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Influence of integrated agronomic and weed management practices on soybean canopy development and yield

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Research Article

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Abstract

The role of weed suppression by the cultivated crop is often overlooked in annual row cropping systems. Agronomic practices such as planting time, row spacing, tillage and herbicide selection may influence the time of crop canopy closure. The objective of this research was to evaluate the influence of the aforementioned agronomic practices and their interaction with the adoption of an effective preemergence (PRE) soil residual herbicide program on soybean canopy closure and yield. A field experiment was conducted in 2019 and 2020 in Arlington, WI, as a 2×2×2×2 factorial in a randomized complete block design, including early (late April) and standard (late May) planting time, narrow (38 cm) and wide (76 cm) row spacing, conventional tillage and no-till, and soil-applied PRE herbicide (yes and no; flumioxazin 150 g ai ha^{-1} + metribuzin 449 g ai ha^{-1} + pyroxasulfone 190 g ai ha^{-1}). All plots were maintained weed-free throughout the growing season. In both years, early planted soybeans reached 90% green canopy cover (T_{90}) before (7 to 9 d difference) and yielded more (188 to 902 kg ha^{-1} difference) than the standard planted soybeans. Narrow-row soybeans reached T_{90} earlier than wide-row soybeans (4 to 7 d difference), but yield was similar between row spacing treatments. Conventional tillage resulted in a higher yield compared to a no-till system (377 kg ha^{-1} difference). The PRE herbicide slightly delayed T_{90} (4 d or less) but had no impact on yield. All practices investigated herein influenced the time of soybean canopy closure but only planting time and tillage impacted yield. Planting soybeans earlier and reducing their row spacing expedites the time to canopy closure. The potential delay in canopy development and yield loss if soybeans are allowed to compete with weeds early in the season would likely outweigh the slight delay in canopy development by an effective PRE herbicide.

Introduction

Introduction of glyphosate-resistant (GR) soybean in 1996 drastically changed weed control practices in U.S. soybean production, allowing growers more flexibility for postemergence (POST) weed control with the use of the systemic and nonselective broad-spectrum herbicide glyphosate. This change resulted in reduced labor and time requirements, herbicide costs, reliance on tillage, and other means of mechanical and cultural weed control (Bradley et al. 2004; Johnson et al. 2000; Reddy and Whiting 2000). The change in herbicide use patterns from preemergence (PRE) followed by POST applications to POST-only applications(s) of glyphosate (Duke 2015; Givens et al. 2009; Powles 2008) contributed to selection pressure for widespread glyphosate resistance evolution. From 1990 to 2021, 17 different weed species evolved resistance to glyphosate in the United States alone (Heap 2021). Restoration of diverse and integrated weed management (IWM) strategies based on the practices of crop rotation, competitive crop cultivars, cover crops, and prudent use of tillage and herbicides are needed to confront herbicide resistance.

Focusing on reduction of weed-crop interference and weed fecundity while maximizing crop yield potential, a holistic and sustainable IWM is achieved through the adoption of numerous weed control measures including cultural, genetic, mechanical, biological, and chemical strategies applied in a systematic manner (Blackshaw et al. 2008; Butts et al. 2016; Liebman et al. 2001; Regnier and Janke 1990; Shaw 1982; Swanton and Murphy 1996; Swanton and Weise 1991; Walker and Buchanan 1982). Agronomic strategies aimed at reducing the time to crop canopy closure represent the foundation of cultural weed control (Jha and Norsworthy 2009). Numerous factors may influence crop canopy development including soil management strategy (i.e., tillage, no-till), planting date, row spacing, seeding rate, soil fertility, herbicide program, and environmental conditions (Arsenijevic 2021; Bradley 2006; Mallarino 1999; Nice et al.

2001; Renner and Mickelson 1997; Yusuf 1999; Zhang et al. 2010). Earlier canopy closure can limit the amount of light reaching the soil surface, which impacts weed seed germination, establishment, and growth (Norsworthy and Oliveira 2007; Sanyal et al. 2008). Soybean is generally a poor competitor during earlier stages of development; however, early planting and narrow row spacing can improve its competitiveness (Klingaman and Oliver 1994; Legere and Schreiber 1989). For instance, Butts et al. (2016) reported that narrow row width (≤38 cm) reduced end of season *Amaranthus* spp. growth and fecundity. A highly competitive soybean crop may translate into a reduced need for in-season herbicide applications and higher yield (Norsworthy and Shipe 2006).

