, Valent U.S.A. Corporation, Walnut Creek, CA) at 77 g ha^{-1} with crop oil concentrate at 1% v/v was applied postemergence (POST) to all plots to control excess grasses (mainly *Setaria* spp.). Plot width was 3 m; with seven, five, and four rows per plot for the 38-, 51-, and 76-cm row widths, respectively. Plot length ranged from 9.1 to 10.7 m, depending on location.

After the crop fully emerged, stand counts were taken in two 3-m sections of row in each plot to determine actual emerged plant populations. In many cases, actual early-season stand counts following emergence fell short of (or, less commonly, exceeded the target populations (Table 4.2). However, within each row width at each site, the highest population resulted in the lowest stand count and the lowest population in the lowest stand count. In fifty-four of sixty site-year-class combinations, stand count was similar enough to target population to essentially maintain the proper relationship of populations among treatments. In six cases, stand count was dramatically lower than target planting population, although still higher than the next lowest population within the row width. Four of these six cases occurred at Richville in 2010 and may have been the result of poor emergence in dry soil (Table 4.3). The small number of interactions between population and row width suggests that the effect of most of these variations from target population had limited impact on the results of these studies.

Precipitation data was obtained throughout the growing season from the Michigan Automated Weather Network (http://www.agweather.geo.msu.edu/mawn/, Michigan State University, East Lansing, MI), which maintains stations on the Michigan State University Horticulture Farm less than a mile from both field locations.

At physiological maturity, dry bean plants were sampled from three 0.25 m^2 areas in each plot. For each plant, the following data were taken: height, number of branches per plant, number of pods on branches, and pods on the main stem. Branch and main-stem pods were individually separated into categories of 1 to 9 seeds per pod. Beans were then threshed, and one hundred seeds were counted and weighed to obtain the weight per hundred seeds. The data was aggregated to obtain average number of pods per plant and average number of seeds per pod for each sample. The ratio of the number of pods on the branches to the number of pods on the main stem and the ratio of the average number of seeds per pod on the branches to the average number of seeds per pod on the main stem were also calculated. In 2011, instead of examining all plants per sample, a subsample of five plants was examined from each 0.25 m^2 area.

Immediately prior to harvest, all plots were visually evaluated for lodging of bean plants. The evaluation system was a 0-5 scale in which 0 indicated no lodging, and 5 indicated that all plants were prostrate. A preharvest treatment of glyphosate (Roundup PowerMax, Monsanto Company, Saint Louis, MO) at 0.84 kg ae ha^{-1} was applied to all plots at both locations in 2011 to expedite bean desiccation. Dry bean plots were direct harvested with a small plot combine (Massey-Ferguson 8XP, AGCO, Duluth, GA) with a 1.5-m header. The center two-, three-, and five-rows were harvested in the 76-, 51-, and 38-cm row width plots, respectively. Dry bean yield was adjusted to 18% moisture.

Data were subjected to ANOVA using PROC MIXED in SAS 9.2 (SAS Institute Inc., Cary, NC) and treatment means were compared using Fisher's protected LSD at the $\alpha \leq 0.05$ level of significance. Some data were log or square root transformed for analysis, but all data is presented untransformed. Data were combined over population, row width, year, and location when no significant interactions were present.

Results and Discussion

Growing conditions. Rainfall from June through September in 2010 was lower than the 30-yr average at both locations (Table 4.3). At East Lansing, above-average rainfall in June and near-average rainfall in July and September allowed dry bean plants to develop normally despite a dry August. At Richville, rainfall was well below average in every month, and much of the June rainfall came prior to planting; by the beginning of September, most bean plants had senesced, rendering September rainfall irrelevant. Only 11 cm of rain fell at Richville between planting and harvest, resulting in stunted crop plants.

In 2011, rainfall from June through September was slightly above the 30-yr average at East Lansing, while at Richville it was once again below the 30-yr average. At East Lansing, rainfall was slightly to moderately below average in three months, but in late July a single weather system brought 16 cm of rainfall over three days, making that month's total dramatically above average and supplying ample water for pod formation, especially with moderate rainfall continuing through September. At Richville, rainfall was below average in every month, but all rainfall in June occurred after planting, and monthly totals were higher than those of the previous year in July and August. Rainfall was sufficient for normal plant development, and pod filling continued into September.

Yield. Yield was significantly greater in 38-cm rows than in 76-cm rows in four of the eight site-year-class combinations: East Lansing 2010 black beans, East Lansing 2011 black beans, East Lansing 2011 small red beans, and Richville 2011 small red beans (Table 4.4). In only one site-year-class combination (Richville 2010 black beans, which experienced severe drought) did the opposite effect occur, and this was not significant at $\alpha \leq 0.05$. In addition, in a companion set of studies in black bean (presented in chapter 3), yield was higher in 38-cm rows than in 76-cm rows in three of four site-years. Yield rarely differed by planting population (Table 4.5).

Lodging. Lodging was always at least 80% greater in small red bean than in black bean in every site-year on a 0-5 evaluation scale (Table 4.6). At Richville in 2010, virtually no lodging was observed in black bean. In four of the remaining seven site-year-class combinations, 38-cm rows significantly reduced lodging compared with 76-cm rows, and in two of four combinations, 51-cm rows resulted in a similar lodging reduction. In only one combination, narrow rows marginally increased lodging ($\alpha \leq 0.1$). Planting population did not affect lodging in any site-year (Table 4.7).

Plant height. Average plant height was consistently greater in small red beans than in black beans in all site-years. At East Lansing in 2010, there was a row width by planting population interaction: black bean height was 6.6 cm greater in 38-cm rows than in 76-cm rows at 327,000 seeds ha^{-1} only. At Richville in 2010, black bean height was 4.2 cm greater in 51-cm rows than in 38-cm rows across all populations; height was intermediate in 76-cm rows (Table 4.8). Planting population did not affect height at either site (Table 4.9). In 2011, plant height was not affected by row width or planting population in either class at either site-year. Small red bean height was unaffected by row width or planting population in all site-years.

