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A Review of Soybean Yield when Double-Cropped after Wheat

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ABSTRACT

Soybean (*Glycine Max* L.) planted after wheat (*Triticum aestivum* L.) harvest in same season (double cropped [DC]) has the potential to increase productivity and sustainability. The objectives of this synthesis review were to (i) quantify attainable yield for DC soybean benchmarking against full-season (FS) soybean; (ii) determine and build probabilistic response models on the effect of previous wheat productivity on DC soybean yields; and (iii) detect and rank factors influencing DC soybean yields via a decision inference tree analysis. A global database on DC soybean studies collected from 1976 to 2017 was divided into three data sets: (i) FS and DC soybean (n = 141 data points); (ii) wheat and DC soybean (n = 463); and (iii) production factors and DC soybean (n = 547). Analysis showed that the yield gap between FS and DC soybeans increased from -31 to 1160 kg ha^{-1} as FS yield improved from 1500 to 3000 kg ha^{-1}. Even though the proportion of the variation accounted for wheat yields in the DC soybean/wheat yield ratio was low (R^2 = 0.15), the probability of soybean yield being equal to wheat yield was 0, 20, 30, and 55% for wheat yields of ≥6, ≥4 and <6, ≥2 and <4, and <2 Mg ha^{-1}. Inference tree analysis indicated that the major factor impacting success of the DC system was wheat yield followed by soybean planting date and maturity group.

Core Ideas

- Relative to full-season soybeans, the double-crop soybean yield gap is delayed and full-season soybean yields improved.
- As wheat yield improved, double-crop soybean has lower probability of presenting greater yields than wheat.
- Previous wheat yield, and soybean planting date and maturity groups influenced the attainable yield for double-crop soybeans.

Soybean and wheat are two important crops that have the potential to produce high protein food. In 2018, wheat and soybean production was 48 and 125 million tons in United States, respectively (USDA–NASS, 2018). These two crops are usually sown separately, followed by a fallow period. Nonetheless, it is possible to produce both crops in immediate succession if the correct management is adopted. Double cropping (DC) soybean immediately after wheat harvest has the potential to increase overall production without expanding land area, potentially increasing net-return for farmers and aiding in sustainably intensifying farming systems (Crabtree et al., 1990; Burton et al., 1996; Kelley, 2003; Kyei-Boahen and Zhang, 2006; Browning, 2011). Additionally, DC soybean system allows farmers to transfer the cost of summer weed control to the soybean crop instead of the wheat crop where there is no direct return on their investment.

Ray et al. (2012, 2013) suggested that current rate of increase in agricultural production (0.9 to 1.6% per year) is not meeting the required rate of yield increase of 2.4% per year to reach needed food production for 2050. Furthermore, most of the increase in food production must be derived from land already under cultivation (Hall and Richards, 2013). Crop intensification is defined as the yield improvement per unit of land area and time (Cassman, 1999; Gregory et al., 2002; Sadras and Roget, 2004) with the focus on increasing cropping intensity (more crops per year); this is one strategy to meet the increasing global food demand.

Following this rationale of intensification, DC planted area in the United States increased 28% from 1988 to 2012 (Seifert and Lobell, 2015). In 2018, the total DC planted area was projected to be 1.81 million hectares, roughly representing 5% of total soybean planted area in the United States (USDA–NASS, 2018). Soybean is one of the most frequent crops utilized for DC systems and in most situations, it is usually planted after wheat harvest. In addition, soybean can generate complementary income to wheat, and can increase potential net-return from the system.

Double-crop soybean is usually planted later than the full-season (FS) soybean due to wheat harvest occurring after optimal soybean planting date. Environmental conditions, such as

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Abbreviations: DC, double crop; DOY, days of the year FS, full-season; MG, maturity group.

radiation, temperature and water availability, have a large influence on the establishment and development of the soybean crop, affecting yield (Wesley, 1998; Dillon, 2014). For mid-southern part of US, DC soybean yield declined for planting dates after mid-May, ranging from 0.09 to 1.69% per day, depending on maturity group (Salmerón et al., 2016). In Argentina, late soybean planting date resulted in diminished yields (Caviglia et al., 2011). Full-season soybean has more time to increase biomass and seed yield because of a longer time to capture radiation (Egli, 2011). Moreover, late-planted soybean is more likely exposed to possible freeze events during seed filling (Seifert and Lobell, 2015) leading to lower yields. Wheat residue (quantity and distribution) also represents a challenge for the success of DC soybean systems, potentially reducing growth and lowering yields (Caviness et al., 1986). Wheat may also reduce water availability for soybean, increasing the risk of soil moisture stress (Pearce et al., 1993; Calviño et al., 2003a) and decreasing seedling emergence (Dillon, 2014). The lack of water availability after the wheat crop can reduce time to canopy closure, reducing light interception (Caviglia et al., 2011). In summary, shorter growing cycles, availability of water and nutrients, presence of undecomposed and poorly distributed wheat residue, are among some of the main factors affecting the attainable yields of DC soybean systems.

