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

José F. Andrade\textsuperscript{a}, Juan I. Rattalino Edreira\textsuperscript{a}, Spyridon Mourtzinib, Shawn P. Conley\textsuperscript{b}, Ignacio A. Ciampittic, James E. Dunphyd, John M. Gaskab, Keith Glewen\textsuperscript{a}, David L. Holshousere, Herman J. Kandelf, Peter Kyverygag, Chad D. Leeh, Mark A. Lichti, Laura E. Lindseyj, Michael J. Statonk, Laura Thompsonm, James E. Specht\textsuperscript{b}, Patricio Grassini\textsuperscript{a,n}, M. Angela McClurek, Seth Naevel, Emerson D. Nafzigerm, John M. Orlowskin, Jeremy Rosso, Ignacio A. Ciampitti, James E. Dunphy, John M. Gask, Keith Glewen, David L. Holshouser, Herman J. Kandel, Peter Kyvertyga, Chad D. Lee, Mark A. Lichti, Laura E. Lindsey, M. Angela McClure, Seth Naevel, Emerson D. Nafziger, John M. Orlowski, Jeremy Ross, Michael J. Staton, Laura Thompson, James E. Specht, Patricio Grassini

\textsuperscript{a}Department of Agronomy and Horticulture, University of Nebraska-Lincoln, Lincoln, NE, 68583-0915, USA
\textsuperscript{b}Department of Agronomy, University of Wisconsin Madison, Madison, WI, 53706, USA
\textsuperscript{c}Department of Agronomy, Kansas State University, Manhattan, KS, 66506, USA
\textsuperscript{d}Department of Crop and Soil Sciences, North Carolina State University, Raleigh, NC, 27695-7620, USA
\textsuperscript{e}Virginia Polytechnic Institute and State University, Tidewater Agriculture Research and Extension Center, Suffolk, VA, 23437, USA
\textsuperscript{f}Department of Plant Sciences, North Dakota State University, Fargo, ND, 58108-6050, USA
\textsuperscript{g}Iowa Soybean Association, Ankeny, IA, 50023, USA
\textsuperscript{h}Department of Plant and Soil Sciences, University of Kentucky, 423 Plant Science Building, Lexington, KY, 40546, USA
\textsuperscript{i}Department of Agronomy, Iowa State University, Ames, IA, 50011-1010, USA
\textsuperscript{j}Department of Horticulture and Crop Science, The Ohio State University, Columbus, OH, 43210, USA
\textsuperscript{k}Department of Plant Science, University of Tennessee, AgResearch and UT Extension Center, Jackson, TN 38301, USA
\textsuperscript{l}Department of Agronomy and Plant Genetics, University of Minnesota, St. Paul, MN, 55108, USA
\textsuperscript{m}Department of Crop Sciences, University of Illinois, Urbana, IL, 61801, USA
\textsuperscript{n}Department of Agronomy, University of Wisconsin-Madison, Madison, WI, 53706, USA
\textsuperscript{o}Department of Plant and Soil Sciences, University of Tennessee, AgResearch and UT Extension Center, Jackson, TN 38301, USA
\textsuperscript{p}Department of Crop, Soil, and Environmental Sciences, University of Arkansas System Division of Agriculture, Little Rock, AR, 72204, USA
\textsuperscript{q}Michigan State University Extension, Allegan, MI, 49010, USA

\textsuperscript{⁎}Corresponding author.
E-mail address: pgrassini2@unl.edu (P. Grassini).

https://doi.org/10.1016/j.fcr.2018.10.014
Received 19 August 2018; Received in revised form 23 October 2018; Accepted 25 October 2018
Available online 06 November 2018
0378-4290/ © 2018 Elsevier B.V. All rights reserved.

