MID-SEASON PREDICTION OF WHEAT GRAIN YIELD POTENTIAL AND NITROGEN RESPONSE

By

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Abstract: Soil nutrient management has made significant advances in efficiency, especially with nitrogen (N) fertilization. Nonetheless, there is still room for improvement surrounding mid-season prediction of grain yield and ensuing fertilizer nitrogen (N) rates. Sequential normalized difference vegetation index (NDVI) measurements from two long-term nutrient management experiments (Experiment 222 and Experiment 502) were used to improve the prediction of yield potential, and to decipher situations where added N would be unlikely to increase winter wheat (Triticum aestivum L.) grain yields in the southern Great Plains. These sequential readings were used by-date, and over dates to evaluate grain-yield-prediction collected from the same plots at harvest. Additional climatological data was also employed by site to improve yield prediction indices, including cumulative growing degree days from planting to sensing greater than zero (GDD>0). The coefficient of determination (r^2) for each NDVI/yield relationship was then plotted as a function of corresponding GDD>0. A linear plateau model was applied to these relationships for Experiment 222 and Experiment 502, resulting in an r^2 of 0.98 and 0.47, respectively. Utilizing the number of days where GDD>0 is more refined than growth stage because it embeds climatological estimates of growth that can be used in another year and/or environment. Knowing this value can serve as a guide as to exactly when the NDVI reading should be collected.

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CHAPTER I

INTRODUCTION

Algorithms based on active sensors for in-season nutrient management in cereals have, in recent years, become affordable, easy to use, and accurate. Solie et al. (2012) advanced a sensor-based approach for winter wheat N recommendations that relies on in-season measurements of normalized difference vegetative index (NDVI) using an active sensor. This comes from work generated by the same group of scientists at Oklahoma State University, which began with passive sensors and a benchmark paper from Stone et al. (1996) that was the first to report accurate grain yield prediction from mid-season NDVI sensor readings, over a range of locations.

Despite the wealth of published work coming from this group (Raun et al., 2001; Raun et al., 2002; Mullen et al., 2003; Raun et al., 2005; Girma et al., 2006; Kanke et al., 2012; Arnall et al., 2013;), a mathematical/climatological method of determining exactly when the mid-season sensor reading should be collected was not attempted. Several of their papers (Raun et al., 2001) suggested that Feekes growth stage 5 (Large, 1954) provided improved prediction of final grain yield, but this inherently morphological method is, in the end, incredibly subjective.

The objective of this work was to evaluate the mid-season collection of sequential NDVI readings for potentially improving the prediction of final wheat grain yields. Present work has shown the benefits of using NDVI collected mid-season, and then computing the number of days from planting to sensing where GDD>0. This work seeks to improve the prediction of wheat grain yields using a more robust/intensive accounting of NDVI data from planting to sensing.

CHAPTER II

REVIEW OF LITERATURE

Influence of Yield Potential on Nitrogen Demand

Accurate prediction of crop yield potential (YP0) has proven to improve in-season nitrogen recommendations and overall nitrogen use efficiency (Arnall et al., 2013). Total N rates vary from season to season and site to site in the majority of trial and producer fields (Dhital and Raun, 2016). Bundy and Andraski (2004) reported site-to-site variability in economic optimum nitrogen rates (EONR) ranging from 0 to 168 kg N/ha over 21 winter wheat locations. The inclusion of a yield potential factor in predicting N recommendations was stressed by Lory and Scharf (2003) who noted that to exclude yield potential is to explain less than 50% of the variation in optimum N rates in maize. In 2001, Raun et al. used early-season NDVI readings to predict yield potential using the difference between two readings collected within a given season and dividing by the growing degree days (GDD). Their work focused more on the collection of NDVI over many sites and years but within the Feekes 4 and 5 growth stages (Large, 1954). This was later advanced to collecting NDVI at any point near to or beyond dormancy, and then dividing by the number of days from planting to sensing where growth was possible. This generally uses a minimum-threshold-average-temperature (4.4°C or 40F) in order to be able to count a ‘day’ as one where ‘growth was possible’. Further, days were counted when GDD>0 [(Tmin+Tmax)/2 -4.4°C] (Raun et al., 2002). This equation has proved to be useful and continues to be used for making fertilizer N rate recommendations both on-line (www.nue.okstate.edu) and documented in published research (Raun et al., 2005). This work has shown that basing mid-season N fertilizer rates on predicted yield potential and a response index resulted in improved NUE’s when compared to conventional methods.

