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# Growth and Yield Responses of Soybean to Row Spacing and Seeding Rate

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## ABSTRACT

**Some growers in northern latitudes plant soybean [*Glycine max* (L.) Merr.] with a row crop planter in 0.38 m rows, but an economic analysis concluded that drilled soybean in rows <0.25 m was optimum in the North-Central United States. We planted two varieties in 0.19, 0.38, and 0.76 m rows at 321,000; 371,000; 420,000; and 469,000 seeds ha$^{-1}$ in New York in 2008 and 2009 to evaluate how soybean compensates to wide rows or low seeding rates in the Northeast United States. Soybean had limited compensation in biomass, pods, and seeds plant$^{-1}$ at wider rows so row spacing had linear responses for biomass accumulation (598, 554, and 497 g m$^{-2}$ in 0.19, 0.38. and 0.76 m rows, respectively) and leaf area index (LAI, 3.64, 3.47, and 3.16) at seed initiation; pod (1012, 935, and 875 pods m$^{-2}$) and seed density (2272, 2230, and 2072 seeds m$^{-2}$, respectively) at harvest; and yield (3.37, 3.12, and 2.86 Mg ha$^{-1}$, respectively). Compensation in biomass, pods, and seeds plant$^{-1}$ at lower seeding rates resulted in similar biomass accumulation (528–570 g m$^{-2}$), LAI (3.38–3.46), pod (921–965 pods m$^{-2}$), and seed densities (2123 to 2234 seeds m$^{-2}$) across seeding rates. Nevertheless, yield showed a quadratic response to seeding rate (3.04, 3.25, and 3.12 Mg ha$^{-1}$ at 321,000; 420,000; and 469,000 seeds ha$^{-1}$, respectively) with no row spacing interaction. Soybean compensated more at lower seeding rates than at wider rows, but field-scale studies are being conducted to evaluate the economics of both practices.**


Some growers in northern latitudes plant soybean in 0.38 m instead of 0.76 m rows because of consistent yield increases at latitudes north of 43 N (Lee, 2006), and increased prevalence of split-row planters allowing soybean planting in 0.38 m rows and corn (*Zea mays* L.) planting in 0.76 m rows with the same planter (De Bruin and Pedersen, 2008b). Lambert and Lowenberg- DeBoer (2003), however, concluded that planting soybean in 0.19 m rows with a grain drill was more economical in an annual corn–soybean rotation in the North-Central United States, based on a summary of studies showing a 4.8% yield advantage for drilled (<0.25 m rows) compared with 0.38 m rows. Furthermore, Kratochvil et al. (2004) reported that drilled soybean in 0.19 vs. 0.38 m rows yielded the same or more in 47 of 48 cultivar/row spacing comparisons in a 3-yr study for full-season and double-cropped soybean in Maryland. Consequently, it is not clear if growers should plant soybean in 0.38 m rows with a row crop planter instead of 0.19 m rows with a grain drill in northern latitudes, especially if growers still plant wheat with grain drills.

Bertram and Pedersen (2004) reported a 5% yield increase for soybean in 0.19 vs. 0.76 m rows in southern Wisconsin, an 8.7% increase in central Wisconsin, and a 9.6% increase in northern Wisconsin in a 3-yr study. In the same study, however, soybean in 0.19 m rows yielded the same as in 0.38 m rows in central and northern Wisconsin and 4.7% less than in 0.38 m rows in southern Wisconsin. In a 4-yr study in southern Wisconsin (Pedersen and Lauer, 2003), average yields did not differ among the three row spacings, but an interaction with years was observed with soybean in 0.19 m rows yielding greater in 2 yr and soybean in 0.38 m rows yielding greater in 1 yr. Janovicek et al. (2006) reported soybean in 0.19 m rows yielded 13% more compared with 0.76 m rows under moldboard plow and no-tillage systems, but yielded only 4% more under moldboard plow and the same under no-till compared with 0.38 m rows in a 3-yr study at three locations in Ontario, Canada. In an Indiana study at three locations (Hanna et al., 2008), soybean in 0.19 vs. 0.38 m rows yielded 9% more in the absence of wheel-track damage associated with postemergence pesticide applications, but yielded the same in the presence of wheel-track damage. Results from the more recent studies in northern latitudes indicate no consistent yield advantage for drilled soybean in 0.19 m rows compared to 0.38 m rows. Consequently, DeBruin and Pedersen (2008b) advocate the adoption of 0.38 m row spacing, based on a 5.6% yield increase in 0.38 vs.0.76 m rows in a 3-yr study at five locations in Iowa, where grain drills are not prevalent because wheat is not a major crop.