Planting population had no effect on plant height in any circumstance, while the effect of row width was inconsistent and often not present at all. Plant height appears to be essentially independent of the factors examined in these studies. This contrasts with the work of Weber et al. (1966) in soybean, who found that soybean height increased with increasing populations, and Horn et al. (2000) in dry bean, who found that dry bean height was lower in narrow rows.

Pods per plant. Black beans had significantly more pods per plant than small red beans except at East Lansing in 2010. Average number of pods per plant in black bean varied widely among site-years from 13.2 at Richville in 2010 to 19.3 at Richville in 2011. Average number of pods per plant in small red beans ranged from 10.4 at Richville in 2010 to 14.4 at East Lansing in 2011.

At East Lansing, there were more pods per plant in 38-cm rows than in 76-cm rows in every site-class combination. In 2010, the number of pods per plant in 38-cm rows was 17% greater in black bean and 18% greater in small red bean than in 76-cm rows. In 2011, number of pods per plant was 36% and 40% greater in 38-cm than in 76-cm rows respectively (Table 4.10).

At Richville, the effect of row width was less consistent. In 2010, there was a row width by population interaction: there were fewer black bean pods per plant in 38-cm rows (8.5 pods plant^{-1}) than in 51- (11.4) or 76-cm rows (10.8) at 327,500 seeds ha^{-1} only. Across populations, there were more small red bean pods per plant in 51-cm rows (11.8) than in 38-cm rows (10.5), and more in either narrow row width than in 76-cm rows (8.8) (Table 4.10). At Richville in 2011, there were more black bean pods per plant in 76-cm rows (21.0) than in 51-cm rows (17.8), with 38-cm rows intermediate (19.4). In small red beans, row width did not have a significant effect on number of pods per plant.

The effect of planting population on number of pods per plant was consistent. In every site-year-class combination, number of pods per plant increased as population decreased. Across all sites, years, and classes, number of pods per plant averaged 11.8 at high populations, 14.3 at medium populations, and 17.7 at low populations (Table 4.9).

In five of the eight site-year-class combinations, there were more pods per plant in 38-cm rows than in 76-cm rows. In one of the four combinations in which 51-cm rows were used, there were more pods per plant in 51-cm rows than in 76-cm rows. In only one case did 76-cm rows result in more pods per plant than 51-cm rows, and in no case did 76-cm rows result in more pods per plant than 38-cm rows across all populations. Thus, narrow rows tended to result in more pods per plant, probably because of the increase in light interception often observed in narrow rows. When combined across site-years and classes, number of beans per pod increased with decreasing population; number of pods per plant was greater at low populations than at either medium or high populations and greater in medium populations than in high populations (Table 4.9). Thus, dry bean plants are able to compensate for low population, producing more pods per plant when fewer plants are present; this should enable them to produce similar yields across a range of populations. This confirms the findings of Goulden et al. (1976), Bennett et al. (1977), and Grafton et al. (1988) that number of pods per plant in dry bean is lower at higher populations. Change in number of pods is an important mechanism controlling yield changes in individual plants.

Seeds per pod. Black beans had significantly more seeds per pod than small red beans in every site-year. Average number of black bean seeds per pod in various site-years ranged from 3.99 to 5.39, while average number of small red bean seeds per pod ranged from 3.07 to 3.65.

The effect of row width on seeds per pod was inconsistent (Table 4.11). At East Lansing in 2010 and Richville in 2011, row width did not have a significant effect on number of seeds per pod. However, at East Lansing in 2011, number of black bean seeds per pod averaged 4.99 seeds pod^{-1} in 38-cm rows compared with just 4.60 seeds pod^{-1} in 76-cm rows; row width did not affect number of seeds per pod in small red bean.

Under drought conditions at Richville in 2010, number of seeds per pod significantly increased with widening row width across classes. In black bean, the average number of seeds per pod was 3.85 in 38-cm rows, 4.04 in 51-cm rows, and 4.43 in 76-cm rows. In small red beans, the average number of beans per pod was 3.15 in 38-cm rows, 3.49 in 51-cm rows, and 3.55 in 76-cm rows.

The fact that the site-year in which number of seeds per pod increased in wide rows was a drought year suggests that number of seeds per pod may have been reduced in narrow rows by intraspecific competition for water between the rows. This may also explain the apparent yield reduction in narrow rows in this site-year-class combination. Number of pods per plant is more likely to play a role in yield differences due to row width than number of seeds per pod, but it appears that seeds per pod may also sometimes be responsive to intraspecific competition. The general lack of difference in number of seeds per pod between different row widths is consistent with the work of Goulden et al. (1976) who saw no differences in seeds per pod between row widths.

Although within most site-year-class combinations the effect of planting population on number of seeds per pod was non-significant, when analyzed across all site-year-class combinations, there were significantly more seeds per pod at low populations than at high populations; low populations averaged 3.99 seeds pod^{-1}, medium populations 3.92 seeds pod^{-1}, and high populations 3.85 seeds pod^{-1} (Table 4.9). This suggests that an increase in the number of seeds per pod plays a role in dry bean compensation for low population. This confirms the finding of Grafton et al. (1988) that number of seeds per pod decreases with increasing population. While this effect was less pronounced than the increase in number of pods per plant with decreasing population, it does appear that an increase in number of seeds per pod plays a role in dry bean compensation for low population.

Weight per hundred seeds. Dry bean seed weight was consistently higher in small red bean than in black bean as both are bred to maintain a relatively uniform seed size. Weight per hundred seeds varied among site-years. Black bean weight per hundred seeds ranged from 15.4 g to 24.0 g, and small red bean weight per hundred seeds ranged from 29.5 g to 41.8 g.

At East Lansing in both years and at Richville in 2010, weight per hundred seeds within each class was not significantly different between row widths (Table 4.12). However, at Richville in 2011, weight per hundred seeds was 11% and 12% greater in 76-cm rows than in 51- or 38-cm rows respectively in black bean and 5% and 8% greater respectively in small red bean.

Across all site-years in small red bean seed weight was higher at 148,000 seeds ha^{-1} than at 262,000 seeds ha^{-1} at the α=0.1 level of significance (Table 4.9). However, population had no effect on seed weight in black bean.