For the application within a fertilizer N rate algorithm, the use of a computed response index (RI, NDVI readings collected mid-season from the high N rate plot divided by the NDVI from a zero N check) was discussed (Mullen et al., 2003). The response index generated from mid-season NDVI readings was later shown to be correlated with an RI computed using the grain yields from the same plots.

Complicit to understanding that mid-season fertilizer N rates could be determined, was knowing that yield level and nitrogen responsiveness were independent (Raun et al., 2010; Arnall et al., 2013). This fundamental understanding was needed in order to decipher appropriate N rates using mid-season data. When Raun et al. (2005) reported on a functional algorithm that could unilaterally increase nitrogen use efficiencies, they still had an imperfect understanding of the independence of yield and N responsiveness.

The INSEY Algorithm

This research acknowledged the importance of yield potential to develop the YP0*RI algorithm for in-season N rate recommendations for winter wheat in the Great Plains (Raun et al., 2002). Specific NDVI readings were divided by a site specific climatological input described as the number of days from planting to sensing where growing degree days were greater than zero (Raun et al., 2002). This algorithm and all of those who have worked to improve it (Raun et al., 2011, Arnall et al., 2013) embody the knowledge that yield potential is independent from response index (RI) and that both estimates are vital for the accurate and efficient prediction of the N fertilizer needs in winter wheat.

The OSU approach to N fertilization has been tested extensively and has shown repeatable results for increasing nitrogen use efficiency and farmer profits. In the Yaqui Valley, Mexico, Ortiz-Monasterio and Raun (2007) reported the use of the YP0*RI approach as yielding the same as the farmer practice but applied 69 kg N ha^{-1} less fertilizer. Tubana et al. (2008) similarly found that the YP0*RI approach yielded accurate N recommendations when compared to flat N rates for rice production in Louisiana.

CHAPTER III

METHODOLOGY

Site and climate information for both Experiments 222 and 502 are outlined in Table 1. Both of these trials employ a randomized complete block experimental design with four replications. Soil nutrient values were collected for both experiments prior to planting. A subsample was taken from 15 cores from each treatment. Subsamples were dried for 2 days at 75˚C, ground to pass through a 240-mesh screen and total N was determined from a LECO Truspec CN dry combustion analyzer (Schepers et al., 1989). Mehlich III was used to determine soil values of phosphorus (P) and potassium (K). These values are reported in Table 2. Figures 1 and 2 depict actual plot plans, including treatment structures, for both long-term trials used in this study.

Over the course of the 2016 winter wheat growing season, eleven and ten NDVI sensor readings were collected for Experiment 502 and Experiment 222, respectively. At both sites readings began at or near the Feekes 2 growth stage and ended at or near Feekes 11 (Table 3). Grain yield was recorded and analysis for total N completed for each plot, at both sites. Growing degree days greater than 0 were retrieved from the Mesonet Wheat Growth Day Counter for each sensing event and location (Mesonet, 2016).The GreenSeeker™ NDVI active sensor (Trimble, Ukiah, CA) was used to collect sensor data at a rate of 70 readings/m^2 when walking at a speed of 5 kilometers per hour, carried 70 cm above the wheat canopy. Since the beginning of the use of the GreenSeeker™ for yield prediction, no more than four NDVI readings per season were recorded for either experiment. For this study, sequential readings were analyzed under the assumption that a larger sample size will deliver more accurate data for modeling growth and resultant grain yields using robust in-season NDVI data. Yield potential (YP_0) estimates were calculated by dividing the NDVI reading by the number of days from planting to sensing where GDDs > 0 (NDVI/days from planting to sensing).