Split-row planters compared to grain drills may allow for reduced soybean seeding rates and seed costs because row crop planters result in more uniform seed depth and distance between seeds in a row, improving emergence and uniformity of final stands (Bertram and Pedersen, 2004). Some studies (Weber et al., 1966; Oplinger and Philbrook, 1992) in northern latitudes, however, have reported row spacing by seeding rate interactions with soybean responding more positively to higher seeding rates in narrow vs. wide rows. Other studies in Ohio (Beurelein, 1988) and Ontario, Canada (Ablett et al., 1991) reported no row spacing by seeding rate interactions with

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**Abbreviations:** LAI, leaf area index.

similar optimum seeding rates in 0.18 vs. 0.36 m or 0.25 vs. 0.50 m rows, respectively. Kratochvil et al. (2004) also reported that drilled soybean had the same response to seeding rates in 0.19 and 0.38 m rows. Consequently, it is not clear if growers should reduce seeding rates, if planting soybean with a spilt-row planter in 0.38 m rows instead of a drill in 0.19 m rows.

Soybean management practices (including variety-growth habit, full-season vs. double-cropped soybean, row spacing, seeding rates, etc.) vary greatly across different regions of the United States and currently no published research exists on row spacing by seeding rate interactions in the Northeast United States. Cox et al. (2010) recently reported that drilled soybean in 0.19 m rows compensated for increased space at lower seeding rates (358,000 seeds $ha^{-1}$) by increasing branch, biomass, pods and seeds $plant^{-1}$, which resulted in similar yield across seeding rates in New York. In contrast, soybeans did not compensate for increased space as thinning rates increased (10, 25, and 50% plant removal) at the sixth node stage (Cox et al., 2010). The objective of this study was to evaluate growth and yield components of soybean at three row spacings and four seeding rates to determine how soybeans compensate under different row spacing and seeding rate combinations.

## MATERIALS AND METHODS

Field experiments were conducted in 2008 and 2009 on a Honeoye silt loam soil (fine-loamy, mixed, active, mesic, Glossic Hapludalfs) at a Cornell University research farm near Aurora, NY (42°44′ N, 76°40′ W). The experimental site has been in a corn–soybean rotation since 1990. Soil tests in both years indicated a pH of 7.8 with high concentrations (Mehlich) of P and K.

The experimental site was chisel plowed the day before planting and disked-harrowed the day of planting in both years. The experimental design was a randomized complete block in a split-split-plot arrangement, replicated three times, with two varieties as main plots, three row spacings (0.19, 0.38, and 0.76 m) as subplots, and four seeding rates as sub-subplots. Main plots measured 35 by 10.7 m, subplots measured 35 by either 4.6 m (0.19 m row spacing) or 3.1 m (0.38 and 0.76 m row spacing), and sub-subplots measured 8.75 m by 4.6 or 3.1 m oriented in a North–South direction. Pioneer brand, "91Y90", a late Maturity Group I variety, and Asgrow brand, "AG2002", an early Maturity Group II variety, were inoculated on the day of planting with *Bradyrhizobium japonicum*. Both varieties have medium canopy widths (according to company ratings). Both varieties were planted on 13 May 2008 and 11 May 2009 with a 4.6-m wide grain drill (Model 5400, Case IH, Racine, WI) in 0.19 m rows or a 3.3 m wide 7-row White Split-Row Planter (Coldwater, OH) with functioning inter-units for 0.38 m rows or nonfunctioning inter-units for 0.76 m rows. Seeding rates approximated 321,000; 370,000; 420,000; and 469,000 seeds $ha^{-1}$ (based on calibration of both varieties at different drill settings or calibration of the White Air Seeder at both row spacings). The area where the planters were adjusted for seeding rate changes served as a 1-m border area to the north and south between the 8.75 m lengths of the sub-subplots. Starter fertilizer was not applied because of high soil test levels for P and K. Glyphosate [*N*-(phosphonomethyl) glycine] was applied at 1.12 kg a.i. $ha^{-1}$ in mid-June of both years for weed control. Some minor hand-weeding was done in August for additional weed control in both years of the study.