In response to widespread herbicide resistance and a shortage of effective POST herbicide options, the use of effective PRE herbicide programs has increased in frequency for chemical weed control in soybeans. For instance, the soybean planted area treated with the PRE herbicides flumioxazin (a protoporphyrinogen oxidase inhibitor; Group 14) and metribuzin (photosystem II inhibitor; Group 5) increased by 3% and 15%, respectively, from 2006 to 2020, and pyroxasulfone (very-long-chain fatty acid [VLCFA]; Group 15) increased by 13% from 2012 to 2020 (USDA-NASS 2021). Early-season soybean injury leading to slower canopy closure and potential for yield reduction is a concern of soybean growers adopting effective PRE herbicides with multiple sites of action (Moomaw and Martin 1978; Niekamp et al. 2000; Nelson and Renner 2001; Osborne et al. 1995; Poston et al. 2008; Sakaki et al. 1991). Research investigating the interaction between cultural agronomic practices and early-season chemical weed control (i.e., PRE herbicides) on crop canopy development and yield is lacking. Thus, the objective of this field experiment was to evaluate the impact of integrated agronomic and weed management practices (i.e., planting time, row spacing, tillage practice, and PRE herbicide application) on soybean canopy development and yield. We hypothesized that the aforementioned practices would influence the time to soybean canopy closure and yield.

Materials and Methods

A field experiment was conducted in 2019 and 2020 at the University of Wisconsin-Madison Arlington Agricultural Research Station near Arlington, WI (43.3097°N, 89.3458°W). The experiment was conducted as a four-way-factorial established in a randomized complete block design (RCBD) with four replications. Experimental units were 3 m wide by 12.2 m long. Treatments consisted of two soybean planting times (early planting [late April] and standard planting [late May]), two row -spacings (38 cm [narrow-row spacing] and 76 cm [wide-row spacing]), two tillage systems (no-till and conventional tillage), and PRE herbicide application (yes PRE and no PRE). The PRE herbicide used (flumioxazin 150 g ai ha^{-1}, metribuzin 449 g ai ha^{-1}, and pyroxasulfone 190 g ai ha^{-1}; Fierce® MTZ, Valent U.S.A. LLC, Walnut Creek, CA) has a broad weed control spectrum and is known to cause early-season soybean injury under adverse environmental conditions (i.e., cool and wet soils; Arsenijevic et al. 2021; Taylor-Lowell et al. 2001).

The soybean variety AG24X7 (seed treatment; Acceleron® Seed Applied Solutions Elite with NemaStrike™ Technology; Asgrow Seed Co. LLC, Creve Coeur, MO) was planted in both years at 360,000 seeds ha^{-1}, at a depth of 3.8 cm. In 2019, soybean was planted on April 25 (early planting) and May 23 (standard planting). The soil type was silt loam (26% clay, 59% silt, and 16% sand), pH 6.9, and 4.8% organic matter (OM). In 2020, soybean was planted on April 21 (early planting) and May 22 (standard planting). The soil type was loam (25% clay, 48% silt, and 28% sand), pH 5.9, and 3.5% OM. No-till corn was the previous crop in both experimental years; the 2019 field was under no-till continuous corn (>5 yr) whereas the 2020 field was under no-till corn-soybean rotation (>5 yr). PRE herbicides were applied the day of each planting to designated plots using a CO_2-pressurized backpack sprayer equipped with Turbo TeeJet® TTI11015 air induction nozzles (Spraying Systems Co., Wheaton, IL) calibrated to deliver 94 L ha^{-1}. Because the objective of this experiment was to evaluate crop canopy closure and grain yield but not weed suppression, experimental units were kept weed-free throughout the study by hand-weeding and/or glyphosate application when weeds were detected (glyphosate 863 g ae ha^{-1}, RoundUp®PowerMax; Bayer AG, Leverkusen, Germany; + ammonium-sulfate 1,430 g ha^{-1}). Monthly precipitation, average air and soil temperature (10 cm depth) for each year, and historical weather data are presented in Table 1.

