MEASURING TECHNICAL AND ECONOMIC EFFICIENCY OF RAINFED DOUBLE CROPPING SYSTEMS IN THE SOUTHERN GREAT PLAINS

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Abstract: As a result of fragile soils and extreme weather events, crop production in the Southern Great Plains (SGP) is below its potential in comparison to other regions. For the period from 1960 to 2004, the SGP states of Kansas, Oklahoma, and Texas ranked 46th, 48th, and 43rd among the contiguous 48 states in agricultural total factor productivity growth (USDA ERS 2010). Double cropping systems (DCS) are one intensification practice being evaluated for its potential to mitigate the adverse effects of rainfed monoculture agriculture with new cropping options and expand profitability for SGP producers. However, there is limited information on the technical and economic efficiency of DCS under different nitrogen application rates. Therefore, the general objective of this research was to identify the most technically and economically efficient system producers could implement in the SGP. Three systems were evaluated from 1995 to 2019: wheat-corn, wheat-grain sorghum, and wheat-soybean. The Environmental Policy Integrated Climate (EPIC) model benchmarked on small plot and field experiment data from trials in the SGP was used to estimate yields. Data envelopment analysis (DEA) was used to quantify the expected technical and economic efficiency of DCS under various nitrogen scenarios with the yields generated in EPIC. Results indicated that the technical efficiency of wheat increased as winter and summer nitrogen rates increased. Cost efficiency decreased as winter and summer nitrogen rates increased. Revenue and profit efficiency increased as nitrogen rates increased across all systems. The most profitable DCS include scenarios of high winter nitrogen applications to wheat within the wheat-corn and wheat-soybean systems most years. However, wheat-grain sorghum was found to have the highest profit efficiency during significant drought periods.

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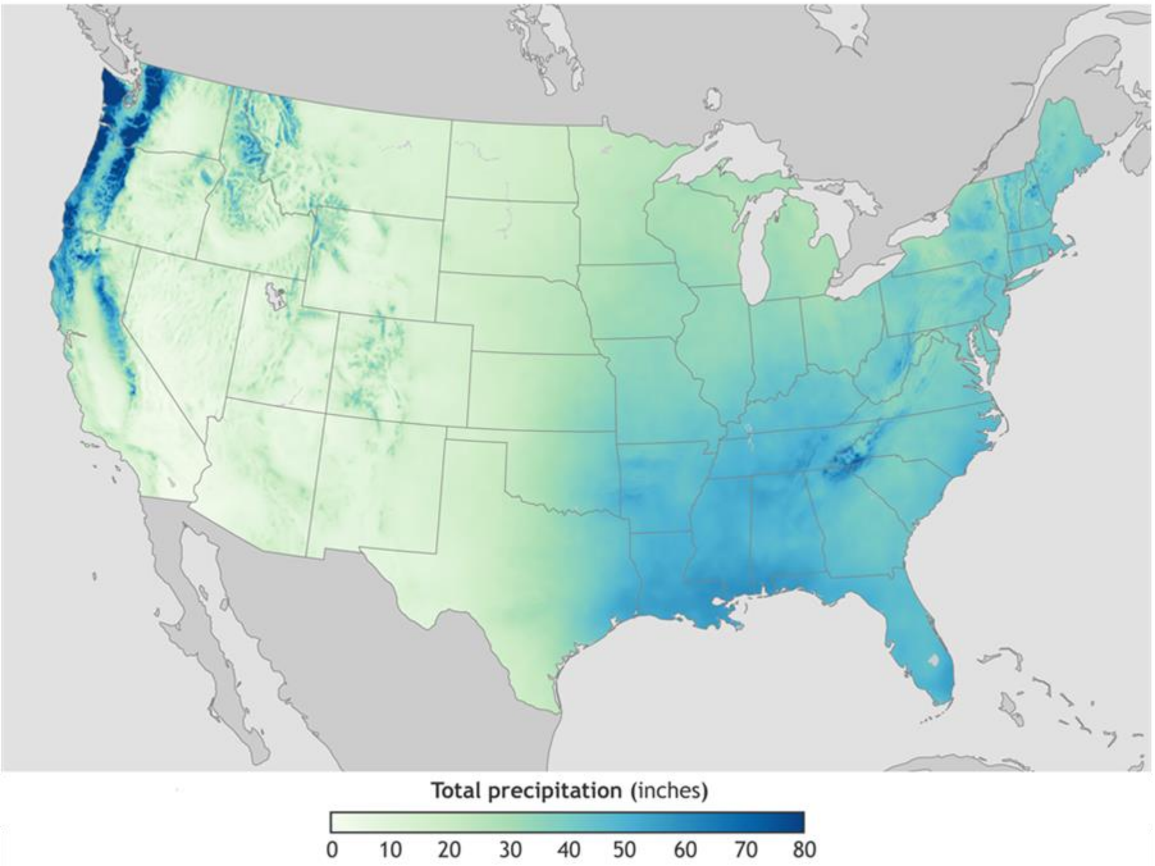
CHAPTER I

INTRODUCTION

Winter wheat (Triticum aestivum L.) is an important commodity for Southern Great Plains (SGP) producers because of its adaptability to semi-arid climates. Although winter wheat is not typically in rotation with other crops, producers in SGP states, such as Kansas, Oklahoma, and Texas, grow wheat for grain, forage, or a combination of both (dual-purpose) in a variety of rainfed agricultural enterprises (Redmon et al. 1995). The success of rainfed agricultural systems in the SGP requires efficient use of highly variable and limited precipitation (Nielsen, Unger and Miller 2005). Almost 80% of the annual precipitation received in the SGP occurs during the spring and summer months from April to September (Saseendran et al. 2013). More than half of the total precipitation received is lost to runoff, soil evaporation, or transpiration of undesirable plants (Warren, Ochsner and Godsey 2017).

Agricultural producers almost universally adopted the use of summer fallowing after the 1930s dust bowl to increase plant available water and reduce yield variability (Greb 1979). The importance of improving water productivity and soil health has increased today as hot, dry, and windy events are occurring more frequently in the SGP (Tavakol, Rahmani and Harrington Jr. 2020). Patrignani, Godsey and Ochsner (2019) divide the SGP's winter wheat cropping systems primarily by two regions. A western region characterized by <23.5 inches of annual precipitation and an eastern region with >23.5 inches of annual precipitation. The western region's cropping system includes wheat-fallow, where 14-month fallow periods occur in between wheat crops every other year. The eastern region's cropping system is defined by shorter fallow periods, ranging from a few weeks to five months depending on the crop sequence. Note this split breaks Kansas, Oklahoma, and Texas essentially down the middle (NOAA 2021).

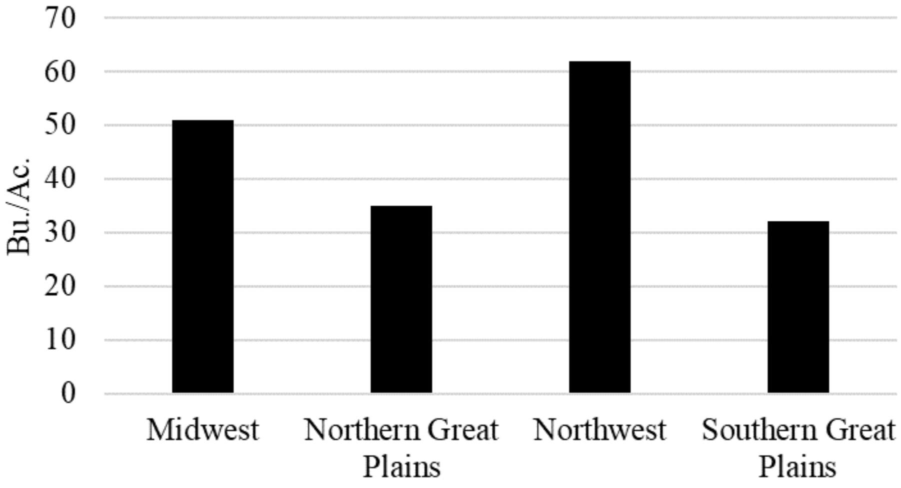
Figure 1. U.S. Annual Average Precipitation, 1991-2020



However, both cropping systems under conventional tillage practices contribute to soil erosion and have poor precipitation use efficiencies (Patrignani, Godsey and Ochsner 2019). The SGP leads the nation in cropland soil erosion via water and wind, with an estimated rate of 8.8 tons per acre per year (USDA NRCS 2007). The existing SGP growing conditions and management practices result in large yield gaps, yield stagnation since the 1980s, and low water and soil nutrient use efficiencies (Patrignani et al. 2014).

The SGP produced nearly 447 million bushels or 38% of the nation's winter wheat in 2020 (USDA NASS 2020a). The SGP is however less efficient at using its resources or the adoption of new technologies to increase output growth in comparison to other regions. For the period from 1960 to 2004, Kansas, Oklahoma, and Texas ranked 46th, 48th, and 43rd respectively among the contiguous 48 states in agricultural total factor productivity growth (USDA ERS 2010). The SGP experiences lower yields in comparison to other regions (USDA NASS 2020b). The SGP averaged 32 bushels per acre compared to the Northwest region's 62 bushels per acre and the Midwest region's 51 bushels per acre winter wheat yield from 1971 to 2020. SGP wheat producers also encounter lower returns per acre as compared to other regions. Net returns for wheat production per acre subtracting operating costs in 2020 was $57 in the Prairie Gateway, which includes most of the SGP, versus the national average of $118 (USDA ERS 2022).

Figure 2. Average Winter Wheat Yield, 1971-2020



Source: (USDA NASS 2020b).
Note: U.S. Global Change Research Program includes MN, IA, MO, IL, WI, MI, IN, and OH in Midwest. MT, WY, ND, SD, and NE in the Northern Great Plains. WA, OR, and ID in the Northwest. KS, OK, and TX in the Sothern Great Plains.

SGP growing conditions compounded with monoculture agriculture limits the SGP's potential and complicates decision-making for producers. Double cropping systems (DCS) are one intensification practice being evaluated because of its potential to better capture summer precipitation, mitigate the adverse effects of rainfed monoculture agriculture with new cropping options, and expand profitability for SGP producers. DCS are a practice in which two crops are grown during one growing season on the same field.

Wheat-soybean double cropping is relatively common across the southern U.S. and SGP where rainfed agriculture dominates (Borchers et al. 2014). The success of double cropping soybeans in the SGP is attributed to the region's extended fall conditions (Lofton et al. 2021). The fall conditions allow the soybeans to mature before the region's first significant freeze. There are other DCS feasible for the SGP, including wheat-grain sorghum and wheat-corn systems.

However, there is limited information on the technical and economic efficiency of these DCS under variations in management options. Therefore, this study seeks to identify "Which system has the highest technical and economic efficiency?" This research uses yield modeling techniques benchmarked to small plot and field experiment data from trials in the SGP to estimate yields. Data envelopment analysis (DEA) is used to quantify the technical and allocative efficiency of each system using the simulated yields. Quantifying the technical and economic efficiency for different DCS is the first step towards scaling up small plot and field trials tailored to the region's agriculture.

CHAPTER II

OBJECTIVE

The general objective of this research is to identify the most technically and economically efficient DCS, including wheat-corn, wheat-sorghum, and wheat-soybean systems, producers could implement in the SGP to boost profitability, productivity, and resiliency to adverse weather events. This research uses the Environmental Policy Integrated Climate (EPIC) model benchmarked on small plot and field experiment data from trials in the SGP to estimate yields from 1995 to 2019 under different fertilizer application rates. A data envelopment analysis (DEA) is used to quantify the technical and economic efficiency of each double cropping system under various nitrogen scenarios. Technical and economic efficiency results provide suggestions to SGP producers seeking to use DCS.

CHAPTER III

LITERATURE REVIEW

Producers are seeking intensification of their cropping systems to improve sustainability and profitability (Borchers et al. 2014). Planting a summer crop after the harvest of a winter crop, double cropping systems (DCS), is one potential way to improve profitability. However, the feasibility of DCS need to be understood, especially in the SGP where precipitation is limited and highly variable. Literature identifying the most technically and economically efficient double cropping system producers could implement in the SGP is limited. There are however studies examining the feasibility of DCS.

Hexem and Boxley (1986) performed a formal report for the USDA ERS on trends in DCS from 1969 to 1986. They listed factors affecting the feasibility of DCS as (1) growing conditions, (2) managerial requirements, and (3) economic conditions. The length of growing season and the amount and distribution of precipitation significantly changes the feasibility of DCS. Long growing seasons are typically defined as having at least 180 days of frost-free periods to which two crops can be grown in the same season. As such the southern states have higher rates of use because of longer growing seasons. However, relatively short growing seasons in the SGP limit the availability of cropping options and often reduces yields for all crops (Hansel et al. 2019).

Hexem and Boxley (1986) state that at least 30 inches of annual precipitation is needed for DCS to be successful. Lower and variable precipitation during the warm season in the SGP increases risk. Producers may be discouraged from using DCS because they become more susceptible to variations in summer precipitation (Burton et al. 1996). In Oklahoma, traversing from east to west, rainfall decreases at an approximate rate of one inch for each 22 miles traveled west (Oklahoma Climatology Survey 2010). The use of DCS increases as you move east to the south coastal states because of adequate rainfall. The Southern Plains, including Oklahoma and Texas, double cropped 2% of their total acres compared to the Southeast's approximately 10% in 1982 (Hexem and Boxley 1986). Today, DCS in the SGP was found to be limited to about 2% compared to the Southeast region's 8% (Borchers et al. 2014). Both reports therefore indicate that DCS have only made up around 2% of the total acres in the SGP for close to 50 years, likely as a result of inadequate precipitation to support rainfed summer crops.

Even if a producer is in an area with long growing seasons and adequate rain, DCS require higher levels of management. The increasing complexity of agricultural systems producers could implement requires a greater focus on management practices (Sassenrath et al. 2008). Producers must make decisions on harvesting and planting dates, summer crop, early-maturing varieties, row spacing, plant population, and herbicides in DCS (Hexem and Boxley 1986). The first crop may need to be harvested earlier and dried in order to plant the summer crop on time. DCS often invoke the need to shift from conventional tillage to conservation tillage because of the shortened growing season. Conservation tillage increases the growing season for the summer crop while helping retain soil moisture at planting. However, conservation tillage equipment results in a reliance on herbicides to control weeds. Existing residue after wheat harvest limits the effectiveness of contact herbicides. The control of weed pressure is a growing concern with increases in weed resistance to herbicides. Globally, over 140 cases of weed resistant species to herbicides in wheat production have been identified, with seven species in Kansas, Oklahoma, and Texas (Heap 2021).

Borchers et al. (2014) found that the availability to obtain insurance on the summer crop and commodity prices are additional limiting factors. There are currently no insurance options for the second crop in our research specific El Reno, OK location and the average double-cropped acres in the U.S. often depend on commodity prices. For example, continuous winter wheat producers only move to double cropping when soybean prices are high enough to counter the loss in yield from short-season soybeans. Hexem and Boxley (1986) also credits commodity prices as the reason for increases in the use of DCS in the U.S. from 5.8 million acres (2%) in the 1970s to 12.4 million acres (4%) of total acres in 1982.