In one site-year, seed weight was greater in wide rows than in narrow rows; the effect was small and did not occur in other site-years. It does appear that small red bean weight was slightly higher at low population than at high population, but this effect was very slight. Seed weight generally appears to be insensitive to row width and population; this is a positive finding because growers would not want substantial variation in bean size from the industry standard for a given class. This is also consistent with the finding of Goulden et al. (1976) that seed weight did not differ between row widths. The reason for the increase in seed weight in wide rows at Richville in 2011 is not obvious, particularly since in one of the classes at that site-year, yield was actually higher in narrow rows. That seed weight should increase at low population does seem to fall into the pattern of plants compensating for low plant density, but the small size of the increase makes it questionable whether this is really the correct explanation.

Branching. Number of branches per plant was unaffected by class except at Richville in 2011 when black beans averaged 0.35 more branches $plant^{-1}$ than small red beans, and at all site-years, the classes were affected in the same manner by planting population and row width, so data is presented across classes. Number of branches per plant was similar at Richville in 2010, at East Lansing in 2011, and in small red beans at Richville in 2011, averaging 1.83-1.95 branches plant^{-1}. Number of branches per plant was higher in black bean at Richville in 2011 at 2.25 branches plant^{-1} and was lower at East Lansing in 2010 at 1.56 branches plant^{-1}.

Narrow rows increased branching in all planting populations in three of the four site-years (Table 4.13). At East Lansing in 2010, plants in 38-cm rows averaged 23% more branches per plant than those in 76-cm rows. At East Lansing in 2011, plants in 38-cm rows averaged 47% more branches than those in 76-cm rows. At Richville in 2011, branching was 18% and 12% greater in 38-cm rows than in 51- or 76-cm rows respectively.

At Richville in 2010 under drought conditions, the effect of row width on branching depended on planting population (Table 4.14). At low populations, branching was 18% higher in 38-cm rows than in 76-cm rows with 51-cm rows intermediate. At medium populations, the effect of row width was non-significant. At high populations, branching was 39% greater in 51-cm rows than in 38-cm rows with 76-cm rows intermediate.

The effect of planting population on branching was consistent across all site-year-class combinations (Table 4.9). Across all combinations, number of branches per plant increased as population decreased, averaging 1.52 branches plant^{-1} at high populations, 1.80 branches plant^{-1} at medium populations, and 2.28 branches plant^{-1} at low populations.

In most cases, plants had a higher number of branches in 38-cm rows than in 76-cm rows; 51-cm rows were either intermediate or similar to 76-cm rows. It appears that narrow rows tend to encourage branching, which may account for a portion of the ability of narrow- row dry beans to develop a more complete canopy than in wide rows; this differs from findings in soybean that row width does not affect branching (Ethredge et al. 1989) or that branching increases in wide rows (Lehman and Lambert 1960). However, an increase in branching in narrow rows makes sense in light of the much greater within-row plant spacing in narrow rows within a given population; presumably, narrow rows allow the plants more room to grow toward one another without coming into competition with one another. Since Bennett et al. (1977) found that branching was associated with higher yields in dry bean, this increase in branching may contribute to observed increases in yield in narrow rows.

Branching increased with decreasing population. This confirms the finding of Bennett et al. (1977) that dry bean plants produce fewer branches with increasing population. Dry bean plants clearly compensate for lower populations by branching, allowing individual plants to grow larger and fill in the gaps between plants; this behavior presumably accounts for the limited effect of planting population on canopy closure, yield, and other parameters observed in other portions of these studies. It is also similar to the findings of Ethredge et al. and Lehman and Lambert that branching increases with decreasing population in soybean.

Pod distribution between main stem and branch. The average number of pods on the main stem was somewhat similar across site-years, ranging from 6.8 to 8.7 in black beans and from 5.6 to 6.0 in small red beans. There were more pods on the main stem in black beans than in small red beans in every site-year. Average number of pods on branches per plant was more variable between site-years, ranging from 5.4 to 10.3 in black bean and from 4.4 to 7.4 in small red bean. The lowest average numbers of branch pods per plant occurred at Richville in 2010, suggesting that drought conditions reduced the number of branch pods despite only a marginal reduction in number of branches.

Main-stem pods. At East Lansing in both years and in small red bean at Richville in 2011, row width did not affect the number of pods on the main stem. In the other cases, the effect was inconsistent (Table 4.15). At Richville in 2010 across classes, main-stem pods per plant was higher in 51-cm rows than in 38-cm rows, but higher in both 51 and 38-cm rows than in 76-cm rows. In contrast, at Richville in 2011, there were more small red bean main-stem pods per plant at 76- or 51-cm than at 38-cm.

In six out of eight site-year-class combinations, lower populations led to more main-stem pods per plant (Table 4.16). At East Lansing in 2010 across classes, there were more main-stem pods per plant at low and medium populations than at high populations; differences were 24% and 15% respectively. At East Lansing in 2011 in black bean, there were more main-stem pods per plant at low population than at medium population or high population; differences were 25% and 33%. At Richville in 2010, main-stem pods per plant decreased with increasing population across classes, with differences ranging from 6-17%. At Richville in 2011, there were more black bean main-stem pods per plant at 196,500 seeds ha^{-1} than at 262,000 or 327,500 seeds ha^{-1}, differences of 14% and 17%. However, in 2011 at both sites, main-stem pods per plant in small red bean was not affected by planting population.

Number of pods on the main stem was often unaffected by row width, but when it was affected, it was maximized in 51-cm rows; this occurred in all three site-year-class combinations in which row width had a significant effect on main-stem pods per plant. In six of eight site-year-class combinations, lower populations increased main-stem pods per plant. It appears that pod development on the main stem is a part of compensation for lower populations in many cases.

Branch pods. In seven of eight site-year-class combinations, narrower rows led to more branch pods per plant in at least some circumstances (Table 4.17 for main effects, Tables 4.18 and 4.19 for interactions).

At East Lansing in both years, number of branch pods per plant was higher in 38-cm rows than in 76-cm rows across both classes. In 2010, there were 33% more branch pods per plant in 38-cm rows than in 76-cm rows. In 2011, there were 73% more branch pods per plant in 38-cm rows than in 76-cm rows (Table 4.17).

