

# Development of an in-season estimate of yield potential utilizing optical crop sensors and soil moisture data for winter wheat

Jacob T. Bushong<sup>1</sup> · Jeremiah L. Mullock<sup>1</sup> · Eric C. Miller<sup>1</sup> · William R. Raun<sup>1</sup> · Arthur R. Klatt<sup>1</sup> · D. Brian Arnall<sup>1</sup>

© Springer Science+Business Media New York 2016

**Abstract** When utilizing optical sensors to make in-season agronomic recommendations in winter wheat, one parameter often required is the in-season grain yield potential at the time of sensing. Current estimates use an estimate of biomass, such as normalized difference vegetation index (NDVI), and growing degree days (GDDs) from planting to NDVI data collection. The objective of this study was to incorporate soil moisture data to improve the ability to predict final grain yield in-season. Crop NDVI, GDDs that were adjusted based upon if there was adequate water for crop growth, and the amount of soil profile (0–0.80 m) water were incorporated into a multiple linear regression model to predict final grain yield. Twenty-two site-years of N fertility trials with in-season grain yield predictions for growth stages ranging from Feekes 3 to 10 were utilized to calibrate the model. Three models were developed: one for all soil types, one for loamy soil textured sites, and one for coarse soil textured sites. The models were validated with 11 independent site-years of NDVI and weather data. The results indicated there was no added benefit to having separate models based upon soil types. Typically, the models that included soil moisture, more accurately predicted final grain yield. Across all site years and growth stages, yield prediction estimates that included soil moisture had an  $R^2 = 0.49$ , while the current model without a soil moisture adjustment had an  $R^2 = 0.40$ .

**Keywords** Optical sensors · Soil moisture · Winter wheat · Yield potential

## Abbreviations

DPG	Days of potential growth
ET	Evapotranspiration
FWI	Fractional water index
GDD	Growing degree day

---

✉ Jacob T. Bushong  
jacob.bushong@okstate.edu

<sup>1</sup> Department of Plant and Soil Sciences, Oklahoma State University, 368 Agricultural Hall, Stillwater, OK 74078, USA

INSEY	In-season estimate of yield
NDVI	Normalized difference vegetation index
PAW	Plant available water
PET	Potential evapotranspiration
RMSE	Root mean square error
SI	Stress index

## Introduction

Grain yield goals have been used for decades to make important in-season agronomic decisions. How they are derived and defined has been highly debated. Dahnke et al. (1988) simply defined a yield goal as the “yield per acre you hope to grow.” Much of the debate is over the difference between a crop’s yield potential and maximum yield. Dahnke et al. (1988) stated that yield potential is the highest possible yield obtainable with ideal management, soil, and weather. Evans and Fischer (1999) defined yield potential as “the yield of a cultivar when grown in environments to which it is adapted, with nutrients and water non-limiting and with pests, diseases, weeds, lodging, and other stresses effectively controlled.” According to Raun et al. (2001), yield potential as defined by Dahnke et al. (1988) and Evans and Fischer (1999) would be defined as maximum yield because potential yield is associated with site-specific soil and climate conditions that can change annually. Other approaches for producers to determine yield goals have been to average the grain yield over the last 4–5 years and increase it by ten percent or rely on variety trials or county averages (Fanning 2012; Geisseler and Horwath 2013). Raun et al. (2001) noted that yield potential is known to change from one site-year to another because of the temporal and spatial variability. Refined definitions, adapted from Raun et al. (2001), for measured grain yield, potential grain yield, and maximum grain yield are described below.

**Measured grain yield:** The grain yield that is actually harvested in a given year for a given site.

**Potential grain yield:** The grain yield that is predicted for a given year and a given site, based upon the assumptions that the level of growth factors that are responsible for early crop development will be maintained.

**Maximum grain yield:** The grain yield that is achievable when all manageable growth factors are non-limiting, and the environment is ideal.

Numerous researchers have documented the significance soil moisture has on estimating final wheat grain yield. Black and Bauer (1988) stated winter wheat yield goal should be based upon the amount of plant available water stored in the soil profile in addition to the amount of potential precipitation throughout the growing season. Rehm and Schmitt (1989) reported that if soil moisture conditions at planting were favorable, they recommended adjusting the grain yield goal to 10–20 percent above the recent averages. Rehm and Schmitt (1989) also noted that if soil moisture is limiting, utilizing averages from previous crop years might not be best for estimating grain yield. Robinson et al. (1999) reviewed 30 plus years of climate and winter wheat grain yield data and concluded that nitrogen (N) fertilizer applications would be most profitable if soil moisture measurements indicated above average soil moisture at planting. Girma et al. (2007) evaluated soil moisture content from the previous growing season and its effect on final grain yield of the subsequent year. They observed that soil moisture content at 0.75 m was a good predictor of grain yield at

one research location and soil moisture content at 0.60 m provided good prediction of grain yield at another site.

Historically, grain yield goals or a field's yield potential have been utilized to make pre-plant N fertilizer recommendations. Recent advancements in sensor-based technologies along with crop and weather modeling have allowed for in-season N fertilizer adjustments based upon crop grain yield potential (Raun et al. 2001). Research conducted over the last three decades has advanced the capability of sensor-based methodologies to assist in making agronomic management decisions. Stone et al. (1996) and Solie et al. (1996) first observed that normalized difference vegetation index (NDVI) measurements of winter wheat at Feekes Physiological Growth Stages 4 and 5 (Large 1954) were able to reliably predict both N uptake and plant/crop biomass. Raun et al. (2001) reported that the sum of two post-dormancy NDVI measurements divided by the cumulative growing degree days (GDD) from the first to the second reading was an accurate predictor of final grain yield and could assist in adjusting in-season applications of N fertilizer. Using 30 site-years of winter wheat grain yield data, Raun et al. (2005) built upon their earlier work and determined that grain yield could then be predicted at any growth stage when the NDVI was divided by the cumulative number of days with a growing threshold temperature value of 4.4 °C. They reported that the non-linear relationship of in-season estimate of yield (INSEY) and grain yield was highly correlated and essentially provided an estimate of biomass produced per day.

