“Re-thinking sorghum crop as a relevant component of crop rotations in US Great Plains”

by

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Abstract

Grain sorghum (*Sorghum bicolor* L. Moench) is a major cereal crop in the United States (U.S.), especially within the "Sorghum belt", in the central US Great Plains region. This study explores the potential for sorghum crop to fit in more intensified crop rotations, with the strategy of shortening the duration of the crop growth cycle and evaluating the opportunity of including a follow up winter cereal in the cropping sequence. The overall outcomes of this project can help to offset the decline in cultivated area experienced during the last decades and promote more investments in crop improvement focusing on short-cycle hybrids for intensifying current agricultural farming systems. More specifically, this study evaluates the adoption of early maturing sorghum hybrids as a strategy to intensify the cropping sequence, suggesting that such hybrids could maintain yields (or have a minor yield reduction) with fewer leaves, tested via integration of field data with a crop growth simulation model (Agricultural Production Systems Simulator, APSIM). Chapter 2 assesses the impact of leaf removal after flowering time on sorghum yields through in-silico analyses and field data, evaluating different commercially available sorghum hybrids with different number of leaves, and varying crop growth cycle. Field experiments to evaluate the hypotheses from chapter 2 were divided into two, the first set was executed using four historical sorghum hybrids with field studies conducted during 9 years (2015-2023). The second set of field experiments consisted of testing 20 modern commercially available sorghum hybrids, during 2022 and 2023 growing seasons. The main outcome across studies is the lack of a significant decrease in sorghum yield when leaf removal was beyond four leaves after flowering time and with negligible yield differences between hybrids with 15 to 21 leaves and 90 to 112 days to maturity. Chapter 3 explores the economic viability and environmental implications of a sorghum-wheat cropping system versus wheat- or sorghum-monocrop, using spatial analysis to identify Kansas regions most beneficial for these alternative cropping scenarios. This study documented three well-defined areas, two favorable for the sorghum-wheat rotation obtaining better profits and one for wheat monocrop as the most profitable option. These findings underscore the importance of including and enhancing the productivity of early-maturing sorghum hybrids in crop improvement programs with the goal of intensifying our current agricultural systems in the central US Grain Plains region. The economic analysis reveals that sorghum-wheat rotation can offer superior profit margins over monocropping in most of Kansas, providing a guide for farmers to optimize land use efficiency and profits over time. This dissertation contributes to the discourse on sustainable agricultural practices by promoting adaptive breeding strategies and rotational systems to navigate the complexities of modern agriculture, stressing the need for improving diversification and intensification of our current farming systems.

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Chapter 1 - Introduction

Sorghum (*Sorghum bicolor* L. Moench) is among the five most cultivated cereals in the world (~47 million hectars; FAO, 2023), and it represents the third-largest cereal grain produced in the United States (*USDA-NASS*, 2023). Within the United States (US), sorghum crop is mainly planted in the states of Kansas, Texas, South Dakota, Colorado, Nebraska, and Oklahoma in the area named as the "Sorghum belt". Noteworthy, Kansas is the state with the largest production area with 1.3 million hectares (*USDA-NASS*, 2023). The main destination for the grain harvested in the US is as animal and poultry feed, followed by renewable fuel production and human consumption (*Sorghum Checkoff*, 2024). Sorghum is well-known for its capacity to tolerate drought and extreme temperatures, and due to its reduced input costs is a valuable asset for farmers looking for yield stability over years mainly under stressful conditions (Staggenborg et al., 2008; Stone et al., 2006). However, the crop land area suffered a substantial reduction of 50 % during the recent decades (*USDA-NASS*, 2023). This reduction in acreage has been mainly produced by the expansion of other crop alternatives such as corn (*Zea mays* L.) and soybean (*Glycine max* L.) due to greater profits (FAO, 2023; *USDA ERS - Commodity Costs and Returns*, 2023; USDA Foreign Agricultural Service, 2022). An unintentional consequence of these better crop alternatives was linked to the investment in crop improvement received by corn and soybeans, in detriment to the reduced capital for sorghum over time (Mason et al., 2008; Parra et al., 2020). This effect of a reduced crop improvement genetic gain in sorghum is more exacerbated for the early maturing hybrids relative to the medium- and late-maturing hybrids (Mayor et al., 2023).

Besides genetic gain, several agricultural practices have evolved due to advances in production technologies and the intensification of farming activities such as irrigation, use of pesticides, and herbicides, traditional farming systems have undergone significant changes (FAO, 2023). The main rotation in Kansas winter wheat (*Triticum aestivum* L.) monocrop (Hansen et al., 2012) has been replaced in some cases by winter wheat-summer crop-fallow rotation or winter wheat-winter wheat-summer crop-summer crop (Assefa et al., 2014b), with limitations depending on the seasonal precipitation. Under low-yielding environments and drought conditions, the main crop for the summer option is sorghum to the overall better land use efficiency in those marginal areas (Assefa et al., 2014b, 2014a). A more intense rotation can be proposed changing it to sorghum-winter wheat. However, the main restriction for the implementation of this rotation is the late harvest of sorghum and the low soil moisture at the time of the planting of winter wheat (Assefa et al., 2014b). To mitigate these effects, an early maturing sorghum hybrid could be a good alternative as a shorter crop duration, reaching maturity earlier and clearing out the field for wheat planting, yet presenting the potential setback of a reduced attainable yield (Baumhardt et al., 2005; Mayor et al., 2023). However, more recent studies pointed out that sorghum hybrids have an excess source (leaves) as related to the sink size (grain number) during the grain-filling period (Gizzi & Gambin, 2016; Ockerby et al., 2001). Those studies suggest that the crop could sustain yield with fewer leaves. Since the phyllochron (time between the appearance of two leaves; Wilhelm & McMaster, 1995) for sorghum is 40-120 °Cd leaf^{-1} (Clerget et al., 2008), a hybrid that grows fewer leaves could have an early maturity without penalizing yield. Therefore, this opens a new avenue to explore improving yield potential for those short-season sorghum hybrids to make sorghum more competitive as a part of an intensified rotation.

Crop growth model simulators have a great variety of applications (Di Paola et al., 2016) such as assisting in the decision making process for farmers evaluating different conditions

(Keating et al., 2003) or aiding the research process via improving the impact of different conditions and cropping systems on the overall productivity (Whisler et al., 1986). The Agricultural Production Systems Simulator (APSIM) is a crop modeling framework designed to replicate biophysical processes within agricultural settings, which can be applied to both the economic and ecological impacts of various management strategies under climate-related uncertainties. Additionally, it serves as a platform for investigating strategies and solutions pertinent to food security, adaptation and mitigation of climate change, and issues related to carbon trading (Holzworth et al., 2014). The APSIM sorghum and wheat crop growth model were implemented in this study. The sorghum model for APSIM (APSIM-sorghum) simulates crop phenology, canopy development, crop growth, and nitrogen dynamics (Hammer et al., 2010). Similarly, the APSIM wheat module simulates winter and spring wheat daily growth and its phenological development (Zhao et al., 2014), responding to weather, soil water, soil nitrogen, and management (Zheng et al., 2015). This crop simulator brings the possibility of testing several traits and management combinations while reducing the necessity of having field experiments, which tend to be far more expensive and time-consuming. In this study, we used APSIM to test different defoliation treatments on historical hybrids and the economical outputs of different farming systems.

This thesis has a structure divided into chapters, with the first one presenting an overall introduction to the problem statement, Chapter 2 evaluating cycle early-maturity sorghum hybrids and testing the impact of leaf removal on yield, Chapter 3 focusing on assessing the economic feasibility for double cropping sorghum-wheat in different regions in Kansas (via in-silico approach), and lastly, with a conclusion chapter providing a summary and future directions for this work. For Chapter 2, the objectives were to i) evaluate via in-silico the effects of leaf removal during the grain filling; and ii) explore those impacts using a field dataset for sorghum yield. For Chapter 3, the main objectives were i) to evaluate the economic feasibility of double cropping sorghum with wheat; ii) to understand the environmental drivers behind the sorghum-wheat rotation; iii) to delimitate the spatial distribution of these proposed rotations. The outcomes of these objectives will provide information to farmers for diversifying crop sequences and for breeders to increase the efforts in early maturing sorghum hybrids (with fewer leaves) with the goal of enhancing yield gain for sorghum adapted to more intensified cropping systems.

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Chapter 2 - An in-silico approach exploring sorghum Source:Sink Balance across Sorghum Hybrids: How many leaves are enough?

Under review, Crop Science journal.

Abstract

Previous literature documented an imbalance for sorghum (Sorghum bicolor (L.) Moench) between source (leaves) and sink (grains), favoring the source. Therefore, a reduction in leaf number with negligible yield penalties might be advantageous for producers to fit another crop in the rotation. The aims of this study were to i) evaluate via in-silico the effects of leaf removal during the grain filling; and ii) explore those impacts using a field dataset for sorghum yield. For the first objective, the APSIM sorghum model was tested with four hybrids across 12 locations in the United States (2015-2023) resulting in an RRMSE of 25% for yield. As a second step, an APSIM defoliation module was developed using field data of one site-year, demonstrating an RRMSE of 17% for yield. As a last step, the model was used to simulate the effect of sequential defoliations on yield, across 38-year of weather data (1984-2022), without showing any yield penalties when removing up to four leaves after flowering. Leaf area removal after flowering indicated a positive imbalance in source:sink ratio (i.e. source excess). For the second objective, a field dataset from 21 sorghum hybrids with different attainable leaf numbers and cycle duration did not result in significant yield differences. Early maturity hybrids with fewer leaves provide farmers with the opportunity to intensify crop sequences. Less focus in sorghum improvement for early relative to late maturing hybrids has been reported, therefore, there is still ample room for future yield gains.

Introduction

The overall decline in crop diversity is leading to greater vulnerability of US food systems, exposing them to environmental and economic changes (i.e., crop pests, agrochemical use, and climate change) (Crossley et al., 2020). In this context, sorghum (Sorghum bicolor (L.) Moench) crop has lost approximately 4 million hectares in the last two decades causing the continuous shrinkage of the US sorghum belt (from 7.726.000 to 4.570.000, *USDA-NASS*, 2023). Considering this, placing sorghum as part of a more intensified rotation would boost its competitiveness while promoting agricultural biodiversity. However, the prolonged stay-green duration of sorghum places the onset of the grain dry-down in sub-optimal weather conditions, extending the length of the crop in the field and hampering the possibility of planting a following crop. Stay-green genotypes with larger biomass at flowering do not have a higher yield than the ones with lower biomass (A. K. Borrell et al., 2014), suggesting that a lower leaf area (hence less photosynthesis production) would not represent a yield penalty. Supporting this concept, previous studies showed that if applied from boot stage to 10 days post-flowering defoliations under 50% of the leaves did not reduce yields (Rajewski et al., 1991; Stickler & Pauli, 1961). Nevertheless, these studies were done more than two decades ago, in older hybrids. Therefore, these insights ignore the changes that sorghum hybrids presented during the last two decades (Demarco et al., 2023; Gizzi & Gambin, 2016; Pfeiffer et al., 2019).

