

Assessing the influence of row spacing on soybean yield using experimental and producer survey data



In a bean pod...

- ▶ We developed an approach to evaluate the influence of row spacing on U.S. soybean yield using both producer and experimental data.
- ▶ Experimental data showed a consistent yield advantage of narrow versus wide row spacing.
- ▶ However, data from producer fields indicate no yield difference between narrow and wide rows.
- ▶ This complementary approach can help evaluate yield increase derived from a management practice.

Soybean (*Glycine max* L.) is one of the most important oilseed crops in the world, with United States (U.S.) accounting for 35% of the global production (<http://www.fao.org/faostat/en/#data/QC>). U.S. soybean producers have progressively shifted from wide (WR; ~30 in.) to narrow (NR; ~15 in.) row spacing in recent decades. Reducing row width from 30 in. to 15 in. in the U.S. soybean producing area can increase soybean yields up to 10-15% based on data collected from experimental plots or strip trials in producer fields (e.g., De Bruin and Pedersen, 2008; Thompson et al., 2015; Walker et al., 2010), when its earlier canopy closure results in greater solar radiation capture during critical stages for yield determination (Andrade et al., 2002; Bullock et al., 1998; Salmeron et al., 2015). However, magnitude of NR-WR yield difference reported in the literature has varied greatly amongst the experiment trial sites, and there are cases in which NR have resulted in a yield penalty (e.g., Hanna et al., 2008). These inconsistent results suggest that magnitude of NR-WR yield difference is influenced by the weather-soil context and management practices.

Analysis of large databases that include experiments conducted across a wide range of environments allows quantification of yield differences between contrasting management practices and identification of management x environment interactions. However, yield differences measured in controlled experiments may not always translate into similar yield differences in producer fields (e.g., Cook et al., 2013; Kravchenko et al., 2017). We argue here that the often overlooked discrepancy between results derived from controlled experiments versus producer fields can be better understood, if in addition to experimental trial data, the analysis includes data collected from producer fields. Such an approach would add confidence (or caution) when results generated from controlled experiments are projected to be directly translatable (i.e., generate similar results in producer fields) and perhaps just as important, to help interpret cases in which that translatability seems to fail.

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(see last page for notes)





To fulfill the dearth of knowledge relative to the causes for variation in NR-WR yield difference, we used in the research reported here two large databases to directly assess variation in NR-WR yield differences across the U.S., and to discern any confounding factors, such as site-specific weather variability and management practice choices, that might play a role in the NR-WR yield difference (magnitude or sign). The two databases contain data collected from the U.S. soybean areas, which collectively produce nearly one third of global soybean production. The approach consisted of using yield and management data collected from (1) an extensive survey of North Central U.S. soybean producers during a recent 4-year period in various climate-soil domains and (2) experimental trials conducted in north, central, and southern U.S. soybean producing regions that were coupled with the derivation of site-specific seasonal weather data and the use of crop modeling to project the dates of key soybean stages. The primary objective was to compare the NR-WR yield difference we detected in the two data sets and to identify the potential confounding factors that interactively modulate that yield difference.

2. Materials and Methods

2.1 Producer field survey data

Data on yield and management practices were collected from 7,044 fields sown with soybean in ten states located within the North Central U.S. region (Iowa [IA], Illinois [IL], Indiana [IN], Kansas [KS], Michigan [MI], Minnesota [MN], North Dakota [ND], Nebraska [NE], Ohio [OH], and Wisconsin [WI]) over four crop seasons (2014-2017). Requested data included field location, average field yield (at 13% grain moisture content), row spacing, water regime (rainfed or irrigated), and other management practices. Detailed description of the survey database is provided elsewhere (Rattalino Edreira et al., 2017; Mourtzinis et al., 2018). Producer fields were classified as either NR (~15 in.) or WR (~30 in.). Subsequently, fields were grouped in areas of similar climate and soil with those sub-groups hereafter called technology extrapolation domains (TEDs). Briefly, each TED corresponds to a specific combination of annual total growing degree-days, aridity index, temperature seasonality, and plant-available water holding capacity (Rattalino Edreira et al., 2018). Thirty-nine TED-water regimes were selected containing a total of 4,879 surveyed soybean fields (average of 125 fields per TED-water regime). Of the 39 selected TED-water regimes, 82% and 18% corresponded to rainfed and irrigated conditions. We also created a map to discern spatial variation in row spacing adoption across states and agricultural districts.