Researchers have attempted to incorporate some form of soil moisture measurement into sensor based technologies to predict wheat grain yield. Girma et al. (2006) evaluated mid-season measurements in winter wheat of sensor derived NDVI and soil moisture, as well as leaf color, chlorophyll content, plant height, canopy temperature, tiller density, plant density, soil  $\text{NH}_4\text{-N}$ ,  $\text{NO}_3\text{-N}$ , organic C, total N, pH, and N mineralization potential. They noted that mid-season NDVI, chlorophyll content, plant height, and total N uptake were good predictors of final winter wheat grain yield; however, they observed soil moisture to be associated with grain yield, but not a reliable predictor of final grain yield. Walsh et al. (2013) measured soil water content at sowing and utilized it along with mid-season NDVI values to predict grain yield in winter wheat. They evaluated soil moisture at three different depths (0.05, 0.25, 0.60 m). By combining the NDVI-based approach with 0.05 m soil moisture data at the time of planting and NDVI data collection at Feekes 5 growth stage they could more accurately predict wheat grain yield.

Crop growth, development, and subsequently grain yield of winter wheat are affected by temperature (Porter and Moot 1998). The concept of GDD, or accumulation of heat units, has been proven to more accurately describe and predict crop development and physiological stages of growth much better than the number of days since planting or time of year (McMaster and Wilhelm 1997). For wheat, extensive research has shown relatively small and consistent standard errors of the cardinal temperatures for many crop growth stages and processes (Porter and Gawith 1999). Other researchers have utilized the concept of biological days to document crop growth, in which there is not only optimal temperature for growth, but other factors such as photoperiod or lack of water stress and nutrient stress that are included (Hunt and Pararajasingham 1995; Soltani and Sinclair 2012).

Knowledge of water use or evapotranspiration (ET) by a winter wheat cropping system could assist in predicting final grain yield, in that a producer would know if the soil moisture content they have at a given time will be enough to carry the crop to maturity. Nix and Fitzpatrick (1969) evaluated how the ratio of plant available soil water to the potential evaporative demand of a growing wheat crop, referred to as a stress index (SI), affected final grain yield. They reported highly significant correlations between SI and final grain yield. Similar results of a strong relationship between a derived SI and grain yield were

observed by Stephens et al. (1989), in that they concluded the lack of adequate water to maintain growth strongly impacts final grain yield.

The early February to June water usage by winter wheat grown in the Southern Great Plains of North America would be very important, as this is the time grain yield potentials would be utilized to make agronomic management decisions, such as in-season N fertilizer applications. Howell et al. (1997) measured ET of winter wheat and observed season-long ET values of 877 mm, with daily values of 3–4 mm per day, and values that rarely exceeded 10 mm per day, but did on days with high-sustained wind speeds. Liu et al. (2002) determined in wheat grown in northern China that after the over-wintering period daily ET values were about 1.2 mm per day and rapidly increased to approximately 4–6 mm per day during the jointing and booting stages. In the semi-arid portion of India, Singandhupe and Sethi (2005) reported daily ET values ranged from 2.6 to 9.6 mm per day between February and April.

Any advances in the ability of grain yield prediction models to estimate winter wheat grain yield in-season will benefit producers in making improved agronomic management decisions. Therefore, the objective of this study was to develop a model that incorporates climatic parameters, such as soil moisture, with NDVI measurements to increase the reliability of predicting wheat grain yield in-season. We hypothesize that the ability to predict grain yield in-season will improve when soil moisture measurements are incorporated into current methodologies for predicting grain yield in winter wheat.

## Materials and methods

### Site descriptions

Grain yield and other crop and soil parameters utilized to calibrate a model to determine grain yield potential were collected from three long-term continuous winter wheat soil fertility experiments at Stillwater (222), Lahoma (502), and Perkins (N&P), Oklahoma. These fertility trials were established in 1969, 1970, and 1996 for Stillwater (222), Lahoma (502), and Perkins (N&P), respectively. The soils at each experimental site are classified and represent soils utilized for wheat production in the South-central Great Plains region of Oklahoma, Kansas, and Texas and that encompass approximately 650,000 hectares of the geographic area (Soil Survey Staff 2012a, b). Grain yield and other crop and soil parameters employed to validate the developed model were collected from the three experiments described above as well as three additional sites: Hennessey (Reg), Lake Carl Blackwell (Reg), and Lake Carl Blackwell (Val). The additional sites were regionally based N fertilizer response trials, in which the same pertinent data was collected. A brief summary of the soils utilized for each experimental site is reported in Table 1.

Plots that were analyzed were those that received no N fertilizer treatment throughout the year or received preplant N fertilizer treatments only with no mid-season N fertilizer applications. The N fertilizer treatments and rates for each trial location are listed in Table 2. The site-years and growth stages where grain yield potential parameters were collected to develop a grain yield potential estimate are listed in Table 3. Altogether, 22 site-years of data were collected to develop the calibration model for grain yield potential. Gaps in years for data collection were due to the crop not being taken to grain yield because of natural occurrences (drought, late freeze, hail, etc.). The site-years and growth stages where grain yield potential parameters were collected to validate the developed model are described in Table 4. Altogether, 11 site-years of data were collected to validate the developed model.

**Table 1** Soil information for experimental sites utilized for model development and validation utilized in this experiment

Location (experiment)	Soil mapping unit	Major component taxonomy <sup>a</sup>	Major component hectares <sup>a</sup>
Stillwater, OK (222)	Kirkland silt loam, 1–3 percent slopes	Fine, mixed, superactive, thermic Udertic Paleustolls	274 050
Lahoma, OK (502)	Grant silt loam, 1–3 percent slopes	Fine-silty, mixed, superactive, thermic Udic Argiustolls	246 692
Perkins, OK (N&P)	Konawa fine sandy loam, 1–3 percent slopes	Fine-loamy, mixed, active, thermic Ultic Haplustalfs	130 241
Hennessey, OK (Reg)	Bethany silt loam, 0–1 percent slopes	Fine, mixed, superactive, thermic Pachic Paleustolls	2 122 838
LCB, OK (Reg)	Port silt loam, 0–1 percent slopes, occasionally flooded	Fine-silty, mixed, superactive, thermic Cumulic Haplustolls	2 662 838
LCB, OK (Val)	Konawa and Teller soils, 3–8 percent slopes, eroded	Fine-loamy, mixed, active, thermic Ultic Haplustalfs	130 241

LCB Lake Carl Blackwell

<sup>a</sup> Soil Survey Staff (2012a)

## Current model for predicting yield

The current model utilized for predicting winter wheat grain yield potential was that described by Raun et al. (2005). The INSEY was calculated by dividing the NDVI by the cumulative number of GDD with a growing threshold value of 4.4 °C. A non-linear relationship was established between INSEY and final grain yield, and the equation from this relationship is thus used to predict grain yield.