ABSTRACT

Narrowing row width in soybean fields leads to earlier canopy closure, which may increase capture of incoming solar radiation during critical crop stages for yield determination. Theoretically, this should enhance seed yield. However, in prior studies, the impact of narrowing row spacing on soybean yield has been inconsistent. To explore on a broader scale the potential factors underlying this inconsistency, we evaluated the yield difference between narrow (NR; \( \approx 38 \) cm) and wide (WR; \( \approx 76 \) cm) row spacing using two sources of yield and management information: (i) data collected from 4879 soybean production fields via a multi-year, multi-state survey of soybean producers in the North Central US region; and (ii) data extracted from 129 site-year experiments that quantified NR-WR yield differences. The producer fields were allocated to their respective climate-soil domains to enable analysis of the NR-WR yield difference within each domain. The experimental trial data originated from three US geographic regions: south, central, and north. Key crop developmental stages in each trial were estimated using a soybean crop simulation model to discern if changes in crop phenology or any weather variable occurring before versus after a specific crop stage modulated the magnitude of the NR-WR yield difference. Analysis of experimental trial data indicated that, while NR yields were overall higher than WR yields, the NR-WR yield difference varied by region: 540 (south), 104 (central), and 240 kg ha\(^{-1}\) (north); the respective NR yields were greater than WR yields in 92%, 68%, and 84% of the cases. In the north and south regions, the NR-WR yield difference increased when the crop cycle length decreased as a consequence of later sowing date, earlier cultivar maturity group, and/or higher temperature. The relatively smaller (and occasionally negative) NR-WR yield difference detected in the central region was likely the result of environmental conditions that favored canopy closure irrespective of row spacing. In contrast to the analysis of the experimental database, no consistent NR-WR yield differences were detected in the producer field database. We hypothesize that the apparent absence of a significant NR-WR effect in the producer dataset is likely associated with the background
management used with narrow spacing, together with yield losses due to wheel damage and greater disease pressure. This complementary approach using both producer and experimental data can help evaluate if practices documented in experimental trials to enhance yield realize equivalent yield increases in producer fields and, if not, explore underlying causes for the discrepancy.

1. Introduction

Soybean (Glycine max L.) is one of the most important oilseed crops in the world, with United States (US) accounting for 35% of the global production (http://www.fao.org/faostat/en/#data/QC). US soybean producers have progressively shifted from wide (WR; ≈76 cm) to narrow (NR; ≈38 cm) row spacing in recent decades, though adoption of 19-cm spacing has been limited (Specht et al., 2014). There is general consensus that reducing row width from 76 to 38 cm in the US 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; Walker et al., 2010; Thompson et al., 2015). In absence of yield-limiting factors, NR result in a yield benefit, compared with WR, when its earlier canopy closure results in greater solar radiation capture during critical stages for yield determination (e.g., Bullock et al., 1998; Andrade et al., 2002; Salmerón 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. Despite interactions, such as row spacing x seeding rate, that have been explored for specific site-years (e.g., Bertram and Pedersen, 2004; Cox and Cherney, 2011), there has been no explicit attempt to understand variation in NR-WR yield difference across a wide range of production environments with diversity in weather, soil, and management factors.

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). There are a number of reasons for this phenomenon. First, the yield benefit associated with a new practice may not be detectable in producer fields if such a practice is consistently associated with other management factors that lead to lower yield (e.g., late sowing), or if there are logistic constraints that result in yield losses (e.g., increasing harvest losses or increased wheel traffic). Second, there is a tendency in applied agronomic research towards publishing only results from experiments in which a statistically significant yield difference between two management practices has been detected. 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.

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 USA, 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 contained data collected from the US soybean areas, which collectively produce nearly one third of global soybean

