Learning from progressive wheat growers: A case-study for the Wheat Yield Content in Kansas, US

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Abstract
There is limited information on agronomic practices affecting wheat (*Triticum aestivum* L.) yield in intensively managed dryland systems despite the opportunity to narrow the existing yield gap (YG). We used a unique database of 100 intensively-managed field-years entered in the Kansas wheat yield contest during the 2010-2017 harvest seasons to i) quantify the YG, ii) describe wheat management, and iii) identify management opportunities and weather patterns associated with yield. We simulated wheat yield potential (Yw) using SSM-Wheat model for each field-year to estimate YG as the difference between Yw and actual yield (Ya), and used eleven statistical approaches to test the association of management practices and weather variables with Ya. Wheat Ya averaged 5.5 t/ha and simulated Yw averaged 6.4 t/ha, resulting in an YG of 0.9 t/ha (15% of Yw). High-yielding fields had lower maximum (Tmax) and minimum (Tmin) temperatures and greater cumulative solar radiation (RS) and precipitation during grain fill. Varieties susceptible to fungal diseases responded to foliar fungicide (0.8 to 1.4 t/ha) while resistant varieties did not. Seeding rate was negatively associated with Ya, as yield quantile 0.99 was 7.5 t/ha and decreased by 2.7 t/ha for every 100 seeds m^{-2} increase in seeding rate above 305 seeds m^{-2}. In-furrow phosphorus fertilizer, previous crop, tillage practice, and nitrogen timing, were also associated with Ya. We conclude that fields entered in yield contests have closed the exploitable YG, and there are opportunities to improve Ya through improved management in regions with stagnant wheat yield.

Key Words
Yield potential, intensive management, yield contest, seeding rate, foliar fungicides, crop modeling

Introduction

Agronomic management can help increase actual wheat yields (Ya) and reduce the yield gap (YG) (Hochman et al., 2017), which is defined as the difference between Ya and yield potential (Yw) (van Ittersum et al., 2013). Usually, replicated research trials where different treatments are imposed on the crop are used to identify opportunities to increase yields (Grassini et al., 2015); however, these trials are costly and impracticable at a large scale (van Ittersum et al., 2013). One alternative is to use on-farm data collected from yield contests or surveys of a large number of production fields where producers provide agronomic management and input information adopted in each field (e.g. Grassini et al., 2015). Grain yield observation derived from yield contests are difficult to replicate (Villamil et al., 2012), but these fields are typically intensively managed as producers usually seek to maximize yield rather than profitability. Thus, they are a good indication of the best genotype × management × environment interaction for that specific location-year (van Ittersum et al., 2013). Databases of grain yield by management, such as those generated in yield contests, can be explored (e.g. Grassini et al., 2015; Villamil et al., 2012) but such information is lacking for intensively managed wheat systems. Thus, our objectives were to explore a database of yield derived from the Kansas wheat yield contest for agronomic practices associated with decreasing the wheat YG.

Methods

Database description

We used a database comprised of 100 field-years entered in the Kansas wheat yield contest during the eight-year period spanning the harvest years of 2010 through 2017 (Fig. 1). All fields entered in the yield contest were managed under dryland conditions. The number of fields entered in the yield contest ranged from 12 in 2013 to 21 in 2012 and 2016; data for 2014 and 2015 were only available for the three contest-winning fields. The database was comprised of previous crop, tillage practices (no-till, reduced-till, or conventional-till), sowing date (days of year, DOY), seeding rate, row spacing, wheat variety, and applied inputs rate, product, and timing (i.e. insecticide; herbicide; fungicide; plant growth regulator; N, P, K, and S fertilizer; and manure).