DCS could increase and stabilize net returns compared to monocropping if the feasibility requirements are met (Burton et al. 1996). Farm equipment cost increases from technological advancements fuels the importance of spreading fixed costs over the production surface. Returns can increase as economies of scale in capital is used in addition to cash flow from a second crop (Hartschuh 2019). Productivity increases can occur by extending the use of inputs such as fertilizer. Heggenstaller et al. (2008) found that fertilization requirements can be reduced depending on which double cropping system is practiced to better capture nitrogen that would otherwise be lost to leaching. Vitale et al. (2014) determined SGP producers earn significantly larger net return across all crops with diversified wheat systems compared to continuous wheat.

Thomason et al. (2017) found that in Virginia soybean double-cropped following wheat had higher net returns than grain sorghum following wheat under no-till practices, due to the lower grain sorghum yield. The DCS had higher net returns than their respective full season summer crop. However, full season soybeans provided higher net returns than the wheat-grain sorghum system.

Hare et al. (2020) examined numerous DCS including wheat-corn, wheat-grain sorghum, and wheat-soybeans using strip tillage in North Carolina. They found that double cropping soybeans following wheat had the highest economic returns than wheat double-cropped with corn and grain sorghum. Citing higher costs of production for corn and grain sorghum as a major factor. Similarly, Sanford, Myhre and Merwine (1973) found that wheat-soybean had significantly higher returns than wheat-grain sorghum in Mississippi.

Crabtree et al. (1986) observed however that monocrop wheat under conventional tillage practices had the highest net returns compared to four other systems in the SGP. The other systems included rainfed double-cropped wheat with rainfed and irrigated double-cropped soybean and grain sorghum.

Many producers double crop wheat with soybeans and grain sorghum in the eastern portions of the SGP (Adesina 1989). However, wheat-soybean double cropping is the most common at around 53% of total double crop acres in the U.S. (Borchers et al. 2014). The success of double cropping soybeans in the SGP is attributed to the extended fall conditions and the fall conditions allow for alternatives such as grain sorghum, sesame, and corn (Lofton et al. 2021). Technological advancements in early-maturing wheat varieties, conservation tillage equipment, improved herbicides, and soybean growth regulators allow wheat double-cropped with soybeans to be the least risky and the most likely to generate the greatest returns in a consistent manner (Hexem and Boxley 1986; Shapiro, Brorsen and Doster 1992). Recognizing the most technically and economically efficient system would be valuable to producers who seek to use DCS in the SGP.

CHAPTER IV

METHODS AND DATA

Conceptual Framework

Agricultural producers in the SGP choose a system of crops to maximize profit subject to input and commodity prices. Figure 3 conceptualizes the framework for identifying the technical and economic efficiency of DCS in the SGP from 1995 to 2019. This research uses the Environmental Policy Integrated Climate (EPIC) model benchmarked on field experiment data in the SGP to generate yields for all DCS under different nitrogen scenarios. Data from multiyear field trials conducted in Oklahoma are used in addition to weather records from the High Plains Regional Climate Center to calibrate the EPIC model. EPIC is a plant growth simulator that generates crop yields conditional on management practices including tillage practice, input application rates and timing, precipitation, temperature, and planting and harvest dates (William et al. 1989).

A Data Envelopment Analysis (DEA) model is used to calculate the technical and economic efficiency of DCS under various nitrogen scenarios with the yields generated in EPIC. Costs and revenues associated with each system are needed for economic efficiency evaluation. Therefore, operating cost per acre were collected from Oklahoma State University budgets and nitrogen and commodity prices from USDA National Agricultural Statistics Service (NASS) database.

Dale silt loam soil type was assumed according to the Soil Survey Geographic database and conventional tillage for El Reno, Oklahoma in EPIC. Wheat-corn, wheat-grain sorghum, and wheat-soybean systems were estimated in EPIC for El Reno, OK from 1995 to 2019 as seen in Table 1. The simulation included 25 nitrogen scenarios for each system except for wheat-soybeans. The wheat-soybean system received no summer nitrogen application as it is typically more practical to apply all the nitrogen up front for both crops in this system (Godsey et al. 2008). Fertilizer application comprised of a split winter treatment and one summer treatment. Application dates included a pre-plant treatment on October 1st for period 1, an in-season top dress on February 15th for period 2, and a pre-plant treatment on May 15th for period 3. Fertilizer was expressed as the total nitrogen basis in urea ammonium nitrate (UAN 28%) applied in pounds per acre. The treatments were arranged with five rates in the winter for each application (0, 26.9, 53.7, 79.9, and 107.4 lbs./ac.) and five rates in the summer (0, 53.7, 107.4, 159.9, and 214.8 lbs./ac.). Planting dates were assumed to be October 1st for winter wheat and May 15th for all summer crops. Harvest dates were assumed to be May 15th for winter wheat and mid-September to early October for the summer crops. It is important to note that planting and harvesting dates vary drastically based upon the weather and Oklahoma typically plants a double crop closer to June following winter wheat harvest.

Figure 3. Conceptual Framework

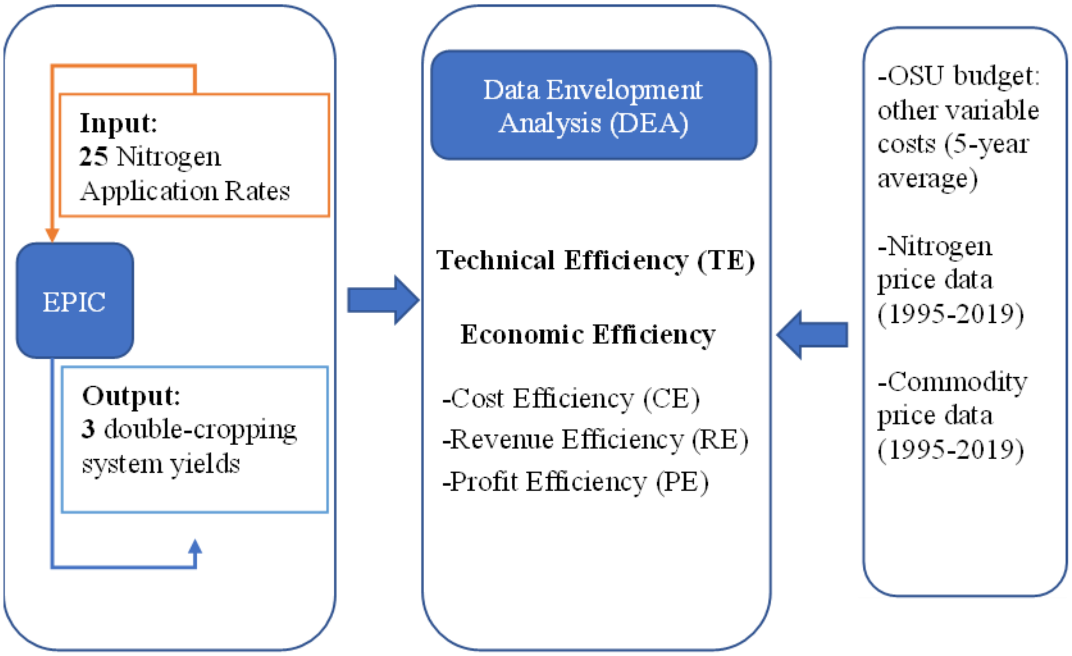


Table 1. Nitrogen Scenarios for all DCS

System	Period	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10	N11	N12	N13	N14	N15	N16	N17	N18	N19	N20	N21	N22	N23	N24	N25
Wheat-Corn	1st	⚪	🟢	🟠	🔴	🟣	⚪	🟢	🟠	🔴	🟣	⚪	🟢	🟠	🔴	🟣	⚪	🟢	🟠	🔴	🟣	⚪	🟢	🟠	🔴	🟣
	2nd	⚪	🟢	🟠	🔴	🟣	⚪	🟢	🟠	🔴	🟣	⚪	🟢	🟠	🔴	🟣	⚪	🟢	🟠	🔴	🟣	⚪	🟢	🟠	🔴	🟣
	3rd	⚪	⚪	⚪	⚪	⚪	🟠	🟠	🟠	🟠	🟠	🟣	🟣	🟣	🟣	🟣	🔵	🔵	🔵	🔵	🔵	⚫	⚫	⚫	⚫	⚫
Wheat-Sorghum	1st	⚪	🟢	🟠	🔴	🟣	⚪	🟢	🟠	🔴	🟣	⚪	🟢	🟠	🔴	🟣	⚪	🟢	🟠	🔴	🟣	⚪	🟢	🟠	🔴	🟣
	2nd	⚪	🟢	🟠	🔴	🟣	⚪	🟢	🟠	🔴	🟣	⚪	🟢	🟠	🔴	🟣	⚪	🟢	🟠	🔴	🟣	⚪	🟢	🟠	🔴	🟣
	3rd	⚪	⚪	⚪	⚪	⚪	🟠	🟠	🟠	🟠	🟠	🟣	🟣	🟣	🟣	🟣	🔵	🔵	🔵	🔵	🔵	⚫	⚫	⚫	⚫	⚫
Wheat-Soybean	1st	⚪	🟢	🟠	🔴	🟣																				
	2nd	⚪	🟢	🟠	🔴	🟣																				
	3rd	⚪	⚪	⚪	⚪	⚪																				
Lbs./Ac.		0	26.9	53.7	79.9	107.4	159.9	214.8																		
		⚪	🟢	🟠	🔴	🟣	🔵	⚫																		
Period		1st		2nd		3rd																				
Application date		Oct. 1		Feb. 15		May 15																				

Data Envelopment Analysis (DEA)

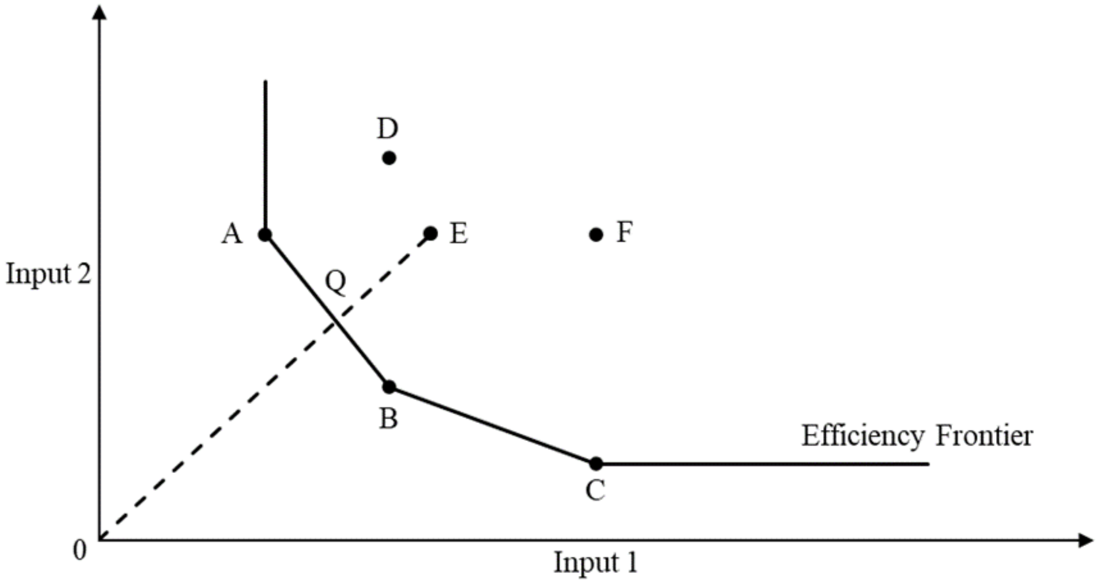
Farrell (1957) created the foundation for nearly all measurements of productive efficiency. The foundation guided Aigner, Lovell and Schmidt (1977) towards a parametric Stochastic Frontier Analysis (SFA) and Charnes (1978) a non-parametric Data Envelopment Analysis (DEA). The SFA technique is often avoided for its difficulty in estimating the efficient production function correctly. Giannakas et al. (2003) explain that misspecification of the efficient production function can lead to biased results with the SFA. Farrell (1957) also noted that it is far better to benchmark efficiencies relative to an achieved reality than some unattainable ideal. This also means that an option maybe efficient in one dataset but inefficient in comparison to another. The other key drawback of DEA is that it is nonparametric, meaning that it does not include errors to attribute to measurement error. All measurement error is therefore incorrectly delegated to inefficiency as a result (Avkiran and Rowlands 2008). However, the DEA technique was chosen because measurement error does not exist for the yields generated in EPIC.

The primary DEA model is often noted in literature as the CCR model since it was constructed by Charnes et al. (1978). The DEA technique uses linear programming to calculate efficiency scores by constructing a piecewise linear frontier from output(s) generated with a given set of inputs. DEA can be (1) input-oriented, (2) output-oriented, or (3) non-oriented. An input-oriented DEA minimizes input use to produce some fixed output. An output-oriented DEA maximizes output while constraining input. A non-oriented DEA attempts to minimize input and maximize output simultaneously. All efficiency models were developed off the linear programming models issued in Coelli et al. (2005) and held under the assumption of variable returns to scale (VRS). The firms or 55 DCS under different nitrogen scenarios for the purposes of this research are considered decision-making units (DMUs). The various scenarios can be viewed as DMUs because producers make decisions on which outputs are produced and how much of the inputs are used.

Measuring Technical Efficiency

Technical efficiency (TE) is defined as the success of producing as much output as possible with a set of inputs (Farrell 1957). Technically efficient firms lie on an efficient production frontier whereas technically inefficient firms are off the frontier. Figure 4 illustrates this efficiency frontier in an input-oriented setting, where all firms produce the same amount of output with some combination use of inputs 1 and 2

Figure 4. Input-Oriented Efficiency Measurement



Firms that produce the same level of output with less inputs are efficient (A, B, and C). Any other firm (D, E, and F) not on the frontier is considered technically inefficient because they are using some larger combination of input 1 and input 2 to produce the same level of output. The distance QE is the level of inputs that need to be proportionally reduced without changing output to be technically efficient. The TE for firm E can be written as a ratio of a perfectly efficient combination use of inputs OQ to an observed combination of inputs OE.

$$TE = \frac{OQ}{OE} \; or \; \frac{Optimal\ Input/Output}{Observed\ Input/Ouput}$$

Firms achieving a TE score of one are technically efficient and those below or equal to zero are inefficient. The measure of inefficiency is one minus the TE score or the distance from the inefficient point to the efficiency frontier. For example, a TE of 0.8 means that all inputs must be proportionally reduced by 20% while producing the same level of output to be efficient.

It should be noted that for all measures of efficiency, the efficiency frontier is the result of running the linear programming model for each observed option in a given year. Therefore, an efficiency frontier comparing each option is benchmarked within the same year. In the input-oriented DEA model, a double cropping system i produces a vector of outputs q_i given a vector of inputs x_i, where $\boldsymbol{X}$ represents the input matrix and $\boldsymbol{Q}$ the output matrix for all options. The TE score under VRS in an input-oriented DEA model is calculated using the following math programming problem:

$$\underset{\theta,\lambda}{Min}\,\theta_i, \tag{1}$$

$$s.t. -q_i + \boldsymbol{Q}\lambda \geq 0, \tag{2}$$

$$\theta x_i - \boldsymbol{X}\lambda \geq 0, \tag{3}$$

$$\lambda \geq 0, \tag{4}$$

$$1'\lambda = 1, \tag{5}$$

where θ_i is the TE score for each system i, λ is a vector of weights for efficient systems, and $1'$ is a vector of ones.