## Proposed model parameters

### *Normalized difference vegetation index (NDVI)*

Spectral reflectance expressed as NDVI was measured using a Greenseeker™ (Trimble, Sunnyvale, CA, USA) ground-based, active, optical sensor. The NDVI was computed from red and near infrared reflectance values. The equation to calculate NDVI is listed below:

$$\text{NDVI} = (\text{NIR} - \text{Red}) / (\text{NIR} + \text{Red})$$

where: NIR and Red are the reflectance measurements in the near-infrared (780 nm) and red bands (660 nm), respectively. The NDVI values were collected at various times throughout the growing season at a height of 0.75–1.00 m over the center portion of the research plots with the ground-based optical sensor and the Feekes (Large 1954) growth stage was documented as well.

### *Days of potential growth (DPG)*

This parameter was collected following the biological day concept described by Soltani and Sinclair (2012). We proposed that for considerable growth to occur in winter wheat

**Table 2** Nitrogen fertilizer application treatments and plot dimensions for research plots utilized in the model calibration and validation of the study

Trial (replications) N source Plot size	Pre-plant N fertilizer applied (kg N ha <sup>-1</sup> )
Lahoma 502 (4)	0
Urea (46-0-0)	22
4.9 × 18.3 m	45
	67
	90
	112
Stillwater 222 (4)	0
Urea (46-0-0)	45
6.1 × 18.3 m	90
Perkins N&P (3)	0
Urea (46-0-0)	56
3.0 × 9.1 m	112
	168
Hennessey reg. (4)	0
UAN (28-0-0)	28
3.0 × 6.1 m	56
	84
	112
	140
	168
	224
Lake Carl Blackwell reg. (4)	0
UAN (28-0-0)	28
3.0 × 6.1 m	56
	84
	112
	140
	168
	224

UAN urea ammonium nitrate

there should be adequate temperature along with adequate soil water. Soil moisture data were downloaded for each experimental site from the nearest adjacent Oklahoma Mesonet climate-monitoring station (Oklahoma Mesonet 2015) for the pertinent time periods of data collection. Soil moisture measurements were recorded at depths of 0.05, 0.25, and 0.60 m below the soil surface. Soil moisture data were collected using a Campbell Scientific 229-L heat dissipation sensor (Campbell Scientific, Inc., Logan, UT, USA). The sensor measures a change in temperature after a pulse of heat is introduced to the system (Basara and Crawford 2000). The magnitude in change can then be calibrated to an estimate of soil moisture content. The sensor's response can be normalized to a fractional water index (FWI), which is a unitless value that ranges from 0.00 for dry soils to 1.00 for wet/saturated soils (Illston et al. 2008). According to Illston et al. (2008), utilizing the FWI is more ideal when operating on a larger scale and may not be limited by varying soil texture across

**Table 3** Years and Feekes growth stages that yield potential measurements were collected for three long-term trials utilized in developing a model for winter wheat yield potential

Location (experiment)	Years	Feekes growth stages
Stillwater, OK (222)	2003	5
	2004	3, 4, 5, 6, 7, 8, 9
	2005	3 <sup>a</sup> , 4, 5, 6, 8
	2006	3, 4 <sup>a</sup> , 5, 6, 7, 8, 9
	2008	4, 5 <sup>a</sup>
	2011	4, 6
Lahoma, OK (502)	2003	5
	2004	3, 5 <sup>a</sup> , 6, 8, 9, 10
	2005	4, 5, 6, 7, 9
	2006	3, 4, 5 <sup>a</sup> , 6, 7, 8, 10
	2007	5 <sup>a</sup>
	2008	5 <sup>a</sup> , 6
	2009	5 <sup>a</sup>
	2010	5
	2011	5
	Perkins, OK (N&P)	2003
2004		3 <sup>a</sup> , 4 <sup>a</sup> , 5, 6, 7, 8, 9
2005		3, 4, 5, 6, 7, 9
2006		3 <sup>a</sup> , 4, 5 <sup>a</sup> , 6, 7, 9
2009		3 <sup>b</sup> , 4 <sup>a</sup> , 5, 6, 7, 8, 9, 10
2010		5
	2011	5

<sup>a</sup> Yield potential measurements collected two times for this Feekes growth stage

<sup>b</sup> Yield potential measurements collected three times for this Feekes growth stage

**Table 4** Years and Feekes growth stages that yield potential measurements were collected for three long-term trials and three regional N fertilizer response trials utilized in validating a model for winter wheat yield potential

Location (experiment)	Years	Feekes growth stages
Stillwater, OK (222)	2012	4, 5, 6, 8, 10
	2013	7
Lahoma, OK (502)	2012	4, 5, 6, 7, 10
	2013	4, 5, 7
Perkins, OK (N&P)	2012	4, 5, 6, 8, 10
	2013	3, 4, 5, 6, 7, 10
Hennessey, OK (Reg)	2012	4, 5, 6, 7
	2013	3, 4, 5, 6, 7, 10
LCB Lake Carl Blackwell	2012	4 <sup>a</sup> , 5, 8
	2013	3, 7, 9
LCB, OK (Val)	2013	3, 4, 5, 7, 10

<sup>a</sup> Yield potential measurements collected two times for this Feekes growth stage

research sites. The DPG were counted as the number of days that not only met the criteria for a GDD described in the current method for predicting grain yield, but also had a weighted average FWI across the 0.80 m soil profile of 0.30 or more. The 0.30 FWI threshold is described by Soltani and Sinclair (2012) as the level at which growth could potentially be inhibited for winter wheat.

**Table 5** Average (avg), minimum (min), and maximum (max) potential evapotranspiration amounts (mm) from February 1 to June 10 for three long-term soil fertility locations

Year	Stillwater, OK			Lahoma, OK			Perkins, OK		
	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max
2003	3.3	0.3	8.1	3.3	0.3	8.1	3.5	0.3	8.6
2004	3.5	0.3	8.4	3.7	0.3	10.9	3.7	0.3	9.4
2005	3.5	0.3	7.9	3.7	0.3	9.1	3.8	0.3	9.4
2006	4.1	0.3	9.4	4.7	0.3	11.9	4.4	0.3	9.9
2007	3.1	0.3	7.4	3.1	0.3	8.9	3.2	0.3	7.6
2008	3.7	0.3	8.9	3.8	0.3	11.2	3.8	0.3	9.9
2009	3.6	0.8	8.4	3.8	0.5	10.2	3.7	0.8	9.4
2010	3.4	0.3	7.9	3.5	0.3	9.4	3.5	0.3	8.4
2011	4.1	0.3	9.4	4.5	0.3	12.4	4.4	0.3	9.7
2012	3.9	0.3	10.4	4.0	0.3	11.4	3.9	0.3	11.7