Fig. 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 distribution in this region (USDA-NASS, 2015), with the red dots and green dots (n = 7044) denoting the locations of all producer fields (used in the Fig. 3 graph), though only the red dot fields (n = 4879) were subsequently used for analysis of yield difference in wide versus narrow spacing. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).
production. The approach consisted of using yield and management data collected from (i) an extensive survey of North Central US soybean producers during a recent 4-year period in various climate-soil domains and (ii) experimental trials conducted in north, central, and southern US soybean producing regions, that were coupled with the derivation of site-specific seasonal weather data and the use of crop modeling to estimate 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 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 7044 fields sown with soybean in ten states located within the North Central US 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). Briefly, soybean producers provided data via returned surveys distributed by local crop consultants, extension educators, soybean grower boards, and Natural Resources Districts. Requested data included field location, average field yield (at 13% seed moisture content), row spacing, water regime (rainfed or irrigated), and other management practices (Supplementary Table S1). 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 (≈ 38 cm; range: 25–57 cm) or WR (≈ 76 cm; range: 61–96 cm). Fields sown with row spacing beyond the two category ranges were excluded from the analysis. The majority of the fields reported row spacing within a 10-cm range within each class, with row spacing varying from 35 to 45 cm and from 71 to 81 cm in 78% and 91% of the NR and WR fields, respectively. Subsequently, fields located in production areas 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). Because yield response to management is likely to be influenced by water regime, fields located in TEDs that included both irrigated and rainfed soybean production areas (mostly in NE and KS) were further clustered into TED-water regime combinations. Only TED-water regime cases with > 30 fields were considered for the analysis, and then only with a minimum of 10 fields in each row spacing category. Following these criteria, 39 TED-water regimes were selected containing a total of 4879 surveyed soybean fields (average of 125 fields per TED-water regime; Fig. 1). Of the 39 selected TED-water regimes, 32 and 7 corresponded to rainfed and irrigated conditions. Weather patterns across TEDs are described elsewhere (Rattalino Edreira et al., 2017).

To analyze the influence of row spacing on yield, we plotted NR versus WR average yields for each of the TED-water regime, and then assessed differences and trends in the NR-WR yield difference using paired t-tests and linear regression analysis. We also created a map to discern spatial variation in row spacing adoption across states and agricultural districts. To create this map, we only considered agricultural districts with > 25 surveyed fields. For other important soybean producing 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). Finally, to assess the quality of the database, we compared statewide frequencies for each row spacing class derived from the producer field database against USDA-NASS statistics available for each state. Drilled soybean sown at 19-cm row width was included in the map and database validation but not in the rest of the analysis.

2.2. Experimental data

We compiled yield and management data from experimental field trials conducted across the US soybean production area in which the influence of row spacing on yield was investigated (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 US 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 (< 24 m⁻²) and/
or severe disease, insect, and weed pressure, although these were not always reported. Following these selection criteria, our final dataset included 129 site-year experiments conducted across 67 locations in 15 states (Fig. 2). Data from these studies have not been published to date, except for two experiments (Holshouser and Taylor, 2008; Lund et al., 2018). 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 38 and 76 cm, respectively, except for trials conducted in MN (25 versus 76 cm) and ND (31 versus 61 cm). 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 US regions (north, central, and south) based upon location and soybean maturity group. These regions accounted for 24% (north), 61% (central), and 15% (south) of total US soybean production (USDA-NASS, 2017). Of the 129 site-year experiments, 30%, 54% and 16% were located in the north, central, and south regions, respectively. All experimental trials were conducted in rainfed conditions, except for one in Tennessee. In all cases, soybean was grown as a single crop (i.e., no previous crop in the same year of the experiment).

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 US 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 < 10 km from a meteorological station; hence, data from those stations were directly used. Alternatively, for those locations (29) situated 10–100 km away from any meteorological stations, we triangulated weather data from three nearest stations located within an area of 100-km radius centered on the experiment and created a synthetic daily weather dataset using inverse distance weighting (IDW) (Yang and Torrion, 2013; http://hybridmaize.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 100 km, 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 20 sites were mostly located in the southern and eastern fringes of the US soybean producing area (Fig. 2).

Yield response to management practices is sensitive to seasonal weather conditions. However, the use of average weather values calculated over the entire crop growing season may mask the influence of weather during specific crop stages (Grassini et al., 2009; Rattalino Edreira et al., 2017). Because measured phenomenology 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). SoySim has a documented capacity for tracking and projecting vegetative and reproductive phenology in monitored soybean fields (Torrion et al., 2011). For each experiment, phenology was simulated via SoySim based on local weather, reported sowing

![Fig. 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 (~19 cm; red), narrow (~38 cm; yellow) or wide (~76 cm; 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 corresponding USDA-NASS statewide row spacing statistics. Note that proportion of 19-cm spacing is shown here for descriptive purposes but these data are not used in the rest of the analysis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).](image-url)
date, and cultivar maturity group. 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 to R7). To assess the degree of seasonal water limitation, a water balance was calculated for rainfall experiments as the difference between total rainfall and grass-based reference evapotranspiration (ET$_{\text{act}}$, Allen et al., 1998). Water balance was assumed to be equal to zero (i.e., no water limitation) for the irrigated experiment in Tennessee.