Measuring Economic Efficiency

Economic efficiencies include a cost efficiency (CE), revenue efficiency (RE), and profit efficiency (PE) (Coelli et al. 2005). The CE measure provides the ratio of least expenditure required to produce a level of output to an observed cost. It determines the maximum amount of inputs that can be decreased proportionally while producing at the least cost output level for a set of input prices.

$$CE = \frac{Minimum\ Cost}{Observed\ Cost}$$

CE can be calculated from the input-oriented DEA model. This score also ranges from zero to one where a value of one indicates full efficiency. The CE under VRS for the input-oriented DEA model is calculated by:

$$\min_{\lambda, x_i^*} (w_i{}' x_i) + c_i, \tag{6}$$

$$s.t. -q_i + \boldsymbol{Q}\lambda \geq 0, \tag{7}$$

$$x_i^* - \boldsymbol{X}\lambda \geq 0, \tag{8}$$

$$\lambda \geq 0, \tag{9}$$

$$1'\lambda = 1, \tag{10}$$

where w_i is a vector of input prices given for each system, x_i^* is the least cost vector of input quantities for each system, c_i is the operational costs for each system, and output levels q_i are given.

RE is the ratio of an observed revenue to the maximum revenue of producing an output. This score determines the maximum amount of output that can be increased to produce at a revenue maximizing output level with a given amount of inputs and output prices.

$$RE = \frac{Observed\ Revenue}{Maximum\ Revenue}$$

Revenue efficiency (RE) is calculated from the output-oriented DEA model. These measures range from zero to one, where one is the efficient score. The RE under VRS for the output-oriented DEA model is calculated by:

$$\max_{\lambda,q_i^*} p_i' q_i, \tag{11}$$

$$s.t. -q_i^* + \boldsymbol{Q}\lambda \geq 0, \tag{12}$$

$$x_i - \boldsymbol{X}\lambda \geq 0, \tag{13}$$

$$\lambda \geq 0, \tag{14}$$

$$1'\lambda = 1, \tag{15}$$

where p_i is a vector of output prices given for each system, q_i^* is the maximum revenue vector of output quantities for each system, and input levels x_i are given.

Lastly, the PE is the ratio of an observed profit to the maximum profit given a set of inputs and outputs. The measure defines the maximum amount of outputs that can be increased while producing at a profit maximizing output level given input and output prices.

$$PE = \frac{Observed\ Profit}{Maximum\ Profit}$$

Profit efficiency (PE) is calculated from the output-oriented DEA model. PE ranges from negative infinity to one because some options may have negative returns. A value of one still indicates full efficiency. The PE under VRS for the output-oriented DEA model is calculated by:

$$\max_{\lambda,q_i^*,x_i^*} (p_i' q_i - w_i' x_i) - c_i, \tag{16}$$

$$s.t. -q_i^* + \boldsymbol{Q}\lambda \geq 0, \tag{17}$$

$$x_i^* - \boldsymbol{X}\lambda \geq 0, \tag{18}$$

$$\lambda \geq 0, \tag{19}$$

$$1'\lambda = 1, \tag{20}$$

where p_i is a vector of output prices given for each system, q_i^* is the maximum revenue vector of output quantities for each system, w_i is a vector of input prices given for each system, x_i^* is the least cost vector of input quantities for each system, and c_i is the operational costs for each system. Input levels x_i and output levels q_i are given.

Efficiency Score Calculation by System

DEA measures efficiency for a set of DMUs with common units of inputs and outputs. The production function in this research setting consists of three like inputs (each nitrogen application) but a combination of different outputs (wheat-corn, wheat-sorghum, and wheat-soybean). In a situation where all else is held equal (equal input usage/cost and wheat yield) the yield of corn cannot be compared with the yield of sorghum. Therefore, the TE and CE can only be measured within the same system (i.e., wheat-corn vs. wheat-corn). The TE and CE were compared across DCS but only when comparing the effects on wheat as seen in Table 2. The monetization of different outputs allows comparison across system as used in the RE and PE models.

Table 2. Efficiency Score Calculation by System per Year

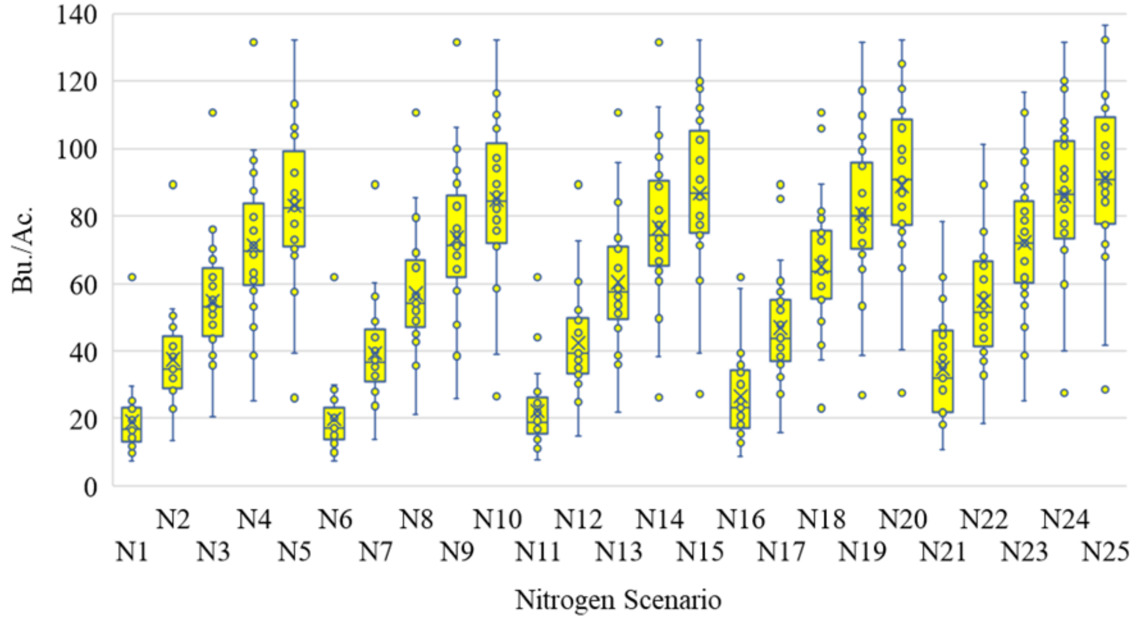
Score	Calculation
TE & CE	Wheat-Corn (25 N-Scenarios) Wheat-Sorghum (25 N-Scenarios) Wheat-Soybean (5 N-Scenarios) Wheat Only (25 + 25 +5 = 55)
RE & PE	All Systems (55 N-Scenarios)

Environmental Policy Integrated Climate (EPIC) Output

This research uses yields simulated in EPIC, crop budgets, and fertilizer and commodity price data to estimate the technical and economic efficiency of DCS to producers. Figures 5 through 10 display EPIC’s generated yields by nitrogen scenario for 1995 to 2019 scaled down to be in reasonable yield ranges. The scaling factor for each summer crop was calculated and applied to each nitrogen scenario by using a ratio of actual Oklahoma non-irrigated average yields to the average EPIC yields under the highest nitrogen scenario (USDA NASS 2020a). Note the

Oklahoma yields were full season summer crop yields as double crop yields are not readily available for all summer crops. El Reno, OK yields were not available for all crops leading to the use of a statewide Oklahoma average. The summer crop yield data however closely resembles actual yields in north central Oklahoma. Lofton et al. (2021) measured double crop yields at 62 bushels per acre for corn, 40 bushels per acre for grain sorghum, and 34 bushels per acre for soybeans. Winter wheat's yield response to the split winter nitrogen rates is as we would expect. Oklahoma State University has found that for roughly every 1.8 pounds of total nitrogen applied per acre, yield increases by one bushel per acre (Reed 2021).