### *Stress index (SI)*

Soil moisture data were downloaded from the adjacent Oklahoma Mesonet climate-monitoring station (Oklahoma Mesonet 2015) for each experimental site for the time periods of data collection. To determine the amount of plant available water (PAW) at the time of NDVI data collection the weighted 0.80 m FWI values were converted to volumetric water content. Gravimetric water content values and soil bulk density values were obtained from the USDA-NRCS SSURGO tabular dataset for each respective experimental site (Soil Survey Staff 2012b). It was assumed that a FWI of 0.00 was permanent wilting point and a FWI of 1.00 was close to saturated conditions. One-third bar water or field capacity was then determined by using the soil physical property data and Eqs. 4, 5, and 6 from Illston et al. (2008). Equations were created to predict PAW in the 0.80 m profile from the weighted FWI values. The SI was then determined similarly to Nix and Fitzpatrick (1969) by dividing the amount of PAW by the amount of water needed to maintain yield from the date of sensing to an assumed harvest date of June 10. Water usage by the crop was assumed to be 5 mm per day. This value was chosen because it is likely the highest average potential evapotranspiration (PET) loss in the Southern Great Plains from February 1 to June 10 according to the literature and Oklahoma Mesonet predicted PET losses for the three model calibration sites (Table 5). To keep from skewing the data for sensing times late in the growing season, SI values were not allowed to exceed 1.00.

### **Statistical analysis**

#### *Weather data*

Weather data were downloaded from the Oklahoma Mesonet and imported into Microsoft Access databases. Structured query language queries were developed to retrieve and summarize weather data to create desired model parameter variables.

#### *Model development*

Multiple linear regression techniques were utilized to develop a model for predicting grain yield from the three proposed parameters (NDVI, DPG, SI). Step-wise regression was



employed to determine which main and interactive effects of the proposed parameters had a significant impact on final grain yield. The maximized adjusted  $R^2$  values were used to determine the appropriate regression equation parameters that best estimated final grain yield. All analyses were conducted using SAS statistical software (SAS Institute, Inc 2011).

To determine if surface soil texture was to have any effect on yield potential, three different models were developed. One model was created from all three calibration sites with no regard to surface texture. The other two models developed were the loamy surface textured model (Stillwater, OK and Lahoma, OK) and the coarse surface textured model (Perkins, OK).

### Model validation

The statistical model developed was validated utilizing datasets from the 2011–2012 and 2012–2013 growing seasons. From this point forward, the growing season will be described by the year of grain harvest. Three of the experimental sites used were the long-term soil fertility trials used in the development of the model. Three additional experimental sites from regional N fertilizer response trials were also used. None of the data sets or site-years used in model validation were part of the model development.

The INSEY values from the current methodology for predicting grain yield and the proposed models described above were evaluated for their effectiveness by regressing the predicted values against the actual grain yield values. Coefficient of determination ( $R^2$ ) values and root mean square error (RMSE) values were then used to determine which methods performed best for predicting grain yield. All analyses were conducted using SAS statistical software (SAS Institute, Inc 2011).

## Results

Step-wise regression techniques revealed that the main effect and all interactive effects of the proposed model parameters had significant effects on final grain yield when data from all three calibration sites were used (Table 6). The same was true when only the data for the two loamy sites were used. For the coarse site model development, DPG, SI, and the interaction of DPG and SI did not have a significant effect on grain yield, however

**Table 6** Model parameter estimates for estimating winter wheat grain yield

Parameter	All sites		Loamy sites		Coarse sites	
	Est.	Pr >  t	Est.	Pr >  t	Est.	Pr >  t
Intercept	8.32	–	9.62	–	4.68	–
DPG	–0.09	<0.0001	–0.08	0.0320	–0.06	0.1261
SI	–10.66	<0.0001	–13.82	<0.0001	–5.03	0.2157
NDVI	–15.68	<0.0001	–17.17	0.0005	–13.19	0.0356
DPG*SI	0.11	<0.0001	0.11	0.0029	0.05	0.2408
DPG*NDVI	0.22	<0.0001	0.18	0.0051	0.23	0.0014
NDVI*SI	25.80	<0.0001	31.44	<0.0001	16.51	0.0250
NDVI*DPG*SI	–0.28	<0.0001	–0.27	<0.0001	–0.22	0.0064

DPG days of potential growth, SI stress index, NDVI normalized difference vegetative index

**Table 7** Coefficient of determination values ( $R^2$ ) for current and proposed models for predicting final winter wheat grain yield by Feekes (FK) growth stage

	FK 3	FK 4	FK 5	FK 6	FK 7	FK 8	FK 9	FK 10
Stillwater, OK (222)								
2012-Current INSEY	–	0.12	0.61	0.31	–	0.77	–	0.83
2012-New INSEY-All	–	0.13	0.59	0.30	–	0.85	–	0.89
2012-New INSEY-Loamy	–	0.13	0.59	0.30	–	0.85	–	0.89
Stillwater, OK (222)								
2013-Current INSEY	–	–	–	–	0.59	–	–	–
2013-New INSEY-All	–	–	–	–	0.58	–	–	–
2013-New INSEY-Loamy	–	–	–	–	0.58	–	–	–
Lahoma, OK (502)								
2012-Current INSEY	–	0.53	0.49	0.38	0.72	–	–	0.30
2012-New INSEY-All	–	0.53	0.61	0.40	0.86	–	–	0.59
2012-New INSEY-Loamy	–	0.53	0.61	0.40	0.86	–	–	0.55
Lahoma, OK (502)								
2013-Current INSEY	–	0.05	0.07	–	0.57	–	–	–
2013-New INSEY-All	–	0.04	0.07	–	0.64	–	–	–
2013-New INSEY-Loamy	–	0.04	0.07	–	0.64	–	–	–
Perkins, OK (N&P)								
2012-Current INSEY	–	0.17	0.04	0.05	–	0.11	–	0.10
2012-New INSEY-All	–	0.19	0.04	0.06	–	0.11	–	0.10
2012-New INSEY-Coarse	–	0.17	0.04	0.06	–	0.11	–	0.10
Perkins, OK (N&P)								
2013-Current INSEY	0.54	0.60	0.45	0.45	0.74	–	–	0.71
2013-New INSEY-All	0.53	0.59	0.48	0.48	0.74	–	–	0.72
2013-New INSEY-Coarse	0.53	0.59	0.48	0.48	0.74	–	–	0.72
Hennessey, OK (Reg)								
2012-Current INSEY	–	0.22	0.20	0.34	0.82	–	–	–
2012-New INSEY-All	–	0.25	0.22	0.39	0.84	–	–	–
2012-New INSEY-Loamy	–	0.25	0.22	0.39	0.84	–	–	–
Hennessey, OK (Reg)								
2013-Current INSEY	0.01	0.31	0.45	0.67	0.80	–	–	0.80
2013-New INSEY-All	0.01	0.30	0.46	0.67	0.84	–	–	0.85
2013-New INSEY-Loamy	0.01	0.30	0.46	0.67	0.84	–	–	0.85
LCB, OK (Reg)								
2012-Current INSEY	–	0.20	0.39	–	–	0.59	–	–
2012-New INSEY-All	–	0.21	0.44	–	–	0.68	–	–
2012-New INSEY-Loamy	–	0.21	0.44	–	–	0.68	–	–
LCB, OK (Reg)								
2013-Current INSEY	0.32	–	–	–	0.60	–	0.33	–
2013-New INSEY-All	0.33	–	–	–	0.62	–	0.34	–
2013-New INSEY-Loamy	0.35	–	–	–	0.62	–	0.34	–
LCB, OK (Val)								
2013-Current INSEY	0.01	0.24	0.64	–	0.64	–	–	0.45