Figure 1. Technology extrapolation domains (TEDs) selected for the analysis of yield differences between narrow and wide row spacing in producer fields. Each differently colored region in the main figure represents a unique TED. The blue shading in the inset map is indicative of soybean harvested area in this region (USDA-NASS, 2015), with the red dots and green dots ($n=7,044$) denoting the locations of all producer fields (used in the Fig. 3 graph), though only the red dot fields ($n=4,879$) were subsequently used for analysis of yield difference in wide versus narrow spacing.

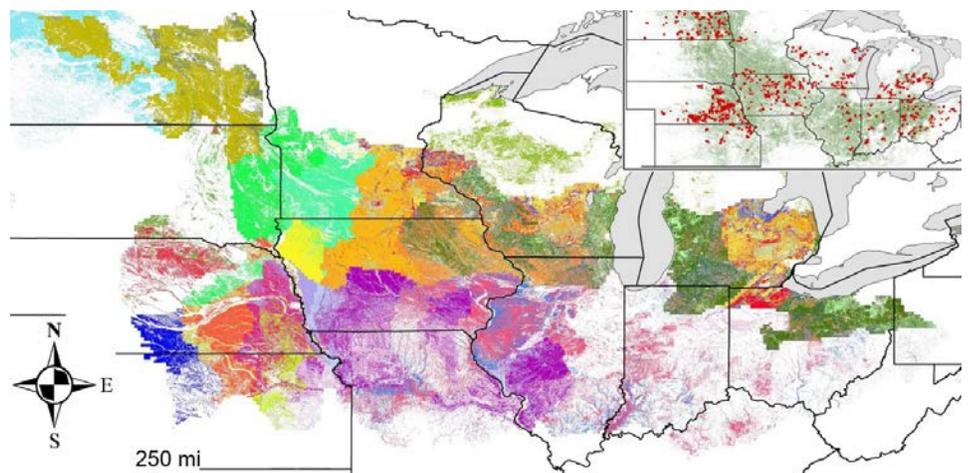
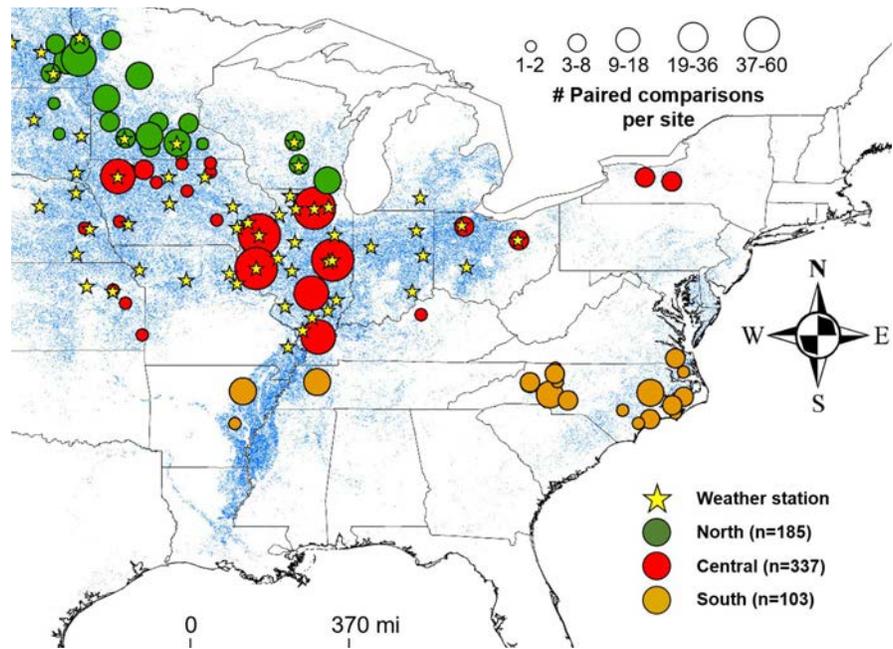


Figure 2. Map showing the location of experimental trials (circles) evaluating the influence of row spacing on seed yield conducted between 1999 and 2017, with circle size indicative of the number of experimental trials and circle color denoting the three U.S. regions: north, central, and south. The stars indicate the location of meteorological stations used to retrieve weather data for the analysis. Distribution of U.S. soybean harvested area is shown in blue (USDA-NASS, 2017).