For each region, we plotted NR and WR yields and used a paired t-test to evaluate the statistical significance of the NR-WR yield difference. Linear regression analysis was used to detect non-uniformity in the NR-WR yield difference across a low-to-high range of yields. Association between NR-WR yield differences and several weather and management practices were investigated using Pearson's correlation. Additionally, we used t-tests to determine the statistical significance of differences between means of weather and management practices between groups of paired observations with large versus small (or even negative) NR-WR yield difference contrasts, for which the large – small categories consisted of the upper and lower terciles of the NW-RR yield difference distribution, respectively.

3. Results

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

Row spacing class frequencies were variable across the US 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 ($\approx 19$ cm) is more frequent in the northern wheat producing regions. Interestingly, the frequency of WR is greater in irrigated fields than in rainfed fields in NE (76% versus 56%; $\chi^2$ test; $p < 0.001$), which is the only state where both large irrigated and rainfed soybean hectarage co-exist within the same geographic region. 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). Differences in row spacing frequencies derived from the two independent databases were undistinguishable from zero for any of the row spacing classes (paired t-test, $p > 0.35$).

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). In fact, the data analysis indicated that average yield was significantly lower in NR versus WR fields in 30% of the domains, and most of these domains corresponded to high-yield production environments. To summarize, we could not detect any consistent yield benefit derived from NR adoption across 39 major soil-climate-water regime domains that span the major US producing region. Magnitude of NR-WR difference increased in TEDs with later average sowing date (Pearson's $r = 0.41$; $p = 0.01$) and decreased in TEDs where NR fields were sown later than WR fields (Pearson's $r = -0.39$; $p = 0.01$) (Supplementary Table S1-S2).

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

Maturity groups ranged from 0.0 to 2.0 and from 1.9 to 3.9, in the respective north and central US areas, where only indeterminate growth habit type cultivars are grown. In contrast, maturity groups ranged from 4.5 to 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 44, 36, and 35 seeds m$^{-2}$ (Fig. 5). Average (and ranges of) sowing date, maturity group, and seeding rates were consistent with the typical management observed in soybean producer fields in these regions (Moutzouzis et al., 2018). Mean daily solar radiation during the early and late phases of the crop cycle was similar in the three regions except for the late phase in the south region (Fig. 6), whereas the mean temperature increased, as expected, along north-south gradient. The water balance data indicated that crop available water in the crop cycle early and late phases was less limiting in the central region trials compared to that availability in the northern and southern region trials (Fig. 6).

Field experiments explored a wide range of environments and management practices that resulted in variable soybean yields, from ca. 1 to 6 Mg ha$^{-1}$, with the range of yields being similar among the three regions (Fig. 7). Average yield was higher in NR versus WR in the three regions ($p < 0.001$); however, analysis of variance revealed a statistically significant row spacing x region interaction, indicating that the magnitude of the NR-WR yield difference varied across regions ($p = 0.02$). The NR-WR yield difference was a respective 540, 240, and 104 kg ha$^{-1}$ for the south, north, and central US regions, with the NR yields respectively averaging 18, 8, and 3% greater than the WR yield (Fig. 8). Similarly, frequency of cases below the $x = y$ line (indicating a yield penalty associated with NR spacing) was relatively small in the south (8% of 103) and north (16% of 185) regions, but higher in the central region (32% of 337). 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.