**Table 7** continued

	FK 3	FK 4	FK 5	FK 6	FK 7	FK 8	FK 9	FK 10
2013-New INSEY-All	0.01	0.27	0.67	–	0.68	–	–	0.47
2013-New INSEY-Coarse	0.01	0.27	0.67	–	0.68	–	–	0.47

*INSEY* in-season estimate of yield, *LCB* Lake Carl Blackwell

including them in the model maximized the adjusted  $R^2$  (Table 6). The parameters described in Table 6 were then employed to evaluate the effectiveness of each model's ability to predict yield for each of the validation sites included in this trial.

In 2012, the Stillwater, OK (222) site did not display a significant difference in model performance between the current INSEY and the proposed INSEY models for the Feekes growth stages 4, 5, 6. The amount of variation accounted for improved in both proposed models later in the growing season when compared to the current INSEY (Table 7). When the ability to predict grain yield was evaluated across all growth stages in 2012, the proposed INSEY model that was developed regardless of soil type performed the best with an  $R^2$  of 0.31 compared to the  $R^2$  values of 0.20 and 0.20 for the current INSEY model and the model developed for loamy textured soils, respectively. In 2013, fall moisture at sowing was negligible and the first stand failed. The wheat was replanted in late November and marginal growth occurred until later in the following spring. One sensor reading was recorded at Feekes 7, however, the ability to predict grain yield was good for the three different models, but no model was significantly superior (Table 7). When the Stillwater, OK (222) plots were pooled across growth stages and growing season, the proposed INSEY model developed from all validation sites and that utilized soil moisture performed better than the current INSEY model and the model developed for loamy textured sites. The RMSE values were not significantly different from one another within each growth stage for the three models evaluated (Table 8). A trend of decreasing RMSE values was observed as the growth stage increased.

For Lahoma, OK (502) in 2012, the ability of the three models to predict grain yield tended to improve later into the growing season (Table 7). At Feekes 4 there was no difference between the three model's ability to predict grain yield. However, as the growing season progressed the two proposed INSEY models that used soil moisture parameters outperformed the current INSEY model. This trend was also observed when the plots were analyzed across all growth stages for 2012. In 2013, fall moisture was negligible, so very little growth occurred until later in the spring when the area received significant rainfall. With low biomass accumulation at Feekes 4 and 5, the ability to predict grain yield was poor. After rain had occurred and vegetative growth resumed, yield prediction for the three models improved at the Feekes 7 growth stage. As in 2012, the two proposed models utilizing soil moisture data outperformed the current INSEY model in the 2013 growing season. When grain yield prediction was analyzed across growth stages in 2013, the poor prediction values at Feekes 4 and 5 seemed to dictate an overall poor performance of predicting grain yield for the 2013 growing season. When the ability to predict grain yield was analyzed across all growth stages and growing seasons, again the two proposed INSEY models that utilized soil moisture outperformed the current INSEY model. The RMSE values for the three models' regression of the predicted versus actual grain yield decreased throughout the growing season (Table 8). Very little difference was observed in the values between the different models except at the Feekes 5, 7, and 10

**Table 8** Root mean square error values for current and proposed models for predicting final winter wheat grain yield by Feekes (FK) growth stage

	FK 3	FK 4	FK 5	FK 6	FK 7	FK 8	FK 9	FK 10
Stillwater, OK (222)								
2012-Current INSEY	–	0.57	0.38	0.50	–	0.29	–	0.25
2012-New INSEY-All	–	0.56	0.39	0.50	–	0.23	–	0.20
2012-New INSEY-Loamy	–	0.56	0.39	0.50	–	0.23	–	0.20
Stillwater, OK (222)								
2013-Current INSEY	–	–	–	–	0.13	–	–	–
2013-New INSEY-All	–	–	–	–	0.13	–	–	–
2013-New INSEY-Loamy	–	–	–	–	0.13	–	–	–
Lahoma, OK (502)								
2012-Current INSEY	–	0.64	0.66	0.74	0.50	–	–	0.37
2012-New INSEY-All	–	0.65	0.59	0.73	0.35	–	–	0.29
2012-New INSEY-Loamy	–	0.65	0.59	0.73	0.35	–	–	0.29
Lahoma, OK (502)								
2013-Current INSEY	–	0.50	0.49	–	0.33	–	–	–
2013-New INSEY-All	–	0.50	0.49	–	0.31	–	–	–
2013-New INSEY-Loamy	–	0.50	0.49	–	0.31	–	–	–
Perkins, OK (N&P)								
2012-Current INSEY	–	0.29	0.31	0.31	–	0.30	–	0.30
2012-New INSEY-All	–	0.29	0.31	0.31	–	0.30	–	0.30
2012-New INSEY-Coarse	–	0.29	0.31	0.31	–	0.30	–	0.30
Perkins, OK (N&P)								
2013-Current INSEY	0.23	0.21	0.25	0.25	0.17	–	–	0.18
2013-New INSEY-All	0.23	0.22	0.24	0.24	0.17	–	–	0.18
2013-New INSEY-Coarse	0.23	0.22	0.24	0.24	0.17	–	–	0.18
Hennessey, OK (Reg)								
2012-Current INSEY	–	0.96	0.97	0.88	0.46	–	–	–
2012-New INSEY-All	–	0.94	0.96	0.85	0.43	–	–	–
2012-New INSEY-Loamy	–	0.94	0.96	0.85	0.43	–	–	–
Hennessey, OK (Reg)								
2013-Current INSEY	0.71	0.59	0.53	0.41	0.32	–	–	0.32
2013-New INSEY-All	0.71	0.60	0.53	0.41	0.29	–	–	0.27
2013-New INSEY-Loamy	0.71	0.60	0.53	0.41	0.29	–	–	0.27
LCB, OK (Reg)								
2012-Current INSEY	–	0.37	0.33	–	–	0.24	–	–
2012-New INSEY-All	–	0.35	0.32	–	–	0.24	–	–
2012-New INSEY-Loamy	–	0.35	0.32	–	–	0.24	–	–
LCB, OK (Reg)								
2013-Current INSEY	0.23	–	–	–	0.18	–	0.23	–
2013-New INSEY-All	0.23	–	–	–	0.18	–	0.23	–
2013-New INSEY-Loamy	0.23	–	–	–	0.18	–	0.23	–
LCB, OK (Val)								
2013-Current INSEY	0.47	0.41	0.28	–	0.28	–	–	0.35