Therefore, a systematic literature review was conducted to better understand the current state of the art for DC soybean systems pursuing the goals to (i) quantify attainable yield for DC soybean systems benchmarking against the FS soybean both grown in the same location–year; (ii) determine and build probabilistic response models on the effect of previous wheat productivity on subsequent DC soybean yields; and (iii) detect and rank factors, available on the review data, influencing DC soybean yields via a decision inference tree approach.

MATERIALS AND METHODS

Data Collection, Criteria, and Databases

The data were gathered using the following search engines: CABI (www.cabi.org), Web of Science Core Collection (https://clarivate.com/products/web-of-science/databases), Scopus (www.scopus.com), SpringerLink (https://link.springer.com), Agricola (https://agricola.nal.usda.gov/), and Google Scholar (https://scholar.google.com/). For the literature review, similar procedures as previously developed by Ciampitti and Vyn (2012, 2013, 2014) were followed. Briefly, there was no restriction in the search for years or countries, which resulted in a worldwide data collection. The keywords used for the search were: "double-crop", "soybean", and "wheat". Using these keywords, the number of publications found were: CABI (475), Web of Science Core Collection (208), Scopus (86), SpringerLink (624), Agricola (69), and Google Scholar (4000). These publications were further evaluated to ensure that the titles and content have the required information about our subject of research. Thereafter, selected publications were reviewed using the abstracts. A total of 126 papers, dissertations, and theses were selected for download and further screened to include information on yield and soybean preceded by a wheat crop. The main criteria for final data inclusion in the database was whether the study presented information on DC soybean yield and reported full season (FS) soybean yield, wheat yield previous to DC soybean and management practices such as planting date, maturity group, among others. Due to this study contemplate worldwide data, we cannot use the term "winter wheat" (applies only to North America) since wheat planted in the Southern hemisphere is not strictly planted during the winter time. Thus, the focus of the study was to evaluate DC soybean when immediately planted after wheat harvest.

Not all studies presented complete information on all these aspects. The studies were analyzed collectively and were used to compile a data table containing results from 16, 31, and 7 studies for Database 1, 2, and 3, respectively (Table 1). The databases were separated based on the yield and management information provided in the studies. Thus, three databases were created with the following objectives: (i) compare DC versus FS soybean on attainable yields when both crops were grown in the same location-year (Database 1); (ii) relate DC soybean and the previous-crop wheat (Database 2), and (iii) when previous wheat yield, and DC soybean yield, maturity group and planting date information were provided to rank factors affecting relative DC soybean (to wheat) yield (Database 3).

A descriptive analyses for yield factor were obtained via implementation of histograms for Databases 1, 2, and 3 (Fig. 1A–D) (GraphPad Prism 6; Motulsky and Christopoulos, 2003). The data for DC soybean and wheat were analyzed relating to older data (1989) to search for possible bias toward yield differences based on when studies were conducted (Supplementary Fig. S2). This showed there was no effect of years on yields of DC soybean and wheat.

Statistical Analysis

For the first database, the comparison between DC versus FS soybean yield, was explored within three different FS soybean yield classes (yield environments): ≤2000 kg ha^{-1}, >2000 to ≤2800 kg ha^{-1}, and ≤2800 kg ha^{-1} (Fig. 2A). The yield environments were divided using terciles to obtain equal number of observations within each group. To explore the effect of the delay in planting date on the maximum DC soybean yield, a 99% quantile regression was performed using upper boundary regression (Fig. 2B). This regression represents the maximum attainable DC soybean yield that was less limited by other factors, but still affected by planting date. In addition, an overall linear regression (50% quantile regression) was fitted to obtain the average DC soybean yield reduction per day of difference on planting date relative to the FS soybeans. This relationship was described using the "quantreg" package (Koenker, 2017) for R software (R Core Team, 2017). Lastly, planting date difference by FS soybean yield environments was tested to avoid bias on the data collection process (Fig. 2C).

For the second database, the relationship between the maximum relative soybean-to-wheat yield (expressed in ratios) versus wheat yield (expressed in absolute values) was explored using the 99% quantile regression fitting a linear plateau model (Fig. 3A). This relationship was analyzed with the objective of understanding how the previous wheat yield affects the subsequent soybean yield. Relative soybean DC/wheat yield ratio was given by DC soybean yield divided by the previous wheat yield from the same area. This ratio was related to absolute values of wheat yield; thus, allowing the observation on the change of DC soybean depending on previous wheat yields. The relation has the objective of helping on decision making toward the next crop (DC soybean) based on a value that is easily available to the wheat grower. The comparison of wheat and DC soybean yields,

Table 1. Authors, publication year, type of publication, region of study, crop year, main characteristics, and number of observations per study for databases 1, 2, and 3.