Table 1. Monthly average air and soil temperature (10 cm depth) and cumulative precipitation in Arlington, WI.[a,b]

	Air temperature			Soil temperature		Precipitation		
	2019	2020	30 yr	2019	2020	2019	2020	30 yr
Month	C					mm		
April	7.5	6.0	7.4	8.5	8.6	77	37	111
May	12.6	12.9	14.1	16.4	15.4	172	113	118
Jun	18.6	20.1	19.5	23.4	23.7	141	110	148
Jul	22.7	22.3	21.6	27.7	26.9	118	142	114
Aug	18.9	19.7	20.5	26.1	24.7	153	97	118
Sep	17.6	14.3	16.2	20.7	20.8	146	76	94
Oct	7.2	6.2	9.2	16.2	13.9	158	21	80
Season[c]	15.0	14.5	15.5	19.9	19.1	965	596	783

[a]Air, soil, and rainfall data obtained from Enviro-weather station (East Lansing: Michigan State University) located at the Arlington Agricultural Research Station.
[b]Thirty-yr air temperature and precipitation averages for the period from 1988 to 2018 obtained in R statistical software (version 4.0.1) using daily Daymet weather data for 1-km grids (Correndo et al. 2021; Thornton et al. 2016; DAYMETR package).
[c]Monthly cumulative precipitation and average temperature throughout the growing season.

Soybean Canopy Development

To evaluate soybean canopy development, three photos per experimental unit of the six rows (narrow-row spacing) and four rows (wide-row spacing) were taken per week. A wooden L-shape pole (2.1 m height) was constructed, and a GoPro Hero 8 Black camera (GoPro Inc., San Mateo, CA) was mounted at the top and paired with an iPhone 6s cellphone (Apple Inc., Cupertino, CA) through the GoPro app (7.2.1 version), which provided view finding capabilities for the camera. Photos were processed using MATLAB (MathWorks®, Natick, MA) via Canopeo add-on (Canopeo Software, Oklahoma State University, Division of Agricultural Sciences and Natural Resources Soil Physics program, Stillwater, OK; https://canopeoapp.com), which allowed for estimation of fractional green canopy cover within each image (Arsenijevic 2021; Liang et al. 2012; Paruelo et al. 2000; Patrignani and Ochsner 2015). Soybean canopy development assessments started 7 d after each planting timing and concluded when >95% green canopy cover was attained in all plots throughout the study.

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Soybean Yield

Soybean grain weight (kilograms per plot) and moisture (%) were collected at crop physiological maturity (October 26, 2019, and October 15, 2020) with an Almaco plot combine (Almaco, Nevada, IA) by harvesting the two center rows of wide row-spacing treatments, and four center rows of narrow row-spacing treatments. All treatments within a year were harvested at the same time. Yield results were standardized to 13% moisture and converted to kilograms per hectare for comparisons.

Statistical Analyses

All analyses were completed in R statistical software version 4.0.1 (R Foundation for Statistical Computing, Vienna, Austria).

Soybean Canopy Closure Modeling

A three-parameter Weibull 2 model was fit to average soybean green canopy cover (%; response variable) regressed on the day of the year (Julian day) when photos were taken (explanatory variable) for each experimental unit within each treatment using the DRC package in R:

$$y = c + (d - c)exp\ \{-exp[b(log(x) - e)]$$

where y is average soybean green canopy cover (%), c is the lower limit (fixed at 0), d is the upper limit (fixed at 100), b is the slope, x is day of year, and e is the inflection point (Ritz and Strebig 2016). The day of year when 90% soybean green canopy cover (T_{90}) occurred in each plot was estimated using the *ED* function in R. T_{90} results are used herein as an indicator of time for canopy closure.

Analysis of Variance

Planting time, row-spacing, tillage system, PRE herbicide, and year were treated as fixed effects, and replications nested within years were treated as a random effect. Linear mixed models with a normal distribution (LME4 package) were fit to T_{90} and yield data. Normality and homogeneity of variance were evaluated using the Pearson chi-square test (NORTEST package) and Levene's test (CAR package), respectively. T_{90} data were log-transformed, and yield data were square root–transformed before analyses to satisfy the Gaussian assumptions of normality and homogeneity of variance. Means were separated when interactions and/or main effects were less than P = 0.05 using Fisher's protected least-significant difference test. Back-transformed means are presented for ease of interpretation. ANOVA summary for T_{90} and soybean yield is displayed in Table 2.