Early plant densities were determined in all sub-subplots at the three-node (V3) stage (Fehr and Caviness, 1977) in mid-June by counting the total number of plants in two 1.14 $m^2$ areas in 0.19 m (six rows) and 0.38 m row (three rows) spacings and two 1.52 $m^2$ areas (two rows) in 0.76 m row spacing. All plants in a 0.57 $m^2$ area in the 0.19 m and 0.38 m rows and a 0.76 $m^2$ area in the 0.76 m row were hand-harvested and counted on 18 August 2008 and 20 August 2009, the beginning of seed development (R5 stage), to determine plant density, leaf area $plant^{-1}$ (using a LI-3100 leaf area meter, LI-COR, Lincoln, NE) and biomass $plant^{-1}$ (after drying the plants in a forced air drier at 60°C for 48 h). We then calculated LAI and aboveground biomass $m^{-2}$, based on the respective sampling areas. All plants in a 0.57 $m^2$ area in the 0.19 and 0.38 m rows and a 0.76 $m^2$ area in the 0.76 m row were hand-harvested and counted on the morning of combine-harvest to determine plant density, branch number and pod number (>10 mm) $plant^{-1}$, and pods $m^{-2}$. The pods were hand-threshed later, and all the seeds from the sample from each sub-subplot were counted with the use of a seed counter (Old Mill Company, Savage, MD) and then weighed. From these data we calculated seeds $plant^{-1}$, seeds $pod^{-1}$, seeds $m^{-2}$, and seed mass (mg). Final plant densities were determined from the average of plant counts at the R5 and harvest sampling dates.

A plot combine (Model 140C, Hege-Wintersteiger Ag Germany) harvested a 5.75 m length of the six center rows (1.14 m) at 0.19 m row spacing, the three center rows (1.14 m) at 0.38 m row spacing, and the two center rows (1.52 m width) at 0.76 m row spacing of each sub-subplot on 7 Oct. 2008 and 25 Sept. 2009. Seed from each sub-subplot was cleaned, weighed, and tested for moisture content. Reported yield was adjusted to 130 g $kg^{-1}$ moisture content. Lodging was evaluated in each sub-subplot at harvest, but minimal lodging was observed so not reported.

Variety, row spacing, and seeding rate were considered fixed, and year and replication were considered random effects in the ANOVA using PROC MIXED (SAS Institute, 2003). The Bartlett test ($P = 0.01$) indicated that all variances were homogeneous across years. The Shapiro-Wilk statistic in the PROC CAPABILITY: NORMAL TEST option of SAS indicated normality for all data. Orthogonal contrasts were used to test the responses of the measured variables to the three row spacings and four seeding rates within the ANOVA by partitioning the sums of squares into linear and quadratic components (the quadratic was also the lack of fit for row spacings because there were only three spacings). The contrast coefficients for seeding rate were $-3 - 1 + 1 - 3$ for the linear and $+1 - 1 - 1 + 1$ for the quadratic contrasts. The contrast coefficients for row spacing were $-1\ 0 + 1$ for the linear and $+1 - 2 + 1$ for the quadratic contrasts. Significance was determined at $P = 0.05$. Varieties showed no three-way and only two two-way interactions with row spacing so results will be averaged over varieties with mention in the text where variety by row spacing interactions were observed.

## RESULTS AND DISCUSSION

Overall growing conditions were similar in 2008 and 2009, despite monthly differences in total precipitation and average temperature (Table 1). Precipitation from May through August totaled 347 mm in 2008 and 372 mm in 2009, close to normal (360 mm). Temperatures from May through August averaged 18.7°C in 2008 and 18.5°C in 2009, slightly cooler than normal (19.0°C). Soybean attained the R7.0 stage (beginning maturity) by 10 September in both years so weather conditions in September had little impact on yields. Average yields were similar across growing seasons (3.3 Mg $ha^{-1}$ in 2008 and 3.0 Mg $ha^{-1}$ in 2009) probably because of similar overall growing conditions.

Early plant densities at the V3 stage did not differ among row spacings (Table 2), despite the potential for higher emergence rates with a row crop planter (Bertram and Pedersen, 2004; Epler and Staggenborg, 2008). Likewise, final plant densities did not differ among row spacings (Table 2), indicating similar plant mortality rates (~2.5%) from the V3 stage to the R5 to R8 growth stages. Final plant densities, as expected, had a linear response to seeding rate with no row spacing by seeding rate interaction (Table 2). The two lower seeding rates had negligible plant mortality, whereas the two higher seeding rates had about 7% plant mortality. Other studies have reported a greater impact of row spacing (Ethredge et al., 1989; Oplinger and Philbrook, 1992; De Bruin and Pedersen, 2008b) or seeding rates (Ethredge et al., 1989; Board 2000) on plant mortality.