	Authors	Region†	Crop year	Main characteristics	No. data points in databases 1	2	3
Database 1	Sanford, 1982	NAM	1974–1976	Straw and tillage management	3		
	Hairston et al., 1984	NAM	1981–1982	Tillage systems	4		
	Grove and Coale, 1987	NAM	1984–1985	Root and shoot development	2		
	Edwards et al., 1988	NAM	1981–1984	Tillage and crop rotation	12		
	O'Kelley, 1989	NAM	1986–1987	Soybean genotypes adapted to DC	12		
	Gesch and Archer, 2013	NAM	2008–2009	DC for fuel and food	12		
Database 1 and 2	Sanford et al., 1986	NAM	1978–1979	Cropping alternatives	3	2	
	Wesley and Cooke, 1986	NAM	1983–1985	DC systems	18	18	
	Kelley, 2003	NAM	1979–1997	Long-term crop rotations	10	10	
	Popp et al., 2003	NAM	1999–2000	Novel bedded system	10	10	
	Andrade and Satorre, 2015	SAM	2003–2008	Environ. effects on single and DC soybean	11	11	
	Andrade et al., 2015	SAM	2010–2011	Intensification of resources	3	3	
Database 1,2 and 3	Kyei-Boahen and Zhang, 2006	NAM	2001–2004	Yield and net returns	10	10	10
	Browning, 2011	NAM	2009–2010	Agronomic and economic comparison	10	6	6
	Meadors, 2015	NAM	2014	Suitability of energy beets for DC	1	1	1
Database 2 and 3	Lewis and Philips, 1976	NAM	1971–1974	Double-cropping		4	
	Wagger and Denton, 1988	NAM	1985–1987	Tillage effects on a rotation		16	
	Moomaw and Mader, 1991	NAM	1987–1989	Double-cropping		1	
	Daniels and Scott, 1991	NAM	1986	Water use efficiency		18	
	Khalilian et al., 1991	NAM	1988–1990	Soil compaction		36	
	Senigagliesi and Ferrari, 1993	SAM	1991–1992	Alternative tillage practices		4	
	Porter, 1995	NAM	1992	Double-cropping		2	
	Wesley, 1998	NAM	1984–1991	Double-cropping		30	
	Pullins and Myers, 1998	NAM	1993–1994	Agronomic and economic performance		4	
	Bauer et al., 2002	NAM	1996	Tillage effect and row spacing		12	
	Dıaz-Zorita et al., 2004	NAM	1994–2000	Soil structural disturbance		14	
	Pearce, 2005	NAM	2003–2004	Wheat stubble managements		16	
	Trusler et al., 2007	NAM	1999	Weed management in winter wheat		4	
	Behera et al., 2007	SAS	1996–2000	Integrated nutrient management practices		18	
	Nelson et al., 2010	NAM	2005	Cultivar selection		6	
	Caviglia et al., 2011	SAM	2000–2002	Wheat yield and quality		2	
	Kumar et al., 2012	SAS	2006–2007	Integrated weed management		9	
	Grey et al., 2012	NAM	2008–2009	Herbicide study		34	
	Nash et al., 2012	NAM	2008–2010	Polymer coated urea		33	33
	Sandler et al., 2015	NAM	2012–2013	Row spacing in wheat and crop effects		2	
Database 1, 2, and 3 (all unpublished data)	Holshouser, 2017	NAM	1998–2002	Double-crop soybeans	20	60	48
	Parvej, 2017	NAM	2015–2016	Maturity groups, planting dates and cultivars		67	380‡
	Hansel, 2017	NAM	2016–2017	Management practices for double-cropping			67
				Total	141	463	545

† NAM, North America; SAM, South America; SAS, South Asia.

‡ Bootstrapped.

as well as the ratio between them, does not have the intention of showing when DC soybean is outyielding wheat. The objective is to give the grower an estimated yield to expect from the DC soybean if planting after specific wheat yield levels. This analysis was previously performed by Rondanini et al. (2012), on rapeseed (*Brassica napus* L.)/wheat yield ratio. Additionally, wheat yield was divided into four yield classes: <2000 kg ha^{-1}, ≥2000 to <4000 kg ha^{-1}, ≥4000 to <6000 kg ha^{-1}, and ≥6000 kg ha^{-1}. The yield environments were divided based on <10, ≥10 to <50, ≥50 to <90, and ≥90 percentiles to compare extreme data points observations (<10 and ≥90%) with where the data was more concentrated (≥10 to <50, ≥50 to <90). The probability density functions of DC soybean/wheat yield ratio was accessed through Bayesian inference (Fig. 3B). In Bayesian analyses, prior distributions are assigned to parameters to represent knowledge or belief about the parameters before collecting observations. The observed data were then used to update that knowledge in the form of a posterior distribution for the parameters. The response variable was assumed to be symmetrical and followed a t distribution. A t distribution was used to describe the data due to a wider distribution than the normal distribution allowing to accommodate more extreme points that otherwise would be considered outliers (Kruschke, 2013). The priors were minimally informative: normal priors with large standard deviation for μ, broad uniform priors for σ, and a shifted-exponential prior for ν, as described by Kruschke (2013). Posterior distributions