Figure 5. Wheat Yield in Wheat-Corn



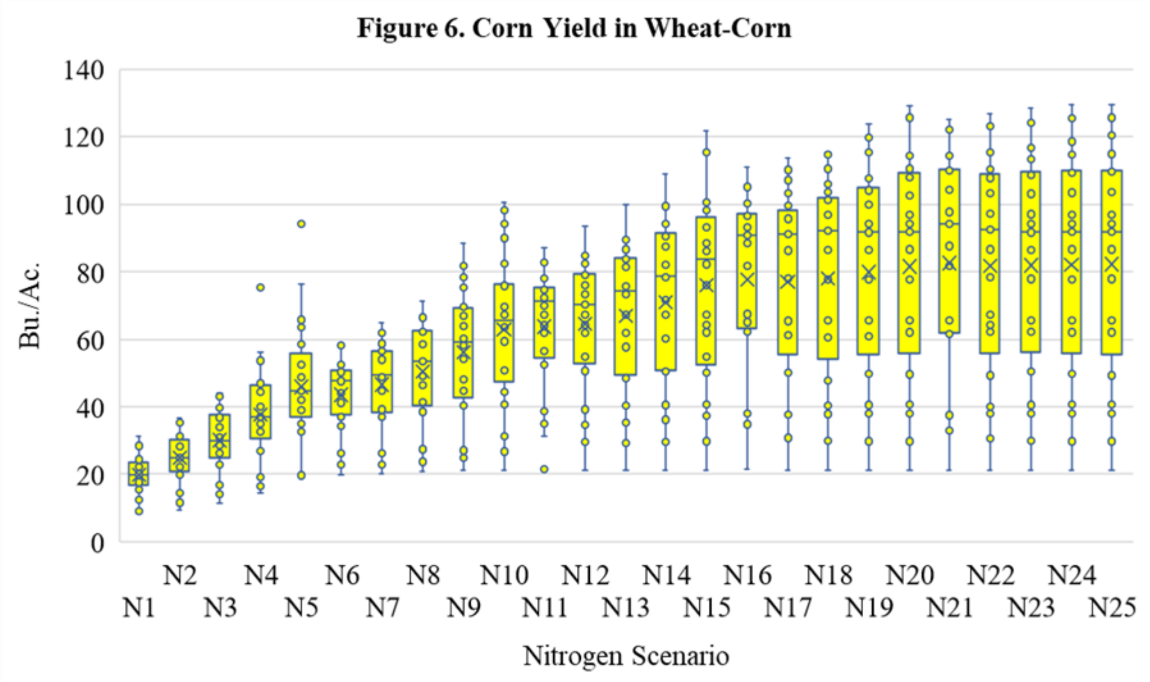


Figure 6. Corn Yield in Wheat-Corn

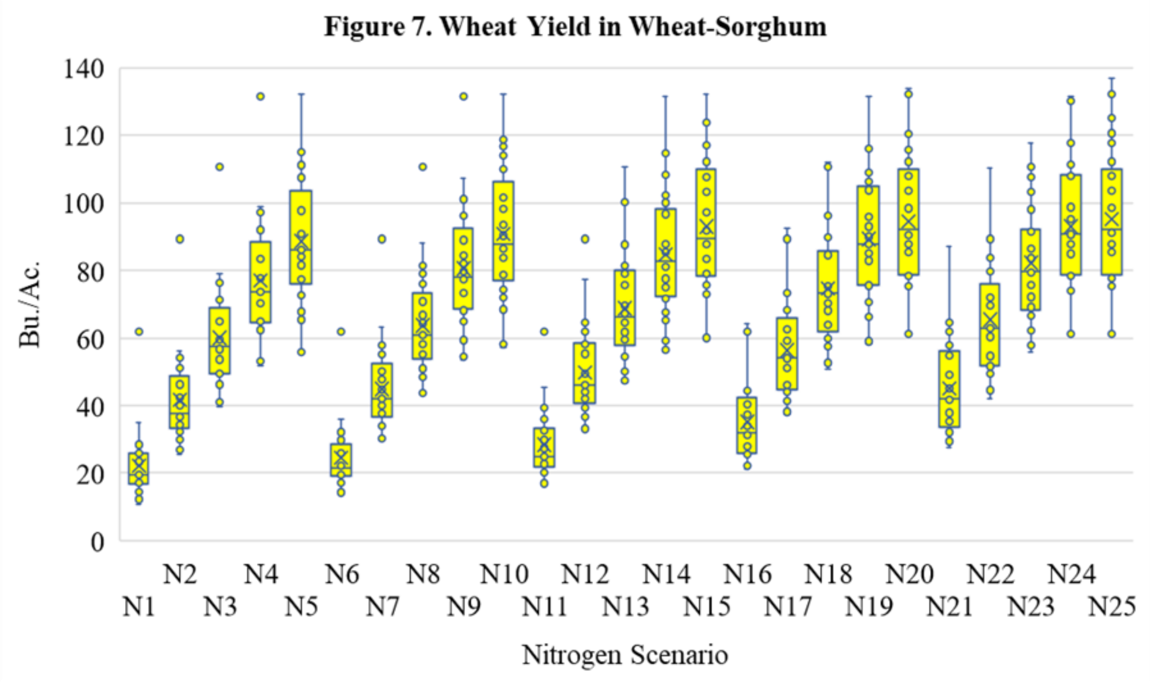


Figure 7. Wheat Yield in Wheat-Sorghum

Figure 8. Sorghum Yield in Wheat-Sorghum

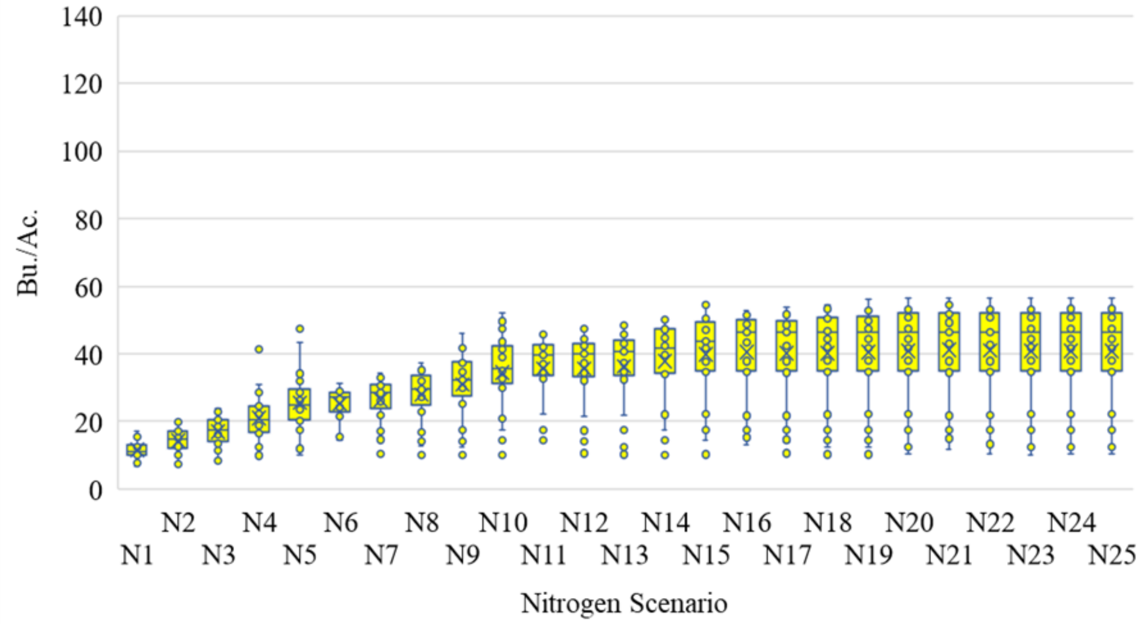


Figure 9. Wheat Yield in Wheat-Soybean

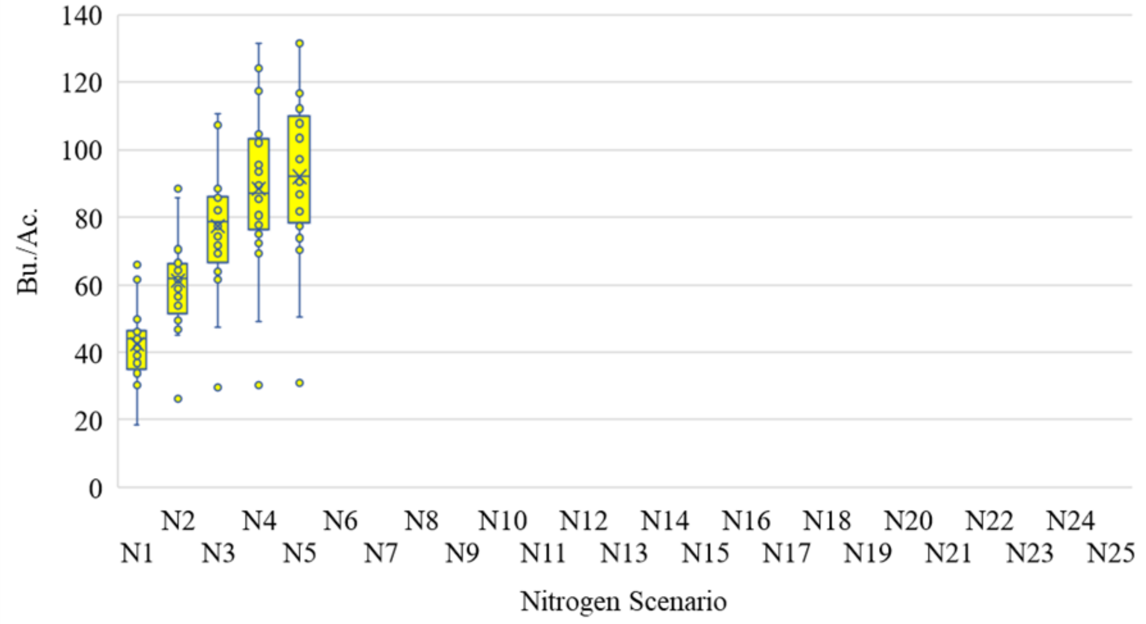
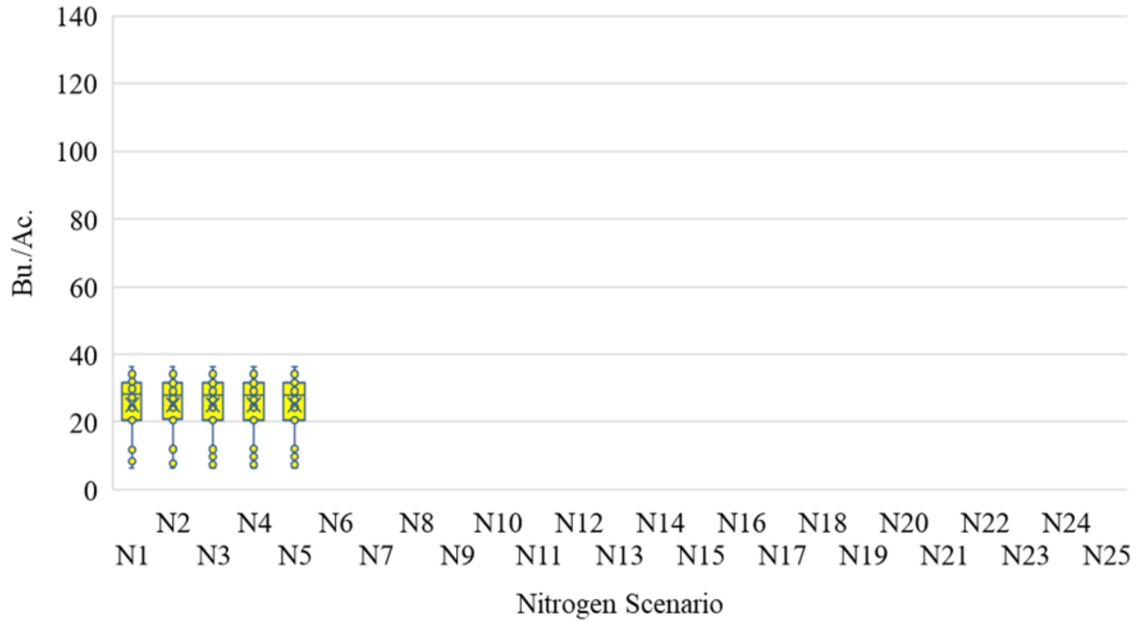


Figure 10. Soybean Yield in Wheat-Soybean



Operational Costs and Historical Fertilizer and Commodity Prices

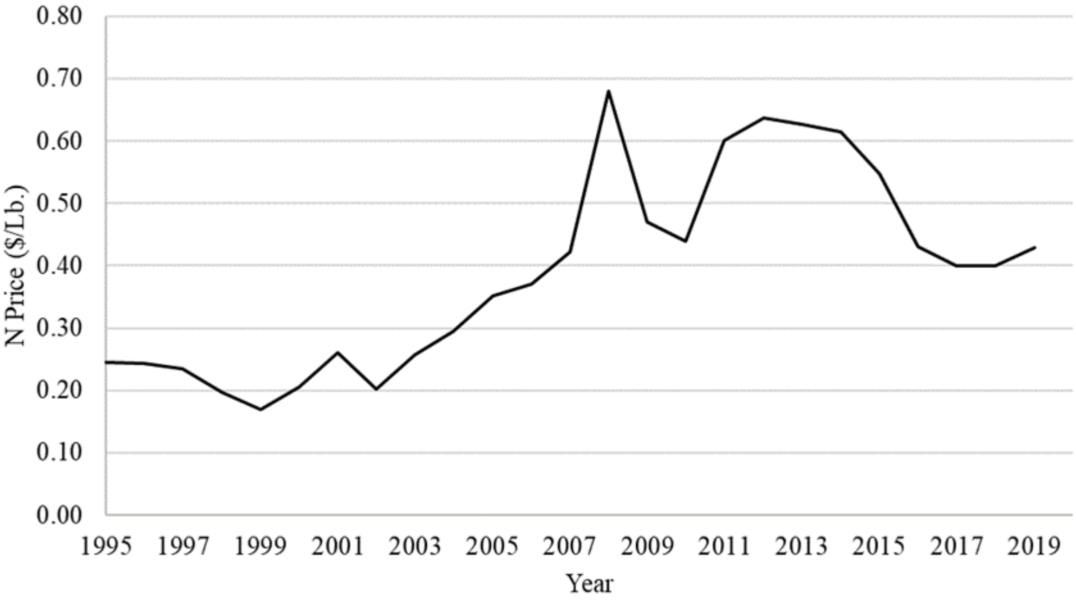
Operational costs per acre for each of the four commodities were averaged from Oklahoma State University's enterprise crop budgets from 2015 to 2019. The operational costs per acre for each summer crop were then added to the winter wheat's cost to calculate a system's operational cost per acre. The budgets assumed a 1,000-acre farm owned and operated in El Reno, OK (Canadian county) under conventional tillage practices. 160 acers were allocated to the relative dryland grain crop using medium size machinery. Each average operational cost included the cost of seed, custom harvest, pesticide, annual operating capital, machinery labor, and machinery fuel, lube, and repairs. The summer crop budgets excluded crop insurance as it is unattainable on the second crop in El Reno, OK (Borchers et al. 2014). Operational costs per acre are higher for corn in comparison to other summer crops. Notable cost gaps include seed, custom harvest, and pesticide costs. Custom harvest rates are higher for corn because the grain has a higher total volume per acre. Harvesting and hauling more grain corresponds to higher costs per acre. The operational costs per acre for each commodity can be seen in Table 3.

Table 3. Average Operational Costs per Acre

Item	Wheat	Corn	Sorghum	Soybean
Seed	11.72	48.50	9.33	42.20
Custom Harvest	33.38	46.39	39.49	35.18
Pesticide	21.02	40.02	17.79	20.14
Crop Insurance	9.94	-	-	-
Annual Operating Capital	6.25	6.67	3.34	2.93
Machinery Labor	16.80	18.75	17.25	12.90
Machinery Fuel, Lube, Repairs	45.85	43.31	39.03	27.07
Total Operating Costs	144.96	203.64	126.23	140.42

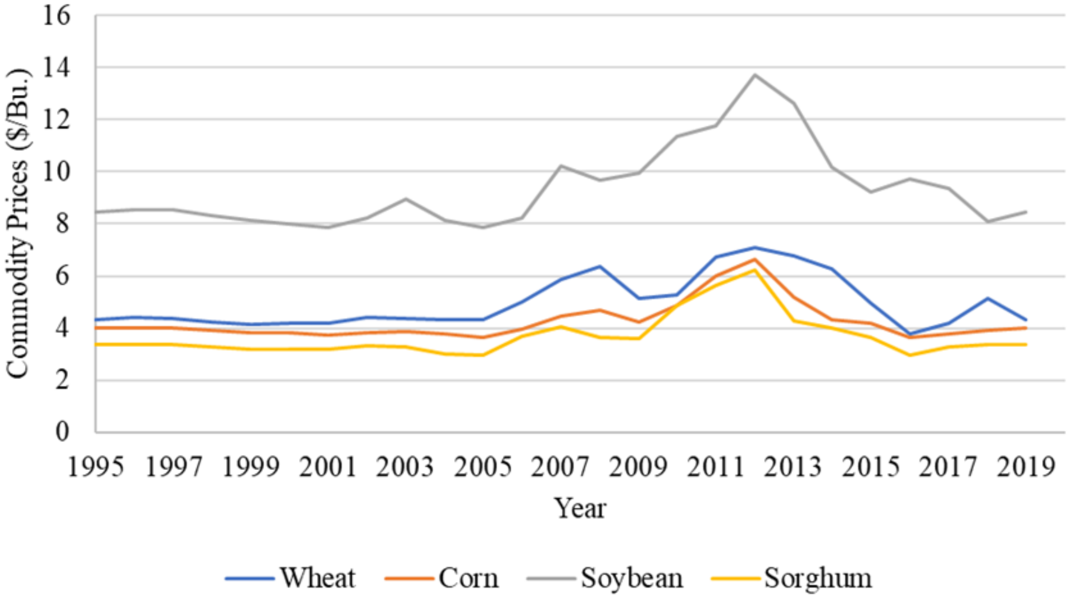
2011 national index for nitrogen prices paid were collected over the same period from the USDA NASS since statewide nominal price data beyond 2014 were not available. The nitrogen prices were benchmarked to a 2019 index and then converted to real prices by using a 2019 UAN-28 price as a proxy for all other years. The 2019 average price per pound of nitrogen basis for UAN-28 was $0.43/lb. according to DTN (Quinn 2019). Nitrogen fertilizer prices from 1995 to 2019 can be seen in Figure 11.

Figure 11. Nitrogen Fertilizer Prices, 1995-2019



Annual commodity market prices were collected for wheat, corn, grain sorghum, and soybeans from 1995 to 2019 from the USDA NASS for revenue and profit efficiency evaluation (USDA NASS 2020). The nominal prices were converted to 2019 constant U.S. dollars using the Bureau of Economic Analysis' gross domestic product deflator (USDC BEA 2022). The real values were then detrended to remove volatility (Arias-Calluari et al. 2022). All commodity prices can be seen in Figure 12.

Figure 12. Commodity Prices, 1995-2019



CHAPTER V

RESULTS

Technical Efficiency Scores

The technical efficiency (TE) of DCS under each nitrogen scenario were calculated for each year (1995-2019) using the DEA approach. Each point in Figure 13 represents the TE result for an individual year when comparing wheat vs. wheat. The TE score of wheat was zero every year when winter nitrogen rates were zero (N1, N6, N11, etc.). This is expected because a zero input/output combination, as a result of a no input case, would result in a TE score of zero. The TE of wheat increased as the winter nitrogen rates increased (i.e., N1-N5). An increase in TE is expected as an additional pound of nitrogen in these scenarios would increase wheat yields substantially. The wheat-soybean system had no noticeable trends in TE score from increasing winter nitrogen rates because it was technically efficient most often compared to the same nitrogen scenarios (N1-N5) of the other systems. The TE of wheat following soybeans was higher as compared to the other crops because wheat yields generated in the EPIC model were higher in this system. Wheat's TE increased as the summer nitrogen rates increased (N1-N25), holding winter nitrogen rates constant, in the wheat-corn and wheat-grain sorghum systems. This indicates that wheat responds to larger amounts of nitrogen following higher summer nitrogen rates. However, wheat was more technically efficient following grain sorghum than corn when looking at high rates of summer nitrogen (i.e., N21-N25).

The TE of all DCS within the same system are reported in Figures 14-16. The TE of each option was at or near one when comparing within the same system. The systems are most likely all TE because there are not two options using equal winter and summer nitrogen rates within the same system and year. A notable discovery occurs with the variability in the TE score. The most variability related to the 27 and 54 pounds per acre winter nitrogen treatments (N2-N3, N7-N8, N12-N13, N17-N18, and N22-N23) in the wheat-corn and wheat-sorghum systems.

Economic Efficiency Scores

The cost efficiency (CE) results comparing wheat vs. wheat are illustrated in Figure 17. Wheat was most cost efficient following all summer crops when winter nitrogen rates were zero (N1, N6, N11, etc.). This is expected as applying no nitrogen would result in the least costly option. The CE decreased for wheat as winter nitrogen rates increased across all systems with no summer nitrogen treatment (N1-N5). However, the CE increased as summer rates increased for wheat-corn and wheat-grain sorghum holding winter rates fixed. This indicates that the wheat yield increases from leftover nitrogen counteracted the cost increases from increasing winter nitrogen rates, similar to the TE of wheat. CE decreased as nitrogen rates increased within the same system as seen in Figures 18-20. However, most options resulted in a CE of one, mirroring the TE scores within the same system.