From a physiological standpoint, at field scale the canopy light (radiation) interception and the duration of the leaf area have a relevant role in determining the crop’s productivity (Borrell et al., 2021). Different canopy structures provide diverse outcomes in terms of radiation interception, which may translate into yield variations (Borrell et al., 2021; Duvick, 2005). Demarco et al. (2023), showed that differences in the canopy profile could distinguish sorghum hybrids from different years of market release, yet less is known about the implications when exploring contrasting maturities hybrids (i.e., different number of leaves and duration). Pointing out that leaf development and growth changes driven by genotypic selection and its interaction with management have a relevant impact on sorghum yield (A. Borrell et al., 2021; Kumudini et al., 2001). However, carrying out experiments to determine the impact of different canopy structures at the field level implies testing several hybrids and detailed measurements to characterize the canopy. This represents a high-cost and time-demanding task. In this context, crop growth models arise as a useful tool to test diverse genotypic changes (Kholová et al., 2014). Modeling allows the creation of hypothetical scenarios with advantages such as the capability to reproduce the same conditions for several hybrids (Chenu et al., 2011). Moreover, it enables the testing of virtual hybrids by varying specific traits creating perfect isolines (Kholová et al., 2014), as well as the evaluation of multiple yearly repetitions across diverse environmental conditions (Keating et al., 2003).

Following this rationale, i) four sorghum hybrids were calibrated and validated to employ in Agricultural Production Systems Simulator (APSIM; Holzworth et al., 2014), ii) an APSIM-sorghum module was developed to represent changes in source availability (defoliations), and it was implemented to quantify the impact of source availability changes (leaf number reduction) around flowering on grain yield; and iii) yield differences of 21 hybrids with different number of leaves (i.e. different growth cycle, maturity hybrids) were quantified with observed field data. Lastly, the objectives of this study were to i) evaluate via in-silico the effects of leaf removal during the grain filling; and ii) explore those impacts using a field dataset for sorghum yield. The outcomes of these objectives will help to provide insights into the feasibility of manipulating leaf number or maturity for adapting sorghum into a more intensified rotation.

Materials and Methods

Summary description

The first objective of this study encompassed two steps: calibration of the APSIM-sorghum model (Hammer et al., 2010), and validation of the APSIM-sorghum model. The second objective consisted in the development and testing of a defoliation module for the APSIM-sorghum model, simulation of leaf defoliation using historical weather data, and a pilot test to compare yields from 20 sorghum hybrids with different final number of leaves. Independent datasets were collected for each step (Table 1).

APSIM model calibration and testing

APSIM is a crop modeling framework, with robust plant modules to simulate physiological processes (Keating et al., 2003). More specifically, the APSIM-sorghum simulates phenology, canopy development, crop growth, and nitrogen dynamics (Hammer et al., 2010). Within the canopy development module, the leaf area is represented as a function of the total leaf area (number of fully expanded leaves, their size, tiller number, and an adjustment for the area of expanding leaves) and the thermal time (Hammer et al., 1993). The final crop leaf area per unit of land area is the product of plant density and leaf area per plant.

Four intermediate maturity sorghum hybrids from different years of release (Table 3) were calibrated and validated to use in APSIM. The calibration dataset consisted of three site-year field experiments (Table 2, experiments from 1-3, Supplementary data 1), conducted in the Corteva Agriscience research station in Pottawatomie, Kansas, US (39.23, -96.27), from 2018 to 2021. The experiment from 2018 was used to calibrate biomass parameters (id 2; Table 2). The experiment from 2019 (id 3; Table 2), was employed in the calibration of the parameters related to biomass, leaf area index (LAI), and leaf number. Data from the 2021 experiment (id 1; Table 2) was employed in the calibration of most parameters: days to flowering, days to maturity (Vanderlip & Reeves, 1972), yield, grain size, and grain number. Parameters related to phenology, leaf area, biomass, and yield (Table 3, Supplementary Data 2). The calibration was done using the function optim_apsim in the R package apsimx (Miguez, 2022), every parameter for each hybrid was calibrated at a time.

The validation dataset consisted of 23 site-year combinations (Table 2 experiments from 4-26) conducted at Corteva Agriscience experimental fields, from 2015 to 2023 growing seasons, located in the states of Kansas (KS), Texas (TX), Oklahoma (OK), and Nebraska (NE), USA (id 4-26; Table 2). From the 23 site-years, seven site-year combinations recorded days to flowering, and only four days to maturity. Grain yield was available for the 23 site-year. The managements tested in this section are representative of the strategies employed by the farmers of the region.

To generate the simulations, weather data was downloaded from MESONET (Kansas Mesonet, 2022; NSCO Mesonet, 2022; Oklahoma Mesonet, 2022; TexMesonet, 2022), and the soil was characterized using SSURGO data (U.S. Department of Agriculture, 2004). R software was used for the calibration and validation process (R Core Team, 2021). The validation metrics were accounted for using Metrica R-package (Correndo et al., 2022). The model performance was evaluated using five metrics: i) the Kling-Gupta efficiency (KGE, the closer to one the better) (Gupta et al., 2009) iii) root mean square error (RMSE, variables units); ii) relative root mean square error (RRMSE, %), iv) percentage lack of accuracy (PLA, %), and v) percentage lack of precision (PLP, %).

Module defoliation and testing

A module to simulate the defoliation of the crop was included in the APSIM-sorghum model. This module considered the variables leaf number, LAI, and green leaf biomass. When applying defoliation, the green leaf biomass diminishes depending on the weight of the leaves removed, and the LAI decreases depending on the area of the leaves removed. The new module simulates leaf removal, allowing the definition of the number of leaves to be removed, the direction (top of the plant to bottom or bottom of the plant to top), and the days before or after flowering in which the removal must be made (Peraza & Marziotte, 2022).

The defoliation module was validated with data from 2021 (id 27; Table 2). The validation was done by comparing the relation between control and defoliated for observed and simulated: i) yield, ii) dry biomass at maturity, iii) harvest index, iv) grain number, and v) grain size. The model performance metrics and the method used are explained in section 2.2.

The 2021 field experimental design was a split plot with a factorial subplot structure with four repetitions. Each plot was divided into 2 subplots corresponding to the control, and defoliated treatments. The subplot with the defoliation treatment consisted of one row inside each plot. The defoliated treatment consisted of removing all leaves but the two uppermost at ten days after flowering. A total of 4 hybrids of different years of release (from 1982 to 2010; Table 3) from Corteva Agriscience were tested. The plots were 5.2 m long and had 8 rows with 0.76 m of interrow spacing. The planting date was the 7 of June 2021, and it was fertilized at planting with 150 kg ha^{-1} of urea. Weed and diseases were controlled.

Leaf defoliation in silico testing

After having calibrated and validated the defoliation model, historical weather data (38 years; 1990-2020) from Mesonet was obtained for Pottawatomie, KS using the R-package apsimx (Miguez, 2022). All simulations were sown on the fourth of June, with a sowing density of 16 pl m2, a row spacing of 0.762 m, and a depth of 3 cm. A unique application of 150 kg ha^{-1} of urea was made at planting. This management is representative of the farmers' management of the region. Within the simulations, nine leaf removal treatments were applied. Each treatment represented a different number of leaves removed, from zero to eight starting from the bottom of the plant. The treatment was applied ten days after flowering, for the four hybrids. The mean yield of the 38-year was obtained per each hybrid and leave removal treatment.

To analyze the yield variations a mixed effects model including leaf number, the hybrid, and the interaction among them as a fixed effect, and years as a random effect was performed. The R-package lme4 was utilized in this analysis (Bates et al., 2015). A Sidak test was applied to define significant differences ($p<0.05$) between the treatments within each hybrid, using the multcomp R-package (Hothorn et al., 2008).

Sorghum leaf number pilot test

Twenty modern commercial hybrids from Corteva Agriscience were grown in the Corteva Agriscience research station in Pottawatomie, Kansas, US in 2022 and 2023. The experiment was planted on June 15 in 2022 and on June eighth in 2023 at a plant population of 13 plants/m2 in both years. The experimental design was a randomized complete block with three repetitions. Leaf number was recorded from the emergence and the final leaf number was defined at maturity. Grain yield was obtained by mechanical harvest of two rows per plot. Yield differences were compared by fitting a mixed-effect model (Bates et al., 2015). Within the model, leaf number was considered as a fixed effect and the repetitions were included as a random component. Finally, a Sidak test was performed to compare the means using R-package multcomp (Hothorn et al., 2008).

Results

APSIM model calibration and testing

Figure 1 shows an adequate (RRMSE ≤ 30%) model performance for grain yield, days to flowering, and days to physiological maturity when comparing simulated vs observed data. Phenology traits presented a better agreement than yield, as shown by the RRMSE values (Figure 1; 10% and 5% for flowering and maturity respectively versus 25% for yield).

Module defoliation and testing

The defoliation module had a good performance (Table 4), as the RRMSE obtained for yield was 17% (RMSE = 1090 kg ha^{-1}). Other important variables such as biomass, harvest index, and grain number had an adequate performance (RRMSE < 30%).

Leaf defoliation in silico testing

Across hybrids, at least five leaves had to be removed to obtain a significant change in yield. This is linked to the positive source:sink ratio, which allows removing approximately 50% of the leaf area index with a yield change of only 5% (Figure 2). A constant yield decrease was observed when removing more leaves (~150 kg ha^{-1} per leaf removed). However, leaf removal affected yield in a different magnitude depending on the hybrid. The changes visualized in Figure 2 showed that yield depends on the hybrid’s year of release (Table 3), being the older hybrids, the ones presenting the lower yields. The yield standard deviation was similar for all the hybrids, not changing with the year of release.

Leaf defoliation in silico testing

Field data supported the predictions made with the in-silico defoliation APSIM module, where non-significant variation in yield was found when up to five leaves were removed (Figure 2). Field results showed no significant yield differences between hybrids counting with 15 to 21 leaves. The hybrids' mean yields ranged from ~ 4000 to ~7500 kg ha^{-1}.

Discussion

This study highlights an opportunity to maintain current sorghum yields with a reduction of the crop growth cycle. This scenario provides a prospect for intensifying crop rotations in the US Great Plains region by offering an opportunity to include a winter crop (e.g. winter wheat, canola) after dryland sorghum crop. Several implications can be derived from these results suggesting i) the resiliency of the crop to cope with hail (Klein & Shapiro, 2011; Stickler & Pauli, 1961) or defoliations caused by insects, mainly after flowering, ii) the possibility for sorghum growers to plant hybrids with shorter growth cycle without penalizing yields, and iii) the opportunity to include a winter crop after sorghum to improve income and diversify of the current farming systems (Can & Yoshida, 1999a, 1999b; Crabtree et al., 1986).