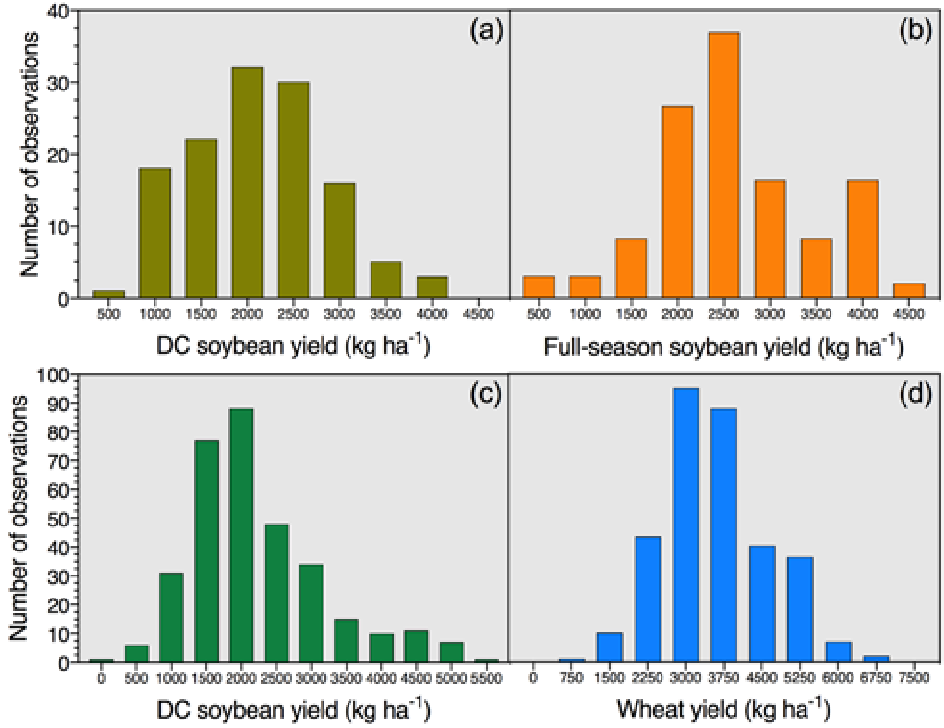

Fig. 1. Descriptive analysis of the dispersion of number of observations for yield data in databases 1 (a and b) and 2 (c and d). Database 3 is included in database 1 and 2 in addition to the unpublished data that also follows the same trend of distribution.

were obtained using Markov-Chain Monte Carlo (MCMC) simulation (Gelman et al., 2004) and Metropolis–Hastings algorithm with 10,000 random draws from each posterior after a suitable burn-in period of about 200 iterations. Posteriors cumulative density functions were built for each yield class to facilitate interpretation.

For the third database, the influence of additional sources of variation (such as planting date and maturity group) in DC soybean relative to wheat yield variability was evaluated. This analysis used a conditional inference using the partykit package in R (Hothorn and Zeileis, 2015) (Fig. 4). This analysis is based on hierarchically ordered and recursively repeated binary splits, where the strength of each association is measured by a *P*-value. To avoid overfitting and enhance interpretability, the maximum tree depth was set to 10 nodes. The data used for the conditional tree analysis contained only field research studies conducted in North America. However, only one study was conducted in South America (Caviglia et al., 2011) and excluded from the analysis to avoid a confounding effect on the planting date evaluation.

Lastly, a yield deviation calculation (yield value of each observation – average yield of the entire experiment) for each study was implemented and plotted against year of the experimentation to check if there was any historical trend related to yield gain and to quantify if the effect of a particular study was influencing the database (Supplementary Fig. S1). Similarly, DC soybean and wheat historical trends (relative yield to an initial point) were compared to avoid a bias toward differential yield gain for one crop relative to the other (Supplementary Fig. S2).

RESULTS AND DISCUSSION

For the entire database, yield showed similar dispersion from the mean throughout the evaluated years (1976–2017) (Supplementary Fig. S1).

The overall distribution of the data points permitted to visually demonstrate lack of a temporal trend. Therefore, it can be concluded that the year of experimentation did not influence the analyses of Databases 1 and 2 (Supplementary Fig. S2).

The histograms of Database 1 and 2 (Fig. 1) portrayed different distributions for DC and FS soybean yields as well as for DC soybean and wheat yields. In Database 1, DC (Fig. 1A) and FS soybean yields (Fig. 1B) displayed similar normal distribution ($p > 0.05$; Shapiro-Wilk test), differing on the mean for DC soybean of 2000 kg ha^{-1} and for FS soybean of 2500 kg ha^{-1}. As for Database 2, both DC soybean (Fig. 1C), and wheat (Fig. 1D) yields portrayed normal distributions ($p > 0.05$– Shapiro-Wilk test). The peaks in yield occur in different yield levels for both crops. The highest frequency occurs for DC soybeans between 1500 and 2000 kg ha^{-1}, while for wheat it occurs between 3000 and 3500 kg ha^{-1}. As expected, yield distribution was generally toward high values for FS soybean related to DC soybean, and similar observation was reported for the wheat yield relative to DC soybean comparison.