2.2 Experimental data

We compiled yield and management data from experimental field trials conducted across the U.S. soybean production area (Fig. 2). We only considered experimental trials that were: (1) replicated relative to NR versus WR treatments; (2) conducted between 1999 and 2018; (3) located within the traditionally bounded U.S. soybean production areas; (4) performed using mostly modern agricultural practices and cultivars (*e.g.* no moldboard plow, only herbicide-resistant soybean varieties). Organic trial data (*i.e.*, herbicide, pesticide or fertilization not allowed) were excluded, as were trials with low seeding rates ($<100,000 \text{ acre}^{-1}$) and/or severe disease, insect, and weed pressure. Our final dataset included 129 site-year experiments conducted across 67 locations in 15 states (Fig. 2). The main focus of all of these experiments was an evaluation of NR-WR yield differences, but in almost all cases, they also included, for context evaluation, other treatment factors such as seeding rate, sowing date, and/or varieties. For the present study, we used these data to conduct a total of 625 paired observations to evaluate NR-WR yield differences within an identical background management context. In this experimental trial data set, the NR and WR row spacing was always 15 in. and 30 in., respectively, except for trials conducted in Minnesota (10 in. versus 30 in.) and North Dakota (12 in. versus 24 in.). For each paired NR-WR yield comparison, collateral data were available for sowing date, maturity group, seeding rate, cultivar, and experimental site coordinates (latitude and longitude). Trials were grouped into three U.S. regions (north, central, and south) based upon location and soybean maturity group. All experimental trials were conducted in rainfed conditions, except for one in Tennessee.

Daily measured weather data were retrieved from 56 meteorological stations managed by the MESONET network (<http://mrcc.isws.illinois.edu/gismaps/mesonets.htm>) and located mostly in the North Central U.S. region (Fig. 2). Weather variables included incident solar radiation, maximum and minimum air temperature, relative humidity, wind speed, and precipitation. Several experimental locations (18) were located <6 miles from a meteorological station; hence, data from those stations were directly used. Alternatively, for those locations (29) situated 6-60 miles away from any meteorological stations, we triangulated weather data from three nearest stations located within an area of 60-mile radius centered on the experiment and created a synthetic daily weather dataset



using inverse distance weighting (IDW) (Yang and Torrión, 2013; <http://hybrid-maize.unl.edu/weather-interpolator>). Briefly, this method calculates a weighted average for each variable for each day, with weights decreasing with increasing distance from the target site. For the remaining locations (20) without any weather stations located within a radius of 60 miles, we used gridded temperature, precipitation, and humidity data from Daymet [Daily Surface Weather Data on a 1-km Grid for North America; Thornton et al. (2014)] and incident solar radiation from the National Aeronautics and Space Administration's POWER database (NASA-POWER, 2017). These trials were mostly located in the southern and eastern fringes of the U.S. soybean producing area.

Because measured phenology data were not available for most of the experiments, we used SoySim model to estimate the date of key crop growth stages (Setiyono et al., 2007; 2010), including emergence (VE), beginning of pod setting (R3), and physiological maturity (R7). Averages of the key weather variables (incident solar radiation, mean temperature, and total water balance) were separately calculated for two crop developmental phases: from emergence to beginning of pod setting (VE-R3), and from beginning of pod setting to physiological maturity (R3-R7). To assess the degree of seasonal water limitation, a water balance was calculated for rainfed experiments as the difference between total rainfall and grass-based reference evapotranspiration (ET₀; Allen et al., 1998). Water balance was assumed to be equal to zero (*i.e.*, no water limitation) for the irrigated experiment in Tennessee.

3. Results

3.1 Evaluation of influence of row spacing on yield using producer survey data

Row spacing class frequencies were variable across the U.S. soybean production region (Fig. 3). While NR prevails in the eastern and northern areas, its adoption is relatively lower in the central-western areas. Drilled soybean (~7.5 in.) is more frequent in the northern wheat producing regions. A graphic comparison of statewide row spacing frequencies in our dataset versus the statewide level row spacing frequencies reported by USDA-NASS indicates that our database reliably portrayed the current adoption of the different row spacing classes across states (Fig. 3, inset).