Previous studies demonstrated that sorghum could benefit from increases in assimilates availability per grain, as positive effects on grain weight were reported (Gambín & Borrás, 2007; Muchow & Wilson, 1976). However, the same authors reported that the positive effect on grain weight was not directly translated into final grain yield. Contrastingly, other studies highlighted that sorghum’s ability to maintain yield despite reductions in leaf area can be attributable to a positive source-sink ratio (Gizzi & Gambin, 2016; Ockerby et al., 2001; Rajewski et al., 1991; Rajewski & Francis, 1991; Stickler & Pauli, 1961). In detail, Rajewski & Francis (1991) and Stickler & Pauli (1961) defoliated around flowering, not showing a significant impact on yield with defoliations of 50% of the leaf area. This study is in accordance with the results presented in the literature, i.e., not showing significant changes in yield when defoliating approximately 50% of the leaf area, which implies a decrease in light interception of around 10% (Hammer et al., 2010). Besides the fact that the decrease in light interception is small, carbohydrate remobilization from stems after flowering has a crucial impact on grain number and grain yield (Demarco et al., 2023). Pointing out a potential path for breeders to emphasize the selection in early maturity hybrids with a reduced leaf number and leaf area while maintaining yield with the main goal of focusing on the productivity of several crops in a rotation, intensifying the current farming systems.

Previous literature highlighted that longer maturity groups had a greater yield than early maturity groups (Baumhardt et al., 2005; Baumhardt & Howell, 2006; Dalton, 1967; Mayor et al., 2023). However, none of these publications focused on the duration of the phenological stages. It has been reported that the duration of the grain-filling period has a relevant effect on determining grain yield (Carcedo et al., 2017; Eastin et al., 1973; Rajewski & Francis, 1991; Saeed et al., 1984; Saeed & Francis, 1986). Furthermore, mid and early maturity sorghum hybrids presented higher stability than late-maturity groups (Baumhardt et al., 2005; Saeed & Francis, 1983). Mayor et al. (2023) showed the rate of genetic gain on short-season hybrids and its potential to increase (e.g. improving for insect and disease resistance, improving phenotyping, select yield stability and potential under stressed environments). Based on the results from our study we can highlight the importance of short-season hybrids and the value of increasing breeding efforts on this maturity segment as a suitable option to consider for intensification of cropping sequences. Higher-yielding short-season hybrids will be highly desirable in double-crop systems as proposed to mitigate potential yield reductions (Minoli et al., 2022).

A few limitations of this study were: i- limited field data available for validating the defoliation module, with restriction on evaluating timing, intensity, and duration of defoliation stress, nevertheless the model efficiency was according to previous studies (Baumhardt et al., 2005; Baumhardt & Howell, 2006; Hammer et al., 2010), ii- even though grain number and grain weight validations are in accordance with previous studies (Gambín & Borrás, 2013), further physiological assessments will need to improve these predictions, iii- no data available on re-translocation dynamics from stem and leaves in the model, and iv- a broader genetic variability could have been tested, mainly considering other public-private materials. Future studies should consider testing the defoliation module and expanding the field evaluation to include different timing, intensity, and duration of defoliation stress considering a broader genetic variation in leaf number and canopy architecture for different relevant sorghum-based farming systems.

Conclusions

The defoliation module developed in this study has the potential to be applied to other studies and in different regions and hybrids after being validated. From the breeding selection standpoint, hybrids that have fewer leaves (i.e., less time to maturity) had no significant difference in yield compared to hybrids with more leaves and time to maturity. This was linked to the positive source-sink ratio, which allows to remove 50% of the leaf area while maintaining grain yields (5% decrease). Highlighting the relevance of promoting early hybrids in sorghum breeding programs toward a more intensified farming system.

Figures

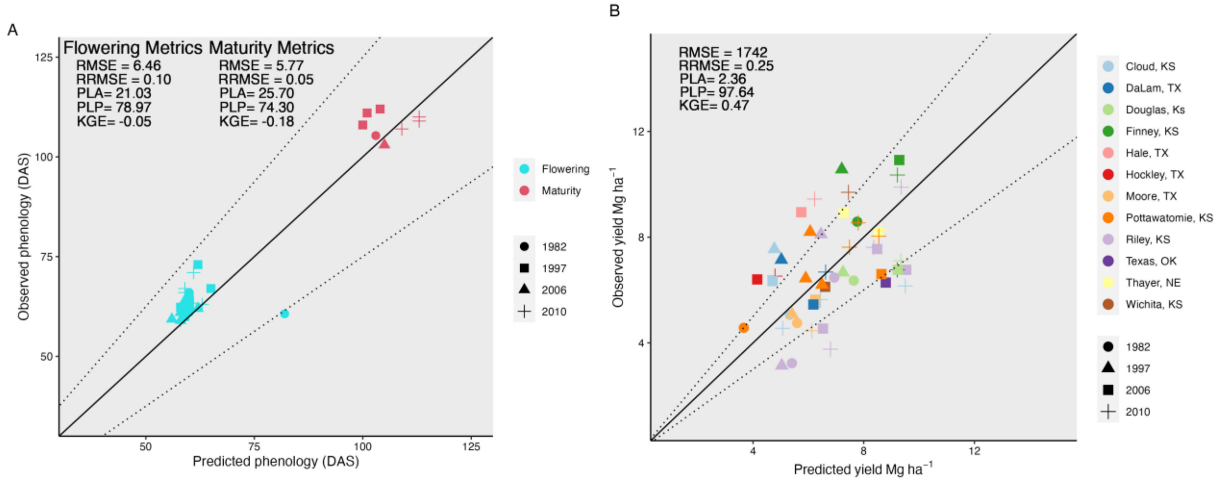

Figure 2.1. Observed versus predicted data for (A) flowering and maturity days; and (B) grain yield (Mg ha^{-1}). Colors represent different phenological stages in Figure (A) and different locations in the states of Kansas, Texas, Nebraska, and Oklahoma in Figure (B). The solid line is the 1:1 relation, and the dotted lines are 25 percent more and less than the 1:1.

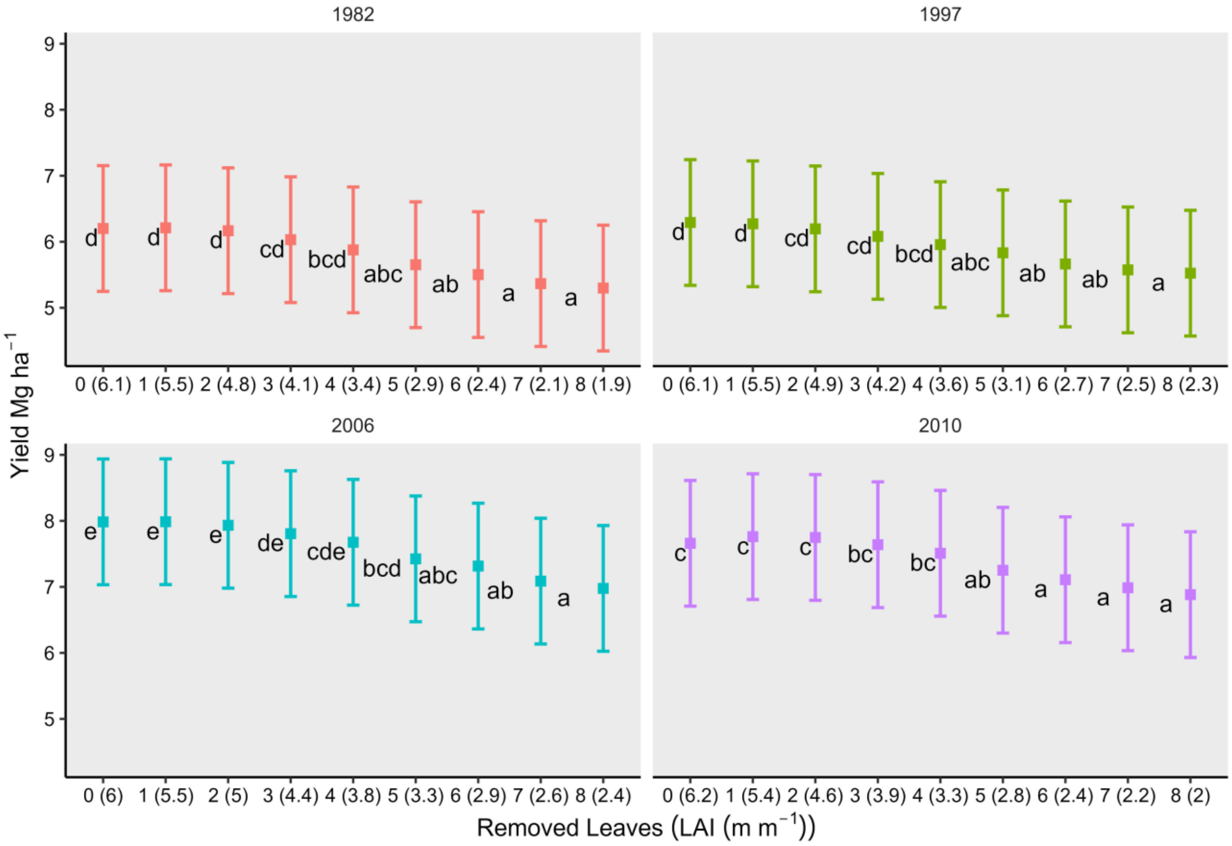

Figure 2.2. Yield as a function of the number of removed leaves and leaf area index (LAI) for four different hybrids. Different letters mean a significative difference between the values of ($p < 0.05$) according to the Sidak test. Vertical lines represent the standard deviation of the mean.

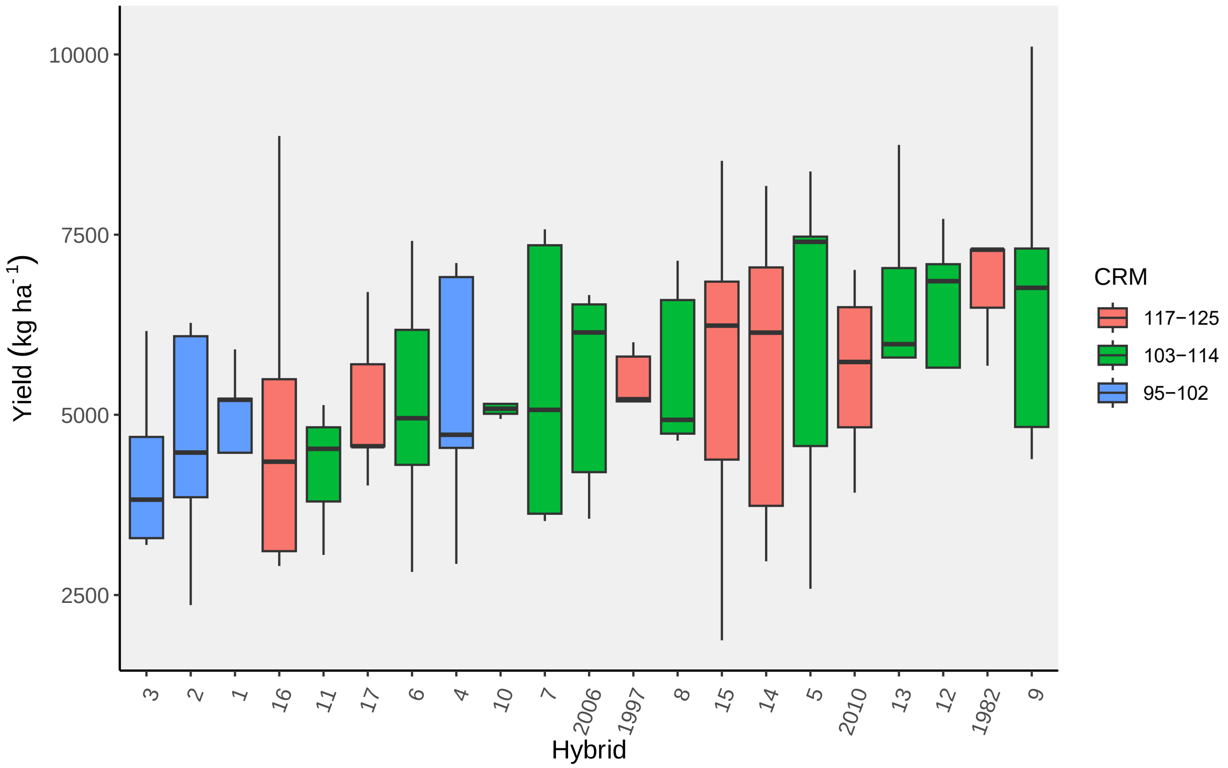

Figure 2.3. Grain yield as a function of comparative relative maturity (CRM) for 21 different hybrids obtained in the 2022 and 2023 growing seasons in Pottawatomie, KS; Cloud, KS; Riley, KS; Lubbock, TX, and Moore, TX. Vertical lines represent the standard deviation of the mean.