Double-Crop versus Full Season Soybean (Database 1)

Full-season soybean out-yielded DC soybean in yield environments where yields were ≥2000 kg ha^{-1}; however, the yield gap between FS and DC soybean increased in higher yielding environments (Fig. 2A). The difference between DC soybean yield and FS soybean yields were 31 ($p > 0.05$), 430 ($p > 0.01$) and 1119 ($p > 0.01$) kg ha^{-1} for yield environment ≤2000 kg ha^{-1}, >2000 to ≤2800 kg ha^{-1}, and >2800 kg ha^{-1}, respectively.

Double-crop soybean was usually planted later than FS soybean due to wheat harvest time (Fig. 2B). Due to late planting, DC soybean had shortened growth cycle and higher risk of an early fall freeze (Egli and Bruening, 2000; Calviño et al., 2002).

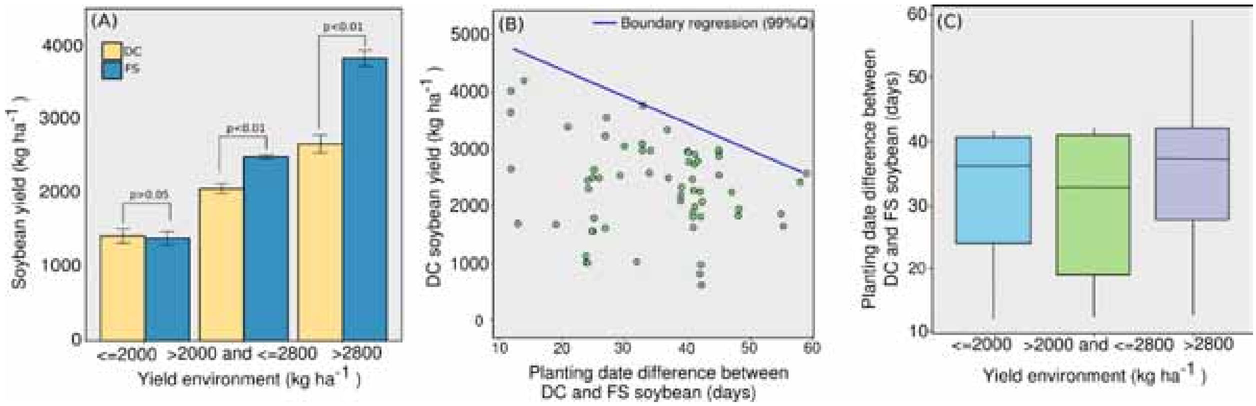

Fig. 2. (A) Double-crop (DC) soybean yields compared to full-season (FS) soybean yield. Yield environments were divided in three yield environments: <2000 kg ha^{-1}, 2000 to <2800 kg ha^{-1}, and ≥2800 kg ha^{-1}. (B) Effect of different planting dates between DC and FS soybean in DC soybean yields. Upper boundary regression (99% quantile) showing the potential yield decline for DC soybean. (C) Planting date difference in days between DC and FS soybean for each yield environment.

These, among other reasons, are likely responsible for the drastic DC yield reduction in potential DC soybean yields, observed when the difference in sowing time between FS and DC soybean increased (Fig. 2B). Yet, the average decline in yield to difference in planting date was not statistically significant ($p > 0.01$, $R^2 = 0.04$) (Fig. 2B). Thus, attainable yield decreased as DC soybean was planted later in the season. Planting date showed a similar difference among all the yield environments (Fig. 2C), indicating that response in the yield gap between FS and DC soybean was primarily due to the yield environment and not confounded with potential differences in planting dates (Fig. 2A).

Wheat versus Double Crop Soybean Yields (Database 2)

Relative DC soybean (to wheat) yield was analyzed with the purpose of predicting DC soybean yields, using previous crop information for a probability analysis (Fig. 3A, B). The ratio for DC soybean/wheat yield was greater as wheat yield decreased. When wheat yield was 2000 kg ha^{-1}, the average DC soybean yield is 86% of the previous wheat yield.