CHAPTER IV

RESULTS

For Experiment 222 and Experiment 502, analysis of variance (4 replications) for the 13 and 14 treatments, respectively, was performed. The significance of replication and treatment effects over all stages of growth are noted for Experiment 222 and Experiment 502 in Table 4 and Table 5, respectively. Also contained within these tables are the calculated mean square error (MSE), standard error of the difference between two equally replicated means (SED), coefficient of variation (CV,%), and mean separation using the least squared difference (LSD) method using an analysis of variance (ANOVA) in SAS version 9.4 (SAS Institute, 2012).

As seen in Table 4 and Table 5, there was a highly significant ($\alpha = 0.01$) N response for all of the NDVI sensing dates at Experiment 222 and for all but one sensing date at Experiment 502. Additionally, significant N responses ($\alpha = 0.01$) were seen for grain yield for both Experiment 222 and Experiment 502.

A significant relationship ($\alpha = 0.05$) between NDVI and final grain yield for each of the sensing date was found. The coefficient of determination (r^2) for each NDVI/yield relationship was then plotted as a function of corresponding GDD>0. A linear-plateau model was then fit to this relationship to determine if a viable joint and/or intersection existed (SAS Institute, 2012). This would be apparent if an increase in GDD>0 no longer resulted in the improvement of the r^2 value (Nelson et al., 1985). Furthermore, it was hoped that a "plateau" could be established. This point or joint (GDD>0) would in theory be the ideal stage for predicting yield or the point where the correlation between NDVI and wheat grain yield was maximized.

This linear-plateau model was first defined and advanced at North Carolina State University (Cate and Nelson, 1971; Anderson and Nelson, 1975).

For Experiment 502, the numeric model was r^2= 0.0458+0.00883(GDD>0), when GDD< 87; a plateau for the r^2 value was found at 0.81 when GDD>= 87 (Figure 4).

For Experiment 222, the numeric model was r^2= 1.30385+0.020455(GDD>0), when GDD<106; a plateau for the r^2 value was found at 0.87 when GDD>=106 (Figure 5).

CHAPTER V

DISCUSSION AND CONCLUSIONS

The linear plateau models for both Experiment 502 and Experiment 222 showed that the correlation between NDVI readings and grain yield increased with advancing GDD>0. The question was: at what point was that relationship maximized, and/or at what point did this reach a plateau? The linear-plateau model employed in this work provided an applied methodology to answer this specific question. For Experiment 502 and Experiment 222, the point at which yield prediction was maximized was 87 and 106 (GDD>0), respectively.

In the past, project work has focused on "growth stage". However, "growth stage" was to a certain extent subjective and that could change depending on the individual collecting the reading. Utilizing the number of days where GDD>0 was considered to be more refined because it embeds climatological estimates of growth that could be tracked or deciphered from one environment to the next. This parameter fits well into what is already a predictive tool, and that could be monitored as any given season progresses. Knowing this value could then serve as a guide as to exactly when the NDVI reading should be collected.

I believe that the linear plateau model for Experiment 222 produced such a significantly higher r^2 (0.98) than Experiment 502 (r^2= 0.47) due to the fact that there were issues with plant stand due to planting error and significant pressure from grassy weeds and gophers. The heterogeneity of plant stand led to uneven canopy cover and crop competition. It would be ideal for the experiment to be repeated for at least another growing season in order to validate my findings. Additionally, confidence intervals for the joint of the linear plateau models could be established as a means of giving producers a window of opportunity for the use of the GreenSeeker™ and nitrogen fertilization.

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TABLES

Table 1. Site and climate description, Stillwater and Lahoma, OK, 2015-2016.