Tables

Table 2.1. Overall description of the study pipeline.

Objective	Step	Description	Data
i	Model calibration	2.2	1 site-year combination
	Model testing	2.2	23 site-year combination
ii	Module defoliation and testing	2.3	1 site-year combination
	Leaf defoliation in silico testing	2.4	38 year of weather data
	Sorghum leaf number pilot test	2.5	5 site-year combination

Table 2.2. Experiments included in the calibration and validation. Grain N stands for the number of grains, LAI stands for leaf area index.

id	Data set	Site	Year	Measurements	Coordinates (lat,long)
1	Calibration	Pottawatomie, KS	2021	Days to flowering, Days to maturity, Yield, Grain size, Grain N	39.2,-96.3
2	Calibration	Pottawatomie, KS	2018	Biomass	39.1,-96.4
3	Calibration	Pottawatomie, KS	2019	Biomass, LAI, Leaf N	39.2,-96.7
4	Validation	Riley, KS	2018	Yield, Days to flowering, Days to maturity	39.2,-96.7
5	Validation	Douglas, Ks	2019	Yield	39.6,-97.5
6	Validation	Riley, KS	2019	Yield	39.2,-96.7
7	Validation	Cloud, KS	2015	Yield	39.6,-97.4
8	Validation	Cloud, KS	2017	Yield	39.7,-97.6
9	Validation	Cloud, KS	2018	Yield, Days to flowering	39.6,-97.6
10	Validation	Thayer, NE	2016	Yield	40.2,-97.4
11	Validation	Thayer, NE	2017	Yield	40.2,-97.4
12	Validation	Riley, KS	2016	Yield	39.3,-96.8
13	Validation	Hockley, TX	2015	Yield	33.4,-102.3
14	Validation	Hale, TX	2019	Yield	34.2,-101.7
15	Validation	Dallam, TX	2019	Yield, Days to flowering	36.1,-102.3
16	Validation	Texas, OK	2017	Yield	36.9,-101.0
17	Validation	Finney, KS	2018	Yield	37.9-100.8
18	Validation	Hale, TX	2016	Yield	34.2,-101.7
19	Validation	Moore, TX	2018	Yield	36.0,-101.8
20	Validation	Wichita, KS	2016	Yield	38.5,-101.4
21	Validation	Wichita, KS	2017	Yield	38.6,-101.4
22	Validation	Texas, OK	2016	Yield	36.9,-101.1
23	Validation	Pottawatomie, KS	2018	Days to flowering, Yield, Grain size, Grain N	39.1,-96.4

24	Validation	Pottawatomie, KS	2019	Days to flowering, Days to maturity, Yield, Grain size, Grain N	39.2,-96.7
25	Validation	Pottawatomie, KS	2022	Days to flowering, Days to maturity, Yield, Grain size, Grain N	39.1, -96.4
26	Validation	Pottawatomie, KS	2023	Days to flowering, Days to maturity, Yield, Grain size, Grain N	39.2, -96.3
27	Defoliation	Pottawatomie, KS	2021	Yield, Biomass, LAI, Grain size, Grain N	39.2,-96.3

Table 2.3. Year of release and parameters calibrated in the study for every hybrid. GDD stands for growing degree days, Tt_emerg_to_endjuv stands for thermal time from seedling emergence to end of the juvenile phase, tt_endjuv_to_init stands for thermal time from the end of the juvenile phase to floral initiation, tt_flower_to_maturity stands for thermal time from flowering to maturity, dm_per_seed stands for dry matter per seed, maxGFRate stands for maximum grain filling rate, aX0 stands for largest leaf multiplier, aMaxS stands for largest leaf area slope, and aMaxI stands for intercept for largest leaf calculation.

	Year of release			
Description	1982	1997	2006	2010
tt_emerg_to_endjuv (GDD)	100	85	102	120
tt_endjuv_to_init (GDD)	147	161	132	119
tt_flower_to_maturity (GDD)	741	688	801	853
dm_per_seed	0.0013	0.0118	0.0011	0.0011
maxGFRate	0.620	0.493	2.952	0.496
aX0	0.736	0.586	0.607	0.652
aMaxS	1.49	0	0	0
aMaxI	455	449	399	527

Table 2.4. Model performance metrics for the ratio between observed defoliation and control versus simulated defoliation and control. KGE, Kling-Gupta efficiency, RMSE, root mean squared error, RRMSE, relative root mean squared error, PLA, percentage lack of accuracy, and PLP, percentage lack of precision.

Metric	Yield	Biomass	Harvest index	Grain number	Grain size
KGE	0.3	-0.6	-1.2	0.4	-1.3
RMSE	1090 kg ha^{-1}	3758 kg ha^{-1}	8	8324 #/m^2	10 g/1000 grains
RRMSE	17 %	23 %	21%	28%	47 %
PLA	37 %	69 %	64 %	99 %	98 %
PLP	63 %	31 %	36 %	1 %	2 %

Table 2.5. Yield, leaf area index (LAI), leaf number, days to flowering (Days to flow), and days to maturity (Days to mat) per hybrid. The variables shown in the table for the hybrids from 1 to 17 and 1997 and 2010 were obtained in the 2022 and 2023 growing seasons in Pottawatomie, Kansas. For hybrids 1982 and 2006 were obtained in the 2021 growing season in Pottawatomie, Kansas.

Hybrid	Yield (kg ha^{-1})	LAI (m/m)	Leaf number	Days to flow	Days to mat
1	5221	1.81	15	51	90
2	6079	2.11	16	52	91
3	6193	2.84	17	52	92
4	6329	2.78	17	53	92
5	7341	2.9	18	51	91
6	5892	2.73	17	52	94
7	6317	2.98	17	54	98
8	6643	3.1	18	54	94
9	6386	3.44	18	60	95
10	6263	3.52	19	60	108
11	7086	3.55	19	60	107
12	7681	4.13	19	61	105
13	7767	4.03	19	60	104
14	7623	3.68	18	61	111
15	4929	3.79	21	70	110
16	6801	4.25	19	67	107
17	5104	3.77	20	70	112
1997	7271	4.06	19	66	112
2010	7478	3.98	19	65	110
1982	7706	5.6	17	61	108
2006	10079	3.48	15	59	104

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Chapter 3 - Intensifying agricultural cropping sequences in US Central Great Plains region: a case study for sorghum crop

Abstract

Over the last decades, Sorghum (*Sorghum bicolor* L.) has reduced its planted area mostly by replacement with other crops, such as corn (*Zea mays* L.) or soybean (*Glycine max* L.). In current cropping systems, these two crops are being utilized as monocrops or in a context of less diversified rotations (e.g., corn-soybeans), resulting in a current decrease in diversity and intensification of US agricultural farming systems. In this context, the objectives of this study are to i) evaluate the economic feasibility of double cropping sorghum with a winter cereal (in this case, wheat crop, *Triticum aestivum* L.); ii) understand the environmental drivers favoring the sorghum-wheat rotation; iii) delimitate the spatial distribution of these rotations. Diverse crop growth APSIM simulations were created with 33 years of weather data, farming practices in Kansas, and sorghum and wheat hybrid coefficients. These simulations consisted of three different systems: sorghum-wheat, sorghum monocrop, and wheat monocrop. The outcomes were analyzed using three different economic scenarios (low, medium, and high profits), and the profit of each simulation was grouped into three profit clusters. The environmental factors of each system and cluster were evaluated to understand the drivers behind the yield outcome. Then, three geoclusters were done using the presence of each profit cluster in each county as an input. The findings show that sorghum-wheat rotations generally outperform monocrops in profitability in two of the three profit clusters. Regarding the geoclusters, three main areas were defined, the northeast part with the sorghum-wheat rotation resulting in higher profits, the south central and western area with the rotation presenting best profits but with reduced returns, and the central west area, where the wheat monocrop resulted in a more profitable system. These

insights highlight the economic and environmental advantages of crop rotation, providing valuable guidance for sustainable farming practices in various Kansas regions.

Introduction

The trend toward monoculture or limited rotations in the Midwest of the United States (corn-soybean rotations) in the last decades (Dimitri et al., 2005) had detrimental effects on diversity, resulting in biological, environmental, and economic costs, including increased dependency on external inputs such as fertilizers (Ciampitti & Lemaire, 2022; R. Mark Sulc & Benjamin F. Tracy, 2007). This scenario exacerbates challenges and renders farmers more susceptible to fluctuating input prices, as evidenced by the urea prices which have ranged between 200 and 800 dollars per ton over the last decade (USDA Foreign Agricultural Service, 2022). Diversified crop rotations have demonstrated the potential to increase returns compared to wheat monocrop (Vitale et al., 2020). Given that monocrop wheat (*Triticum aestivum* L.) is still a relevant crop sequence (or lack of it) for some of the current farming systems in Kansas (Jaenisch et al., 2021), the inclusion of other crop in the rotation holds the promise of enhancing economic returns and sustainability.

Over the last two decades, sorghum (*Sorghum bicolor* L.) has witnessed a significant reduction in the planted area, resulting in the halving of the US sorghum belt (USDA-NASS, 2023). During this transition, sorghum has been relegated to more vulnerable fields where its capacity to tolerate stress (Stone et al., 2006) and yield stability (ability to maintain yield under more stressful conditions) are valued. However, the potential of integrating sorghum into more intensified rotations to enhance its competitiveness with other crops remains largely unexplored, despite the promise it holds for diversifying farming systems while maintaining profitability.

Several factors currently impede the wider adoption of sorghum under more intensified rotations. One such factor is the late harvest of sorghum, which consequently delays the planting of the subsequent crop (Assefa et al., 2014). Ostmeyer et al. (2020) proposed early planting as a solution to this issue, linked to the development of cultivars with enhanced chilling tolerance to attain uniform emergence. However, the same authors found that early planting often results in an extended vegetative stage compared to regular planting failing to optimize land use and timely field turnover for subsequent crops. Another approach involves the use of early-maturing hybrids, offering shorter crop cycle duration, and placing the dry-down period in more favorable environmental conditions (i.e., warmer weather). Nonetheless, early maturing hybrids present a shorter growth cycle, implying fewer leaves, hence less leaf area; also, less time intercepting radiation, and determining a lower yield potential. The introduction of shorter crop growth cycle hybrids will permit the movement to double cropping (e.g., sorghum-wheat) favoring crop diversification, improving conservation, and enhancing land utilization within the season.