At Richville in 2010, there was an interaction of row width with planting population across classes with regard to branch pods (Table 4.18). At low populations, there were more branch pods per plant in 38-cm rows than in 76-cm rows, with 51-cm rows intermediate, whereas at high populations, there were more branch pods per plant in 51-cm rows than in 38-cm rows, with 76-cm rows intermediate. At medium populations, row width did not have a significant effect on branch pods. At Richville in 2011 in small red bean, there was also an interaction of row width with planting population (Table 4.19). At 196,500 and 327,000 seeds ha^{-1}, row width did not have a significant effect on branch pods; at 262,000 seeds ha^{-1}, branch pods per plant was higher in 38-cm rows than in 76-cm rows, with 51-cm rows intermediate.

At Richville in 2011 in black bean, there were 25% more branch pods per plant in 76-cm rows than in 51-cm rows, with 38-cm rows were intermediate.

In all year-class combinations at East Lansing, there were more branch pods per plant in narrow rows than in wide rows. At Richville, there were interactions in two of the four year-class combinations in which branch pods per plant were higher in narrow rows than wide rows in certain cases, and in an additional combination, the intermediate row width had more branch pods per plant than the wide row width. In only one year-class combination were there more branch pods per plant in wide rows, and this occurred during the 2010 Richville drought.

Across all site-year-class combinations, number of branch pods plant^{-1} increased with decreasing population (Table 4.9, footnote c.). At high populations, number of branch pods per plant averaged 5.22, at medium populations 6.81, and at low populations 9.47.

Branch pods are highly responsive to planting population and likely play a major role in allowing dry bean plants to compensate for low population. They are also often responsive to narrow rows and likely play a major role in the increase in yield often observed in narrow rows.

Ratio of branch pods to main-stem pods. The ratio of pods on the branches to pods on the main stem (branch-stem ratio) was similar between classes except at East Lansing in 2010 when it was 1.15 in black beans and 0.71 in small red beans. In black beans, the branch-stem ratio was similar across site-years, ranging from 1.12 to 1.18 except at Richville in 2010 when it was 0.70. The branch-stem ratio in small red beans differed by year, being 0.68-0.71 in 2010 compared to 1.03-1.11 in 2011. The low ratios at Richville in 2010 suggest that in drought conditions, a higher percentage of pods develop on the main stem than is typical in a year of adequate moisture.

In six of the eight site-year-class combinations, the branch-stem ratio increased with narrowing rows (Table 4.20). Across all site-year-class combinations, the branch-stem ratio increased with reduced populations (Table 4.9).

In three site-years, the branch-stem ratio was lower in wide rows than in narrow rows. At East Lansing in both years, the black bean branch-stem ratio was lower in 76-cm rows than in 38-cm rows in both classes. In 2010, the ratios in 76-cm and 38-cm rows were 0.62 and 0.82 for black bean and 0.98 and 1.39 for small red bean; in 2011, across both classes, they were 0.89 and 1.52. At Richville in 2011, the black bean branch-stem ratio was marginally lower (α=0.1) in 51-cm rows at 1.02 than in 38-cm rows at 1.22 with 76-cm rows intermediate at 1.14. The small red bean branch-stem ratio was lower in 51- and 76-cm rows at 0.98 and 0.84 respectively than in 38-cm rows at 1.25. Under drought conditions at Richville in 2010, row width did not affect the branch-stem ratio in either class.

The branch-stem ratio was higher in 38-cm rows than in 76-cm rows in five of the eight site-year-class combinations and was higher in 38-cm rows than in 51-cm rows in one of these five combinations plus an additional one (Table 4.20). The only exceptions to higher branch-stem ratios in narrow rows occurred at Richville in 2010 under drought conditions, and the reverse effect never occurred. This indicates that in narrow rows, a higher percentage of pods produced are often borne on the branches. It appears that the increased formation of branch pods is a major mechanism by which yield may be increased in narrow rows. This is probably due at least partly to the greater within-row spacing between seeds in narrow rows for a given population. Each plant has more room to spread out toward neighboring plants in narrow rows, thus encouraging branching parallel to the row.

Across all site-year-class combinations, the branch-stem ratio increased with decreasing population (Table 4.9). At high populations, the branch-stem ratio averaged 0.71, at medium populations 0.87, and at low populations 1.25. This indicates that forming branch pods is a major means by which dry beans compensate for low populations and that more branch pods are formed due to this compensation than main-stem pods.

Distribution of seeds per pod between main stem and branch. Average number of seeds per pod on the main stem in black bean ranged from 3.98 to 5.44 and in small red bean from 2.99 to 3.7. Average number of seeds per pod on the branches in black beans ranged from 3.94 to 5.34 and in small red beans from 3.15 to 3.6. In every site-year-class combination, there more seeds per pod both on the main stem and on the branches in black bean than in small red bean.

Seeds per main-stem pod. At East Lansing in 2010, there were more black bean seeds per main stem pod in 38- than in 76-cm rows; row width did not affect seeds per main-stem pod in small red beans. Conversely, at Richville in 2010 under drought conditions, number of seeds per main-stem pod increased with increasing row width across classes. In 2011, row width did not affect seeds per main-stem pod at either site, and planting population did not affect seeds per main-stem pod in any site-year.

One case in which narrow rows increased the number of seeds per pod on the main stem was observed, suggesting the possibility that this may occasionally play a role in increasing yields, but this was hardly definitive. The observation of reduced seeds per main-stem pod in narrow rows under drought conditions at Richville in 2010 corresponded to the overall reduction in seeds per pod in that site-year, which may indicate intra-specific competition for water between the rows in narrow rows.

Seeds per branch pod. At East Lansing in 2011, number of seeds per branch pod was higher in 38- than in 76-cm rows. Conversely, at Richville in 2010, number of seeds per branch pod increased with increasing row width across classes. At East Lansing in 2010 and at Richville in 2011, row width did not affect seeds per branch pod in either class, and planting population never significantly affected seeds per branch pod.