In contrast, when wheat yields are above 4000 kg ha^{-1}, DC soybean will yield an average 65% of the previous wheat, and when above 6000 kg ha^{-1}, DC soybean will yield 45% of the previous wheat yield (Fig. 3A). Also, DC soybean yields decreased after this threshold. Based on the average percentage of DC soybean in relation to wheat, the farmer can have an estimate of the expected yield level for the upcoming DC soybean crop. The linear regression (50% quartile) showed an average of 13 kg ha^{-1} decrease in DC soybean for each 100 kg ha^{-1} increase in wheat yield (slope −0.014% kg ha^{-1}). The upper bilinear regression (99% quartile– upper boundary regression) shows the potential DC soybean yields, in relation to wheat. This relationship between the maximum soybean/wheat yield ratio, reaches 170% until wheat yield increases to 2900 kg ha^{-1}. After this, the DC soybean/wheat yield ratio decreased 0.054% kg ha^{-1}, resulting in 54 kg ha^{-1} decrease of potential yield for DC soybean for each 100 kg ha^{-1} of increase in wheat yield. Although wheat is an excellent choice to pair with DC soybean (Evans et al., 1993), it may negatively affect the soybean crop (Pearce et al., 1993; Calviño et al., 2003a). Superior wheat yields will demand use of more resources (e.g., water, nutrients) (Daniels and Scott, 1991; Caviglia et al., 2004; Andrade et al., 2015), depleting those resources for the following soybean crop. Thus, previous studies concluded that soybean yields were affected by wheat yield and its residue, reducing soybean yield as wheat yield increases (Caviness et al., 1986; Kyei-Boahen and Zhang, 2006; Nelson et al., 2010). Due to that, many researchers have studied the effect of quantity of wheat residue on soybean yield, although conclusions vary on how to manage wheat stubble (Pearce, 2005; Cordell et al., 2007; Amuri et al., 2010). Still, no-tillage of the DC soybean presented greater net return relative to conventional tillage combinations (Amuri, 2008). In addition, the effect of greater wheat residue on DC soybean yields can be due to the effect of the residue itself, per se residue effect, or due to the greater wheat yield that utilized more resources (water and nutrients), directly affecting the ability of the DC soybean crop to grow early in the season and indirectly impacting yields. Double-crop soybean yields are likely a direct consequence of the interaction between environmental conditions experienced by the crop and effects of the previous wheat yield. However, the decline in the ratio DC soybean/wheat can be due to greater wheat yields, with soybean yields remaining constant. Regardless, for the upper boundary function (Fig. 3A), maximum DC soybean/wheat yield ratio reached 100%, at a wheat yield of approximately 5500 kg ha^{-1}.

Thereby, there are many factors interacting on the final DC soybean yield response, increasing the complexity and challenges for providing science-based management decisions.

To help in the decision-making process toward DC soybean and, a posterior predictive probability analysis was performed (Fig. 3B). Thus, when wheat yield environment was greater than 6000 kg ha^{-1}, there is zero probability of DC soybean to yield more than the wheat yields (ratio >100%). In this high yielding wheat environment, the probability shows that the maximum DC soybean yield, would be 50% of the previous wheat yield (ratio <50%). As wheat yield decreased, the likelihood of DC soybean yielding more than the yield observed for wheat increased, reaching 20, 30, and 55% of probability of greater DC soybean yield than wheat, when wheat yield ranged from 4000 to 6000, 2000 to 4000, and <2000 kg ha^{-1}, respectively (Fig. 3B). There was a 75% probability that DC soybean would yield 25, 50, 70, and 75% of the previous wheat yield, when wheat yield ranged from ≥4000 to <6000 kg ha^{-1}, ≥2000 to <4000 kg ha^{-1}, and <2000 kg ha^{-1}, respectively. Likewise, Porter et al. (1997) showed increased benefits for DC soybean yields in lower wheat yield environments.