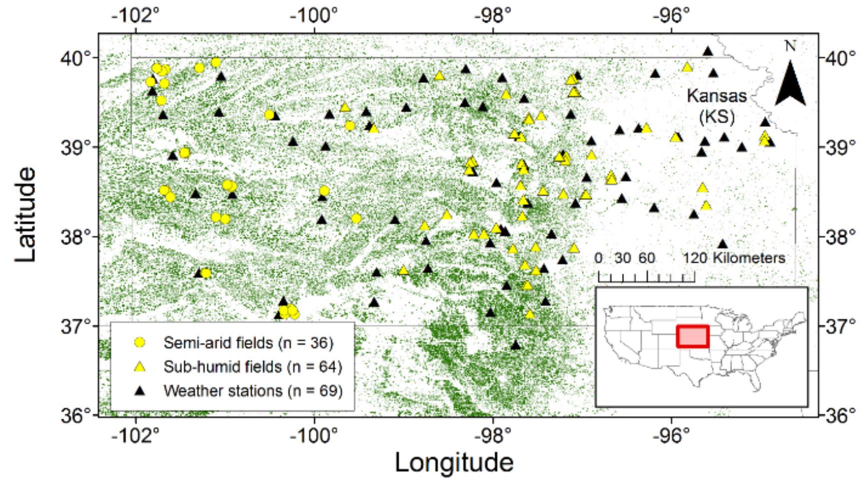

Figure 1. Map of Kansas showing wheat area in green, locations of fields studied fields as yellow circles and triangles, weather stations as solid triangles, and state boundaries.

Crop phenology, yield potential, and yield gap estimation

We used the Simple Simulation Model (SSM)-Wheat crop model calibrated at 7 site-years and validated at 43 site-years to simulate wheat yield potential and phenology at each field entered in the yield contest. These simulations used field-specific soil physical characteristics, daily weather data interpolated from the three nearest weather stations (Fig. 1), and optimum sowing date and plant population. We also used these simulations to define dates for stem elongation and anthesis, and to calculate crop evapotranspiration. After simulating Yw, we calculated YG for each field-year as the difference between Yw and Ya.

Statistical analysis

Due to the unbalanced nature of the dataset, we analysed the yield data against the different management practices reported using a series of statistical models, all of which had strengths and weaknesses when dealing with unbalanced data. We used multi-level modelling, regression analyses (stepwise, forward selection, backward elimination, least angle regression (LAR), least squared shrinkage operator (LASSO), elastic net, and random forest regression), analysis of variance, and conditional inference trees.

Results

Grain yield, yield potential, and yield gaps

Mean Ya across all fields was 5.5 t/ha and ranged from 2.2 to 8.3 t/ha. No Ya values in the database exceeded literature-reported transpiration efficiency (Fig. 2b). Simulated Yw averaged 6.4 t/ha and ranged from 2.7 to ~10 t/ha. The mean YG was 0.8 t/ha (15% of Yw) and ranged from 2% in 2014 to 24% in 2017. The high-end of simulated Yw (>8.5 t/ha) only occurred 9% of times and agreed with yield measured in variety performance tests in Kansas. The fields entered in the Kansas yield contest narrowed the YG in most years, but not consistently.

Environmental conditions leading to increased wheat yields

Across all field-years, in-season precipitation ranged from 172 to 751 mm, crop evapotranspiration ranged 335 to 760 mm, cumulative RS from 2,770 to 4,400 MJ m^{-2}, Tmin from -1.7 to 4.5°C, and Tmax from 12.5 to 18.2°C. Comparison between high- and low-yielding field-years (6.8 vs. 4.3 t/ha) suggested the weather during the jointing to anthesis and the anthesis to physiological maturity intervals (i.e., reproductive period) had greater influence on grain yield than weather during the entire growing season or vegetative stages. During the reproductive period, high-yielding fields had greater precipitation, lower Tmax, lower Tmin, and greater RS than lower yielding fields.

The conditional inference tree of weather variables and their effect on grain yield (R^2 = 0.59 and RMSE = 0.75 t/ha) is shown in Fig. 2. Maximum temperature during grain fill was the most important meteorological variable influencing wheat yields. Highest yields (7.2 t/ha) were achieved in fields in which mean Tmax during grain fill was lower than 27°C and growing season precipitation was less than 440 mm. Growing season precipitation greater than 440 mm under similar cool grain filling conditions resulted in grain yields of 5.6-6.9 t/ha, depending on cumulative RS during the growing season. Fields with mean grain filling Tmax

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greater than 27°C had lower grain yield (c.a. 4.5 to 5.1 t/ha), a scenario within which greater RS (> 798 MJ m^{-2}) resulted in greater grain yield.