Following this rationale, the objectives of this study are: i) to evaluate the economic feasibility of double cropping sorghum with wheat; ii) to understand the environmental drivers behind the sorghum-wheat rotation; and ultimately, iii) from a profit standpoint, to delimitate the spatial distribution of this more intensified crop rotation within the state of Kansas.

Materials and Methods

A description of the methods is presented in Figure 1. Briefly, the APSIM model was employed to simulate sorghum-wheat rotation and the monocrops across 198 sites in Kansas over the last 33 years utilizing historical weather data. The simulations were employed to evaluate the profit distribution of three cost scenarios (low, intermediate, high). With the three scenarios three profit clusters were created (S+W $$, S+W $, W). Followed by an evaluation of the environmental factors affecting the profit of each cluster. Finally, three geoclusters were defined across the state (S+W $$, S+W $, W).

APSIM Model Simulations

The study utilized the Agricultural Production Systems Simulator (APSIM) to model both sorghum and wheat. APSIM is a widely recognized simulation tool for agricultural systems (Keating et al., 2003). Specifically, the APSIM sorghum module simulates phenology, crop growth, and development, using the demand and supply concept (Hammer et al., 2010). Similarly, APSIM wheat module simulates winter and spring wheat daily growth and its phenological development (Zhao et al., 2014), responding to weather, soil water, soil nitrogen, and management (Zheng et al., 2015).

The study explored three different scenarios for alternative crop rotation: i) monocrop sorghum, ii) monocrop wheat, and iii) sorghum-wheat. Temperature and precipitation data spanning 33 years was obtained from NOAA for 198 counties in Kansas (National Oceanic and Atmospheric Administration, 2023). Radiation and relative humidity were obtained from NASA (*NASA POWER*, 2023) considering the latitude and longitude of the weather stations. SSURGO (U.S. Department of Agriculture, 2004) was used as the source of information for soil data; and the soil parameters required by APSIM were calculated employing the apsimx package (Miguez, 2022).

To estimate the planting date of wheat in the rotation after the sorghum harvest, a dry-down module was developed and incorporated into APSIM. The harvest of sorghum was triggered the day before the end of the wheat sowing window (Shroyer et al., 1996), or by attaining of 14% grain moisture in sorghum crop. Equation 1 (Martinez-Feria et al., 2019) was used to calculate the grain dry-down period with a 35% grain moisture as the initial value and 14% moisture as the final harvestable value. The sorghum dry-down parameters were obtained from Paulsen & Thompson (1973). The validation of this dry-down module is available in Supplementary Figure 1.

$$\frac{dM}{dx} = -k \cdot (M - M_e) \cdot n \cdot x^{n-1}$$

Equation 1. Dry-down equation. M stands for % grain humidity at the time, M_e stands for equilibrium moisture content, k stands for proportionality drying coefficient, and x is the days since maturity.

Two sorghum hybrids previously validated in Kansas; USA (Carcedo & Ciampitti, 2023) were employed to perform the crop growth simulations. For the rotation, an early-maturity hybrid was employed (Buster), and a full maturity one was used as a monocrop (Apollo). The wheat variety “Batten winter”, previously validated in Kansas (Berhe et al., 2017) was employed in the wheat simulations (Coefficients available in supplementary Tables 1, 2, and 3 respectively). For both crops fertilization was calculated following the recommendations described in Leikam et al., (2003) considering the expected yield as the average over the las 10 years (USDA-NASS, 2023) and a 2.5% estimated soil organic matter content. Plant population and planting dates were determined following Shroyer et al. (1996). For wheat, planting dates ranged from September 10 to October 25, and for sorghum, from May 15 to July 10. Plant populations were based on rainfall, with ranges from 45 to 84 kilograms per hectare for wheat, and a range of 60000-170000 plants per hectare for sorghum.

Profit classification analysis

Following the completion of simulations, data extraction and analysis were conducted. Profit calculations were based on seed and fertilizer as inputs, which typically constitute 40% or more of the total inputs for both crops (Tsoodle & Li, 2023). Grain prices were obtained from USDA/NASS QuickStats Ad-Hoc Query Tool (quickstats.nass.usda.gov). The reported prices were considered representative of the central Kansas area. This value was adjusted for the western and eastern areas for wheat. Regarding sorghum, costs were determined based on the average for areas receiving between 20-26 inches and 26-32 inches of rain. To provide a comprehensive economic analysis, three economic scenarios representing low, intermediate, and high-cost conditions were established. These scenarios were formulated using seed and fertilization costs over the last 9 years (2014 to 2022; available in Supplementary Tables 4, and 5).

Data analysis

The data analysis was conducted using R software (R Core Team, 2021). Initially, a k-means cluster was performed using the average yield from the three rotations over 33 years for each county. The number of clusters was defined using the function fviz_nbclust, from the R package factoextra (Kassambara & Mundt, 2020) (Supplementary Figure 2). The k-means function from the package stats (R Core Team, 2021) was used for the cluster definition. To analyze the profit variations a linear model using the cluster, economy, and rotation as factors was performed using lm from the stats package (R Core Team, 2021). The R-package emmeans (Lenth, 2023) was utilized in this analysis.

A linear model incorporating cluster, economic scenario, and rotation as factors was executed using the lm function from the stats package (R Core Team, 2021) was used to assess different profit scenarios. These scenarios were compared using a multiple comparison test with

Sidak correlations in the emmeans package (Lenth, 2023). A principal component analysis was performed to reduce the dimensionality of the different factors affecting the profit for each scenario. The variables included were radiation, precipitation, thermal time, water deficit, latitude, longitude, interquartile ratio (IQR), and yield. The function prcomp from the stats R package (R Core Team, 2021) was used and was plotted using fviz_pca_biplot from the R package factoextra (Kassambara & Mundt, 2020). Finally, to assess the spatial distribution of the k-means clusters across Kansas, a fuzzy c-means was performed using the function SFCMeans from the package geocmeans (Gelb & Apparicio, 2021). As input for this analysis, the frequency of each cluster in each county over the 33 years was employed. The resulting geoclusters were named based on the cluster showing the higher proportion.

Results

The sorghum yield was similar for both rotation and monocrop, showing no significant differences (Table 1). However, there was a noticeable decrease in wheat yield when placed after the sorghum crop (59%). When analyzing profit, the sorghum-wheat rotation consistently yielded higher profit in all the economic scenarios (Table 1). Notably, the high-profit category exhibited the largest differences among the management options, with profits of 584 USD ha^{-1} for sorghum, 704 USD ha^{-1} for wheat, and 776 USD ha^{-1} for sorghum-wheat. Additionally, wheat monocrop presented the smallest IQR across economic scenarios, indicating less variability in profit compared to the other farming systems.

The profits obtained by different county x year combinations and economic scenarios were classified into three clusters based on the farming system attaining higher profits: combinations where sorghum-wheat rotation presents better profits and with higher incomes

(S+W $$), instances where sorghum-wheat presents better profit, but with lower incomes (S+W $), and lastly instances where the wheat monocrop had better profits (W). Notably, the low and intermediate economic scenarios presented similar profits across clusters and rotations (means of 491 USD ha^{-1} and 520 USD ha^{-1} respectively; Table 2). In the cluster S+W $$, it was consistently advantageous to opt for the sorghum-wheat rotation over sorghum or wheat in monocrop, irrespective of the economic scenario (mean across economic scenarios of 855 USD ha^{-1}, 776 USD ha^{-1}, and 576 USD ha^{-1} respectively; Table 2). Conversely, in the cluster S+W $, while the sorghum-wheat rotation was more profitable in the low and intermediate economic scenarios, in the high economic scenario there was no significant difference between sorghum-wheat rotation and wheat monocrop (744 USD ha^{-1} vs 743 USD ha^{-1} respectively, Table 2). In the case of the W cluster, planting wheat was consistently more profitable across all economic scenarios (a difference of 160 USD ha^{-1} with sorghum and 40 USD ha^{-1} with sorghum-wheat rotation; Table 2). Standard deviation remained consistent across rotations, clusters, and economic scenarios (from 89 USD ha^{-1} to 215 USD ha^{-1}; Table 2).

The percentage of times that sorghum-wheat was the farming system with better profits was similar within the clusters S+W $ and S+W $$ in low and intermediate scenarios (64-69%). The main difference relies on the percentage of times that sorghum or wheat crops as monocrops have a better profit, in S+W $ wheat was higher in 20% of the total of county x year combinations and sorghum only 10% of the times. However, on S+W $$ wheat crop never presented higher profits than the sorghum-wheat rotation or sorghum. In the high economic scenario and cluster S+W $, the sorghum-wheat rotation and wheat monocrop presented 47% as the most profitable situation (Figure 2). This is correlated to both systems having no significant differences in profit (Table 2). In the W cluster under all the economic scenarios, wheat has a higher profit in more than 55% of the total of county x year combinations followed by sorghum-wheat rotation (~30%).

The PCA for the sorghum-wheat rotation captured the variance less efficiently than for sorghum or wheat as monocrop (~68 in sorghum-wheat vs ~85 in sorghum and wheat monocrop; Figure 3). For all the farming systems, W cluster was less related to profit and had a wider variability as visualized in the PCA showing the distribution of its points was farther from the vectors than the other clusters and more dispersed (Figure 3 panels A, B, and C). On the other hand, cluster S+W $$ independently of the rotation was more correlated to profit and had less dispersed yields (Figure 3 panels A, B, and C. The profit of the rotation was mainly driven by sorghum yield (it showed a longer vector with a small angle with profit vector), wheat yield was positively related but not in the same proportion (Figure 3, panel A). In the case of sorghum, the profit was related to the IQR and yield, latitude also changes the profit (Figure 3, panel B). The main effect on wheat profit is due to yield followed by longitude which has a positive effect on profit, together with rain and wh_swdef (water deficit). Radiation, latitude, thermal time, and the IQR did not affect wheat profit (~90-degree angle between the variables and the profit vector) (Figure 3, panel C).

This analysis generated three geoclusters that were named based on the profit cluster with the higher frequency (over 50%): W; S+W $; and S+W $$ (Table 3, Figure 4). S+W $$ profit cluster was predominantly found towards the northeast and north central Kansas. S+W $ profit cluster was found towards south-central Kansas and the western counties. Lastly, W profit cluster concentrated in the counties located in the central west of the state. There was no difference in the geoclusters when comparing the three economic scenarios.