Table 2. ANOVA summary for estimated time to 90% soybean canopy closure (T_{90}) and yield.[a]

Effect[b]	Soybean canopy closure (90%)	Yield
	T_{90} (day of year)	kg ha^{-1}
	P-value	
Planting time	**<0.0001**	**<0.0001**
Row spacing	**<0.0001**	0.7500
Preemergence herbicide	**<0.0001**	0.0977
Tillage	**<0.0001**	**<0.0001**
Year	**<0.0001**	**<0.0001**
PT × RS	0.4391	0.8792
PT × H	0.2964	0.0760
RS × H	0.7613	0.6643
PT × T	0.0706	0.1033
RS × T	0.8388	0.9729
H × T	0.9048	0.1124
PT × Yr	**<0.0001**	**<0.0001**
RS × Yr	**0.0109**	0.3387
H × Yr	0.1576	0.6561
T × Yr	0.3411	0.6599
PT × RS × H	0.1544	0.8642
PT × RS × T	0.1211	0.9115
PT × H × T	**0.0359**	0.5162
RS × H × T	0.6553	0.5162
PT × RS × Yr	0.6135	0.4923
PT × H × Yr	**0.0168**	0.4962
RS × H × Yr	0.7164	0.3712
PT × T × Yr	0.5321	0.1633
RS × T × Yr	0.6457	0.3876
H × T × Yr	0.4851	0.4129
PT × RS × H × T	0.1308	0.7978
PT × RS × H × Yr	0.6369	0.9184
PT × RS × T × Yr	0.1241	0.8219
PT × H × T × Yr	0.0598	0.4796
RS × H × T × Yr	0.4663	0.9354
PT × RS × H × T × Yr	0.9446	0.7527

[a]ANOVA conducted on a significance level of $\alpha = 0.05$.
[b]Abbreviations: H, preemergence herbicide; PT, planting time; RS, row spacing; T, tillage; Yr, year.

Results and Discussion

Soybean Canopy Development (T_{90})

All factors evaluated in this study had an impact on soybean canopy closure (Table 2). According to the ANOVA results, T_{90} was influenced by planting time × PRE × year (P = 0.0168), planting time × PRE × tillage (P =0.0359; Table 2), and the row spacing × year (P = 0.0109) interactions.

In 2019, early planted soybean reached T_{90} 6 to 11 d before the standard planted soybean (Table 3). The use of a PRE delayed T_{90} by 4 d in the early planting whereas it had no impact during the standard planting time. In 2020, early planted soybean within the same PRE treatment reached T_{90} at 3 to 4 d before the standard planted soybean. The use of a PRE delayed T_{90} by 3 to 4 d for both planting times. Following a PRE herbicide application, extended cool and wet soil conditions during crop emergence can lead to crop injury and delayed canopy formation (Arsenijevic et al. 2021; Moomaw and Martin 1978; Nelson and Renner 2001; Niekamp et al. 2000; Osborne et al. 1995; Sakaki et al. 1991). Moreover, rainfall during crop emergence can result in the splashing of PRE herbicides onto soybean hypocotyl and cotyledons, causing injury (Hartzler 2004; Wise et al. 2015). Such conditions (cool and wet soils), which are common in the spring in Wisconsin and neighboring states, occurred in this experiment following a PRE application.

Under conventional tillage, early planted soybean reached T_{90} at 4 to 9 d before the standard planted soybean (Table 4). The use of a PRE delayed T_{90} by 4 d in the early planting whereas it had no impact during the standard planting time. Under no-till, early planted soybean within the same PRE treatment reached T_{90} 4 to 5 d before the standard planted soybean. The use of a PRE delayed T_{90} by 3 d for the standard planting time. Yusuf et al. (1999) observed greater crop growth rate in soybean under conventional tillage when compared to the no-till, with differences persisting until the R2 growth stage.