Analysis of producer reported data did not reveal any consistent NR-WR yield difference across the 39 TED-water regime combinations (paired *t*-test; $p=0.69$) (Fig. 4). Though a statistically significant positive NR-WR yield difference was detected in two TED-water regimes, the yield difference was significantly negative in 12 TED-water regimes (*t*-test; $p<0.05$). The NR-WR yield difference in the other TED-water regimes (64%) was not significantly different from zero. The computed linear regression slope of 0.90 was significantly different from the null hypothesis of unity ($p=0.01$), suggesting that the NR yield advantage is less likely to occur in high-yield production environments (Fig. 4).

3.2 Evaluation of influence of row spacing on yield using data from controlled experiments

Maturity groups ranged from 0.0-2.0 and from 1.9-3.9, in the respective north and central U.S. areas, where only indeterminate growth habit type cultivars are grown. In contrast, maturity groups ranged from 4.5-7.6 in the south region, where both determinate and indeterminate cultivars can be grown. Average sowing date was May 13 (north), May 20 (central), and June 2 (south), with respective average seeding rates of 178,000, 145,000, and 142,000 seeds a⁻¹ (Fig. 5).

Figure 3. Pie charts showing frequency of soybean producer fields relative to three row spacing classes in rainfed (main figure) and irrigated (left inset) USDA-NASS agricultural districts. Row spacing classes were drilled (~7.5 in.; red), narrow (~15 in.; yellow) or wide (~30 in.; green). For those states without survey data (Arkansas [AR], Missouri [MO], and South Dakota [SD]), statewide frequencies for each row spacing class were retrieved from official statistics (USDA-NASS, 2015). Right inset: statewide row spacing frequencies derived from the producer database plotted against the coordinate USDA-NASS statewide row spacing statistics. Note that proportion of 7.5 in. spacing is shown here for descriptive purposes but these data are not used in the rest of the analysis.

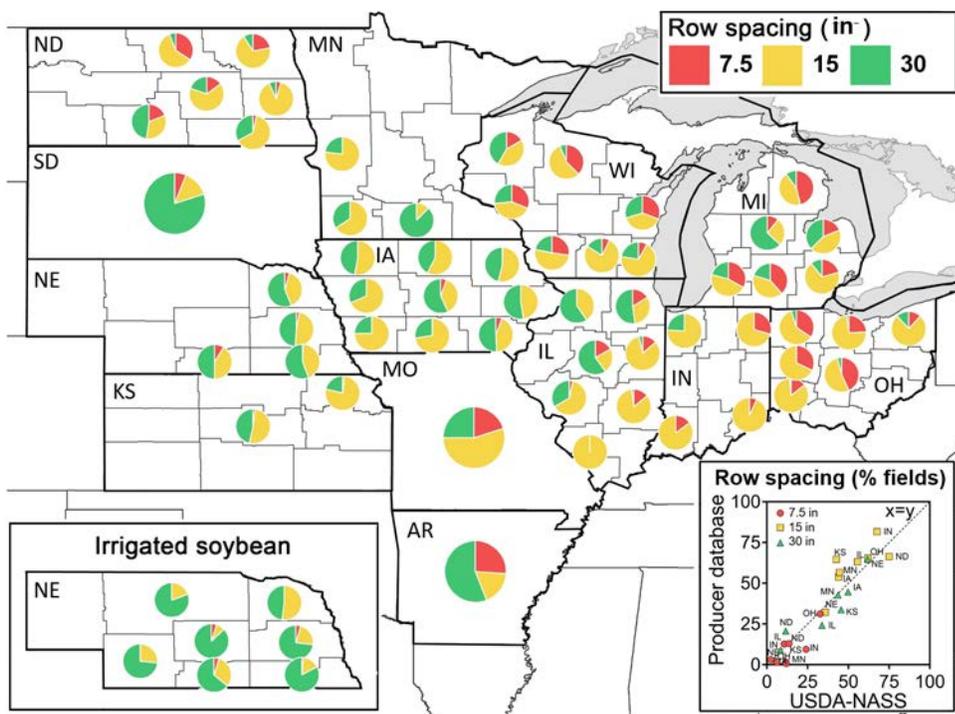


Figure 4. Average producer reported soybean yield in producer fields with wide versus narrow row spacing. Each data point represents 4-y (2014-2017) average NR and WR yields calculated from producer fields located within each of the 39 climate-soil-water regimes. Different colors are used for rainfed (green) and irrigated fields (blue). Dashed and dotted lines represent $x=y$ and $\pm 5\%$ yield differences, respectively, while the solid line is the fitted linear regression (parameters and coefficient of determination [r^2] are shown). Stars within symbols indicate statistically significant ($p < 0.05$) yield differences between wide and narrow rows.