**Table 8** continued

	FK 3	FK 4	FK 5	FK 6	FK 7	FK 8	FK 9	FK 10
2013-New INSEY-All	0.47	0.40	0.27	–	0.27	–	–	0.34
2013-New INSEY-Coarse	0.47	0.40	0.27	–	0.27	–	–	0.34

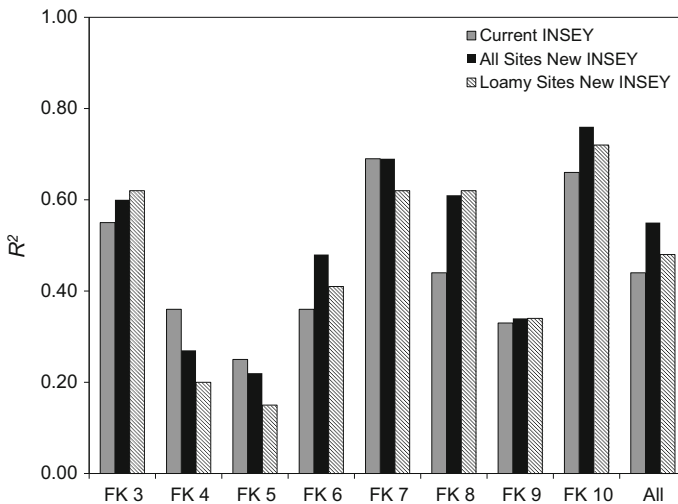
*INSEY* in-season estimate of yield, *LCB* Lake Carl Blackwell

growth stages in 2012, and there was a slight improvement for the two models utilizing soil moisture compared to the current *INSEY* model (Table 8).

The ability of the three models to predict grain yield improved as the growing season progressed in 2012 at the Hennessey, OK (Reg) site (Table 7). Negligible, but lower coefficient of determination values were observed between the current *INSEY* model and the two proposed *INSEY* models for all growth stages in 2012. This was also observed when the 2012 data were analyzed across all growth stages; however, the proposed *INSEY* model developed from all calibration sites had improved grain yield predictions as compared to the proposed *INSEY* model that was developed for loamy textured soils. In 2013, it was impossible to predict yield at Feekes 3 due to minimal available water for vegetative growth. After the site received significant rainfall, the trend of improving yield prediction as the growing season progressed was observed. At the Feekes 4, 5, and 6 growth stages, no differences were observed in the three models' performances; however, at Feekes 7 and 10 the models utilizing soil moisture gave slight improvements in predicting yield (Table 7). When analyzed across all growth stages for the 2013 growing season, the same trend as 2012 for the proposed *INSEY* model developed from all sites outperformed the other two models. This was then again observed when the data were analyzed across all growth stages and both growing seasons. No differences were observed in the RMSE values for each model, but again the values decreased as the growing season progressed. Of all the site-years analyzed, the values were the highest for the 2012 growing season. This could likely be explained by significantly higher average grain yields harvested at this site for that growing season.

In 2012 at the Lake Carl Blackwell, OK (Reg) site, slight improvements in the ability to predict grain yield were observed for the proposed *INSEY* models that included soil moisture parameters (Table 7). When the data were analyzed across all growth stages in 2012, the proposed *INSEY* model that was developed from all sites outperformed the other two models. For the 2013 growing season, very little differences were observed in the three models' abilities to predict grain yield until they were analyzed across all growth stages. Unlike the other previously described site-years, there was a decrease in model performance between Feekes 7 and 9. This may be because of a potentially damaging freeze that occurred between these two growth stages. When analyzed across all growth stages, the current *INSEY* model outperformed the other two proposed *INSEY* models. This same trend, though not as prominent, was observed when the data were analyzed across growth stages and both growing seasons. The RMSE values for the 2012 growing season decreased as the season progressed and there were not any differences between the values for each model (Table 8). In 2013, the RMSE values were not different amongst models and there was no observable trend (Table 8).

When all the validation sites classified as loamy were analyzed across site and growing season, no distinct patterns between model performance and growth stage were observed (Fig. 1). When just observing the Feekes 4 through 10 growth stages, the ability to predict grain yield did tend to increase throughout the growing season (Fig. 1) with the exception



**Fig. 1** Validation sites with a loamy surface soil texture coefficient of determination ( $R^2$ ) values for the current model of determining winter wheat in-season estimation of yield (INSEY), and proposed new models that incorporate soil moisture data into yield prediction. Two proposed new models are displayed, one that predicts yield regardless of soil type and one that predicts yield for soils with a loamy textured surface. Predictions are grouped together by Feekes (FK) growth stage across the 2012 and 2013 growing seasons

of the Feekes 9 growth stage which can likely be explained by the late season freeze at Lake Carl Blackwell, OK (Reg) in 2013. When all loamy sites were analyzed across all growth stages, the two proposed INSEY models outperformed the current INSEY model with the proposed INSEY model developed from all sites performing the best with a coefficient of determination value of 0.55 (Fig. 1).