![Fig. 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 ± 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. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).](image-url)
Magnitude of NR-WR yield differences depended upon weather and background management practices. Categorization of experiments into three different regions with different biophysical characteristics (Fig. 6) allowed us to investigate the sources of variation influencing 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 high VE-R3 temperature (Tables 1 and 2, Supplementary Tables S3–S5). 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. 9). 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 US region (Table 1), which comparatively produces more soybean seed than the other regions. Using relative yield difference (as % of the wide-row yield) instead of absolute soybean seed difference for the analysis generated almost identical results.

4. Discussion

Analysis of data from controlled experimental trials conducted across a wide range of environments in the US 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. This finding is consistent with previous studies reporting greater soybean yield with NR relative to WR. In two of the three US regions, magnitude of NR-WR yield difference was strongly associated with length of the 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 beginning 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. These findings are consistent with findings reported in experiments conducted in the USA and elsewhere (Board and Harville, 1994, 1996; Andrade et al., 2002; De Bruin and Pedersen, 2008; Salmerón et al., 2015). 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 US region. This is of particular interest as this region accounts for 61% of total US soybean production (USDA-NASS, 2017). We speculate that favorable temperature and water balance during this two-decade set of recent experimental trials (Tables 1 and 2), 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).

Analysis of producer survey data can help evaluate performance of recommended management practices and determine the degree to which yield differences found in controlled experiments are consistent with those observed in producer fields. In our case, 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 US 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 (-60 versus 104 kg ha\(^{-1}\)). 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 (-6 versus 240 kg ha\(^{-1}\)). 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. For example, TED-water regime domains with > 5% yield penalty in NR, compared with WR, corresponded to cases with higher frequency of late sowing and/or early maturity group in NR versus WR fields ( Supplementary Tables S1–S2). Likewise, we note that most of TEDs used for the NR-WR comparison based on producer data were located in the central region (34 of 39 TEDs) which, in turn, exhibited the smallest (and more inconsistent) NR-WR yield difference. Finally, a yield penalty of 1–5% is expected in NR crops as a consequence of wheel track damage caused when spraying canopy fungicide and/or insecticide during reproductive stages (Hanna et al., 2008; Holshouser and Taylor, 2008). Sprayer wheel-track induced yield loss usually does not occur in controlled experiments.

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 64 kg ha\(^{-1}\) y\(^{-1}\) to match the investment (De Bruin and Pedersen, 2008). Note that this calculation is based on a 300-ha farm with 30% soybean sown area and using average (2014–2018) soybean price of US $0.412 kg\(^{-1}\). 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 US region, especially for producers already following other best management practices, such as early sowing date and optimal cultivar maturity group for a given region, or those located in very favorable production environments as it is the case of irrigated soybean. Finally, we note that despite the small and inconsistent yield benefit associated with NR, other factors can still justify its adoption (e.g., soil erosion control, better weed control).

The main strength of our approach to analyze NR-WR yield differences relies on using databases collected from controlled experiments and producer fields. Such an approach allowed us to detect discrepancies between results derived from controlled experiments versus

---

**Table 2**

Average maturity group, seeding rate, sowing date (day of year; DOY), length of emergence-pod setting (VE-R3) and pod setting-physiological maturity (R3-R7) phases, mean incident solar radiation, mean lower temperature for two groups of experimental paired NR-WR observations. The means for each group, termed large or small in this table, were calculated from the upper and lower terciles of the NR-WR yield difference when ranked by magnitude. Average differences (Diff.) between the large and small groups are shown for each variable in each region.