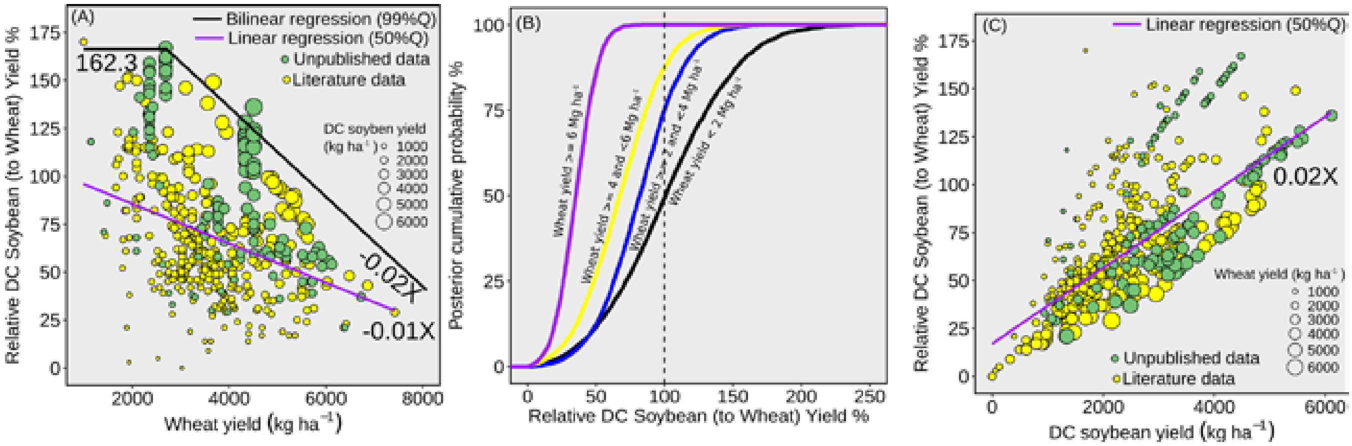

Fig. 3. Relative soybean (to wheat) yield response to previous wheat yield. The potential yield is given by the bilinear regression– upper boundary regression (99% quartile). The mean response is given by the 50% quartile line (R^2 = 0.15) (A). Posterior predictive probability for DC soybean (to wheat) yields for four yield environments of previous wheat yield <2000 kg ha^{-1}, ≥2000 to <4000 kg ha^{-1}, ≥4000 to <6000 kg ha^{-1} and ≥6000 kg ha^{-1} (B). Influence of DC soybean yields on the ratio of relative soybean (to wheat) yield response. The mean response is given by a 50% quartile line (R^2 = 0.52) (C). Green circles are unpublished data, and yellow circles are for literature data. Size of circles represent soybean yield absolute values.

Although DC soybean yields can be predicted in relation to the previous wheat yields, there are many factors that influence both responses. Wheat yields can predict only 15% confidence on the decline in DC soybean yields. The effects from DC soybean itself and its interactions with the environment can be accountable with 51% of the response from yields (Fig. 3C). Even though the proportion of the variation accounted for wheat yields in the DC soybean/wheat yield ratio was low (R^2 = 0.15), several factors influence the final attainable soybean yields (e.g., weather, genotype, and management) (Pearce, 2005; Navarro, 2010; Nelson et al., 2010; Andrade and Satorre, 2015; Liu et al., 2015; Norman et al., 2016).

Relevance of Management Decisions on Double Crop Soybean Yield (Database 3)

Based on the management data gathered for this review, including seven studies from North America, the most important factor influencing DC soybean was the previous wheat yield, with a different response when wheat yield values >2800 and ≤2800 kg ha^{-1} (Fig. 4).

In wheat yield environments ≤2800 kg ha^{-1}, neither soybean maturity group (MG) nor DC sowing time (expressed as day of the year [DOY]) were relevant factors; 80% of all data points (n = 47) presented greater DC soybean yields relative to wheat yield (Node 2 in Fig. 4). For this wheat yield level (≤2800 kg ha^{-1}), the average ratio for relative DC soybean to wheat, was 146%. However, for wheat yields >2800 kg ha^{-1}, DOY followed by MG influenced DC soybean yields. Many studies have found that later sowing date reduced yields (Egli and Bruening, 2000; Calviño et al., 2003b; Salmeron et al., 2014). Rattalino Edreira et al. (2017), conducted in the North-Central US region, utilizing a large self-reported farmer database found that yield potential was reduced for each day planted later than 1 April (DOY 91). According to our analysis (Fig. 4), when soybean was planted after DOY 180 ("late" planted), corresponding to the end of June, there was no difference in DC yield ratio for early or late MGs (Node 9 in Fig. 4). The average DC soybean/wheat yield ratio was 67%. Soybean yielded less than the previous wheat, for an overwhelming majority (>90% of all observations, n = 73) of the observed data analyzed (Node 9 in Fig. 4). If soybean planting date was earlier than DOY 180 ("early" planted), there was a different response for wheat yields that ranged from >2800 to 4500 kg ha^{-1} and with yields above 4500 kg ha^{-1}. Regarding the latter group, more than 80% of all data points (n = 55) presented lower ratio for relative DC soybean/wheat (<100%). The average relative DC soybean/wheat yield for these data points was 70% (Node 8 in Fig. 4). Although, when wheat yield was between >2088 and ≤4500 kg ha^{-1}, and MG was above 4.5, 70% from all the data points (n = 17) portrayed DC soybean yields lower than wheat, at the average of 57% relative DC soybean to wheat yield (Node 7 in Fig. 4). When soybean MG was ≤4.5, 60% of the data points (n = 22) presented DC soybean yields greater than the observed wheat yield, with average of 115% relative DC soybean to wheat yield (Node 6 in Fig. 4). Agreeing to the observed in this study, mid-MG 3 was observed as the ideal to maximize yields for DC in Missouri (Minor and Wiebold, 1998). Holshouser (2015) observed that late MGs allow more time for plant growth, although the plant has to reach maturity before the first frost.

Main Limiting Factors in a Double Crop Soybean System

There are many limiting factors related to DC soybean systems. To better understand the yield-limiting factors in the DC soybean system, 19 studies were reviewed. The main factors impacting yield were late planting date or short crop cycle, lack of water, low temperature, radiation/photoperiod, residue, limitation of soil nutrients, and early frost and machinery requirements. From the 19 studies, yields in 15 were limited by water (Crabtree et al., 1990; Ritter and Scarborough, 1992; Lehrsch et al., 1994; Duncan and Schapaugh, 1997; Calviño et al., 2002; Pearce, 2005; Behera et al., 2007; Bruinsma, 2009; Nelson et al., 2010; Smith, 2013; Dillon, 2014; Qin et al., 2015; Gesch and Johnson, 2015; Liu et al., 2015; Norman et al., 2016). Of these, only five reported soil water status (Lehrsch et al., 1994; Gesch and Johnson, 2015; Liu et al., 2015; Qin et al., 2015; Norman et al., 2016). Therefore, it is evident that soil water status should be investigated further.