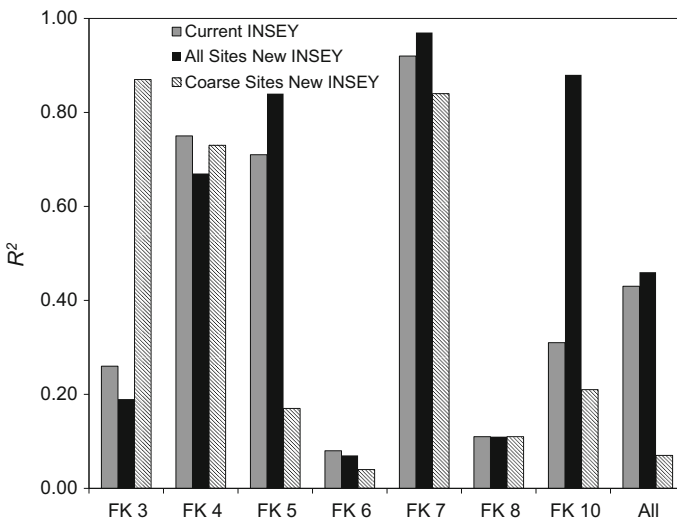
Days with above average temperatures prior to and during grain fill at Perkins, OK (N&P) in 2012 likely led to the very poor performance of the three models at predicting grain yield, with all coefficient of determination values being  $<0.20$  (Table 7). In 2013, grain yield prediction values decreased from Feekes 4 to 5 and 6, but increased for Feekes 7 and 10. The current INSEY model had slightly higher prediction capabilities at Feekes 3 and 4 compared to the two proposed models that utilize soil moisture parameters. The opposite trend was observed for Feekes 5 and 6, but there was no difference between the three models at Feekes 7 and 10. When the data were analyzed across all growth stages in 2013, the proposed INSEY model that was developed from all soil types outperformed the other two models. When the data were analyzed across all growth stages and both growing seasons, no discernable best model was revealed. This again is likely due to grain yields that were marred by climatic conditions post sensing in 2012. No observable differences were detected in the RMSE values between models and growth stages for the 2012 growing season. In 2013, the RMSE tended to decrease throughout the growing season, much like the previously described loamy textured sites (Table 8).

An additional N fertilizer response trial was added at Lake Carl Blackwell, OK (Val) on a coarse textured soil in 2013. The three models failed to predict yield early in the growing season when growth was limited due to lack of water. As precipitation increased, vegetative growth resumed and differences were observed at the remaining growth stages (Table 7). At Feekes 4, 5, 7, and 10 the proposed INSEY models that incorporated soil moisture parameters performed slightly better than the current INSEY model (Table 7). The ability to

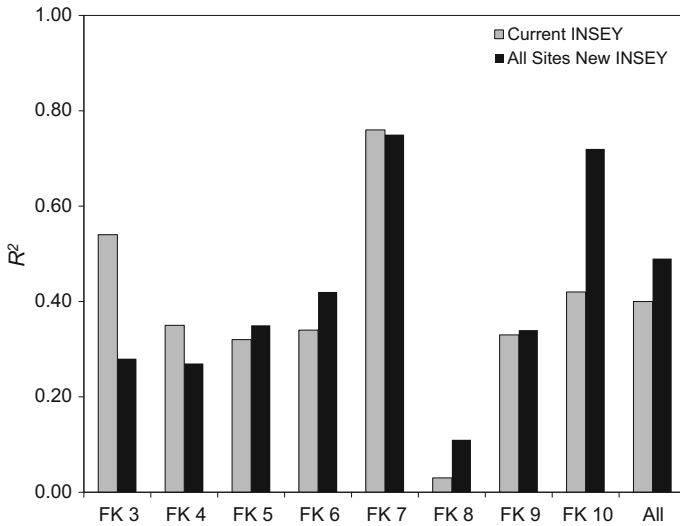
predict yield did increase from Feekes 4 to 7, but decreased from 7 to 10. This decrease is likely due to an unseasonably late freeze. When data were analyzed across all growth stages, extremely poor grain yield predictions were observed. Though the current INSEY performed the best of the three models, all the coefficient of determination values were less than 0.15. Like many of the previously described validation sites, the RMSE values decreased throughout the growing season from Feekes 3 to 7, but increased from 7 to 10 (Table 8).

No observable trends could be reported when the coarse textured validation sites were aggregated across site-years and analyzed (Fig. 2). This could be because of a lack of site-years and the 2012 data collected from the Perkins, OK (N&P) research site. One item to note would be when the data were analyzed across site-years and growth stages, the proposed INSEY model that was developed by all the calibration sites slightly outperformed the current INSEY model. The model that was developed for coarse textured soils performed poorly with a coefficient of determination value  $<0.10$  (Fig. 2).

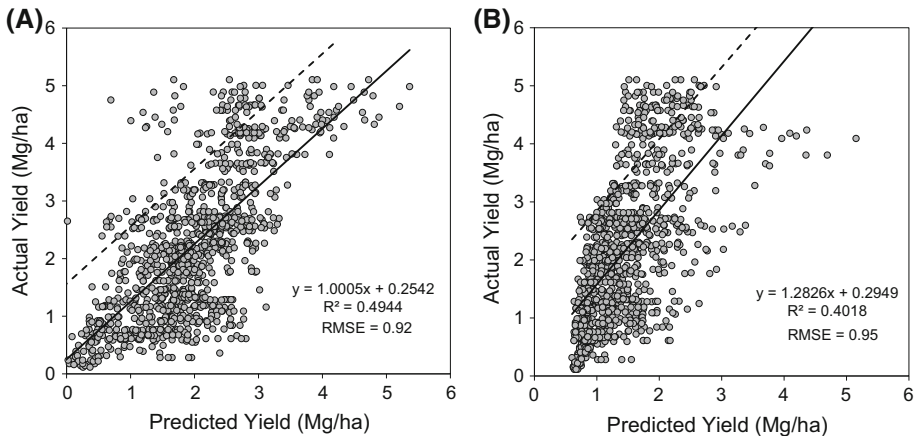
When the data were grouped across all site-years and analyzed at all growth stages, differences were observed between the current INSEY and proposed INSEY developed using soil moisture data. At growth stages Feekes 3 and 4, the current INSEY outperformed the proposed INSEY, but the proposed INSEY outperformed the current INSEY at Feekes 5, 6, 8, and 10. No significant difference was observed between the two models at Feekes 7 and 9. (Figure 3). When the data were aggregated across all site-years and growth stages, the proposed INSEY model outperformed the current INSEY model with a coefficient of determination value of 0.49 compared to 0.40 (Fig. 4). The RMSE values didn't differ between the two models. It should also be noted that the linear regression equation for the proposed INSEY did not have a slope significantly different from one and an intercept different from zero. The regression equation for the current INSEY model had a slope significantly different than one, but the intercept was not significantly different from zero.