The increase in seeds per branch pod at one site-year once again suggests the possibility that an increase in the number of seeds per pod may sometimes play a small role in positive yield responses to narrow rows. Once again, the increase in seeds per branch pod in wide rows at Richville in 2010 suggests the possibility of intra-specific competition for water reducing number of seeds per pod.

Ratio of branch seeds per pod to main-stem seeds per pod. The ratio of the average number of seeds per pod on the branches to the average number of seeds per pod on the main stem (branch-stem seed ratio) tended to be close to 1.0, indicating that the number of seeds per pod does not strongly differ between the main stem and the branches. In black bean, the stem-branch seed ratio ranged from 0.93 to 1.03 while in small red beans, it ranged from 0.91 to 1.05. The branch-stem seed ratio differed very little or not at all between classes. The lowest branch-stem seed ratios occurred at Richville in 2010, suggesting that drought conditions may cause bean plants to form more seeds per pod on the main stem than on the branches. The next lowest branch-stem seed ratios were at East Lansing in 2010 and were 0.97 in small red beans and 0.98 in black beans; at the other two site-years, ratios were 1.0 or higher.

The branch-stem seed ratio remained near 1.0 regardless of row width. At East Lansing in both years and at Richville in 2011, row width did not affect the branch-stem seed ratio (Table 4.21). However, under drought conditions at Richville in 2010, the branch-stem seed ratio was lower across both classes in 38-cm rows than in 51- or 76-cm rows; in 38-cm rows, the branch-stem seed ratio was 0.89, while in both wider row widths, it was 0.93, another possible indication of drought conditions favoring seed production on the main-stem and of drought stress being increased by intraspecific competition in narrow rows.

The branch-stem seed ratio was also remained near 1.0 regardless of population. In seven of the eight site-years, planting population did not affect the branch-stem seed ratio (Table 4.22). The only exception was at East Lansing in 2010 in small red bean; at 262,000 seeds ha^{-1}, branch-stem seed ratio was just 0.93 compared to 1.01 at 196,500 seeds ha^{-1} and 0.99 at 148,000 seeds ha^{-1}.

The branch-stem seed ratio is fairly stable; the decrease in the ratio in narrow rows under drought conditions and the decrease at high population in one other site-year-class combination suggest that intra-specific competition can result in disequilibrium in the number of seeds per pod between the main stem and branches, with the main stem being favored; however, this effect is not large. It does not appear that any increases in yield with branching are due a higher number of seeds per pod in branch pods than in main-stem pods.

Conclusions. Neither row width nor planting population were found to consistently affect plant height. However, lodging was often reduced in narrow rows, probably due to the mutual support of the rows across the smaller inter-row space. Planting population did not have a pronounced effect on lodging. Branching was often increased in narrow rows and always increased with increasing population.

The yield component that was most sensitive to row width and planting population was number of pods per plant, which was often higher in narrow rows and always increased with decreasing population.

Number of pods on the main stem was often unaffected by row width but was maximized in 51-cm (intermediate width) rows when it was affected. Number of pods on the main stem was often higher at lower populations, but this did not always occur. However, just as branching was highly sensitive to row width and population, number of branch pods was highly sensitive to row width and population. Branch pods often increased in response to reduced row width and always increased in response to reduced population. In addition, percentage of pods on the branches was higher in both narrow rows and at low populations, indicating that much of the increase in number of pods per plant was occurring on the branches.

Number of seeds per pod was less sensitive to changes in row width and population than number of pods. In only one site-year-class combination did narrow rows have a positive effect on average number of seeds per pod; however, low populations had an average of 0.14 more seeds per pod than high populations across all site-years. This suggests that increases in seeds per pod may at times play a role in yield responses to row width and do play a role in yield compensation for low population, but it also suggests that this role is relatively small. Under drought conditions at Richville in 2010, number of seeds per pod increased with increasing row width, an increase observed in both the main-stem and branch fractions, and at low populations the number of branch seeds per pod was marginally higher than at high population. This suggests that narrow rows and high populations may lead to intraspecific competition for water in drought conditions, which can be expressed in a reduction in the number of seeds per pod.

Differences in bean seed weights between treatments were few and small, with two instances of average weight being reduced in narrow rows and a marginally significant increase in small red bean weight at low population compared to high population overall. It seems unlikely that these differences reflect a significant contribution of seed weight variation toward yield differences between row widths, although it is possible that seed variation does play a small role in small red bean compensation for low population.

Thus, the primary driver of yield increases in narrow rows and yield compensation for low populations seems to be increasing numbers of branch pods. While main-stem pods did sometimes change in response to the treatments, especially planting population, and number of seeds per pod showed some response to them, branch pods demonstrated the most responsiveness. It appears that increased branching is key for increasing plant yield; this is because yield increases seem to be largely the result of adding more pods on the branches and because branches enable the plants to more efficiently fill the canopy, thereby capturing more light energy that can be used to form more pods.

The often-observed yield advantage in narrow rows presumably occurs because a higher percentage of available resources may be appropriated to the crop plants in narrow rows. While this is likely due in part to the greater efficiency of narrow rows – the distance between rows is more similar to the difference between plants within the row – it may also be partially the result of increased branching in narrow rows. Resources are then allocated to form a greater number pods per plant, especially on the branches. This may at times be supplemented by a small advantage in the average number of seeds per pod. In addition, the reduction in lodging in narrow rows may play a small role in causing higher yields by reducing yield loss at harvest.

Similarly, the often-observed failure of high populations to increase yield apparently occurs because more branching occurs at low populations. This allows plants to compensate for lower populations by growing larger and branching, thus filling the canopy as well or nearly as well as they would at higher populations. There may also be a corresponding increase in the extent of the root system, though this has not been confirmed. Resources are again allocated to form a greater number of pods per plant, especially on the branches. This may typically be supplemented by a small advantage in the average number of seeds per pod and, in small red bean, by a small increase in seed size.

Table 4.1. Within-row plant spacing for Type II black and small red beans planted in three row widths and at three planting populations.