Plant height had a linear response to row spacing but no response to seeding rate and no row spacing by seeding rate interaction (Table 2). Differences in plant height among row spacings, however, were small (86–90 cm). Branches $plant^{-1}$ did not respond to row spacing, but had a linear response to seeding rate with no row spacing by seeding rate interaction (Table 2). Soybean produced about 20% more branches $plant^{-1}$ at the lower seeding rates (~2.5 branches $plant^{-1}$) compared with the higher seeding rates (~2.05 branches $plant^{-1}$). Compensation in branch number is the main vegetative growth mechanism for yield compensation in soybean (Board, 2000) so increased branch number at the lower seeding rates increased the potential for yield compensation in this study. In contrast, soybean produced similar branches $plant^{-1}$ in 0.19 m rows (2.3) and 0.76 m rows (2.1), which decreased the potential for yield compensation at wider row spacing in this study.

Leaf area $plant^{-1}$ at the R5 stage had linear and quadratic responses to row spacing but no response to seeding rate and no row spacing by seeding rate interaction (Table 3). Biomass $plant^{-1}$ had a quadratic response to row spacing and a linear response to seeding rate with no interaction between row spacing and seeding rate (Table 3). Leaf area and biomass $plant^{-1}$ increased by about 20% as row spacing widened from 0.19 to 0.38 m, but then decreased by about 5% as row spacing increased to 0.76 m. Apparently, individual soybean plants compensated in leaf area and biomass as row spacing increased to 0.38 m, but no further compensation occurred in 0.76 m rows. Biomass $plant^{-1}$ increased by 24% as seeding rate decreased from 469,000 (19.9 g $plant^{-1}$) to 321,000 seeds $ha^{-1}$ (26.3 g $plant^{-1}$), similar to the 20% increase in biomass $plant^{-1}$ as seeding rates decreased from 580,000 to 358,000 seeds $ha^{-1}$ in a previous study in New York (Cox et al., 2010). Carpenter and Board (1997) also reported an increase in biomass $plant^{-1}$ as seeding rates decreased because of less intraplant competition at the lower seeding rate.

Leaf area index (LAI) and biomass accumulation at the R5 stage had linear responses to row spacing but no responses to seeding rate and no row spacing by seeding rate interaction (Table 3).

**Table 1. Monthly precipitation and average monthly temperatures at Aurora, NY, during the 2008 and 2009 growing seasons.**

| Month | Precipitation | | | Avg. Temperature | | |
|---|---|---|---|---|---|---|
| | 2008 | 2009 | 30-yr avg. | 2008 | 2009 | 30-yr avg. |
| | | mm | | | °C | |
| May | 35 | 96 | 80 | 12.2 | 14.5 | 14.2 |
| June | 97 | 121 | 104 | 20.9 | 18.1 | 19.3 |
| July | 138 | 62 | 84 | 22.1 | 19.8 | 21.8 |
| August | 77 | 93 | 92 | 19.6 | 21.5 | 20.9 |
| September | 46 | 66 | 107 | 16.1 | 18.4 | 16.7 |

As row spacing increased from 0.19 to 0.76 m, the LAI decreased by 13% (3.64–3.16) and biomass accumulation decreased by 17% (598 and 497 g $m^{-2}$, respectively). Holshouser and Whittaker (2002) proposed a critical LAI value of 3.5 to 4.0 at the R5 stage for maximum light interception and yield, and Board and Modali (2005) proposed a critical threshold level of 600 g $m^{-2}$ at the R5

**Table 2. Early stand (mid-June), final stand (averaged at the beginning of seed development and at harvest), plant height and branches $plant^{-1}$ at harvest of soybean in three row spacings at four seeding rates, averaged over two varieties and the 2008 and 2009 growing seasons at Aurora, NY.**