In 2019, narrow row space soybean reached T_{90} 7 d before wide row space (day of the year 198 [95% confidence interval; 196–199] and 205 [203–207], respectively). In 2020, narrow row space

Table 3. Estimated day of year when soybean reached 90% canopy closure (T_{90}) according to planting time, year, and preemergence herbicide interaction (P = 0.0168).[a]

Planting time[b]	Preemergence herbicide[c]	T_{90} 2019	T_{90} 2020
		day of the year[d]	
Early	No	195 (193–197) a	187 (185–189) a
	Yes	199 (197–201) b	190 (188–191) b
Standard	No	205 (203–207) c	190 (198–191) b
	Yes	206 (204–208) c	194 (192–196) c

[a]Comparisons of means are split by year. Means within a year followed by the same letter are not different according to Fisher's least significant difference test (P = 0.05).
[b]Soybean early planting: (April 25 [115] and 21 [112]; 2019 and 2020, respectively); soybean standard planting: (May 23 [143] and 22 [143]; 2019 and 2020, respectively). Information in brackets refers to day of year.
[c]Fierce® MTZ (1,170 g ha $^{-1}$; flumioxazin 150 g ai ha^{-1}, metribuzin 449 g ai ha^{-1}, and pyroxasulfone 190 g ai ha^{-1}).
[d]For reference, day of the year 195 in 2019 was July 14, and July 13 in 2020. Information in parentheses represents the lower and upper limits of 95% confidence intervals.

Table 4. Estimated day of year when soybean reached 90% canopy closure (T_{90}) according to planting time, preemergence herbicide and tillage interaction (P = 0.0359).[a]

Planting time[b]	Preemergence herbicide[c]	T_{90} Conventional tillage	T_{90} No-till
		day of the year[d]	
Early	No	189 (187–190) a	194 (192–196) a
	Yes	193 (191–195) b	196 (194–198) ab
Standard	No	197 (195–199) c	198 (196–200) b
	Yes	198 (196–200) c	201 (200–203) c

[a]Comparisons of means are split by tillage systems for better interpretation. Means within a tillage system followed by the same letter are not different according to Fisher's least significant difference test (P = 0.05).
[b]Soybean early planting: (April 25 [115] and 21 [112]; 2019 and 2020, respectively); soybean standard planting: (May 23 [143] and 22 [143]; 2019 and 2020, respectively). Information in brackets refers to day of year.
[c]Fierce® MTZ (1,170 g ha^{-1}; flumioxazin 150 g ai ha^{-1}, metribuzin 449 g ai ha^{-1}, and pyroxasulfone 190 g ai ha^{-1}).
[d]For reference, day of year 190 is July 9. Information in parentheses represents the lower and upper limits of 95% confidence interval.

soybean reached T_{90} 4 d before wide row space (day of the year 188 [187–189] and 192 [191–194], respectively). Several researchers have documented faster canopy closure in narrow row spacing soybeans (<76 cm) compared to wide row spacing soybeans (76 cm; Alessi and Power 1982; Bertram and Pedersen 2004; Bradley 2006; Elmore 2013; Harder et al. 2007). Soybean canopy closure occurred earlier in 2020 compared with 2019, which can be attributed to warmer temperatures in May and June in 2020 compared with 2019 (Table 1).

Even though early and standard treatments were planted approximately a month apart, the maximum difference detected in 90% canopy closure was 11 d in 2019. Nevertheless, a 4- to 11-d difference in T_{90} can contribute to cultural suppression of weed species with extended emergence window (i.e., redroot pigweed [*Amaranthus retroflexus* L.], waterhemp, Palmer amaranth; Franca 2015; Werle et al. 2014). PRE herbicide either had no impact or delayed the T_{90} by up to 4 d in this weed-free study. As a caution, DeWerff et al. (2014) reported that soybean canopy development was delayed in treatments in which no PRE was sprayed and weeds were allowed to compete with the crop.

Soybean Yield

Soybean yield was influenced by the planting time × year interaction (P < 0.0001) and the main effect of tillage (P < 0.0001). PRE herbicide and row spacing treatments did not influence yield in this experiment (P > 0.05; Table 2).