Exp.	Long., Lat.	Location	Year Est.	Soil Type	Tillage	Number of Replications	Annual avg. rainfall (mm)	Range (mm)	Mean annual temperature (˚C)	Planting Date
222	36˚7'7"N 97˚5'30"W	Stillwater, OK	1969	Kirkland Silt Loam	No-Till 2011-present	4	922	606-1493	15.0	10/12/2015
502	36˚23'13"N 98˚6'29"W	Lahoma, OK	1970	Grant Silt Loam	No-Till 2011-present	4	771	503-1314	15.6	10/20/2015

Table 2. Surface soil characteristics for Exeperiment 222, Stillwater, OK and Experiment 502, Lahoma, OK

			Soil Test Level			
			mg/kg		g/kg	
Exp.	Trt	pH	P	K	Organic C	Total N
222	1	5.50	101.56	240.68	8.71	0.87
	2	5.35	82.00	210.37	9.07	0.92
	3	5.22	74.53	201.76	9.39	0.97
	4	4.90	78.35	197.70	10.25	1.00
	5	5.13	30.06	212.09	9.40	0.95
	6	5.03	59.47	203.40	9.67	0.94
	7	5.21	100.10	189.95	9.37	0.93
	8	5.25	83.50	171.03	9.32	0.90
	9	5.30	66.95	216.07	9.65	0.92
	10	5.58	30.84	185.20	8.79	0.83
	11	4.96	99.81	234.28	9.50	0.96
	12	5.22	102.98	161.68	9.62	0.99
	13	5.35	59.42	169.66	9.63	0.95
502	1	6.46	324.36	66.18	10.27	1.00
	2	6.25	444.28	117.51	8.00	0.74
	3	6.07	415.14	124.63	8.13	0.83
	4	5.75	341.18	77.60	8.51	0.82
	5	5.86	376.36	90.85	9.29	0.91
	6	5.52	422.11	87.81	8.71	0.91
	7	5.52	429.29	123.49	8.81	0.89
	8	6.05	401.35	57.54	8.47	0.84
	9	5.84	417.08	82.36	8.57	0.82
	10	5.65	414.63	110.80	8.81	0.86
	11	5.56	405.96	146.11	8.93	0.89
	12	5.63	325.97	125.94	9.24	0.85
	13	5.34	401.32	147.14	9.14	0.89
	14	5.81	413.22	79.94	8.77	0.87

Table 3. Sequential NDVI sensing dates, GDD>0, and estimated Feekes growth stages of Experiment 222 and Experiment 502

Exp.	Sensing Dates	GDD>0	Feekes Growth Stage
222	12/23/2015	64	2
	1/28/2016	73	3
	2/4/2016	78	4
	2/11/2016	84	4
	2/18/2016	90	4
	2/25/2016	96	5
	3/3/2016	103	5
	3/24/2016	123	7
	3/31/2016	130	8
	4/7/2016	137	9
502	12/18/2015	48	2
	2/2/2016	67	3
	2/9/2016	69	3
	2/18/2016	76	4
	2/23/2016	81	4
	3/1/2016	87	5
	3/15/2016	101	6
	3/22/2016	106	7
	3/29/2016	113	8
	4/5/2016	120	9
	4/12/2016	127	11

Table 4. Analysis of variance and significance of replication and treatment effects over all stages of growth, Experiment 222, Stillwater, OK.

Source of variation	df	Grain yield	NDVI-64	NDVI-73	NDVI-78	NDVI-84	NDVI-90	NDVI-96	NDVI-103	NDVI-123	NDVI-130	NDVI-137
Replication	3	*	**	**	**	NS	NS	*	**	**	**	NS
Treatment	12	**	**	**	**	**	**	**	**	**	**	**
Error	36											
MSE		125126.5	0.000622	0.001120	0.000624	0.000763	0.000636	0.000615	0.000653	0.000778	0.000905	0.001205
SED		289	0.02036	0.02733	0.02040	0.02256	0.02059	0.02025	0.02086	0.02278	0.02457	0.02834
CV, %		10	5	6	4	5	5	4	5	6	6	8
LSD		578	0.041	0.055	0.041	0.045	0.041	0.040	0.042	0.046	0.049	0.057

@, *, **, - significant at the 0.10, 0.05, and 0.01 probability levels, respectively.