Row width	Target black bean population			Target small red bean population		
	196,500 ha^{-1}	262,000 ha^{-1}	327,500 ha^{-1}	148,000 ha^{-1}	196,500 ha^{-1}	262,000 ha^{-1}
		cm			cm	
38 cm	13	10	8	18	13	10
51 cm	10	8	6	13	10	8
76 cm	7	5	4	9	7	5

Table 4.2. Early-season stand counts of black and small red beans compared with target planting populations at East Lansing and Richville in 2010 and 2011.

	East Lansing				Richville					
Target planting	2010		2011		2010			2011		
Populations (seeds ha^{-1})	38-cm	76-cm	38-cm	76-cm	38-cm	51-cm	76-cm	38-cm	51-cm	76-cm
Black beans	plants ha^{-1}				plants ha^{-1}					
196,500	197,500	175,500	187,500	168,000	174,000	163,000	165,500	183,000	183,000	131,000*
262,000	252,000	246,000	222,500	226,000	226,000	210,000	196,500*	233,500	246,000	218,500
327,500	313,500	305,000	286,500	263,000	327,500	274,000	253,000*	295,000	300,000	228,500*
Small red beans										
148,000	149,500	162,000	141,000	139,500	141,000	131,000	138,500	142,000	148,000	135,000
196,500	211,000	207,500	175,500	173,000	187,500	148,000*	179,000	175,500	186,500	165,500
262,000	289,000	267,000	246,000	236,000	233,500	153,000*	222,000	238,500	221,000	205,000

*Stand count was at or below the next lowest target population.

Table 4.3. Monthly and 30-yr average precipitation at the Harry and Hazel Box Farm in East Lansing, MI and at the Saginaw Valley Research and Extension Center in Richville, MI in 2010 and 2011.[a]

Month	East Lansing 2010	East Lansing 2011	East Lansing 30-yr avg.	Richville 2010	Richville 2011	Richville 30-yr avg.[c]
	cm			cm		
June	10.6 (4.1)[b]	4.4	8.4	6.9 (2.8)[b]	3.8	9.3
July	6.4	17.8	8.2	2.3	3.4	7.6
August	3.4	6.4	8.3	3.2	7.6	8.0
September	9.2	6.7	9.3	2.9	5.8	10.7
Total	29.6	35.3	34.2	15.3	20.6	35.6

[a] Michigan Automated Weather Network, http://www.agweather.geo.msu.edu/mawn/, Michigan State University, East Lansing, MI

[b] Precipitation data in parenthesis is from the time of planting.

[c] 30-yr average for Caro, MI; none was available for Richville

Table 4.4. Main effect of row width on yield of black and small red bean at East Lansing and Richville in 2010 and 2011[a].

	East Lansing				Richville			
	2010		2011		2010		2011	
Row width	Black	Small red	Black	Small red	Black[b]	Small red	Black	Small red
	kg ha^{-2}							
38 cm	3257 a	2553 a	4494 a	3329 a	1488 b	1612 a	3040 a	2592 a
51 cm	-	-	-	-	1553 b	1674 a	2924 a	2550 a
76 cm	2785 b	2486 a	3903 b	2830 b	1814 a	1797 a	2896 a	2339 b
Mean	3021	2520	4198	3080	1618	1694	2953	2494

[a] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq$ 0.05 level of significance unless otherwise noted.

[b] Significance level of $\alpha \leq 0.1$

Table 4.5. Main effect of planting population on yield of black and small red bean at East Lansing and Richville in 2010 and 2011[a].

	East Lansing				Richville			
	2010		2011		2010		2011	
Planting population[b]	Black	Small red	Black	Small red[c]	Black	Small red	Black	Small red
	$kg\ ha^{-1}$							
Low	3020 a	2425 a	4232 a	2958 b	1674 a	1694 ab	2915 a	2427 a
Medium	3138 a	2554 a	4103 a	3059 ab	1656 a	1774 a	2984 a	2523 a
High	2902 a	2577 a	4258 a	3222 a	1751 a	1582 b	2956 a	2619 a

[a] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq$ 0.05 level of significance unless otherwise noted.

[b] Low population targets were 148,000 seeds ha^{-1} in small red beans and 196,500 in black beans; medium population targets were 196,500 seeds ha^{-1} in small red beans and 262,000 in black beans high population targets were 262,000 seeds ha^{-1} in small red beans and 327,500 in black beans.

[c] Significance level of $\alpha \leq 0.1$

Table 4.6. Main effect of row width on lodging in black and small red bean at East Lansing and Richville in 2010 and 2011[a].

	East Lansing				Richville			
	2010		2011		2010		2011	
Row width	Black	Small red	Black	Small red	Black	Small red	Black	Small red
	(0-5 scale)							
38 cm	0.38 a	3.92 a	2.12 a	3.25 b	0 a	0.62 b	1.83 b	2.83 b
51 cm	-	-	-	-	0 a	1.17 a	1.83 b	2.96 b
76 cm	0.71 a	4.00 a	1.77 a	4.21 a	0.21 a	1.29 a	2.5 a	3.44 a
Mean	0.54	3.96	1.94	3.73	0.07	1.03	2.05	3.08

[a] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq$ 0.05 level of significance.

Table 4.7. Main effect of population on lodging in black and small red bean at East Lansing and Richville in 2010 and 2011[a].

Planting population	East Lansing 2010 Black	East Lansing 2010 Small red	East Lansing 2011 Black	East Lansing 2011 Small red	Richville 2010 Black	Richville 2010 Small red	Richville 2011 Black	Richville 2011 Small red
	(0-5 scale)							
Low	0.56 a	3.75 a	1.97 a	4.0 a	0 a	1.00 a	1.81 a	3.25 a
Medium	0.56 a	3.94 a	1.81 a	3.62 a	0 a	1.08 a	1.94 a	3.04 ab
High	0.50 a	4.19 a	2.06 a	3.56 a	0.21 a	1.00 a	2.42 a	2.93 b

[a] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq$ 0.05 level of significance.

Table 4.8. Main effect of row width on plant height in black and small red bean at East Lansing and Richville in 2010 and 2011[a].