<table>
<thead>
<tr>
<th>Variable</th>
<th>North Large</th>
<th>North Small</th>
<th>Diff.</th>
<th>Central Large</th>
<th>Central Small</th>
<th>Central Diff.</th>
<th>South Large</th>
<th>South Small</th>
<th>South Diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maturity group</td>
<td>1</td>
<td>1.4</td>
<td>−0.4**</td>
<td>3.3</td>
<td>3.3</td>
<td>0</td>
<td>5.4</td>
<td>6.1</td>
<td>−0.7**</td>
</tr>
<tr>
<td>Seeding rate (m(^{-1}))</td>
<td>43</td>
<td>46</td>
<td>−3</td>
<td>37</td>
<td>36</td>
<td>1</td>
<td>37</td>
<td>35</td>
<td>2</td>
</tr>
<tr>
<td>Sowing date (DOY)</td>
<td>135</td>
<td>130</td>
<td>5**</td>
<td>136</td>
<td>139</td>
<td>−3</td>
<td>160</td>
<td>148</td>
<td>12**</td>
</tr>
<tr>
<td>Phase length (d)</td>
<td>VE-R3 51</td>
<td>56</td>
<td>−5***</td>
<td>54</td>
<td>52</td>
<td>2*</td>
<td>52</td>
<td>60</td>
<td>−8***</td>
</tr>
<tr>
<td></td>
<td>R3-R7 41</td>
<td>42</td>
<td>−1</td>
<td>56</td>
<td>56</td>
<td>0</td>
<td>54</td>
<td>53</td>
<td>1</td>
</tr>
<tr>
<td>Mean solar radiation</td>
<td>VE-R3 22.6</td>
<td>21.9</td>
<td>0.7**</td>
<td>22.6</td>
<td>22.2</td>
<td>0.4</td>
<td>22.2</td>
<td>22.1</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>R3-R7 20.0</td>
<td>20.0</td>
<td>0</td>
<td>20.5</td>
<td>20.1</td>
<td>0.4</td>
<td>19.0</td>
<td>19.6</td>
<td>−0.6</td>
</tr>
<tr>
<td>Mean temperature (°C)</td>
<td>VE-R3 20.1</td>
<td>19.3</td>
<td>0.8**</td>
<td>22.2</td>
<td>22.8</td>
<td>−0.6</td>
<td>25.5</td>
<td>24.7</td>
<td>0.8*</td>
</tr>
<tr>
<td></td>
<td>R3-R7 20.8</td>
<td>20.7</td>
<td>0.1</td>
<td>22.5</td>
<td>22.5</td>
<td>0</td>
<td>23.7</td>
<td>24.3</td>
<td>−0.6</td>
</tr>
<tr>
<td>Water balance (mm)</td>
<td>VE-R3 −281</td>
<td>−290</td>
<td>9</td>
<td>−93</td>
<td>−120</td>
<td>27</td>
<td>−135</td>
<td>−248</td>
<td>113**</td>
</tr>
<tr>
<td></td>
<td>R3-R7 −167</td>
<td>−184</td>
<td>17</td>
<td>−143</td>
<td>−133</td>
<td>−10</td>
<td>−160</td>
<td>−170</td>
<td>10</td>
</tr>
</tbody>
</table>

Asterisks indicate statistically significant differences based on \(t\)-test at \(*p < 0.05; \**p < 0.01; \***p < 0.001.\)
producer field results, which can serve as a starting point to postulate testable hypotheses about the underlying causes of research-to-field non-translatability that can be confirmed or refuted in subsequent research. Likewise, our use of (mostly) unpublished experimental data was useful given the bias associated with journals more regularly publishing experiments that generate statistically significant yield differences than experiments that do not. Finally, the use of these databases, coupled with crop modeling and weather databases, allowed us to explore the drivers for variation in NR-WR yield differences across a wide range of environments that would have been very difficult to assess with a single experiment conducted in a few site-years. The approach proposed here is generic enough to be applied to evaluate any agronomic practices in any agricultural systems as long as primary and ancillary data required for the analysis are available.

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 US 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.

Acknowledgments

The authors acknowledge the North Central Soybean Research Program, Nebraska Soybean Board, and Wisconsin Soybean Marketing Board for funding this work. We wish to thank Haihun Yang for assisting with the weather interpolation and Daren Mueller, Jordan Stanley, Shaun Casteel, and Adam Roth for helping collect the producer data. We also thank Lim Davy, Agustina Diale, Laurie Gerber, Clare Gietzel, Mariano Hernandez, Ngu Kah Hui, Caleb Novak, Juliana de Oliveira Hello, Matt Richmond, and Paige Wacker for inputting and cleaning the survey data. Finally, we thank South Dakota Soybean On-Farm Research Program and the Iowa On-Farm Network for making experimental data available through their websites.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fcr.2018.10.014.

References