SED - standard error of the difference between two equally replicated means

CV - coefficient of variation, %

LSD - least squared difference

NS- no significance

SED = sqrt(2 * MSE / reps)
t,dfe,0.05 * SED = LSD

Table 5. Analysis of variance and significance of replication and treatment effects over all stages of growth, Experiment 502, Lahoma, OK.

Source of variation	df	Grain yield	NDVI-48	NDVI-67	NDVI-69	NDVI-76	NDVI-81	NDVI-87	NDVI-101	NDVI-106	NDVI-113	NDVI-120	NDVI-127
Replication	3	*	*	**	**	**	**	**	**	**	*	NS	NS
Treatment	13	**	**	@	**	**	**	**	**	**	**	**	**
Error	39												
MSE		267008	0.000527	0.000493	0.000482	0.000724	0.000948	0.001412	0.002140	0.002012	0.001760	0.007669	0.006557
SED		365	0.0162	0.0157	0.0155	0.0190	0.0218	0.0266	0.0327	0.0317	0.0297	0.0619	0.0573
CV, %		12	8	7	6	7	7	8	7	7	7	15	15
LSD		731	0.0325	0.0314	0.0310	0.0380	0.0435	0.0532	0.0654	0.0634	0.0593	0.1238	0.1145

@, *, **, - significant at the 0.10, 0.05, and 0.01 probability levels, respectively.

SED - standard error of the difference between two equally replicated means

CV - coefficient of variation, %
NS- no
significance

SED = sqrt(2 * MSE / reps)

t,dfe,0.05 * SED = LSD

FIGURES

Figure 1. Treatment structure and plot plan, Experiment 222, Stillwater, OK

WHEAT FERTILITY EXPERIMENT NO.222

Agronomy Research Station
Established 1969

Location: **Stillwater**

Plot size: 20' x 60'
Alley: 17'

Total Trial Area:
137' x 520'

OBJECTIVE: To study fertilizer nitrogen, phosphorus, and potassium in winter wheat. In recent years, this study has also been used to develop yield potential models and yield predictions through sensor based technologies.

TRT	Pre-plant N rate (lb N / ac)	Pre-plant P rate (lb P_2O_5 / ac)	Pre-plant K rate (lb K_2O / ac)
1.*	0	60	40
2.*	40	60	40
3.*	80	60	40
4.*	120 ^	60	40
5.	80	0	40
6.	80	30	40
7.	80	90	40
8.	80	60	0
9.	80	60	80
10.*	0	0	0
11.	120 ^	90	80
12.	120 ^	90	0
13.	80	60	40 (Sul-Po-Mag)

N applied as 46-0-0 (Urea)
P applied as 0-46-0 (Triple Super Phosphate)
K applied as 0-0-60 (Potash)
* - YP plot
^ - Split 120 lb N rates to 60 lb N (fall) and 60 lb N (spring)

1, 2 – Harvest Sequence Number
1, 2 – Treatment Number
1, 2 – Soil Sample Sequence Number