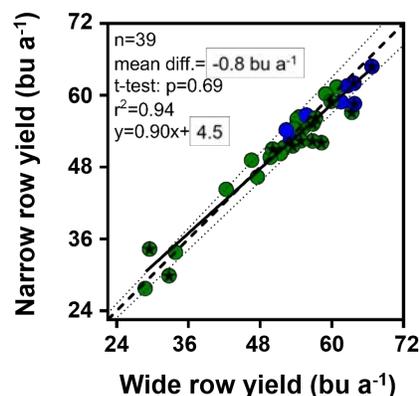
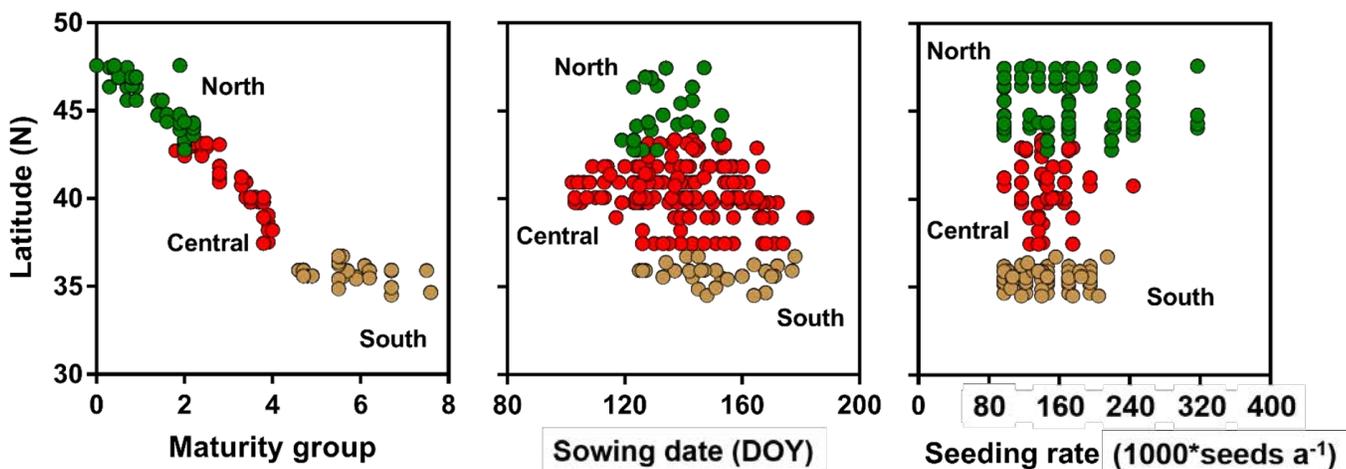


Figure 5. Maturity group, sowing date (day of year, DOY), and seeding rate across experiments used for the analysis. In each graph, the y-axis is latitude. Colored circles denote the three US regions: north (green), central (red), and south (brown).





Field experiments explored a wide range of environments and management practices that resulted in variable soybean yields, from ca. 20-90 bu a⁻¹, with the range of yields being similar among the three regions (Fig. 6). Average yield was higher in NR versus WR in the three regions ($p < 0.001$); however, the magnitude of the NR-WR yield difference varied across regions ($p = 0.02$). The NR-WR yield difference was a respective 8.1, 3.6, and 1.6 bu a⁻¹ for the south, north, and central U.S. regions, with the NR yields respectively averaging 18, 8, and 3% greater than the WR yield (Fig. 7). Slopes of the fitted linear regression were not statistically different from one (t -test, $p > 0.71$), indicating that magnitude of NR-WR yield difference measured in the experimental trials was not different across the entire yield range in any of the three regions.

Magnitude of NR-WR yield differences depended upon weather and background management practices. Categorization of experiments into three different regions with different biophysical characteristics allowed us to investigate the sources of variation influencing for the NR-WR yield differences. In the north and south regions, NR-WR yield difference was larger when coupled with early maturity group cultivars, late sowing dates, and higher VE-R3 temperatures (Table 1). Consistent with these findings, there was a strong negative relationship between NR-WR yield difference and simulated length of the VE-R3 phase in both regions (Fig. 8). In other words, NR-WR yield difference was larger when the duration of the VE-R3 phase was shorter, which in turn, was associated with late sowing, high temperature, and/or early maturity group. Surprisingly, we could not detect any statistically significant relationship between the NR-WR yield difference and weather and management variables in the central U.S. region (Table 1), which comparatively produces more soybean seed than the other regions.