In 2019, early planted soybean yielded an average of 6,026 kg ha^{-1} (95% confidence interval: 5,837 to 6,221 kg ha^{-1}) whereas standard planted soybean yielded 5,124 kg ha^{-1} (4,950 to 5,299 kg ha^{-1}). In 2020, early planted soybeans yielded 4,183 kg ha^{-1} (4,021 to 4,338 kg ha^{-1}), whereas standard planted soybeans yielded 3,995 kg ha^{-1} (3,840 to 4,149 kg ha^{-1}). The early-planted soybean yielded on average 902 kg ha^{-1} and 188 kg ha^{-1} more than standard planted soybean in 2019 and 2020, respectively. In field studies conducted by Mourtzinis et al. (2017a, 2018) across several locations in Wisconsin and Minnesota, the highest soybean yields were achieved with earlier planting (late April); the authors concluded that planting time was the most consistent management factor influencing soybean yield. Matcham et al. (2020) surveyed management decisions deployed in 5,682 soybean fields across ten North Central states (Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, North Dakota, Nebraska, Ohio, and Wisconsin) and reported that soybean planting from April 18 to May 11 had a higher yield potential than soybeans planted between May 22 to June 13. Thus, our results corroborate the findings reported by Mourtzinis et al. (2017a, 2018) and Matcham et al. (2020). Even though earlier planted soybeans outyielded standard planted soybeans in both years of this experiment, the yield in 2020 was substantially lower (a decrease of 27%). The 2020 growing season exhibited lower precipitation amounts, particularly in August and September (Table 1), when the lower observed soybean yield in the 2020 growing season was likely due to decreased soil water availability during the pod-filling phase, a crucial yield development stage (Alessi and Power 1982; Kirnak et al. 2008). In addition, soybeans in 2019 were planted after several years of continuous corn crops, which likely contributed to a higher yield potential. Pedersen and Lauer (2003) observed an 8% increase in first-year soybean yield after 5 yr of continuous corn in an experiment conducted in Wisconsin.

Treatments under conventional tillage yielded on average 5,016 kg ha^{-1} (4,895 to 5,144 kg ha^{-1}), whereas treatments under no-till yielded 4,640 kg ha^{-1} (4,525 to 4,761 kg ha^{-1}), a 376 kg ha^{-1} difference. Mourtzinis et al. (2017b) observed 8% to 10% higher soybean yield under conventional tillage compared to no-till in two out of three years of their experiment. However, the increase in soybean yield under conventional tillage system in this experiment is in contrast to the results from a long-term experiment by Pedersen and Lauer (2003), reporting an 8% increase in soybean yield under no-till system.

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The yield advantage of narrow space soybeans was not observed in this experiment (P = 0.75), contrary to many findings in the literature in which narrow-row soybean outyielded wide-row soybeans (DeBruin and Pedersen 2008; Lee 2006). It is important to emphasize that there was no impact of PRE herbicide on soybean yield in this study (P = 0.0977; Table 2), despite the observed early-season herbicide injury and subsequent impact on soybean canopy development observed in some treatments (Tables 3 and 4). Previous research reported similar findings of early season soybean injury when other PRE herbicides were used, with no detrimental impact on final yield (Arsenijevic et al. 2021; Belfry et al. 2015; Swantek et al. 1998; Taylor-Lowell et al. 2001).

The findings from this experiment corroborate previous published research and support our initial hypothesis that soybean canopy development can be influenced by integrated agronomic and weed management practices. Herein, early planted soybeans closed canopy earlier and yielded more; narrow row spacing closed canopy earlier but did not influence yield; conventional tillage increased soybean yield. Although PRE herbicide application slightly delayed canopy development in some treatments, it did not impact yield. PRE herbicides are an important component of IWM programs and the delay in canopy development if soybeans were allowed to compete with weeds early in the season in the absence of an effective PRE herbicide would outweigh the slight delay in canopy development by PRE herbicides observed herein. Enhancing the competitive ability of the cultivated crop early in the season will reduce the weed management efforts required in the remainder of the growing season. Agronomic practices that reduce the time to soybean canopy closure (e.g., earlier planting of narrow soybeans) combined with an effective PRE herbicide program can contribute to management of troublesome weeds and mitigate further herbicide-resistance evolution.

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