The second most reported limiting factors were late planting (Lehrsch et al., 1994; Calviño et al., 2003b; Caviglia et al.,

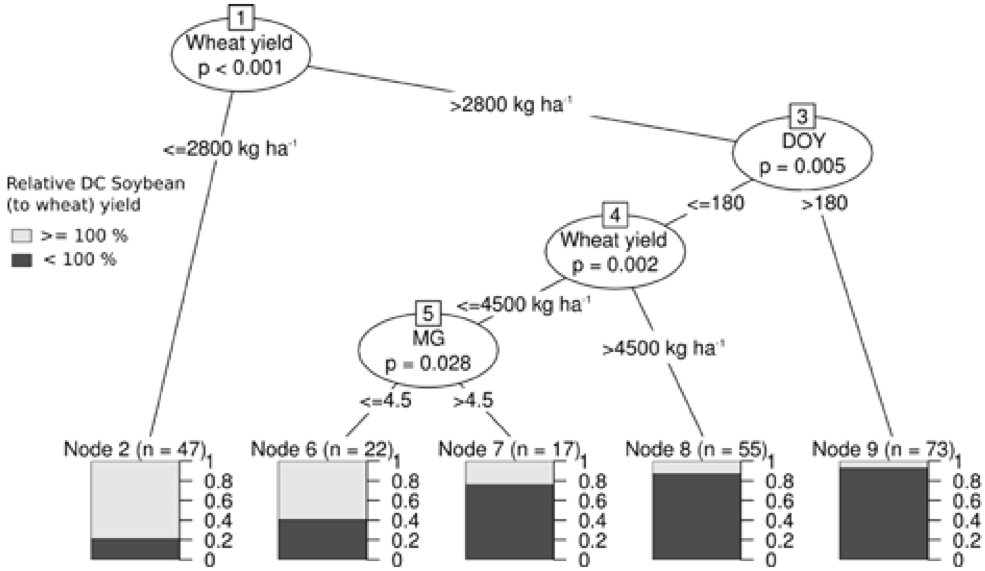

Fig. 4. Inference tree showing the hierarchical order of importance in the response of relative soybean (to wheat) yields to main management factors (wheat yield, day of the year [DOY] and maturity group [mat. group]). In this Fig., 1 being higher and 10 lower hierarchical order; least significant difference $p < 0.05$.

2004; Dillon, 2014; Salmeron et al., 2014) and soil nutrient availability (Behera et al., 2007; Nelson et al., 2010; Andrade and Satorre, 2015; Qin et al., 2015). Other factors, were temperature, radiation/photoperiod, residue and early frost (Pearce, 2005; Bruinsma, 2009; Navarro, 2010; Nelson et al., 2010; Holshouser, 2015; Andrade and Satorre, 2015; Liu et al., 2015; Norman et al., 2016). Lastly, machinery requirements were also cited as a limiting factor (Navarro, 2010).

Identification of the major limiting factors affecting DC soybean yields and then determination of the best management practices should be further investigated with the goal of not only increasing attainable DC soybean yields but for improving the overall productivity of the wheat–DC soybean farming system.

CONCLUSIONS

The most striking outcomes from this review paper were (i) as yield environments are greater (from 1500 to 3000 kg ha^{-1}), yield gap of DC soybean compared to FS soybean widens from –31 to 1162 kg ha^{-1}; (ii) even though the proportion of the variation accounted for wheat yields in the DC soybean/wheat yield ratio was low ($R^2 = 0.15$), the probability of DC soybean yield being equal to wheat yield was 0, 20, 30, and 55% for wheat yields of ≥6, ≥4 and <6, ≥2 and <4, and <2 Mg ha^{-1}; thus, more than 50% probability to obtain similar DC soybean and wheat yields was obtained with low wheat yields (<2 Mg ha^{-1}); and (iii) the inference tree analysis ranked wheat yield as the main factor, followed by planting date and maturity group as secondary factors influencing DC soybean yields. In summary, the probability of obtaining greater DC soybean yields (relative to wheat) is reduced as the wheat yield improves and planting date for soybeans after wheat is delayed.

There is still the need to critically evaluate and identify best management practices to produce greater and stable DC soybean yields. Deployment of comprehensive field studies investigating multi-factors under different soil and environment conditions are needed to identify factors influencing DC soybean farming systems around the globe. In addition, consideration of using crop simulation models to evaluate different scenarios (soil, water, environment, and management and their interactions) and improved knowledge on site-specific best management practices recommendations (including sowing time, variety selection, seeding rate, and row spacing, among other factors) are potential avenues to be explored for increasing attainable soybean yields under the complex genotype × environment × management interaction.

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