Discussion

The present study focuses on positioning sorghum as a rotational crop in a broader context of circular agriculture, to provide competitive management strategies, limit the fallow periods and overall increase the profitability of the farming operation. The main outcome of this project was the delimitation of suitable areas for the sorghum-wheat rotation within the US central Great Plains region (Kansas, US). This could be useful for farmers in the path of intensifying their systems. According to Hansen et al. (2012), the changes in technologies adopted by farmers have permitted the switch from winter wheat-fallow into more intensive rotations as winter wheat-summer crop-fallow. Several studies have shown the advantages of this rotation versus the wheat-fallow rotation (Hansen et al., 2012; Nielsen et al., 2002), but to the extent of our knowledge the sorghum-wheat rotation has not been explored yet. This study revealed the economic benefits of using early-maturing sorghum hybrids in a sorghum-winter wheat rotation versus wheat monocrop or sorghum monocrop, these results are in agreement with other studies comparing several rotations with wheat-fallow (Anderson et al., 1999; Bushong et al., 2012; Massigoge et al., 2024).

Economic profit significantly influences farmers' choices in farming systems, but factors like water availability, pests, and weeds are also critical (Socolar et al., 2021). Implementing more intensive and diverse crop rotations helps to extend the duration and extent of soil coverage leading to a decrease in weeds and pests (Liebman & Dyck, 1993; Rosenzweig et al., 2018; Wicks, 1984). Additionally, intensive rotations can impact crop water availability, as this compared to monocrop implies less available water per crop, but a better infiltration in the soil, higher precipitation allocation, and less evaporation due to soil coverage (Holman et al., 2020;

Simão et al., 2023). In Kansas, the limited precipitations are challenging, especially in western counties (Deines et al., 2019; Kansas Office of the State Climatologist, 2024; L. R. Stone et al., 2006).. Assefa et al. (2014) described that wheat after sorghum could be more stressed than wheat after corn. However, in this study, we found that the water deficit did not have a significant impact on profit in any of the tested farming systems. Having a sorghum-wheat rotation would also increase the land and water use efficiency which can improve when having a summer crop included in the rotation (Hansen et al., 2012; Nielsen et al., 2002). The areas where the cluster with higher profit for the sorghum-wheat rotation was located, have higher precipitations and lower temperatures (*Kansas Office of the State Climatologist · Kansas Climate*, n.d.), which is in accordance with other studies implying that lower temperatures and higher precipitations increase yield for both crops (Miller et al., 2021; Staggenborg et al., 2008; Tack et al., 2015). Following the same concept, the clusters W and S+W $ were located in the areas of the state where the rainfall is lower, and the temperatures are higher.

This study presents limitations that will need to be addressed in future research for robustness of the crop rotation recommendations.: i) the lack of extensive datasets to more independently validate the available crop parameter in a sorghum-wheat rotation; ii) limited genetic variability in both crops and iii) in this study wheat was considered the main crop, and sorghum crop cycle was shortened to fit wheat recommended planting date, yet the sorghum crop as priority was not tested. In addition, including other alternative winter crops such as canola could be more attractive due to the current demand for biofuels. Future steps could be focused on integrating new field datasets on this rotation and test other rotations to evaluate changes in both productivity (including quality parameters, protein, and oil) and profit over time.

Conclusions

The comparative analysis revealed that the profit margin for the sorghum-wheat rotation system outperformed both the sorghum and wheat monocrop in Kansas. The study identified three distinct profit clusters: two where the sorghum-wheat rotation was the superior choice (with varying levels of profitability), and one where wheat monocropping was more advantageous. The generated map delineating these geoclusters offers a practical tool for farmers, suggesting optimal rotations designed for specific regions within Kansas. Notably, in certain areas, intensifying crop rotation not only promises higher profits but also enhances land use efficiency and promotes sustainable agricultural practices. Conversely, other regions may see greater financial gains from maintaining a wheat monocrop system. Interestingly, the analysis found no correlation between these geographical clusters and the economic scenarios.

Figures

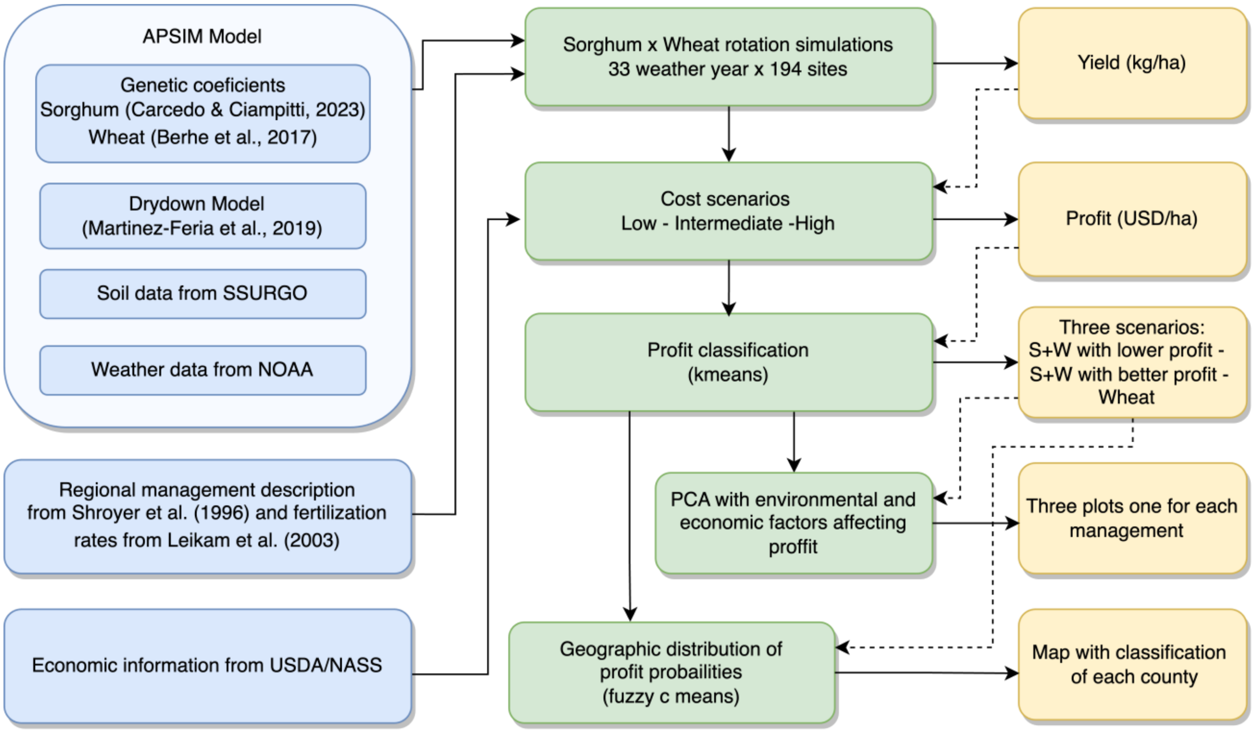

Figure 3.1. Figure 1. Diagram of the workflow from input sources through analytical procedures to final outputs. Blue boxes represent the data sources, green boxes represent the process, and yellow the outputs. The data sources include APSIM model simulations for sorghum and wheat genetic coefficients, Kansas regional management practices, and USDA/NASS economic data. As a first step, the simulation of sorghum monocrop, wheat monocrop, and sorghum-wheat rotations across 33 years and 198 sites was done. The output yields from the simulations are used to calculate profits across three different economic scenarios. These profits are then grouped into three clusters. Subsequently, a Principal Component Analysis (PCA) is conducted for each cluster to evaluate the environmental factors influencing profitability. Lastly, a fuzzy c-means clustering technique is applied to visualize the geographic distribution of these profit clusters on a map.

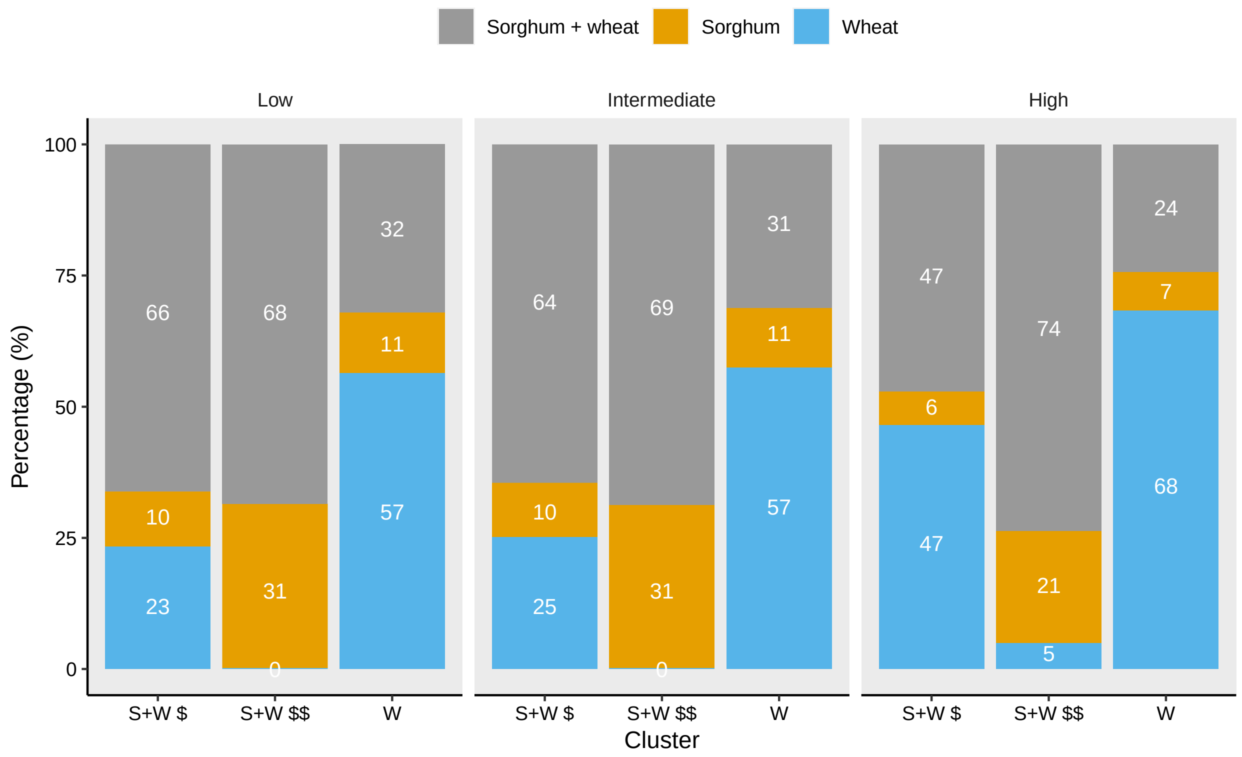

Figure 3.2. Percentage of times that each farming system has higher profits for each cluster and economic scenario. The colors represent each farming system. The bars represent each cluster for each economic scenario. S+W $$ means the sorghum-wheat rotation presented higher profits and the income was higher, S+W $ means the sorghum-wheat rotation presented higher profits and the income was lower, and W means wheat monocrop presented higher profits.