Revenue efficiency (RE) increased as winter and summer nitrogen rates increased for the wheat-corn and wheat-grain sorghum systems as seen in Figure 21. This is expected because as yields increase, revenue increases. The wheat-soybean system showed no trends as it was revenue efficient most often, likely a result of soybean prices being significantly higher. The high rates of nitrogen (N21-N25) in the wheat-corn system resulted in the most revenue efficient option from 1995 to 2019 as well. 2011 was selected as the National Integrated Drought Information System considers it to be the most intense period of drought for the SGP (US NIDIS 2022). The wheat-grain sorghum system was more revenue efficient in 2011 compared to the other systems as outlined in Figure 22. Wheat-grain sorghum outperformed the other systems in a drought because of its high drought tolerance. Therefore, the poor growing conditions negatively affected corn and soybean yields by larger proportions. Wheat-corn and wheat-soybeans under high nitrogen rates had the highest RE in a normal production year (2016).

Profit efficiency (PE) increased as nitrogen rates increased across all systems as seen in Figure 23. High rates of winter and summer nitrogen for wheat-corn and high winter rates for wheat-soybeans had the highest PE most often. However, there were years in which scenarios under the highest winter nitrogen scenario (N5, N10, etc.) performed as well as the high nitrogen scenarios of wheat-corn and wheat-soybeans. The wheat-grain sorghum had the highest PE during a drought year (2011) as illustrated in Figure 24. This is possible because of the drought resistant characteristics of grain sorghum. Similar to most years, a normal production year (2016) resulted in wheat-corn and wheat soybean under high rates of nitrogen having the highest PE. When comparing high and low commodity prices, no noticeable changes occurred in Figure 25. The slight increase in PE for wheat-grain sorghum benchmarked to the other systems in a given year might be a result of lingering drought conditions in 2012.