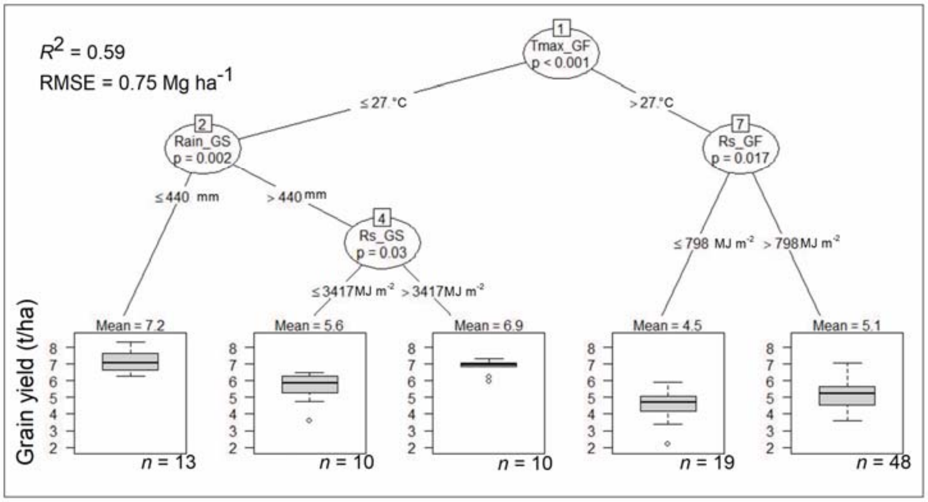

Figure 2. Conditional inference tree of meteorological variables' impact on wheat grain yield. Number of observations (n), mean, and model fit statistics (R^2 and root mean square error, RMSE) are shown. Legend: Tmax_GF, maximum temperature during grain filling; Rain_GS, cumulative rainfall during the growing season; and Rs_GF and Rs_GS, cumulative solar radiation during grain filling and the entire crop cycle.

Impact of agronomic practices on wheat grain yield

Analysis of the eight different regression models and the multi-level model previously described allowed us to identify variables more consistently associated with Ya, including tillage practice, N timing, genetic resistance to leaf rust, rate of P fertilizer, use of in-furrow P fertilizer, fungicide application at flag leaf, and previous crop. Individual analysis of each factor most often associated with wheat yield among the several regression models tested is shown in Fig. 3. Wheat fields following canola had greater Ya (6.5 ± 0.5 t/ha) than wheat fields following soybeans or wheat (5.5 ± 0.4 t/ha). Concentrating N application in the spring increased Ya (5.7 ± 0.3 t/ha) as compared to concentrating N in the fall (5.2 ± 0.3 t/ha), and both resulted in similar Ya as split applications (5.4 ± 0.3 t/ha). Fields adopting in-furrow P fertilizer resulted in greater Ya (5.8 ± 0.3 t/ha) than fields not adopting in-furrow P (5.2 ± 0.3 t/ha). Fields receiving an application of foliar fungicide after flag leaf emergence had greater Ya (5.7 ± 0.3 t/ha) than fields not receiving it (5.0 ± 0.4 t/ha), and there was a significant yield penalty by not applying foliar fungicide to varieties with high susceptibility to leaf (1.4 t/ha) and stripe rusts (0.8 t/ha), but no differences for resistant varieties. Seeding rate was negatively related to wheat yield; however, more interestingly, a plateau-linear regression model developed based on the 0.99 percentile suggested that high seeding rates imposed an upper limit to attainable wheat yield. Attainable yield was 7.5 t/ha and decreased by 2.7 t/ha for every increase in 100 seeds m^{-2} above a threshold of 305 (± 12) plants m^{-2} seeding rate. Two fields planted at extremely high seeding rates (>667 seeds m^{-2}) and about 15-d after the end of the optimum sowing window were not represented by this model.