| Seeding rates | Row spacing | | | |
|---|---|---|---|---|
| | 0.19 m | 0.38 m | 0.76 m | Avg. |
| Early stand, plants $m^{-2}$ | | | | |
| 321,000 seeds $ha^{-1}$ | 24.7 | 22.5 | 20.7 | 22.6 |
| 371,000 seeds $ha^{-1}$ | 26.0 | 21.7 | 24.5 | 24.1 |
| 420,000 seeds $ha^{-1}$ | 31.6 | 29.6 | 28.9 | 30.0 |
| 469,000 seeds $ha^{-1}$ | 30.2 | 33.0 | 31.3 | 31.5 |
| Avg. | 28.1 | 26.7 | 26.4 | |
| Final stand, plants $m^{-2}$ | | | | |
| 321,000 seeds $ha^{-1}$ | 24.8 | 21.1 | 23.6 | 23.2 |
| 371,000 seeds $ha^{-1}$ | 27.0 | 25.1 | 23.5 | 25.2 |
| 420,000 seeds $ha^{-1}$ | 27.6 | 28.1 | 29.6 | 28.4 |
| 469,000 seeds $ha^{-1}$ | 31.2 | 28.5 | 26.4 | 28.7 |
| Avg. | 27.7 | 25.7 | 25.8 | |
| Plant height, cm | | | | |
| 321,000 seeds $ha^{-1}$ | 89 | 87 | 85 | 87 |
| 371,000 seeds $ha^{-1}$ | 90 | 89 | 85 | 88 |
| 420,000 seeds $ha^{-1}$ | 91 | 90 | 87 | 89 |
| 469,000 seeds $ha^{-1}$ | 90 | 89 | 87 | 89 |
| Avg. | 90 | 89 | 86 | |
| Branches, no. $plant^{-1}$ | | | | |
| 321,000 seeds $ha^{-1}$ | 2.4 | 2.9 | 2.2 | 2.5 |
| 371,000 seeds $ha^{-1}$ | 2.5 | 2.8 | 2.2 | 2.5 |
| 420,000 seeds $ha^{-1}$ | 2.1 | 2.2 | 1.9 | 2.1 |
| 469,000 seeds $ha^{-1}$ | 2.1 | 2.0 | 2.1 | 2.1 |
| Avg. | 2.3 | 2.5 | 2.1 | |
| Significance ($P$ values) | Early stand | Final stand | Plant height | Branches |
| Row spacing | 0.07 | 0.08 | 0.02 | 0.08 |
| Linear | 0.04 | 0.06 | 0.007 | 0.21 |
| Quadratic | 0.05 | 0.20 | 0.25 | 0.06 |
| Seeding rate | <0.0001 | <0.0001 | 0.17 | 0.01 |
| Linear | <0.01 | <0.0001 | 0.07 | 0.004 |
| Quadratic | 0.54 | 0. 52 | 0.27 | 0.90 |
| Row spacing × Seeding rate | 0.11 | 0.16 | 0.99 | 0.53 |

**Table 3. Leaf area and biomass plant$^{-1}$, leaf area index (LAI), and aboveground biomass accumulation at seed initiation (R5) stage of soybean in three row spacings at four seeding rates, averaged over two varieties and the 2008 and 2009 growing seasons at Aurora, NY.**

| Seeding rates | Row spacing | | | |
|---|---|---|---|---|
| | 0.19 m | 0.38 m | 0.76 m | Avg. |
| Leaf area, cm$^2$ plant$^{-1}$ | | | | |
| 321,000 seeds ha$^{-1}$ | 1360 | 1848 | 1610 | 1606 |
| 371,000 seeds ha$^{-1}$ | 1042 | 1444 | 1510 | 1332 |
| 420,000 seeds ha$^{-1}$ | 1414 | 1644 | 1435 | 1498 |
| 469,000 seeds ha$^{-1}$ | 1325 | 1299 | 1371 | 1332 |
| Avg. | 1285 | 1559 | 1481 | |
| Biomass plant$^{-1}$, g plant$^{-1}$ | | | | |
| 321,000 seeds ha$^{-1}$ | 22.6 | 30.8 | 25.7 | 26.3 |
| 371,000 seeds ha$^{-1}$ | 17.4 | 21.3 | 23.2 | 20.6 |
| 420,000 seeds ha$^{-1}$ | 21.6 | 25.7 | 21.2 | 22.8 |
| 469,000 seeds ha$^{-1}$ | 20.0 | 19.1 | 20.5 | 19.9 |
| Avg. | 20.4 | 24.2 | 22.7 | |
| LAI, m$^2$ m$^{-2}$ | | | | |
| 321,000 seeds ha$^{-1}$ | 3.65 | 3.45 | 3.21 | 3.44 |
| 371,000 seeds ha$^{-1}$ | 3.45 | 3.54 | 3.21 | 3.40 |
| 420,000 seeds ha$^{-1}$ | 3.72 | 3.43 | 3.24 | 3.46 |
| 469,000 seeds ha$^{-1}$ | 3.71 | 3.46 | 2.98 | 3.38 |
| Avg. | 3.64 | 3.47 | 3.16 | |
| Biomass, g m$^{-2}$ | | | | |
| 321,000 seeds ha$^{-1}$ | 595 | 580 | 534 | 570 |
| 371,000 seeds ha$^{-1}$ | 600 | 534 | 484 | 539 |
| 420,000 seeds ha$^{-1}$ | 595 | 580 | 506 | 561 |
| 469,000 seeds ha$^{-1}$ | 601 | 520 | 462 | 528 |
| Avg. | 598 | 554 | 497 | |
| Significance (*P* values) | | | | |
| Row spacing | 0.03 | 0.05 | 0.02 | 0.01 |
| Linear | 0.04 | 0.14 | 0.006 | 0.004 |
| Quadratic | 0.05 | 0.05 | 0.62 | 0.80 |
| Seeding rate | 0.10 | 0.002 | 0.98 | 0.56 |
| Linear | 0.11 | 0.003 | 0.88 | 0.32 |
| Quadratic | 0.56 | 0.28 | 0.87 | 0.95 |
| Row spacing × Seeding rate | 0.56 | 0.31 | 0.96 | 0.95 |