Figure 13. Technical Efficiency Wheat vs. Wheat

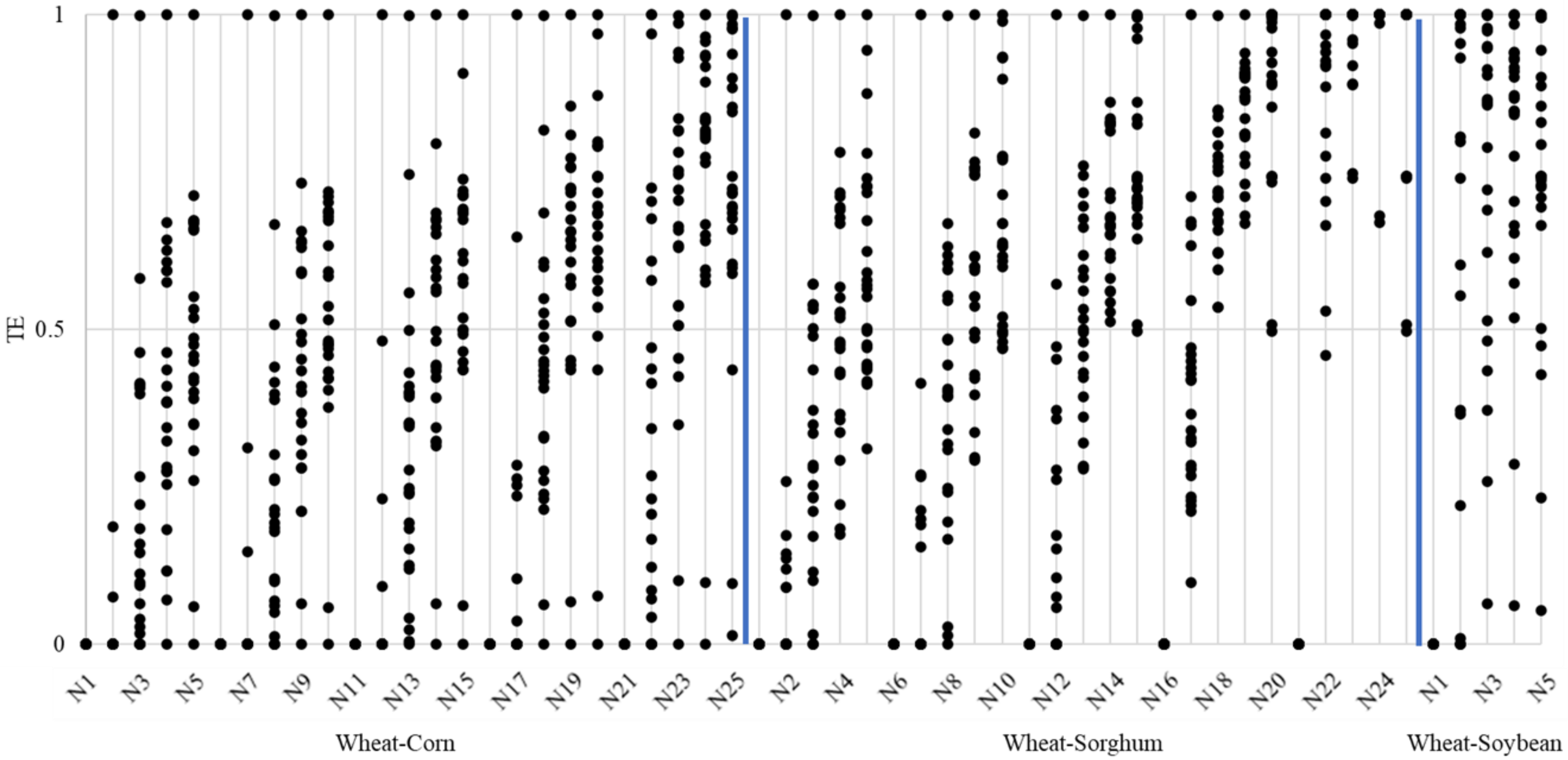


Figure 14. Technical Efficiency Wheat-Corn

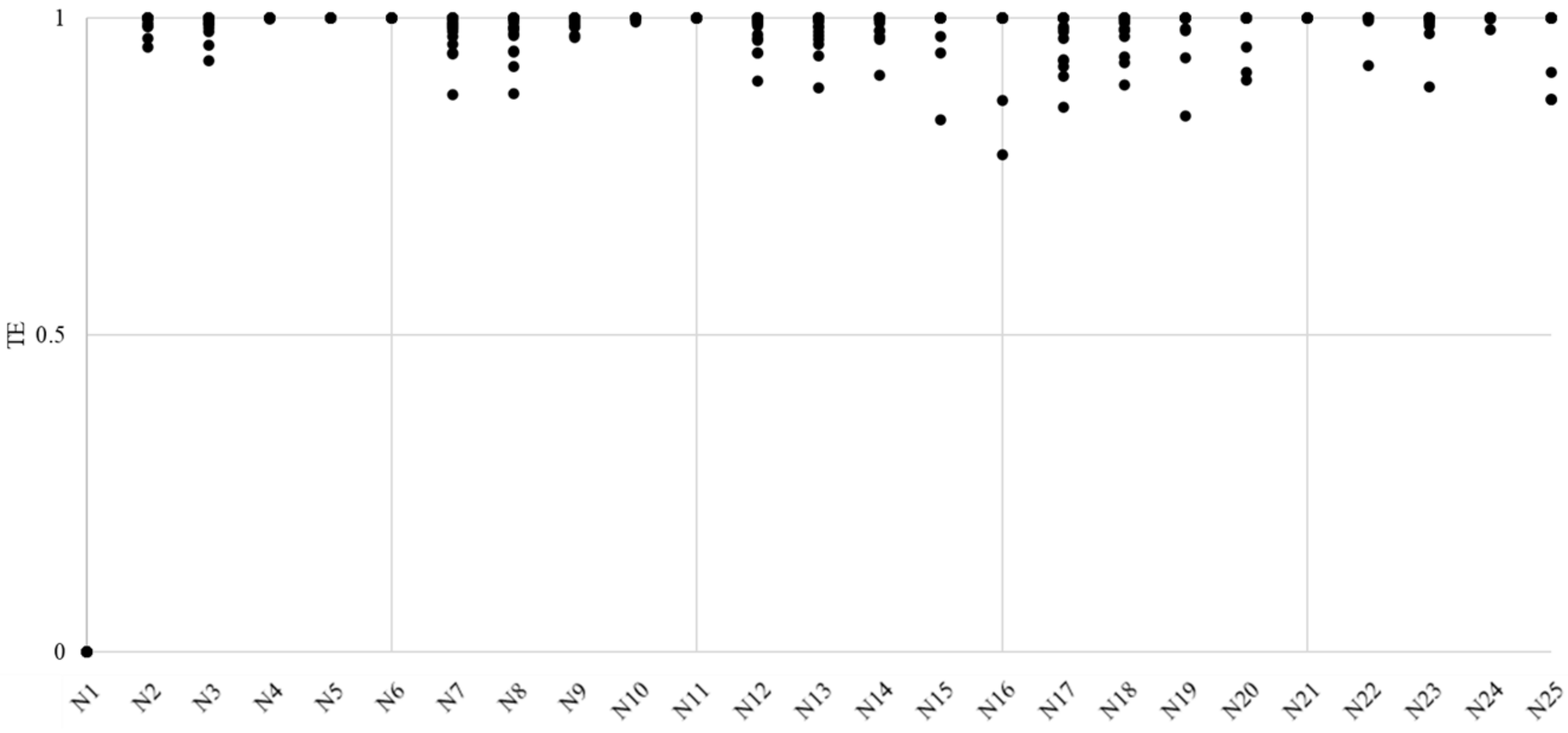


Figure 15. Technical Efficiency Wheat-Sorghum

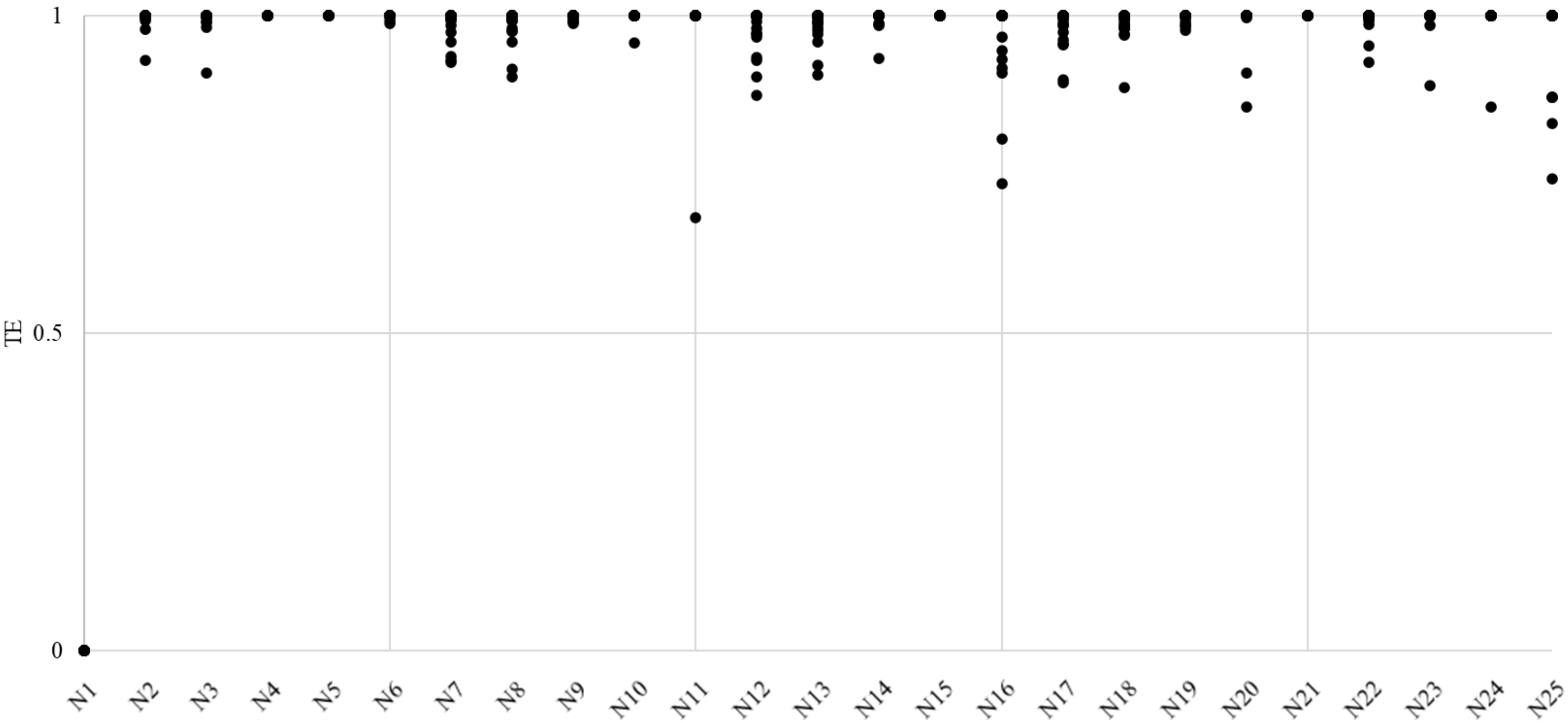


Figure 16. Technical Efficiency Wheat-Soybean

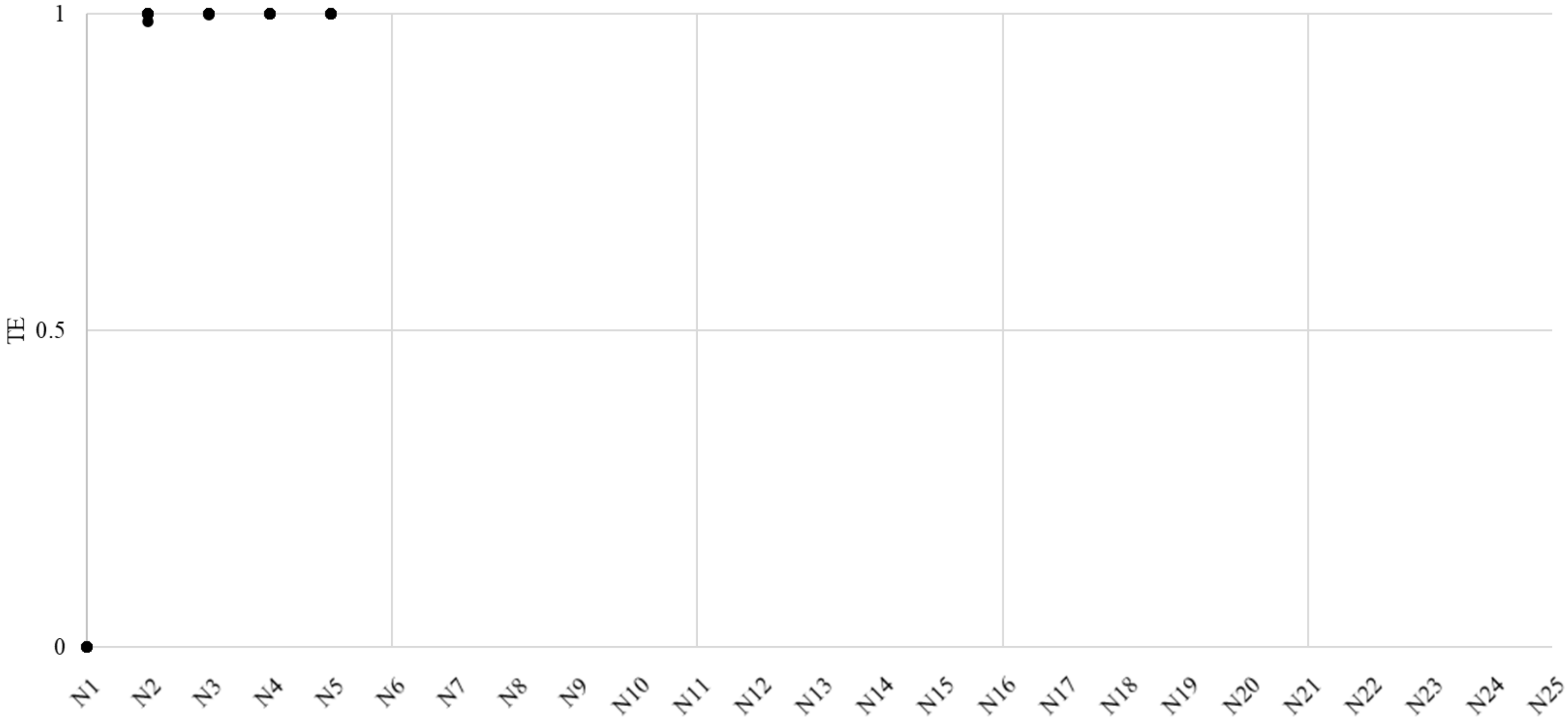


Figure 17. Cost Efficiency Wheat vs. Wheat

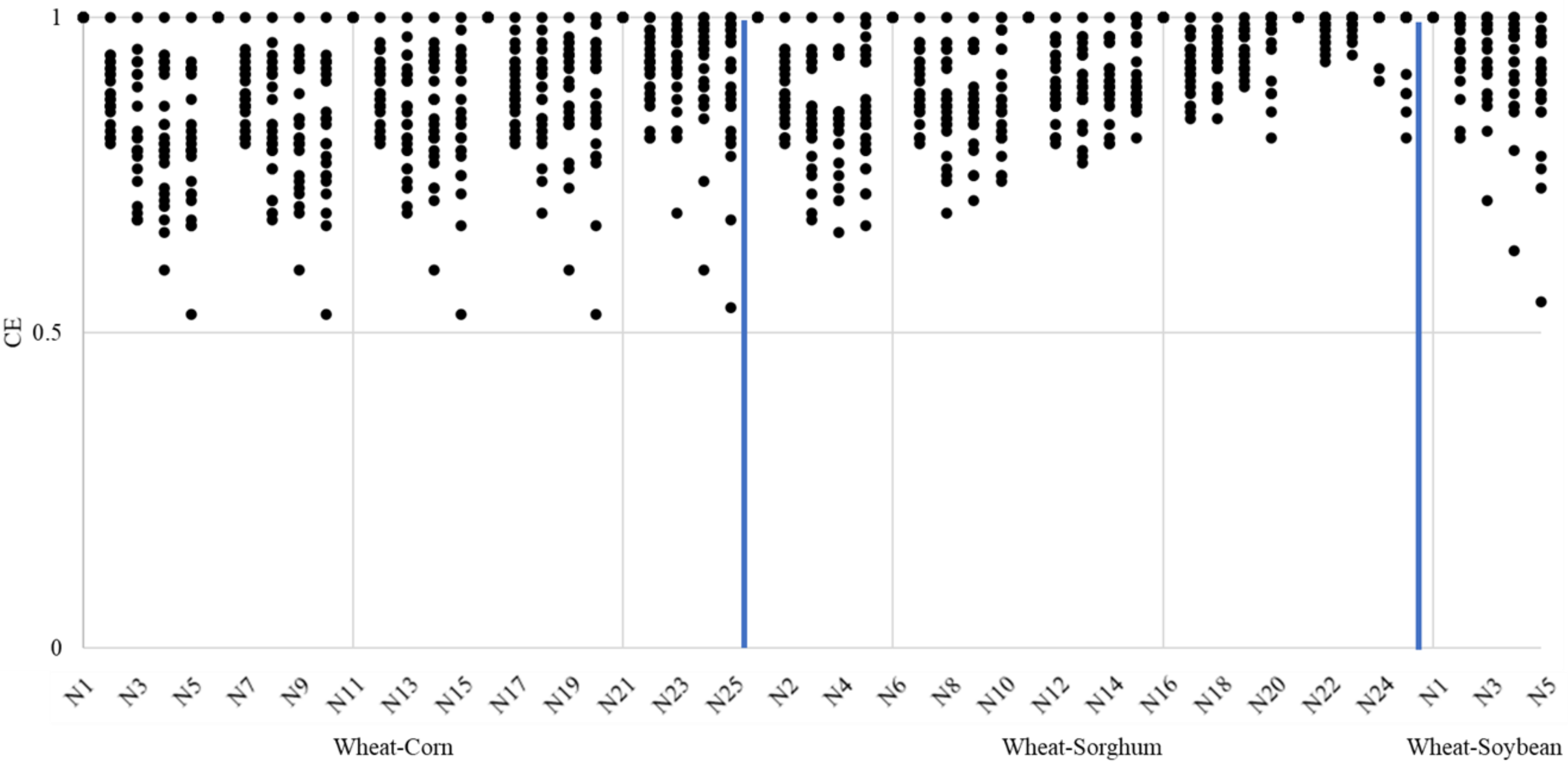


Figure 18. Cost Efficiency Wheat-Corn

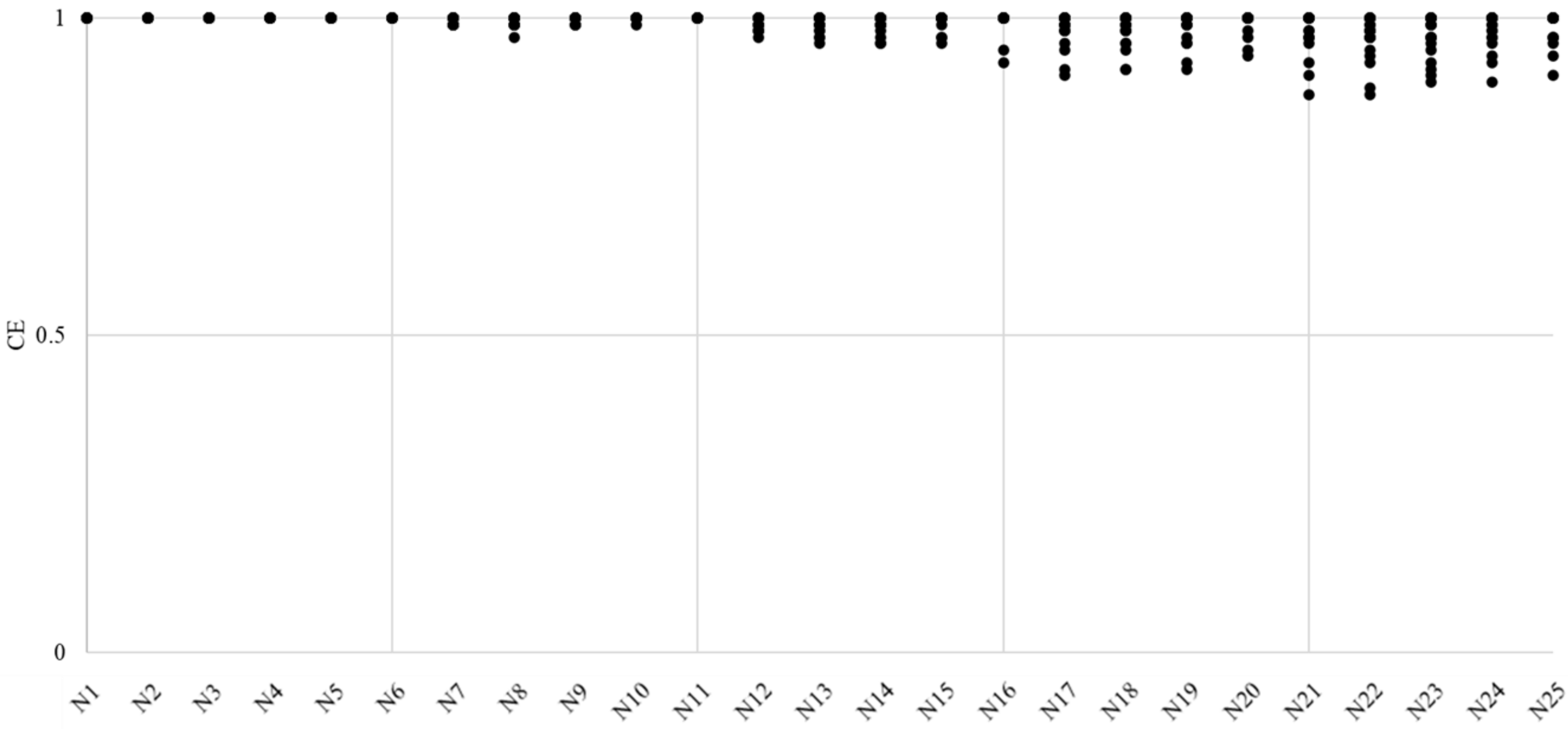