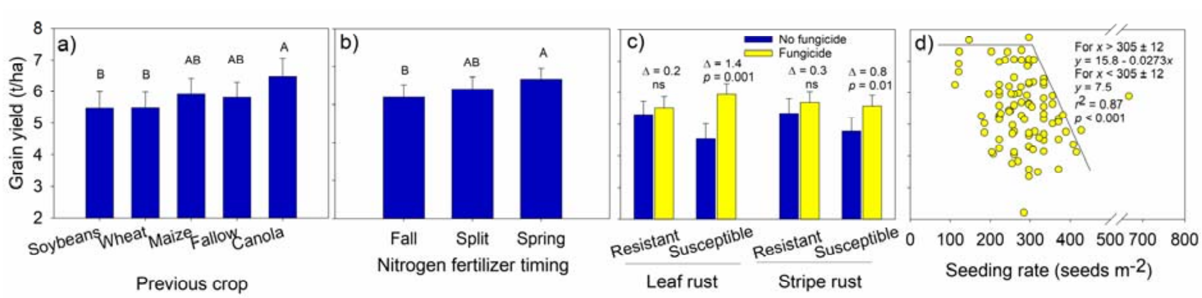

Figure 3. Analysis of individual management practices considering year and region nested within year as random effects. Effects of a) previous crop, b) nitrogen fertilizer timing, c) foliar fungicide and variety resistance to leaf and stripe rust, and d) seeding rate on wheat grain yield. In panels a-c, vertical lines represent standard errors of the mean and yields with the same letter were not significantly different at alpha = 0.05. In panel d, the boundary function (yield quantile: 0.99) represents a plateau-linear model.

The above analysis highlighted individual practices associated with yield but overlooked interactions. The conditional inference tree of management practices (R^2 = 0.47 and RMSE = 0.85 t/ha) helped untangle potential interactions (Fig. 4). Foliar fungicide applied at flag leaf was the most important practice impacting wheat yields, and its absence resulted in Ya ranging between 3.6 and 5.4 t/ha, depending on adoption of in-furrow P fertilizer. For fields receiving a foliar fungicide application at flag leaf, greatest Ya (7.0 t/ha) were achieved under no-tillage practice sown to varieties susceptible to leaf rust and receiving an additional fungicide application at jointing. Under this scenario, the absence of the jointing fungicide application resulted in grain yield of 5.9 t/ha. Lowest Ya among fields receiving a foliar fungicide at flag leaf occurred under conventional or reduced tillage (5.2 t/ha) or under no-till at seeding rates greater than 293 seeds m^{-2}. Fields with seeding rates less than 293 seeds m^{-2} had greater grain yield (6.3 t/ha).

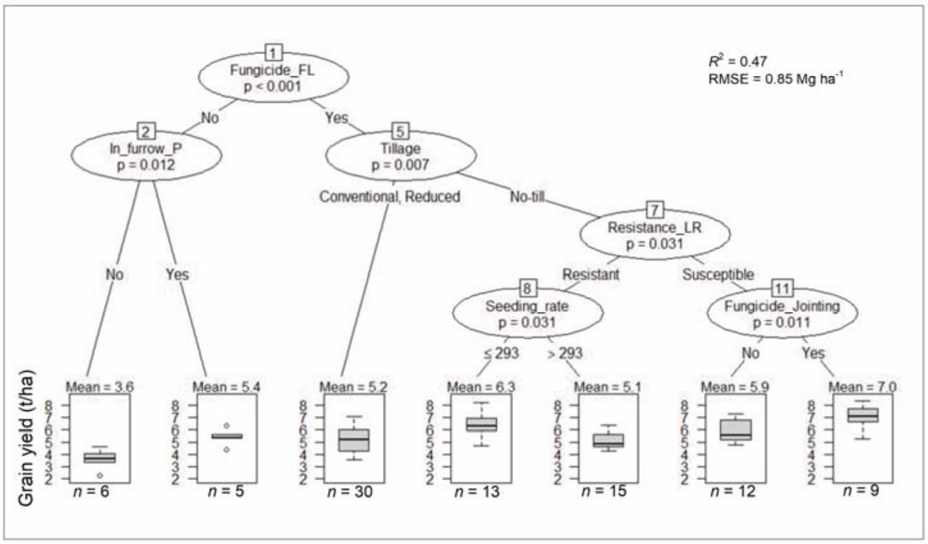

Figure 4. Conditional inference tree of management practices' impact on wheat grain yield. Number of observations (n), mean, and model fit statistics (R^2 and root mean square error, RMSE) are shown. Legend: Fungicide_FL and Fungicide_jointing, foliar fungicide applications at flag leaf emergence and jointing; In_furrow_P, in-furrow phosphorus fertilizer; Resistance_LR, variety resistance to leaf rust.

Conclusion

Wheat yield was about 85% of the yield potential in this cohort of intensively managed fields, suggesting that these producers minimized the yield gap and further increases in yield would not be economical. The weather between jointing and anthesis, and between anthesis and maturity, had greater effect on wheat yield than the weather during the vegetative phase. Finally, we highlighted management practices more often associated with higher wheat yield, including: foliar fungicide and its interaction with variety resistance to fungal diseases, foliar fungicide, tillage practices, seeding rate and N timing, among others.

Acknowledgments

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