**Table 4. Pods plant$^{-1}$, pod density (pods m$^{-2}$), seeds pod$^{-1}$, and seeds plant$^{-1}$ of soybean in three row spacings and four seeding rates, averaged over two varieties and the 2008 and 2009 growing seasons at Aurora, NY.**

| Seeding rates | Row spacing | | | |
|---|---|---|---|---|
| | 0.19 m | 0.38 m | 0.76 m | Avg. |
| | | no. | | |
| Pods plant$^{-1}$ | | | | |
| 321,000 seeds ha$^{-1}$ | 40.2 | 40.8 | 34.5 | 38.5 |
| 371,000 seeds ha$^{-1}$ | 37.4 | 38.6 | 31.8 | 35.9 |
| 420,000 seeds ha$^{-1}$ | 31.3 | 29.4 | 30.2 | 30.3 |
| 469,000 seeds ha$^{-1}$ | 28.7 | 30.9 | 31.1 | 30.2 |
| Avg. | 34.4 | 35.0 | 31.9 | |
| Pods m$^{-2}$ | | | | |
| 321,000 seeds ha$^{-1}$ | 1020 | 944 | 840 | 934 |
| 371,000 seeds ha$^{-1}$ | 1056 | 953 | 820 | 943 |
| 420,000 seeds ha$^{-1}$ | 1003 | 948 | 945 | 965 |
| 469,000 seeds ha$^{-1}$ | 970 | 898 | 895 | 921 |
| Avg. | 1012 | 935 | 875 | |
| Seeds pod$^{-1}$ | | | | |
| 321,000 seeds ha$^{-1}$ | 2.33 | 2.45 | 2.36 | 2.38 |
| 371,000 seeds ha$^{-1}$ | 2.27 | 2.30 | 2.46 | 2.34 |
| 420,000 seeds ha$^{-1}$ | 2.33 | 2.44 | 2.32 | 2.36 |
| 469,000 seeds ha$^{-1}$ | 2.28 | 2.31 | 2.34 | 2.31 |
| Avg. | 2.30 | 2.37 | 2.37 | |
| Seeds plant$^{-1}$ | | | | |
| 321,000 seeds ha$^{-1}$ | 94 | 100 | 82 | 92 |
| 371,000 seeds ha$^{-1}$ | 85 | 89 | 78 | 84 |
| 420,000 seeds ha$^{-1}$ | 73 | 72 | 70 | 72 |
| 469,000 seeds ha$^{-1}$ | 66 | 71 | 73 | 70 |
| Avg. | 80 | 83 | 76 | |
| Significance (*P* values) | Pods plant$^{-1}$ | Pods m$^{-2}$ | Seeds pod$^{-1}$ | Seeds plant$^{-1}$ |
| Row spacing | 0.21 | <0.001 | 0.04 | 0.12 |
| Linear | 0.79 | <0.001 | 0.05 | 0.82 |
| Quadratic | 0.09 | 0.76 | 0.07 | 0.05 |
| Seeding rate | 0.0001 | 0.65 | 0.67 | <0.001 |
| Linear | <0.0001 | 0.87 | 0.27 | <0.001 |
| Quadratic | 0.90 | 0.30 | 0.77 | 0.99 |
| Row spacing × Seeding rate | 0.07 | 0.39 | 0.03 | 0.11 |

stage for maximum yield. Individual soybean plants in this study did not compensate adequately in 0.76 m rows to maintain an LAI of 3.5 and to produce 600 g of biomass m$^{-2}$. In contrast, LAI averaged from 3.38 to 3.46 and biomass accumulation from 528 to 570 g m$^{-2}$ across seeding rates because of compensation in individual plant growth at lower seeding rates. In 0.19 m rows, soybean had an LAI of 3.45 to 3.71 and biomass accumulation of 595 to 601 g m$^{-2}$ across all seeding rates, close to the proposed critical values, and similar to a previous study on drilled soybeans (Cox et al., 2010). The LAI and biomass accumulation data indicate that wider row spacing, especially 0.76 m rows, may have more of a negative impact on yield than lower seeding rates, especially in 0.19 m rows, in this environment.