Row width	East Lansing 2010 Black[b]	East Lansing 2010 Small red	East Lansing 2011 Black	East Lansing 2011 Small red	Richville 2010 Black	Richville 2010 Small red	Richville 2011 Black	Richville 2011 Small red
	Plant height (cm)							
38 cm	47 a	62 a	55 a	73 a	35 b	54 a	56 a	73 a
51 cm	-	-	-	-	39 a	56 a	55 a	72 a
76 cm	47 a	61 a	53 a	69 a	38 ab	55 a	56 a	78 a
Mean	47	61.5	54	71	37.3	55	55.7	74.3

[a] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq$ 0.05 level.

[b] 196,500 and 262,000 seeds ha^{-1} only; within 327,500 seeds ha^{-1}, plant height in 38-cm rows averaged 51 cm, which was statistically different from 76-cm rows, in which plant height averaged 44 cm.

Table 4.9. Main effect of planting population on yield components and plant architecture in black and small red beans at East Lansing and Richville in 2010 and 2011[a].

Planting population[b]	Pods per plant[c]	Seeds per pod	Weight per hundred beans (g) Black	Weight per hundred beans (g) Small Red[d]	Plant height (cm)	Branches per plant	Ratio of branch pods to main-stem pods
Low	17.68 a	3.99 a	19.47 a	36.61 a	57 a	2.28 a	1.25 a
Medium	14.27 b	3.92 ab	19.72 a	35.79 ab	57 a	1.80 b	0.87 b
High	11.84 c	3.85 b	19.27 a	35.34 b	57 a	1.52 c	0.71 c

[a] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq$ 0.05 level unless otherwise noted.

[b] Low population targets were 148,000 seeds ha^{-1} in small red beans and 196,500 in black beans. Medium population targets were 196,500 seeds ha^{-1} in small red beans and 262,000 in black beans. High population targets were 262,000 seeds ha^{-1} in small red beans and 327,500 in black beans.

[c] Pods plant^{-1} on branches also increased with decreasing row width across all site-year-class combinations, averaging 5.22 plant^{-1} at high populations, 6.81 plant^{-1} at medium populations, and 9.47 plant^{-1} at low populations. Pods plant^{-1} on the main stem did so in six of eight combinations (Table 4.16)

[d] Significance level of $\alpha \leq 0.1$

Table 4.10. Main effect of row width on number of pods per plant in black and small red bean at East Lansing and Richville in 2010 and 2011[a].

	East Lansing				Richville			
	2010		2011		2010		2011	
Row width	Black	Small red	Black	Small red	Black[b]	Small red	Black	Small red
	Number of pods per plant							
38-cm	16.2 a	15.2 a	19.7 a	16.8 a	15.2 a	10.5 b	19.4 ab	12.8 a
51-cm	-	-	-	-	14.3 a	11.8 a	17.8 b	13.4 a
76-cm	13.8 b	12.9 b	14.5 b	12.0 b	14.6 a	8.8 c	21.0 a	13.3 a
Mean	15.0	14.0	17.1	14.4	14.7	10.4	19.4	13.2

[a] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq$ 0.05 level unless otherwise indicated.

[b] 196,500 and 262,000 seeds ha^{-1} only; within 327,500 seeds ha^{-1}, there were more pods per plant in 76-cm (10.8) or 51-cm rows (11.4) than in 38-cm rows (8.5).

Table 4.11. Main effect of row width on number of seeds per pod in black and small red bean at East Lansing and Richville in 2010 and 2011[a].

	East Lansing				Richville		
	2010		2011		2010	2011	
Row width	Black	Small red	Black	Small red	Combined	Black	Small red
	Seeds per pod						
38 cm	5.48 a	3.59 a	4.99 a	3.11 a	3.47 c	3.99 a	3.02 a
51 cm	-	-	-	-	3.74 b	3.96 a	3.09 a
76 cm	5.29 a	3.71 a	4.60 b	3.09 a	3.95 a	4.02 a	3.10 a
Mean	5.38	3.65	4.80	3.10	3.72	3.99	3.07

[a] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq 0.05$ level.

Table 4.12. Main effect of row width on weight per hundred seeds in black and small red bean at East Lansing and Richville in 2010 and 2011[a].

	East Lansing				Richville			
	2010		2011		2010		2011	
Row width	Black	Small red	Black	Small red	Black	Small red	Black	Small red
	Weight per hundred seeds (g)							
38 cm	15.67 a	28.72 a	24.06 a	42.47 a	18.37 a	34.58 a	19.34 b	35.26 b
51 cm	-	-	-	-	18.44 a	33.93 a	19.40 b	36.51 b
76 cm	15.21 a	30.25 a	24.00 a	41.04 a	19.55 a	35.5 a	21.07 a	38.70 a
Mean	15.44	29.48	24.03	41.76	18.79	34.67	19.94	36.82

[a] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq 0.05$ level.

Table 4.13. Main effect of row width on number of branches per plant combined across black and small red bean at East Lansing and Richville in 2010 and 2011[a].

	East Lansing		Richville
Row width	2010	2011	2011
	Branches per plant		
38 cm	1.72 a	2.32 a	2.27 a
51 cm	-	-	1.92 b
76 cm	1.40 b	1.58 b	2.03 b

[a] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq 0.05$ level.

Table 4.14. Interaction between row width and planting population with regard to number of branches per plant in black and small red bean at Richville in 2010[a].

	Planting population[b]		
Row width	Low	Medium	High
	Branches per plant		
38 cm	2.51 a	1.86 cd	1.13 f
51 cm	2.29 ab	1.78 cde	1.56 de
76 cm	2.12 bc	1.77 cde	1.44 ef

[a] Means throughout the table that have the same lower-case letter are statistically similar to one another at the $\alpha \leq 0.05$ level.
[b] Low population targets were 148,000 seeds ha^{-1} in small red beans and 196,500 in black beans. Medium population targets were 196,500 seeds ha^{-1} in small red beans and 262,000 in black beans. High population targets were 262,000 seeds ha^{-1} in small red beans and 327,500 in black beans.

Table 4.15. Main effect of row width on number of pods on the main stem in black and small red beans at East Lansing and Richville in 2010 and 2011[a].