Figure 6. Soybean yield in narrow versus wide row spacing measured in experiments conducted in the north (left), central (middle), and south (right) regions. Each data point represents average yield for narrow and wide row spacing treatments in each experiment. Other management practices (besides row spacing) were identical for any given paired combination. Dashed and dotted lines represent $x=y$ unity and $\pm 5\%$ yield differences, respectively. Solid lines are the fitted linear regression, for which parameters and coefficient of determination [r^2] are provided at the upper left, along with the number of paired observations and mean yield difference (diff.) between narrow and wide rows. All mean differences were statistically significant at $p < 0.001$. Average producer reported soybean yield in surveyed fields with wide versus narrow row spacing are shown for comparison (yellow diamonds), but excluded from the statistical analysis.

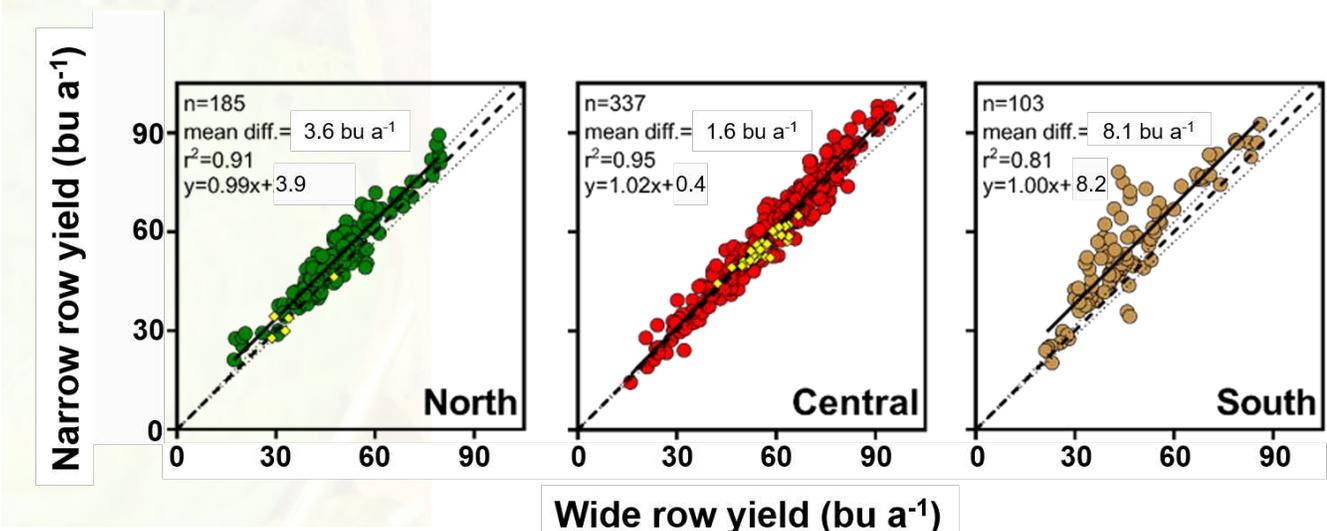


Figure 7. Average soybean yield difference (%) in narrow versus wide rows per experimental site. Number of paired comparisons per site is denoted by circle size, with different colors indicating the magnitude of the yield difference.