Pods plant$^{-1}$ had no response to row spacing but a linear response to seeding rate with no row spacing by seeding rate interaction (Table 4). Soybean produced 27% more pods plant$^{-1}$ at 321,000 (38.5 pods plant$^{-1}$) compared with 469,000 (30.2 pods plant$^{-1}$) seeds ha$^{-1}$. Consequently, pod density had no response to seeding rate (921–965 pods m$^{-2}$) because the increase in pods plant$^{-1}$ at the lower seeding rates offset the decrease in plant densities (Table 4). A variety by row spacing interaction was observed for pod density, however, because AG2002 had a quadratic response to row spacing (960, 1006, and 917 pods m$^{-2}$ at 0.19, 0.38, and 0.76 m row spacing, respectively), whereas 91Y90 showed a linear decrease to wider row spacing (1064, 866, and 834 pods m$^{-2}$, respectively). Board et al. (1999) concluded from numerous studies that an increase in pods plant$^{-1}$, mainly on the branches, is the secondary yield component most responsible for soybean yield compensation to increased space either within or between rows. Compensation in pods plant$^{-1}$ at the lower seeding rates resulted in similar pod density and yield potential among seeding rates, which is consistent with another study on drilled soybeans in 0.19 m rows in New York (Cox et al., 2010). In contrast, fewer pods

$m^{-2}$ at the 0.76 m row spacing indicate less yield potential for soybeans at the wider row spacing in this environment.

Seeds $pod^{-1}$ responded to row spacing and not to seeding rates in this study but a row spacing by seeding rate interaction occurred (Table 4). Seeds $pod^{-1}$ is a yield component that typically does not respond to seeding rates or row spacing (Egli, 1994; Board, 2000), although Epler and Staggenborg (2008) did report a linear decrease as plant densities increased with drilled soybean in 1 yr of a 2-yr study. Seeds $pod^{-1}$ showed a different response in 0.76 m rows compared with narrower row spacing in this study but it is not clear why such an interaction would occur.

Seeds $plant^{-1}$ had a linear response to seeding rate but did not respond to row spacing or have a row spacing by seeding rate interaction (Table 4). Soybean produced 31% more seeds $plant^{-1}$ at 321,000 (92 seeds $plant^{-1}$) compared with 469,000 seeds $ha^{-1}$ (70 seeds $plant^{-1}$), resulting in similar seed densities across seeding rates (2123–2234 seeds $m^{-2}$, Table 5). In contrast, the lack of compensation in seeds $plant^{-1}$ to wider rows resulted in a linear decline in seed density as row spacing widened, but there was a variety by row spacing interaction. The variety, AG2002, had a quadratic response to row spacing (2157, 2366, and 2132 seeds $m^{-2}$ in 0.19, 0.38 and 0.76 m rows, respectively) and 91Y90 had a linear decrease to wider rows (2386, 2094, and 2011 seeds $m^{-2}$, respectively). The 9% lower seed density in 0.76 compared with 0.19 m rows, but similar seed density among seeding rates indicate that the primary soybean yield component, seed density (Board et al., 1999), compensates less at wider rows than at lower seeding rates in this environment.

Seed mass, the second primary yield component affecting yield (Board et al., 1999), did not respond to row spacing or seeding rate and there was no row spacing by seeding rate interaction (Table 5). Board et al. (1999) reported that management practices such as row spacing or seeding rates typically affect seed density rather than seed mass in southern latitudes. The results from this study indicate that row spacing and seeding rates also affect seed density more than seed mass in this environment.

Seed yield had a linear response to row spacing and a quadratic response to seeding rate with no row spacing by seeding rate interaction (Table 5). Soybean yielded 7% more in 0.19 compared with 0.38 m rows and 17% more compared with 0.76 m rows, similar to differences in biomass accumulation at the R5 stage. The 7% yield advantage in 0.19 compared with 0.38 m rows is not consistent with findings in Wisconsin (Pedersen and Lauer 2003, Bertram and Pedersen, 2004) and Ontario, Canada (Janovicek et al., 2006) where soybean generally yielded the same in 0.19 and 0.38 m rows. Despite similar LAI and biomass accumulation at the R5 stage and similar pod and seed density at harvest among seeding rates, soybean yielded 7% more as seeding rates increased from 321,000 (3.04 Mg $ha^{-1}$) to 420,000 seeds $ha^{-1}$ (3.25 Mg $ha^{-1}$), but then declined by 4% as seeding rate increased to 469,000 seeds $ha^{1}$ (3.12 Mg $ha^{-1}$). The lack of row spacing by seeding rate interaction in this study is consistent with a Maryland study (Kratochvil et al., 2004) comparing soybean in 0.19 and 0.38 m rows. Soybean growers in the Northeast United States may not benefit by switching from a grain drill to a split-row crop planter, especially if a reduction in seeding rate is a goal, as indicated by soybean yields of 3.42 Mg $ha^{-1}$ in 0.19 m rows compared with 3.06 Mg $ha^{-1}$ in 0.38 m rows at a seeding rate of 321,000 seeds $ha^{-1}$.