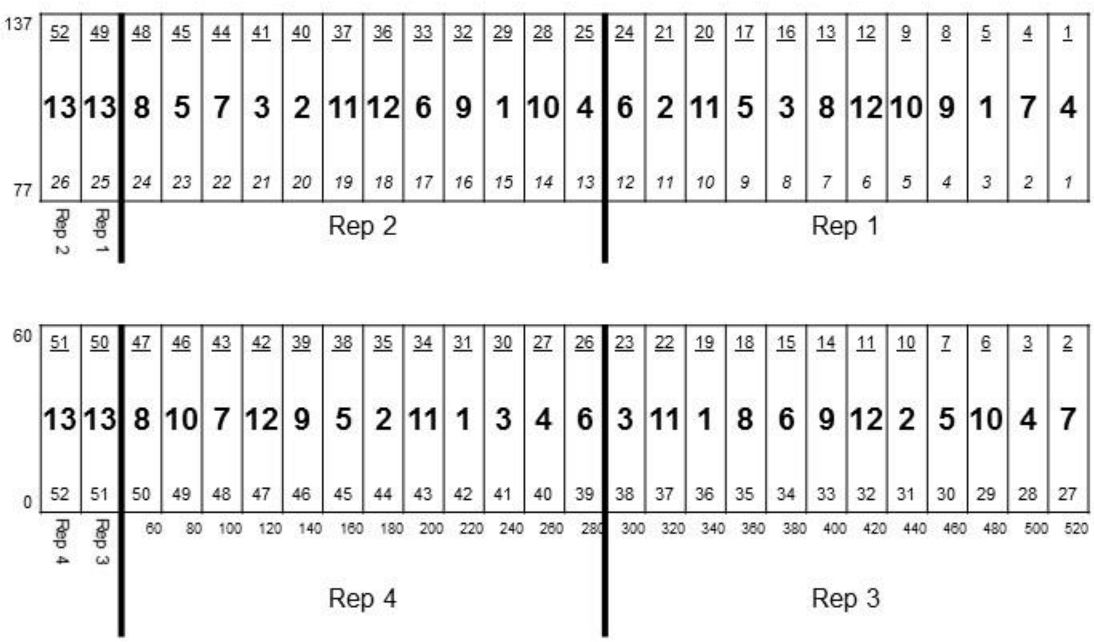


Figure 2. Treatment structure and plot plan, Experiment 502, Lahoma, OK

WHEAT FERTILITY EXPERIMENT NO.502

North Central Experiment Station
Established 1970

Location: **Lahoma**

Plot size: 16' x 60'
Alley: 20'

Total Trial Area:
224' x 300'

OBJECTIVE: To study fertilizer nitrogen, phosphorus, and potassium in winter wheat. In recent years, this study has also been used to develop yield potential models and yield predictions through sensor based technologies.

TRT	Pre-plant N rate (lb N / ac)	Pre-plant P rate (lb P_2O_5 / ac)	Pre-plant K rate (lb K_2O / ac)
1.*	0	0	0
2.*	0	40	60
3.*	20	40	60
4.*	40	40	60
5.*	60	40	60
6.*	80	40	60
7.*	100	40	60
8.	60	0	60
9.	60	20	60
10.	60	60	60
11.	60	80	60
12.	60	60	0
13.	100	80	60
14.	60	40	60 (Sul-Po-Mag)

N applied as 46-0-0 (Urea)
P applied as 0-46-0 (Triple Super Phosphate)
K applied as 0-0-60 (Potash)
* - YP plot

1, 2 – Harvest Sequence Number
1, 2 – Treatment Number
1, 2 – Soil Sample Sequence Number

	300	4	5	12	13	20	21	28	29	36	37	44	45	52	53
Rep 4		**3**	**5**	**13**	**6**	**10**	**2**	**4**	**7**	**12**	**1**	**8**	**14**	**9**	**11**
	240	*43*	*44*	*45*	*46*	*47*	*48*	*49*	*50*	*51*	*52*	*53*	*54*	*55*	*56*
	220	3	6	11	14	19	22	27	30	35	38	43	46	51	54
Rep 3		**1**	**14**	**2**	**7**	**11**	**3**	**9**	**12**	**5**	**13**	**4**	**8**	**10**	**6**
	160	*29*	*30*	*31*	*32*	*33*	*34*	*35*	*36*	*37*	*38*	*39*	*40*	*41*	*42*
	140	2	7	10	15	18	23	26	31	34	39	42	47	50	55
Rep 2		**4**	**8**	**3**	**1**	**11**	**13**	**12**	**7**	**14**	**6**	**9**	**10**	**2**	**5**
	80	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*27*	*28*
	60	1	8	9	16	17	24	25	32	33	40	41	48	49	56
Rep 1		**8**	**2**	**4**	**6**	**14**	**9**	**10**	**5**	**7**	**12**	**1**	**3**	**13**	**11**
		1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*

0 16 32 48 64 80 96 112 128 144 160 176 192 208 224

Figure 3. Relationship between the coefficient of determination and GDD>0 for NDVI data collected over time, Experiment 502, Lahoma, OK