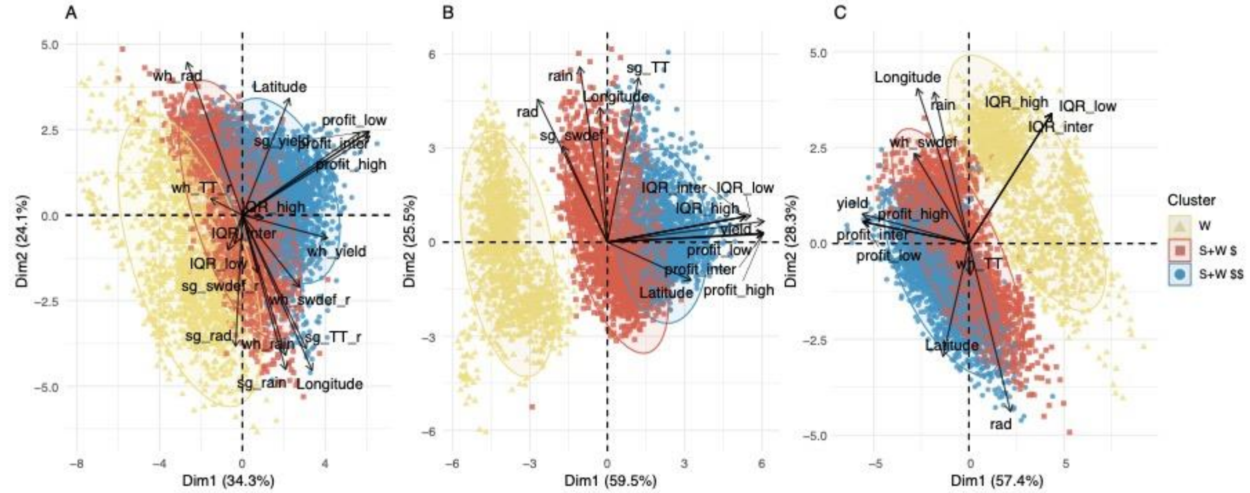

Figure 3.3. PCA of the three farming systems. The arrows represent the different economic and environmental factors. The different colors stand for the profit clusters. Panel A) is the PCA for the sorghum-wheat rotation; panel B) is the sorghum monocrop; and panel C) is the PCA for the wheat monocrop. S+W $$ means the sorghum-wheat rotation presented higher profits and the income was higher, S+W $ means the sorghum-wheat rotation presented higher profits and the income was lower, and W means wheat monocrop presented higher profits.

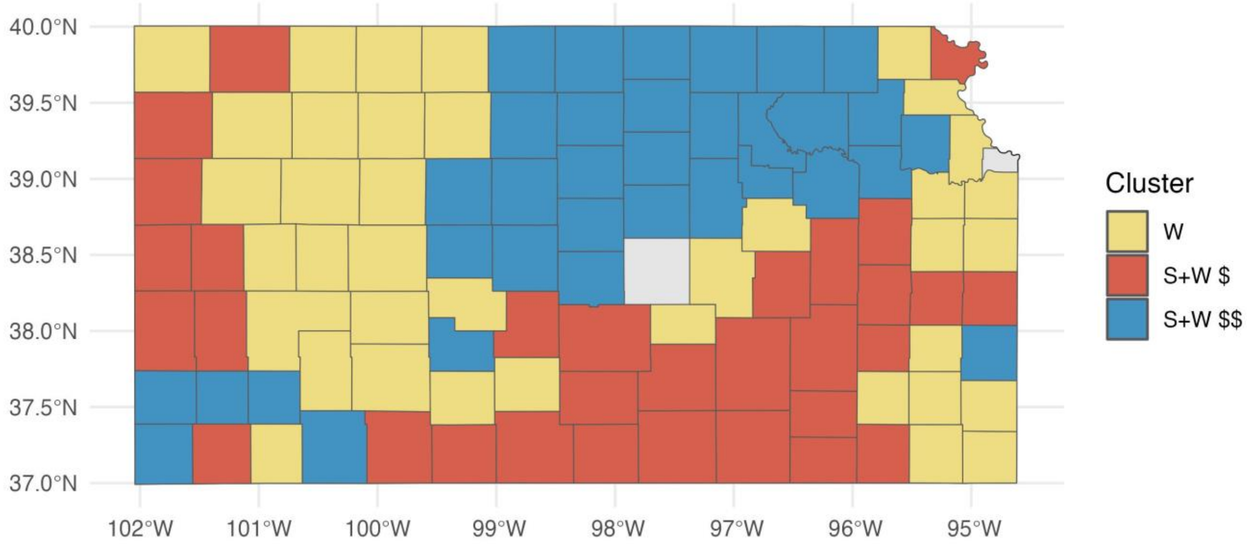

Figure 3.4. Map of the spatial distribution of the geoclusters. The different colors represent the different geoclusters. S+W $$ means the county has a larger proportion of S+W $$ cluster, S+W $ county has a larger proportion of S+W $$cluster, and W means the county has a larger proportion of W cluster.

Tables

Table 3.1 Yield for each crop in the different farming systems, and profit and interquartile ratio (IQR) for each farming system and economic scenario. Different letters mean a significative difference between the values of ($p < 0.05$) according to the Sidak test.

Farming system	Wheat yield (kg ha^{-1})	Sorghum yield (kg ha^{-1})	Economic scenarios	Profit (USD ha^{-1})	IQR
Sorghum-Wheat rotation	1358	4082	Low	576 c	288
			Intermediate	608 c	301
			High	776 c	371
Sorghum monocrop		4184	Low	465 b	361
			Intermediate	488 b	382
			High	584 a	460
Wheat monocrop	3273		Low	431 a	161
			Intermediate	463 a	172
			High	704 b	258

Table 3.2. Profit and standard deviation for each management, cluster, and economic scenario. Different letters mean a significative difference between the values of ($p < 0.05$) according to the Sidak test. Sd stands for standard deviation. S+W $$ means the sorghum-wheat rotation presented higher profits and the income was higher, S+W $ means the sorghum-wheat rotation presented higher profits and the income was lower, and W means wheat monocrop presented higher profits.

Farming system	Cluster	Economic scenario	Profit (USD ha^{-1})	Sd
Sorghum Wheat Rotation	S+W $$	Low	756 c	103
		Intermediate	798 c	109
		High	1012 c	144
	W	Low	293 b	111
		Intermediate	311 b	118
		High	411 b	150
	S+W $	Low	545 c	89
		Intermediate	576 c	94
		High	744 b	124
Sorghum monocrop	S+W $$	Low	702 b	118
		Intermediate	739 b	125
		High	887 b	152
	W	Low	197 a	102
		Intermediate	207 a	108
		High	249 a	130
	S+W $	Low	408 a	110
		Intermediate	429 a	117
		High	513 a	141
Wheat monocrop	S+W $$	Low	467 a	106
		Intermediate	501 a	113
		High	761 a	169
	W	Low	305 b	134
		Intermediate	327 c	144
		High	503 c	215
	S+W $	Low	456 b	112
		Intermediate	489 b	120
		High	743 b	180

Table 3.3. The proportion of each cluster in the geoclusters with the standard deviation. S+W $$ means the county has a larger proportion of S+W $$ cluster, S+W $ county has a larger proportion of S+W $$ cluster, and W means the county has a larger proportion of W cluster.

Geocluster	S+W $$	S+W $	W
S+W $	31 ± 24	56 ± 19	14 ± 16
S+W $$	67 ± 24	24 ± 15	9 ± 24
W	7 ± 14	38 ± 26	55 ± 31

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Chapter 4 - Final Remarks

Efforts for increasing intensification of crop rotations is critical to address emerging agriculture challenges, providing alternatives to the less diverse (e.g., monocrop) agricultural systems. This study proposes a more intensified rotation that could significantly enhance farm productivity and improve diversification, leveraging the unique physiological characteristics (e.g., high degree of tolerance to drought and heat) of sorghum crop.

In Chapter 2, the observed source:sink imbalance during the grain filling period indicates the potential for increasing the sink capacity (via improvement in grain number) or reducing source size (via reduction in number of leaves). This new information suggests that sorghum crop can withstand defoliation during the reproductive period without yield penalties (at least under the yield environment tested in this current study), presenting a strategic direction for breeders to develop hybrids with fewer leaves and consequently shorter crop growth cycle. Modern early-maturity sorghum hybrids have demonstrated comparable yields respective to their longer duration counterparts, offering a promising pathway for incorporating sorghum into more intensified farming systems and potentially boosting profitability.

Chapter 3 underlines the economic and environmental viability of including early-maturing sorghum hybrids in rotations, particularly in the context of double cropping with wheat. The APSIM simulations and economic analyses across various Kansas regions reveal that sorghum-wheat rotations generally outperform monocropping systems in terms of profitability. These findings advocate for the strategic implementation of crop rotations tailored to regional conditions, enhancing both economic returns and sustainable land use.

Future research should extend beyond evaluating new and more intensified crop rotations within Kansas to encompass the entire "sorghum belt" and explore the broader applicability of early-maturing hybrids in intensifying agricultural systems. For example, new winter crops such as canola and a shorter summer crop such as mungbean could be a great alternative following sorghum in rotation, opening a potential for a sorghum-canola-mungbean-wheat rotation, 4 crops in 3 years. The prospect of early maturing sorghum hybrids, characterized by their shorter growth cycles and resilience to defoliation, provides a promising avenue for future changes in the current agricultural landscape. Progress on more diversified and intensified rotations needs to be supported by greater investment in both crop improvement and technologies for the success of the implementation of these complex systems.

Appendix A - Chapter 2

Field experiments

For the first experiment five consecutive plants per subplot were tagged and used to record phenology (Vanderlip and Reeves, 1972). During the vegetative stage, the number of fully expanded leaves was recorded every 15 days. In the same plants, the flowering date and maturity date were recorded. Aboveground biomass was measured at seven stages: i) growth stage 1 (3 leaves fully expanded; Vanderlip and Reeves, 1972); ii) growth stage 2-3 (7 leaves fully expanded; Vanderlip and Reeves, 1972), iii) flowering, iv) ten days after flowering, v) 30 days after flowering, vi) maturity and vii) harvest. After the defoliation, each subplot was sampled individually (samples from v to vii). In each sampling, five plants were collected, and the distance between plants was recorded. The samples were partitioned into leaves, stems, and panicles. Dry weight was obtained after drying plant fractions in an air-forced oven at 65 °C until constant weight.

Five plants were collected for biomass for both treatments to determine the impact of the defoliation treatment. Total leaf area per plant (cm^2) was measured using Li-Cor 3000 equipment, on the day of the treatment application (ten days after flowering).