**Table 5. Seed density (seeds $m^{-2}$), seed mass, and seed yield at harvest at three row spacings and four seeding rates, averaged over two varieties and the 2008 and 2009 growing seasons at Aurora, NY.**

| Seeding rates | Row spacing | | | |
|---|---|---|---|---|
| | 0.19 m | 0.38 m | 0.76 m | Avg. |
| Seeds $m^{-2}$, no. | | | | |
| 321,000 seeds $ha^{-1}$ | 2286 | 2327 | 1975 | 2196 |
| 371,000 seeds $ha^{-1}$ | 2412 | 2205 | 2020 | 2212 |
| 420,000 seeds $ha^{-1}$ | 2218 | 2294 | 2188 | 2234 |
| 469,000 seeds $ha^{-1}$ | 2170 | 2095 | 2104 | 2123 |
| Avg. | 2272 | 2230 | 2070 | |
| Seed mass, mg $seed^{-1}$ | | | | |
| 321,000 seeds $ha^{-1}$ | 149 | 142 | 145 | 145 |
| 371,000 seeds $ha^{-1}$ | 149 | 145 | 143 | 145 |
| 420,000 seeds $ha^{-1}$ | 146 | 147 | 147 | 147 |
| 469,000 seeds $ha^{-1}$ | 144 | 144 | 144 | 145 |
| Avg. | 147 | 145 | 145 | |
| Seed yield, Mg $ha^{-1}$ | | | | |
| 321,000 seeds $ha^{-1}$ | 3.42 | 3.06 | 2.63 | 3.04 |
| 371,000 seeds $ha^{-1}$ | 3.21 | 2.99 | 2.90 | 3.03 |
| 420,000 seeds $ha^{-1}$ | 3.53 | 3.24 | 2.98 | 3.25 |
| 469,000 seeds $ha^{-1}$ | 3.30 | 3.17 | 2.90 | 3.15 |
| Avg. | 3.37 | 3.12 | 2.86 | |
| Significance (P values) | Seeds $m^{-2}$ | Seed mass | Seed yield | |
| Row spacing | 0.02 | 0.50 | 0.0008 | |
| Linear | 0.008 | 0.36 | 0.0002 | |
| Quadratic | 0.36 | 0.46 | 0.88 | |
| Seeding rate | 0.60 | 0.64 | 0.004 | |
| Linear | 0.46 | 0.62 | 0.01 | |
| Quadratic | 0.30 | 0.38 | 0.05 | |
| Row spacing × Seeding rate | 0.38 | 0.72 | 0.07 | |

## CONCLUSIONS

Drilled soybean in 0.19 m rows had a higher yield potential when compared with soybean planted with a row crop planter in wider rows because greater crop growth by the R5 stage (greater LAI and biomass accumulation) resulted in greater pod and seed density at harvest and subsequent yield. Despite similar LAI and biomass accumulation at the R5 stage and similar pod and seed density at harvest, soybean yield had a quadratic response to seeding rate with maximum yield of all three row spacings at 420,000 seeds $ha^{-1}$. Apparently, soybean compensation in both vegetative and reproductive growth to increased space within the row was not adequate to maintain soybean yield at a seeding rate of 321,000 seeds $ha^{-1}$. The results indicate that soybean has the greatest yield potential in 0.19 m rows at seeding rates of 420,000 seeds $ha^{-1}$ in this study. In addition to crop growth and yield potential, however, equipment costs (De Bruin and Pedersen, 2008a), prevalence of Sclerotinia stem rot (*Sclerotinia sclerotiorum*) or white mold (Grau and Radke, 1984), wheel-track damage from postemergence pesticide applications (Hanna et al., 2008), and weed competitiveness at different row spacing (Norsworthy and Frederick, 2002) also influence optimum soybean row spacing in a particular environment. Furthermore, optimum economic seeding rates are often less than seeding rates that result in maximum yield because of the high costs of soybean seed (Lee et al., 2008; De Bruin and Pedersen, 2008b).

We are currently conducting field-scale studies on three farmers' fields to determine if the greater yield potential of drilled soybean in 0.19 m rows at 420,000 seeds $ha^{-1}$ translates into the economic optimum soybean row spacing and seeding rates in the Northeast United States.

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