Figure 19. Cost Efficiency Wheat-Grain Sorghum

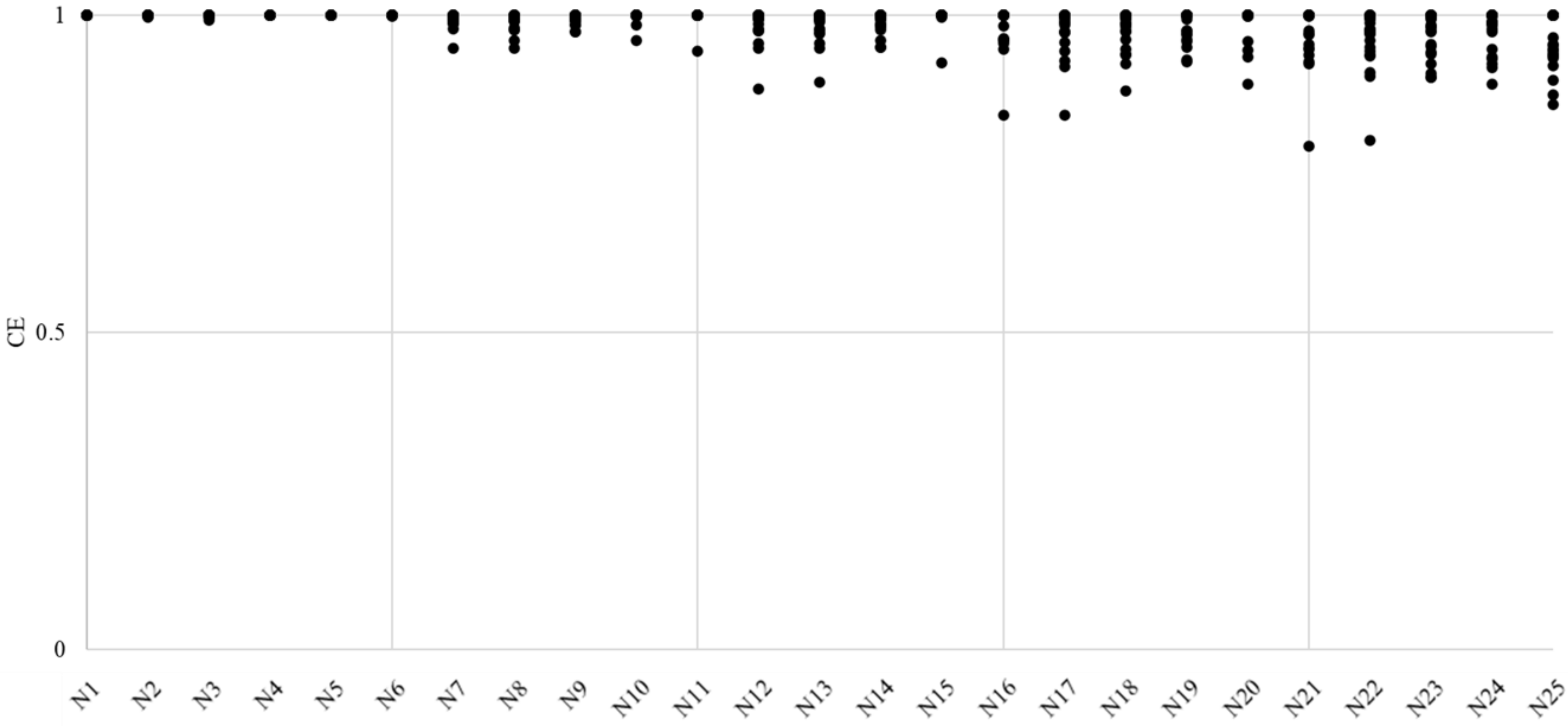


Figure 20. Cost Efficiency Wheat-Soybean

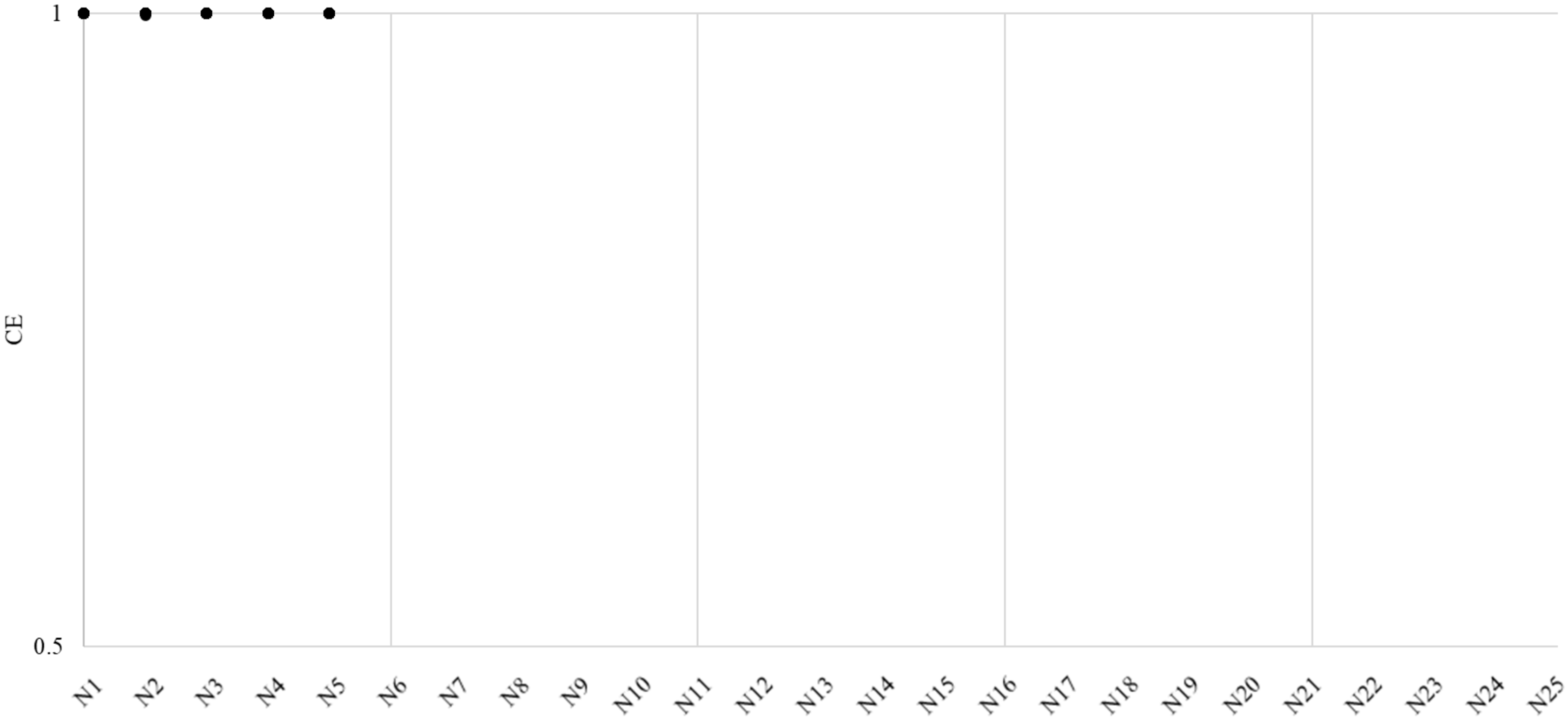


Figure 21. Revenue Efficiency

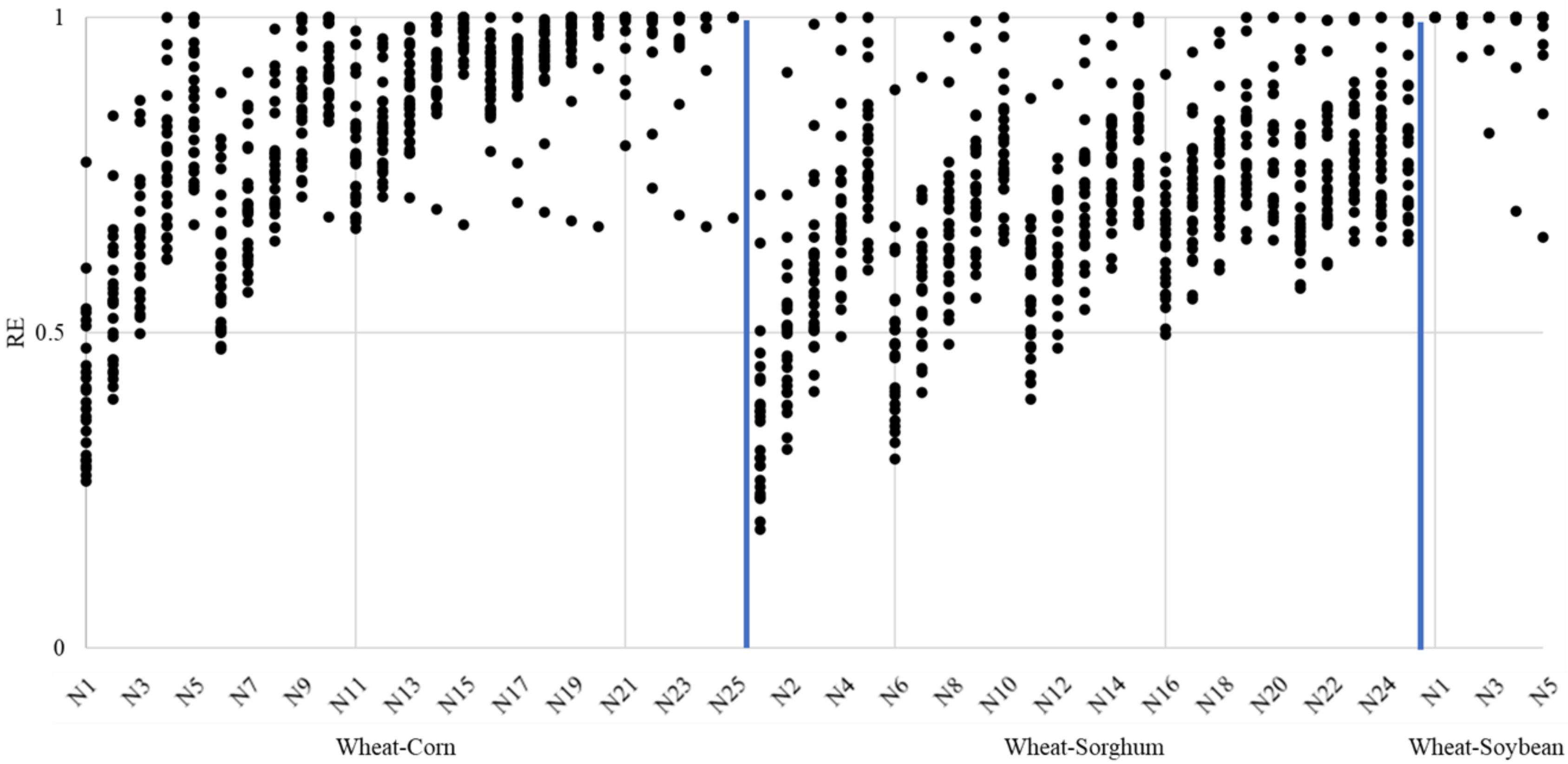


Figure 22. Revenue Efficiency (Weather)

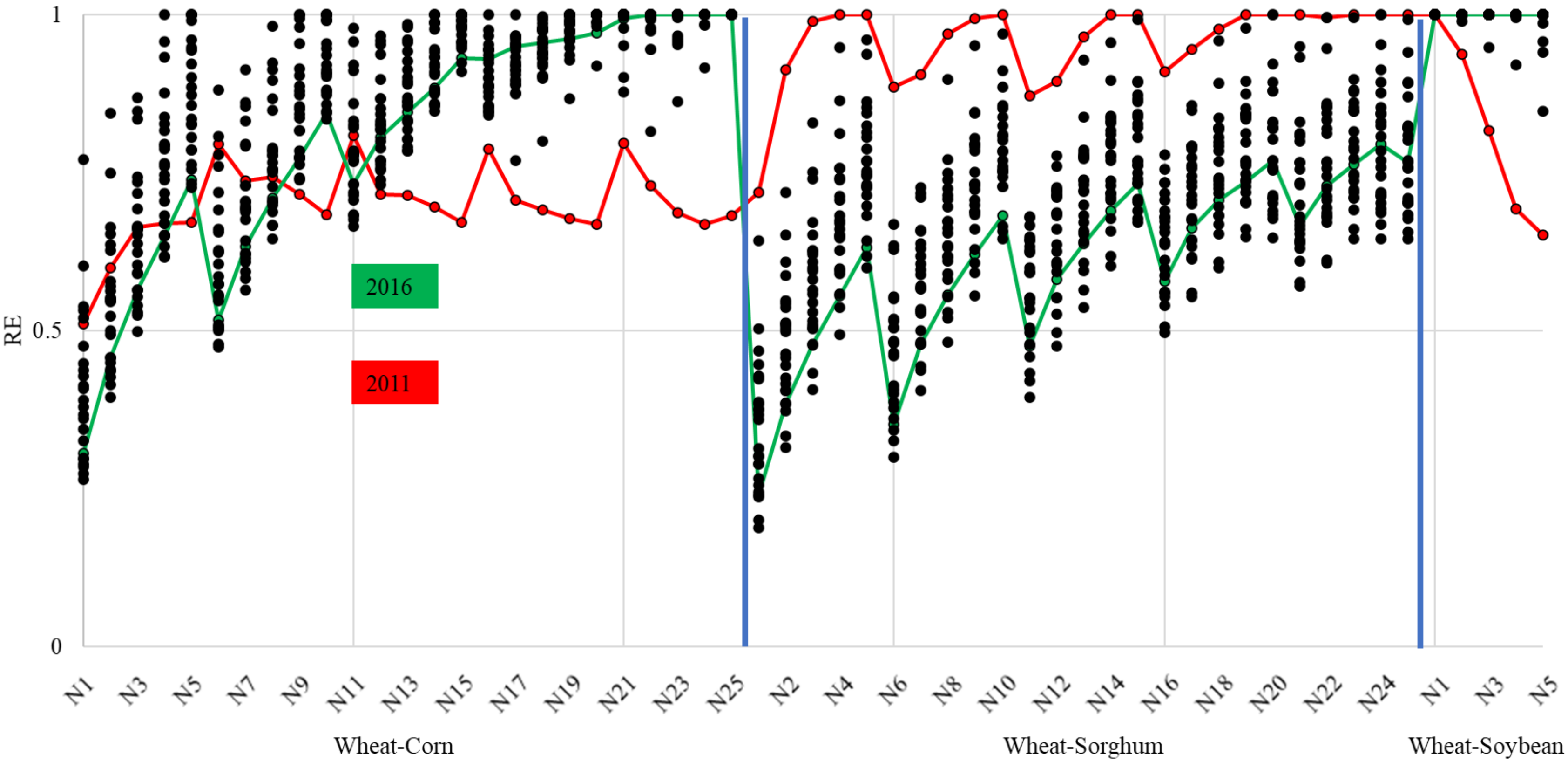


Figure 23. Profit Efficiency

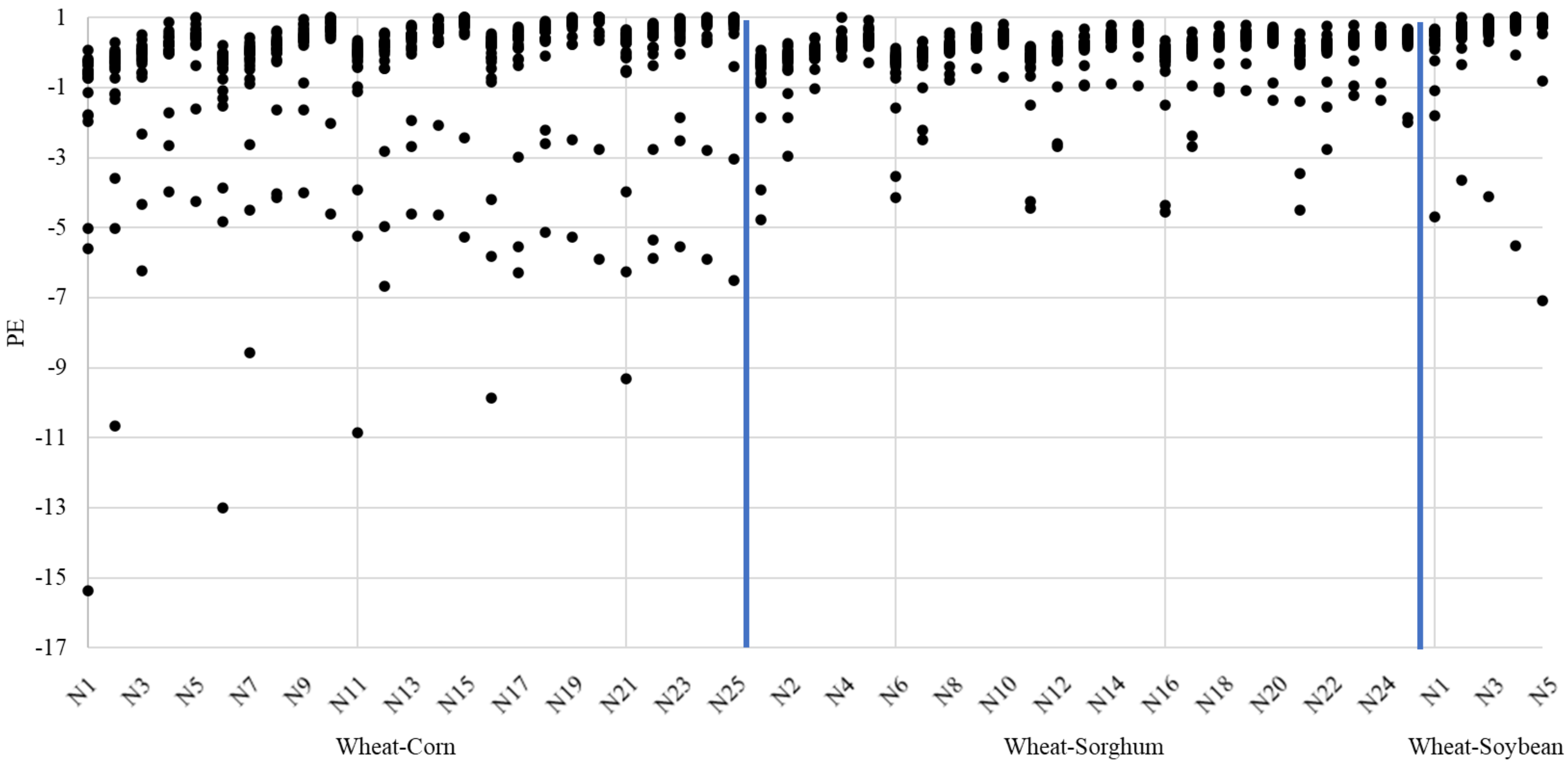


Figure 24. Profit Efficiency (Weather)

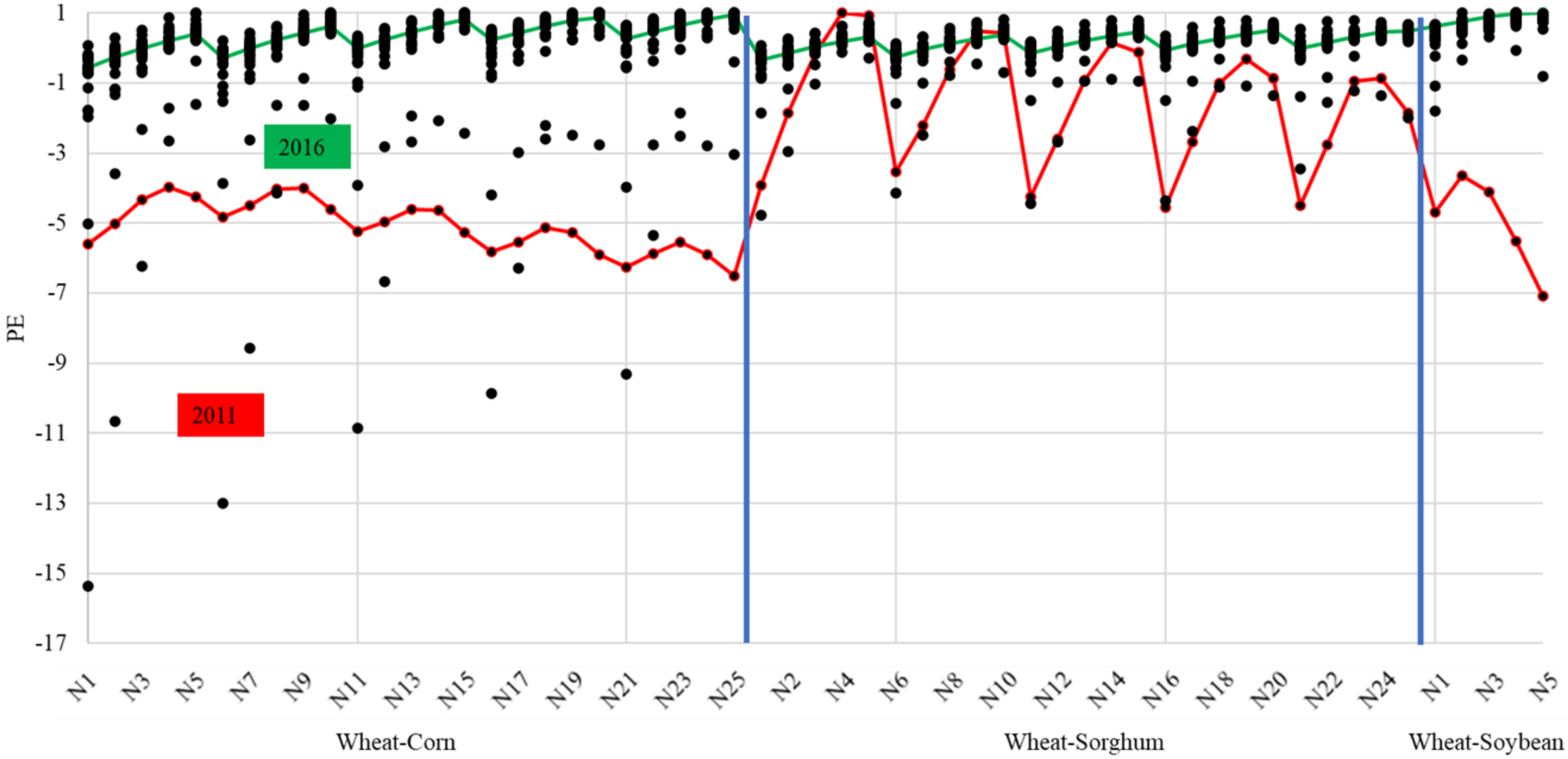


Figure 25. Profit Efficiency (Commodity Prices)