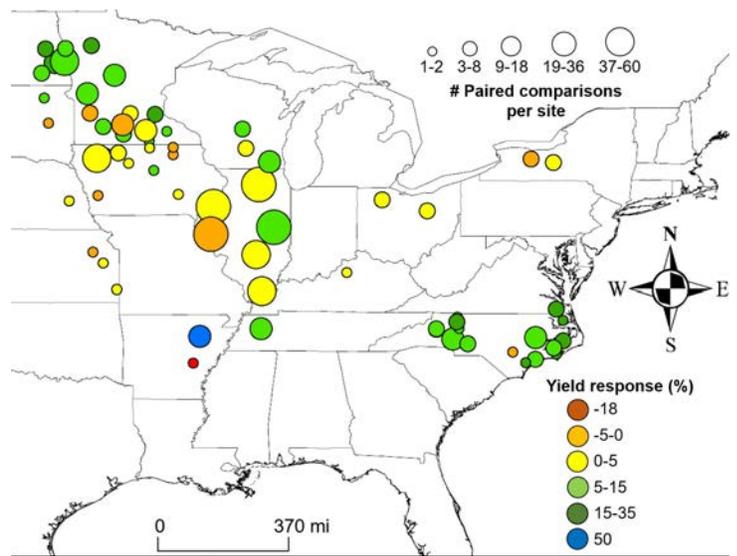
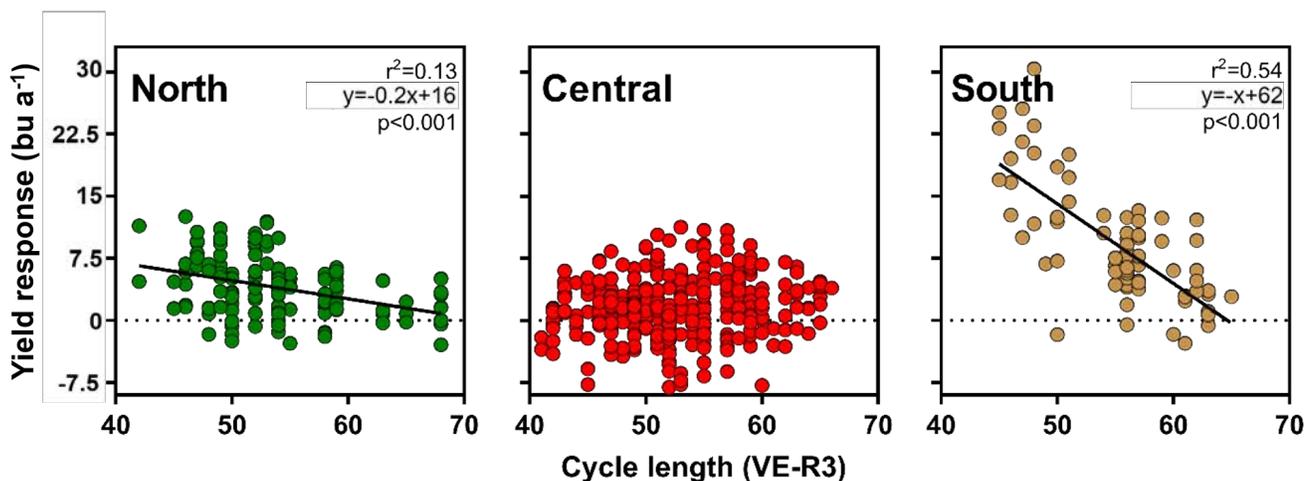


Table 1. Pearson's correlation coefficients for yield differences between narrow and wide rows as measured in experiments versus weather and management factors for each region and for the pooled database containing experimental data from the three regions.

Variable	North	Central	South	Pooled
Maturity group	-0.29***	-0.01	-0.44***	0.15**
Seeding rate (seeds a ⁻²)	-0.10	0.07	0.08	0.01
Planting date (DOY)	0.25***	-0.07	0.30†	0.16***
Phase length (d)				
VE-R3	-0.36***	0.11	-0.73***	-0.07*
R3-R7	-0.13	0.04	0.00	-0.1
Mean solar radiation (MJ m ⁻²)				
VE-R3	0.31***	0.11	0.05	0.08
R3-R7	0.04	0.11	0.06	-0.04
Mean temperature (°F)				
VE-R3	0.24**	-0.11	0.48***	0.17***
R3-R7	-0.01	0.03	-0.07	0.11
Water balance (inches)				
VE-R3	0.01	0.03	0.38***	-0.04
R3-R7	0.09	-0.07	-0.13	-0.07

Asterisks indicate that slope of the fitted regression was statistically different from zero at *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$. VE: emergence; R3: beginning of pod setting; R7: physiological maturity.

Figure 8. Yield difference between narrow and wide rows measured in experiments as a function of crop cycle length from emergence to beginning of pod setting (VE-R3). Each data point represents the yield difference between narrow and wide rows in each paired comparison. Solid line shows the fitted linear regression for the north and south regions; fitted linear regression for the central region (not shown in the figure) had little explanatory power (t -test; $P=0.06$; $r^2=0.01$).