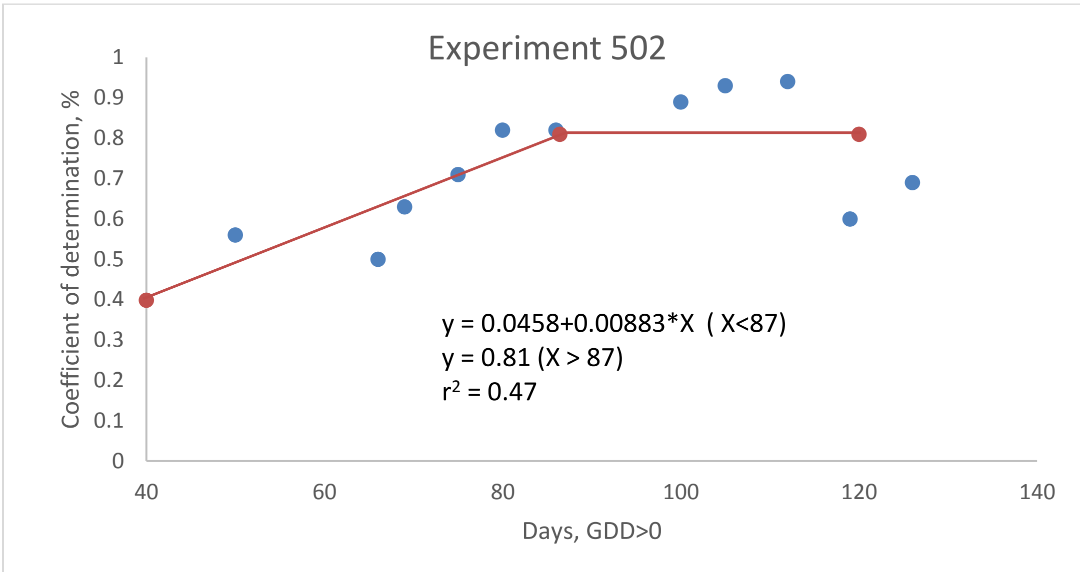
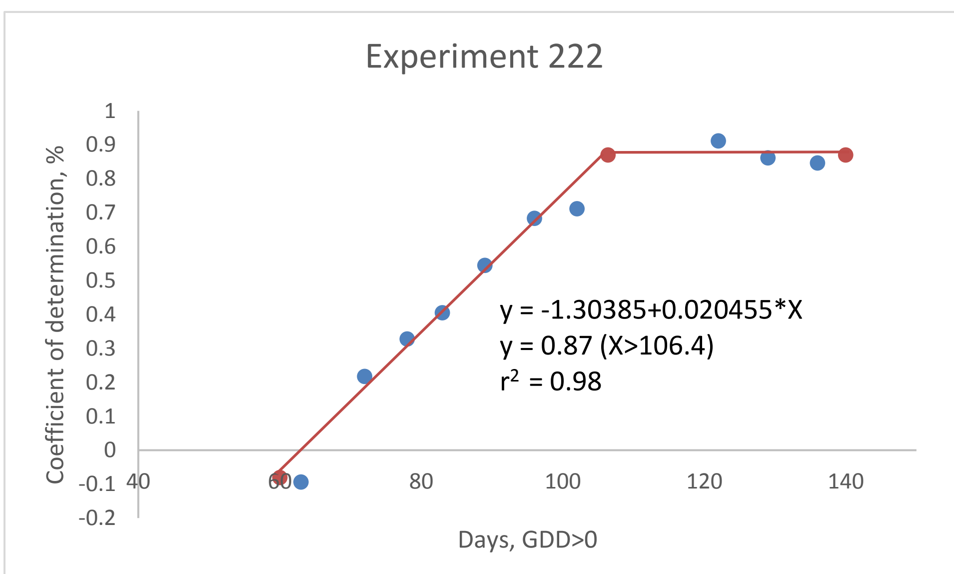


Figure 4. Relationship between the coefficient of determination and GDD>0 for NDVI data collected over time, Experiment 222, Stillwater, OK



VITA

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