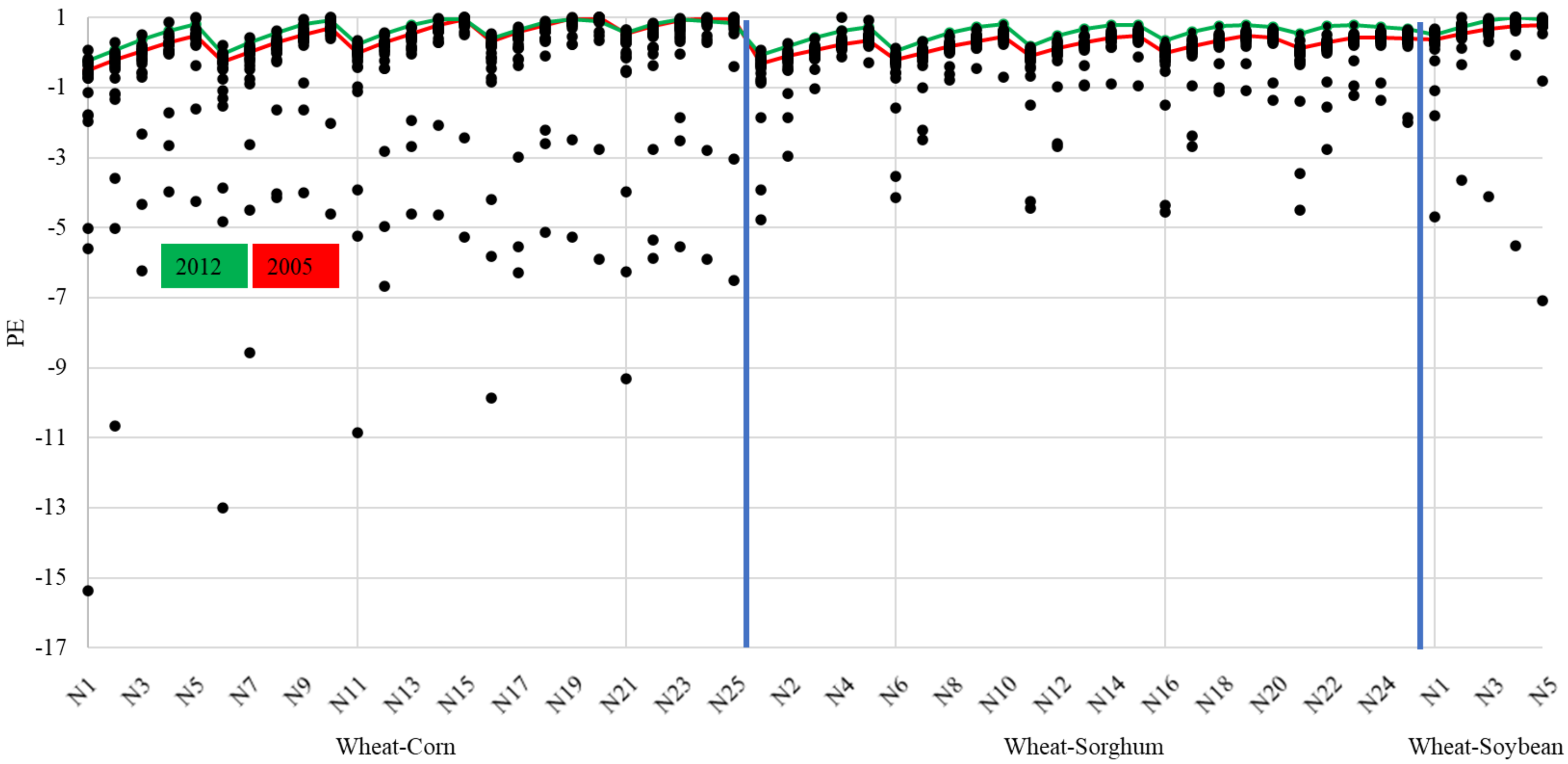
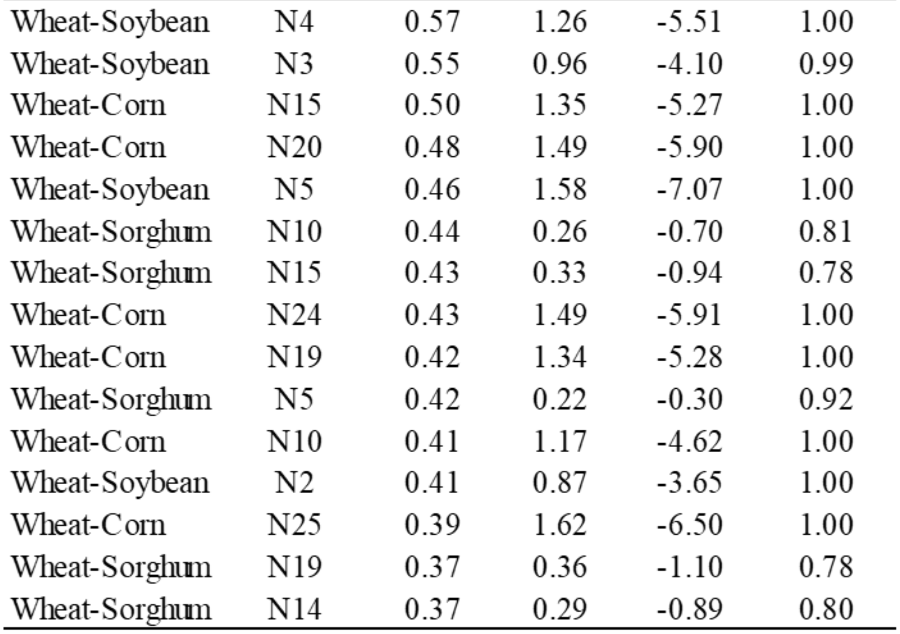


Table 5 lists the top 15 DCS ranked by mean PE from 1995 to 2019. The most profitable DCS include scenarios of high winter nitrogen applications to wheat within the wheat-corn and wheat-soybean systems on average. This indicates that the profitability of DCS is highly dependent upon the performance of wheat rather than the summer double crops. Summer nitrogen rates do not need to be the highest all the time on average. The wheat-corn and wheat-grain sorghum systems had a higher PE for the mid-level summer nitrogen rates instead of the high. Although the wheat-grain sorghum systems typically had lower PE scores, it can be assumed to be a less risky option. Wheat-grain sorghum systems had lower variances, as indicated by standard deviation.

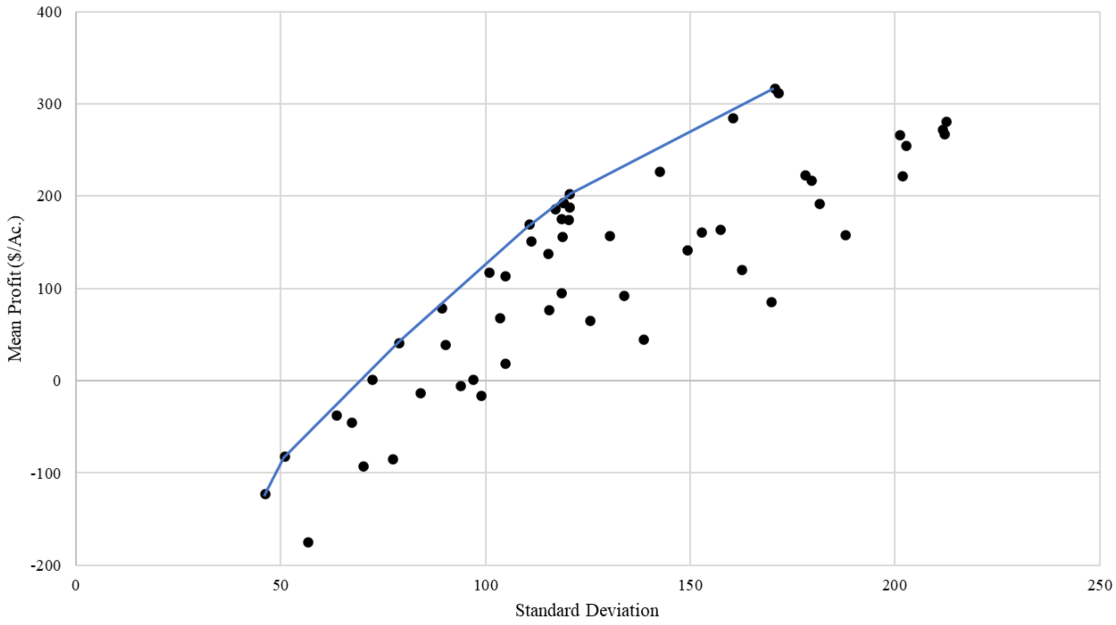
Table 4. Top 15 PE Results



System	N Scenario	Mean	s.d.	Minimum	Maximum
Wheat-Soybean	N4	0.57	1.26	-5.51	1.00
Wheat-Soybean	N3	0.55	0.96	-4.10	0.99
Wheat-Corn	N15	0.50	1.35	-5.27	1.00
Wheat-Corn	N20	0.48	1.49	-5.90	1.00
Wheat-Soybean	N5	0.46	1.58	-7.07	1.00
Wheat-Sorghum	N10	0.44	0.26	-0.70	0.81
Wheat-Sorghum	N15	0.43	0.33	-0.94	0.78
Wheat-Corn	N24	0.43	1.49	-5.91	1.00
Wheat-Corn	N19	0.42	1.34	-5.28	1.00
Wheat-Sorghum	N5	0.42	0.22	-0.30	0.92
Wheat-Corn	N10	0.41	1.17	-4.62	1.00
Wheat-Soybean	N2	0.41	0.87	-3.65	1.00
Wheat-Corn	N25	0.39	1.62	-6.50	1.00
Wheat-Sorghum	N19	0.37	0.36	-1.10	0.78
Wheat-Sorghum	N14	0.37	0.29	-0.89	0.80

Figure 26 displays the mean-variance distribution for each scenario over the 25-year period based on the observed profit calculated in the PE evaluation. The frontier here identifies systems having the highest expected profit and lowest variance in comparison to other options. It is important to note that some options resulted in negative returns on average and as expected profit increased, risk increased.

Figure 26. Mean-Variance Distribution for Observed Profit



Listed in Table 5 are the systems that lie on the frontier with the highest mean profit and lowest variance. Wheat-soybeans using 80 pounds per acre of nitrogen on the winter applications with no summer nitrogen (N4) had the highest expected profit. The system resulted in $316 per acre on average from 1995 to 2019. The DCS rank based on expected profit differed from the PE score ranking. This is likely a result of the way the DEA model calculates PE for each option. The DEA model calculates a different optimal level of profit for each option. Therefore, one option may have a lower PE score than another option but have a higher actual observed profit.

Table 5. Optimal Observed Profit Results

System	N Scenario	Expected Profit	Variance
Wheat-Soybean	N4	$316.91	170.65
Wheat-Sorghum	N15	$202.46	120.48
Wheat-Sorghum	N5	$169.01	110.79
Wheat-Sorghum	N3	$41.06	78.92
Wheat-Sorghum	N6	($82.04)	51.04
Wheat-Sorghum	N1	($122.56)	46.22

CHAPTER VI

CONCLUSION

The Southern Great Plains (SGP) growing conditions complicate decision making for producers and cause a reliance upon monoculture agriculture. In turn the SGP ranks at the bottom in terms of total agricultural factor productivity growth in comparison to other regions. Producers today seek innovative cropping systems to reduce the impacts of monoculture agriculture and increase profitability. Double cropping systems (DCS) are one practice being evaluated. DCS could reduce soil erosion, better capture summer rainfall, and increase profitability and the efficiency of using inputs.

The objective of this research was to identify the most technically and economically efficient DCS producers could implement in the SGP. Yields for wheat-corn, wheat-sorghum, and wheat-soybean systems were estimated in the Environmental Policy Integrated Climate (EPIC) model for El Reno, OK from 1995 to 2019. The technical and economic efficiencies were calculated using EPIC's yields in conjunction with a Data Envelopment Analysis (DEA) model. The results allowed for a benchmarking of each system for each year.

The results determined that wheat's technical efficiency (TE) increased as nitrogen rates increased. The wheat-soybean system under each nitrogen scenario was technically efficient most often because wheat yields were the highest following soybeans. The TE scores were all near full efficiency when comparing within the same system except for the 0 pounds per acre nitrogen treatment. Cost efficiency (CE) of wheat decreased at lower summer nitrogen rates as winter nitrogen rates increased. However, wheat became more cost efficient as winter nitrogen rates increased in the high summer nitrogen rates. When looking at the CE within the same systems, CE decreased as both winter and summer nitrogen rates increased.

Revenue efficiency (RE) increased for all DCS across all years as winter and nitrogen rates increased. The most revenue efficient systems included wheat-corn and wheat-soybean under high nitrogen scenarios. However, wheat-grain sorghum had higher RE scores during a significant drought period. Similar to the RE, profit efficiency (PE) increased as winter and summer nitrogen rates increased. Wheat-corn and wheat-soybean under high nitrogen rates were the most profitable among all years. A drought event pushed wheat-grain sorghum to the highest PE across all nitrogen scenarios.

While this study provides insight as to which double cropping system should be implemented under various nitrogen scenarios, it is limited by the settings selected in EPIC. Future research should analyze the technical and economic efficiencies of different management practices (i.e., no tillage, nitrogen application timing, planting date) and locations. The addition of a wheat-fallow scenario instead of double cropping would also be useful as most producers are primarily wheat producers first. This would provide a “do nothing” scenario for producers if and when double cropping is neither feasible nor profitable.

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