4. Discussion

Analysis of data from controlled experimental trials conducted across a wide range of environments in the U.S. soybean producing region revealed a positive NR-WR yield difference in 76% of the paired comparisons, with NR yield averaging 7% more than WR yield across all observations. In two of the three U.S. regions, magnitude of NR-WR yield difference was strongly associated with length of emergence to pod-setting phase, indicating that NR can serve as a 'rescue treatment' in situations in which the crop vegetative phase is expected to be shortened to the degree that full canopy closure cannot be achieved in WR prior to, or during, the critical period for yield determination in soybean (*i.e.*, from initiation of pod-setting [R3] to beginning of seed filling [R5]). Such situations typically occur when the sowing date is delayed and/or when early maturity group cultivars are used. In contrast, NR-WR yield difference was negligible in experiments sown early with a full-season cultivar.

The NR-WR yield difference was smaller and less consistent for the experiments located in the central U.S. region. This is of particular interest as this region accounts for 61% of total U.S. soybean production (USDA-NASS, 2017). We speculate that favorable temperature and water balance during this two-decade set of recent experimental trials, together with deep soils with high available soil water at sowing, favored canopy closure by R3 in soybean crops in the central region irrespective of row spacing. Furthermore, NR soybean crops are typically more susceptible to greater disease pressure, especially in wet seasons (*e.g.*, white mold *Sclerotinia sclerotiorum*; Willbur et al., 2018). Consistent with this hypothesis, July total rainfall was higher in the group of experimental trials exhibiting a negative NR-WR yield difference in the central region relative to those trials with largest NR-WR yield difference (*t*-test, $p < 0.05$).

We could not detect a consistent NR-WR yield difference based on producer soybean field data collected across 39 major climate-soil-water regime domains in the North Central U.S. region where soybean is grown. In fact, there was evidence of yield penalty due to NR in 30% of these domains. The lack of NR-WR yield differences in producer fields calculated for the TEDs located within the central region were consistent with the very small NR-WR yield difference found for the same region using the experimental data. Conversely, the lack of NR-WR yield difference in producer fields in TEDs located in the northern region conflicted with the large yield difference detected in the north region using experimental data. We note that performing the same comparison for the south region was not possible because no survey data were available for this region, where NR is most likely to be beneficial as indicated by analysis of the experimental data. We speculate that the lack of yield benefit derived from NR in producer fields may be associated with other management practices that may lessen or mask the NR yield advantage. In addition, a yield penalty of 1-5% is expected in NR crops as a consequence of wheel track damage caused when spraying canopy fungicide during reproductive stages (Hanna et al., 2008; Holshouser and Taylor, 2008). Sprayer wheel-track induced yield loss usually does not occur in controlled experiments. Finally, we note that despite the small and inconsistent yield benefit associated with NR, other factors can still justify adoption of NR (*e.g.*, soil erosion control, better weed control).

Small, or even *nil* or negative, NR-WR yield differences may have limited NR adoption in the central region, especially in irrigated fields (Fig. 3). Another possible explanation is the high cost of purchasing a split-row planter, which would require an extra bushel $a^{-1} y^{-1}$ to match the investment (De Bruin and Pedersen, 2008). Note this calculation is based on a 740 ac farm with 30%

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soybean sown area and using average (2014-2018) soybean price of \$11 bu⁻¹. Given extra cost of the planter and sprayer-wheel track damage, the mean NR-WR yield difference calculated in the south and north regions based on the experimental data would still justify adoption of narrow rows, but it would be less acceptable (financially) to producers in the central U.S. region, especially for producers already following other best management practices, such as early sowing date and optimal variety MG for a given region, or those located in very favorable production environments as it is the case of irrigated soybean in Nebraska.

5. Conclusions

Overall, we found a positive NR-WR yield difference, although its magnitude depended upon region and management practices that influenced the duration of the VE-R3 crop phase. Large NR-WR yield differences were found in the north and south U.S. regions, especially with late sowing dates and/or the use of early maturity group cultivars that resulted in shorter crop cycle. However, producer data from the North Central region indicated no yield difference between NR compared with WR, which presumably arose from background management practices that confound the NR-WR yield effect and post-sowing wheel damage in NR. The approach followed here can be used to evaluate management practices and determine the degree to which findings in controlled experiments translate into comparable yield gains in producer fields.

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