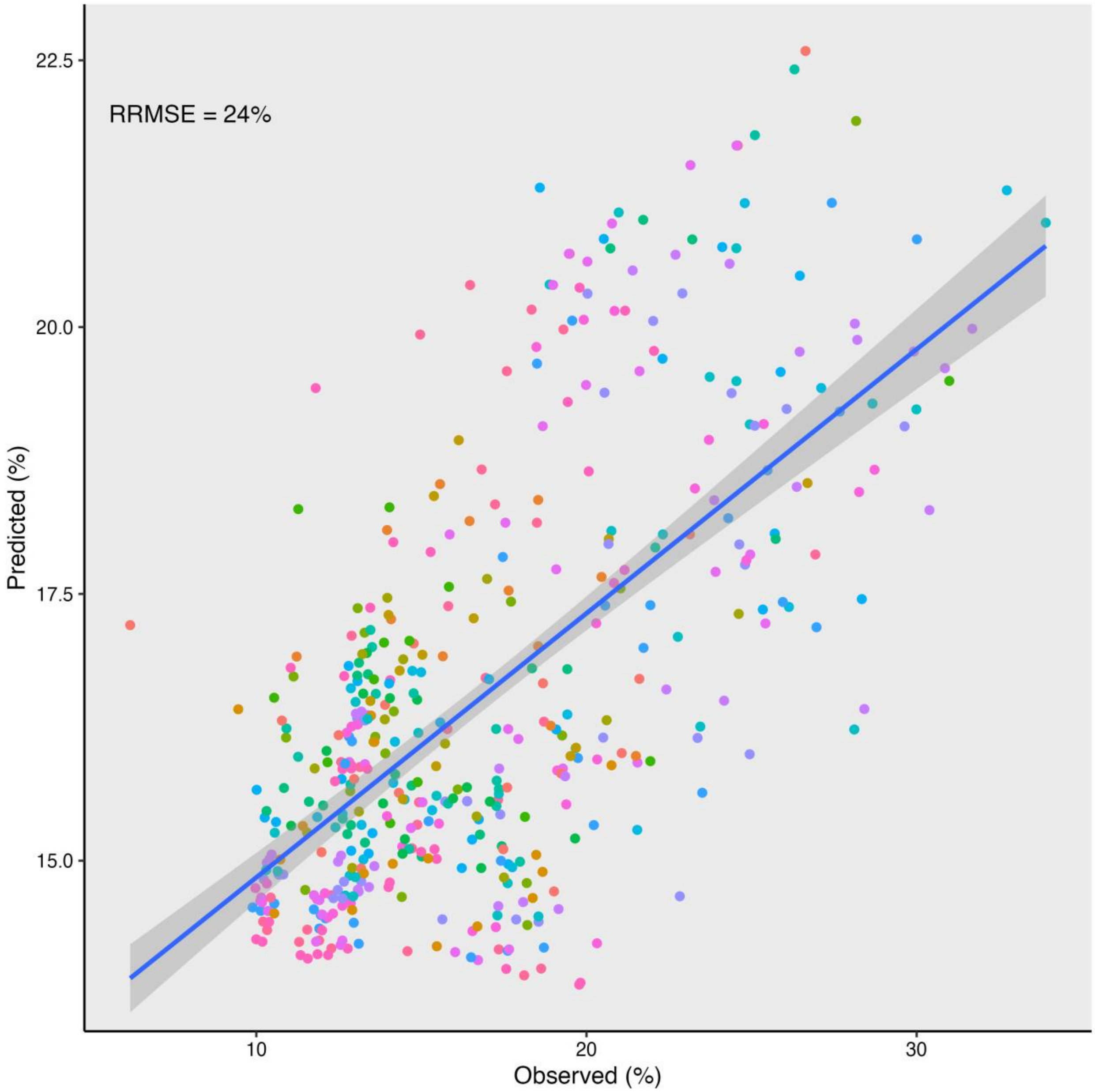
APSIM model calibration

With the first set of data, phenology was calibrated. For this, three parameters were modified, being those tt_emerg_to_enjuv (thermal time from Seedling emergence to end of the juvenile phase), tt_enjuv_to_init (thermal time from the end of the juvenile phase to Floral initiation), and tt_flower_to_maturity (thermal time from flowering to physiological maturity). For this, data on leaf number, flowering, and maturity dates were used.

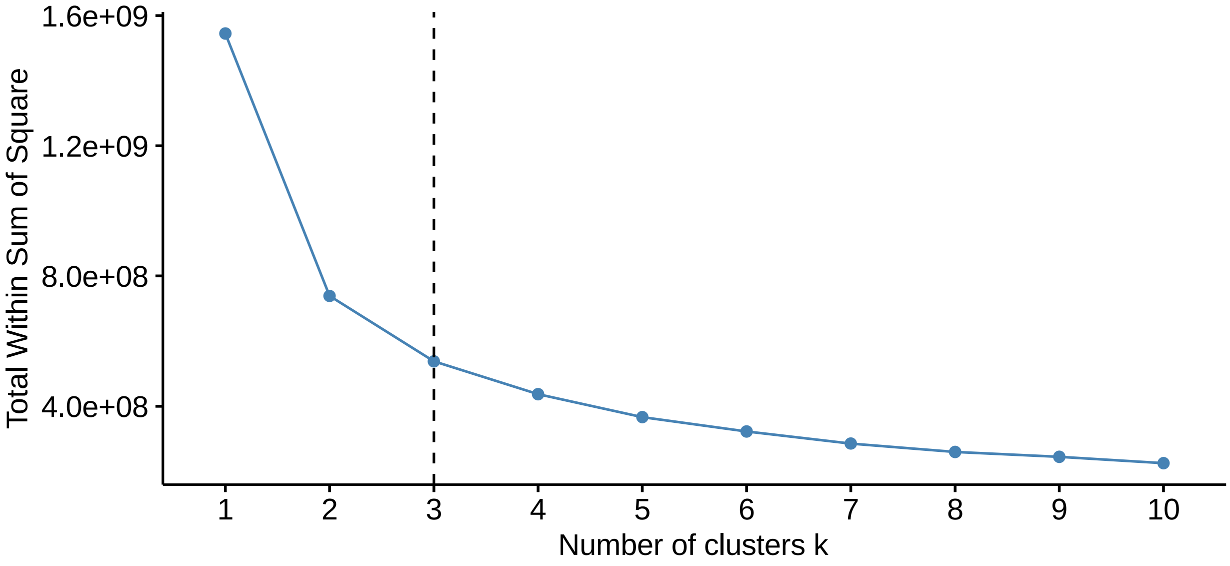
For biomass and yield, both sets of data were used. For the parameters maxGFRate (max grain filing rate) and, x_stem_wt_units (lookup table for canopy height), 2021 results were used. In the case of aX0 (Largest leaf multiplier), aMaxS (Largest Leaf Area Slope), and aMaxl (Intercept for Largest leaf calculation) data of LAI and biomass from 2019 was used.

Due to the special importance of the parameter dm_per_seed (dry matter per seed) for the objectives of this study, this parameter was parametrized and set as fixed during the calibration of the rest of the parameters. According to (Demarco et al., 2023), biomass did not change during the decades, but grain numbers did. To calculate this parameter, the slope of the linear part of the growing sigmoid curve was needed. For this, average temperatures for the years 2018 and 2019 were used to obtain thermal time during the lower and upper points of the line. Also, the average biomass from all the hybrids was obtained. To get the slope the formula dm = (B2-B1)/TT was used, as all was done with an average of the four hybrids, there was one number for all. Using Y = 27 (±8) x + 5524(±285), a formula taken from Demarco, et al., (2022) the number of grains for each hybrid was obtained. Having those two results the parameter dm_per_seed was calculated by making dm_per_seed = dm/seed Number.

Appendix B - Chapter 3



Appendix Figure B.1. Dry-down model validation. The different colors represent the different hybrids tested.



Appendix Figure B.2. Optimal number of clusters.

Appendix Table B.1. Sorghum Buster hybrid coefficients.

Description	Coefficient	Value
tt_emerg_to_endjuv	tt_emerg_to_endjuv	100
photoperiod_crit1	photoperiod_crit1	11.5
photoperiod_crit2	photoperiod_crit2	13.5
photoperiod_slope	photoperiod_slope	11.5
tt_endjuv_to_init	tt_endjuv_to_init	160
tt_flag_to_flower	tt_flag_to_flower	170
tt_flower_to_start_grain	tt_flower_to_start_grain	80
tt_flower_to_maturity	tt_flower_to_maturity	761
tt_maturity_to_ripe	tt_maturity_to_ripe	1
dm_per_seed	dm_per_seed	0.00083
maxGFRate	maxGFRate	0.09
look up table for canopy height	x_stem_wt	0 80
plant canopy height">	y_height	0 2000
Largest leaf multiplier	aX0	0.786
Largest Leaf Area Slope	aMaxS	46.312
Intercept for Largest leaf calculation	aMaxI	321.13

Appendix Table B.2. Sorghum Apollo hybrid coefficients.

Description	Coefficient	Value
tt_emerg_to_endjuv	tt_emerg_to_endjuv	100
photoperiod_crit1	photoperiod_crit1	11.5
photoperiod_crit2	photoperiod_crit2	13.5
photoperiod_slope	photoperiod_slope	0
tt_endjuv_to_init	tt_endjuv_to_init	185
tt_flag_to_flower	tt_flag_to_flower	130
tt_flower_to_start_grain	tt_flower_to_start_grain	80
tt_flower_to_maturity	tt_flower_to_maturity	810
tt_maturity_to_ripe	tt_maturity_to_ripe	1
dm_per_seed	dm_per_seed	0.00083
maxGFRate	maxGFRate	0.09
look up table for canopy height	x_stem_wt	0 80
plant canopy height">	y_height	0 2000
Largest leaf multiplier	aX0	0.71
Largest Leaf Area Slope	aMaxS	37
Intercept for Largest leaf calculation	aMaxI	101
radiation use efficiency	rue	1.75

Appendix Table B.3. Wheat Batten winter hybrid coefficients.

Description	Coefficient	Unit	Value
Sensitivity to vernalization	Plv	1(lowest)-5(highest)	1.0
Sensitivity to photoperiod	pld	1(lowest)-5(highest)	2.0
Thermal time from beginning of grain filling to maturity	p5	°Cd	600
Coefficient of kernel number per stem weight at the beginning of grain filling	Grno	g per stem	22
Potential kernel growth rate	Fillrate	Mg per kernel per day	1.9
Potential final dry weight of a single stem, excluding grain	Stwt	G per stem	3.0
Phyllocron interval	Phint	-	100

Appendix Table B.4. Seed, fertilizer, and grain prices for sorghum and wheat from 2014 to 2022. The classification was done in base of seed and fertilizer for both crops. Inter stands for Intermediate.

		2022	2021	2020	2019	2018	2017	2016	2015	2014
	Classification	High	Inter	Low	Inter	Low	Low	Inter	High	High
Sorghum	Seed	13.2	12.1	11.7	11.6	13.2	13.4	13.6	12.8	12.7
	Fertilizer	80.6	43.1	36.3	40.4	29.9	31.2	34.7	41.0	41.4
	Price	7.0	5.5	4.4	3.3	3.2	3.1	2.7	3.5	3.5
Wheat	Seed	10.9	10.1	9.8	9.8	10.0	9.8	11.9	12.6	12.3
	Fertilizer	66.2	34.9	29.7	33.2	30.8	29.9	28.7	33.9	36.5
	Price	9.2	6.0	4.3	4.6	5.0	4.0	3.7	5.3	6.8
	Sum	170.8	100.1	87.5	95.0	83.9	84.3	88.8	100.3	102.9

Appendix Table B.5. Costs and price for sorghum and wheat under the three economic scenarios.

	Classification	High	Intermediate	Low
Sorghum	Seed	12.9	12.4	12.8
	Fertilizer	54.3	39.4	32.5
	Price	4.65	3.81	3.56
Wheat	Seed	11.9	10.6	9.89
	Fertilizer	45.5	32.3	30.1
	Price	7.06	4.75	4.43