	East Lansing				Richville		
	2010		2011		2010	2011	
Row width	Black	Small red	Black	Small red	Combined	Black	Small red
	Main-stem pods plant^{-1}						
38 cm	7.6 a	5.7 a	6.7 a	5.8 a	6.2 b	8.6 a	5.3 b
51 cm	-	-	-	-	6.6 a	8.5 a	6.3 a
76 cm	7.5 a	5.8 a	6.9 a	5.4 a	5.8 c	9.0 a	6.6 a
Mean	7.55	5.75	6.80	5.60	6.27	8.7	6.07

[a] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq$ 0.05 level.

Table 4.16. Main effect of planting population on number of pods on the main stem in black and small red beans at East Lansing and Richville in 2010 and 2011[a].

	East Lansing			Richville		
	2010	2011		2010	2011	
Planting population[b]	Combined	Black	Small red	Combined	Black	Small red
	Main-stem pods plant^{-1}					
Low	7.3 a	8.0 a	5.4 a	6.8 a	9.6 a	6.4 a
Medium	6.8 a	6.4 b	6.1 a	6.4 b	8.4 b	5.9 a
High	5.9 b	6.0 b	5.4 a	5.8 c	8.2 b	5.9 a

[a] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq$ 0.05 level.
[b] Low population targets were 148,000 seeds ha^{-1} in small red beans and 196,500 in black beans. Medium population targets were 196,500 seeds ha^{-1} in small red beans and 262,000 in black beans. High population targets were 262,000 seeds ha^{-1} in small red beans and 327,500 in black beans.

Table 4.17. Main effect of row width on number of pods on the branches in black and small red beans at East Lansing in 2010 and 2011 and in black beans at Richville in 2011[a].

	East Lansing		Richville
	2010	2011	2011
Row width	Combined	Combined	Black
	Branch pods per plant		
38 cm	7.7 a	10.7 a	10.6 ab
51 cm	-	-	9.2 b
76 cm	5.8 b	6.2 b	11.5 a

[a] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq$ 0.05 level.

Table 4.18. Interaction of row width and planting population with regard to number of pods on the branches in black and small red beans at Richville in 2010[a].

Planting population[b]	38-cm rows	51-cm rows	76-cm rows
	Branch pods per plant		
Low	7.5 a	6.8 ab	6.3 b
Medium	4.7 c	5.0 c	4.4 c
High	2.5 e	4.0 cd	3.0 de

[a] Means throughout the table that have the same lower-case letter are statistically similar to one another at the $\alpha \leq 0.05$ level.
[b] Low population targets were 148,000 seeds ha^{-1} in small red beans and 196,500 in black beans. Medium population targets were 196,500 seeds ha^{-1} in small red beans and 262,000 in black beans. High population targets were 262,000 seeds ha^{-1} in small red beans and 327,500 in black beans.

Table 4.19. Interaction of row width and planting population with regard to number of pods on the branches in small red bean at Richville in 2011[a].

Planting population (seeds ha^{-1})	38-cm rows	51-cm rows	76-cm rows
	Branch pods per plant		
148,000	8.4 a	7.9 ab	8.8 a
196,500	8.0 a	6.9 abc	5.4 bc
262,000	4.8 c	5.3 bc	4.5 c

[a] Means throughout the table that have the same lower-case letter are statistically similar to one another at the $\alpha \leq 0.05$ level.

Table 4.20 . Main effect of row width on the ratio of branch pods to main-stem pods in black and small red beans at East Lansing and Richville[a].

Row width	East Lansing				Richville			
	2010		2011		2010		2011	
	Black	Small Red	Black	Small Red	Black	Small Red	Black[b]	Small Red
	Ratio of branch pods to main stem pods							
38 cm	0.82 a	1.39 a	1.75 a	1.44 a	0.67 a	0.63 a	1.22 a	1.25 a
51 cm	-	-	-	-	0.70 a	0.77 a	1.02 b	0.98 b
76 cm	0.62 b	0.98 b	0.89 b	0.90 b	0.72 a	0.64 a	1.14 ab	0.84 b
Mean	0.72	1.18	1.32	1.17	0.70	0.68	1.13	1.02

[a] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq 0.05$ level unless otherwise indicated.

[b] Significant at $\alpha \leq 0.1$

Table 4.21. Main effect of row width on the ratio of number of seeds in branch pods to number of seeds in main-stem pods in black and small red beans at East Lansing and Richville in 2010 and 2011[a].

Row width	East Lansing		Richville	
	2010	2011	2010	2011
	Ratio of seed number per pod on branch pods to seed number per pod on the main stem			
38-cm	0.97 a	1.02 a	0.89 b	1.02 a
51-cm	-	-	0.93 a	1.03 a
76-cm	0.98 a	1.01 a	0.93 a	1.04 a

[a] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq 0.05$ level.

Table 4.22. Main effect of planting population on the ratio of number of seeds in branch pods to number of seeds in main-stem pods in black and small red beans at East Lansing and Richville in 2010 and 2011[a].

	East Lansing				Richville			
	2010		2011		2010		2011	
Planting population[b]	Black	Small Red	Black	Small Red	Black	Small Red	Black	Small Red
	Ratio of seed number per pod on branch pods to seed number per pod on the main stem							
Low	0.99 a	0.99 a	1.05 a	1.00 a	0.93 a	0.92 a	1.00 a	1.06 a
Medium	1.03 a	1.01 a	1.00 a	1.00 a	0.94 a	0.92 a	1.02 a	1.05 a
High	0.99 a	0.93 b	1.03 a	1.01 a	0.93 a	0.90 a	1.00 a	1.04 a
Mean	1.00	0.98	1.03	1.00	0.93	0.91	1.01	1.05

[a] Means within each column that the same letter are statistically similar to one another at the $\alpha \leq 0.05$ level.

[b] Low population targets were 148,000 seeds ha^{-1} in small red beans and 196,500 in black beans. Medium population targets were 196,500 seeds ha^{-1} in small red beans and 262,000 in black beans. High population targets were 262,000 seeds ha^{-1} in small red beans and 327,500 in black beans.

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