**Fig. 2** Validation sites with a coarse surface soil texture coefficient of determination ( $R^2$ ) values for the current model of determining winter wheat in-season estimation of yield (INSEY), and proposed new models that incorporate soil moisture data into yield prediction. Two proposed new models are displayed, one that predicts yield regardless of soil type and one that predicts yield for soils with a coarse textured surface. Predictions are grouped together by Feekes (FK) growth stage across the 2012 and 2013 growing seasons



**Fig. 3** Coefficient of determination ( $R^2$ ) values for the current model of determining winter wheat in-season estimation of yield (INSEY), and a proposed new model that incorporate soil moisture data into yield prediction. Predictions are grouped together by Feekes (FK) growth stage across all validation sites for the 2012 and 2013 growing seasons



**Fig. 4** Linear relationships between predicted winter wheat in-season estimations of yield based upon soil moisture parameters (A) or the current model (B) used to predict actual grain yield. Data presented is from all validation sites across all growth stages. *Dashed line* represents one standard deviation above the actual yield

## Discussion

Proper validation of developed prediction models should be conducted to determine the legitimacy of a model to accurately predict grain yield. Little to no work similar to that described in this paper, with an emphasis being placed on remotely sensed NDVI, has been published that truly validates a developed grain yield prediction model that could be



compared to actual grain yield. The current model for predicting INSEY (Raun et al. 2005), described the goodness of fit of the data used to develop the exponential relationship. The grain yield prediction model was only evaluated on its ability to improve N fertilizer recommendations and was not evaluated with an independent data set to predict grain yield. Other researchers have employed multi-parameter models that utilize remotely sensed NDVI from ground based optical sensors and climate parameters to try and predict grain yield. Both Girma et al. (2006) and Walsh et al. (2013) developed models and made suggestions of what type of parameters could be reliable predictors of grain yield, but did not validate their conclusions with an independent dataset.

The common trend of the ability to accurately predict grain yield increasing with the progression of the growing season seems logical. As one moves later in the growing season the probability of unexpected climatological events, such as freeze or extreme heat, between sensing and grain harvest decreases. The decrease in grain yield and thus a decrease in the ability to predict yield for the Perkins (N&P) validation site in 2012 is a prime example of what can happen even when there is just a short period of time in which temperatures exceed 31–35 °C during the grain filling process. Wheat grain yields can be significantly impacted even when as little as five percent of the grain filling process occurs under excess heat (Stone and Nicolas 1994; Wheeler et al. 1996; Ferris et al. 1998). The decrease in the models' ability to predict yield for the Feekes 10 growth stages for the Lake Carl Blackwell (Reg) and Lake Carl Blackwell (Val) validation sites in 2013 may be attributed to a yield damaging late freeze. The amount of damage to grain yield would depend on the stage of the wheat crop at the time of the freeze (Thakur et al. 2010). Because dry matter accumulation and partitioning during grain fill can be strongly influenced by N fertilizer nutrition (Demotes-Mainard et al. 1999), the fact that the data utilized in this experiment came from N response trials would explain why plots had differing degrees of damage due to the freeze. This would also explain the increase in RMSE values later in the growing season for the 2013 Lake Carl Blackwell sites.

Based on the results, there is no benefit to having a different model based on soil type. Though no similar winter wheat research exists, Sharma and Franzen (2013) reported contrary results while investigating the ability to predict maize grain yield with optical sensors and other maize plant measurements. They developed two different grain yield prediction curves for clayey and medium textured soils. The differences in the curves were due to soils potentially being water-logged and having different responses to N fertilization. Excess water, typically is not a problem for winter wheat grown in the region of the calibration and validation trials. Likely, the fact that soil physical properties were incorporated into the SI model parameter for the proposed INSEY model would negate the need for different grain yield prediction models based on soil type.

## Conclusions

The ability of grain yield prediction models to estimate winter wheat grain yield in-season will aid producers in making better agronomic management decisions. Regardless of the model, the ability and the accuracy at which grain yield could be predicted increased as the growing season progressed, unless rare unseasonable climatic events occurred after NDVI data collection. No added benefit was observed for creating two separate models based on soil type. One universal model developed with soil moisture data was sufficient for predicting grain yield. When comparing the ability to estimate grain yield of proposed INSEY

models that utilize soil moisture data with the current INSEY model, the proposed INSEY models typically outperformed the current INSEY model at most validation sites. When data were combined over sites the current INSEY model did perform better at earlier growth stages (Feekes 3 and 4), but the opposite was observed for the mid to late growth stages (Feekes 5–10). Lastly, the proposed INSEY model outperformed the current INSEY model, with a coefficient of determination value of 0.49 compared to 0.42, when data were analyzed across all growth stages, thus providing a model in which producers would not be required to stage wheat growth in order to determine an appropriate model for grain yield prediction.

**Acknowledgments** The authors would like to thank the Oklahoma Soil Fertility Research and Education Advisory Board for their funding of this research project and their continued financial support of soil fertility research at Oklahoma State University. The authors would also like to express their sincere gratitude to all the current and former soil fertility graduate students who aided in the data collection and maintenance of trials.

### Compliance with ethical standards

**Conflict of Interest** The mention of any trademarked products or equipment utilized in this experiment was for research purposes only and does not act as an endorsement by Oklahoma State University. The authors and Oklahoma State University have no direct financial relation with any of the named manufacturers, thus the authors declare there is no conflict of interest regarding the publication of this manuscript.

## References

- Basara, J. B., & Crawford, T. M. (2000). Improved installation procedures for deep layer soil moisture measurements. *Journal of Atmospheric and Oceanic Technology*, 17(6), 879–884.
- Black, A.L., & Bauer, A. (1988). Setting winter wheat yield goals. In J.L. Havlin (Ed.), *Proceedings of the workshop central great plains profitable wheat management, wichita, KS. 17–20 1988* (pp. 24–34). Atlanta, GA: Potash and Phosphate Institute.
- Dahnke, W.C., Swenson, L.J., Goos, R.J., & Laholm, A.G. (1988). Choosing a crop yield goal. SF-822. Fargo: North Dakota State Extension Service.
- Demotes-Mainard, S., Jeuffroy, M.-H., & Robin, S. (1999). Spike dry matter and nitrogen accumulation before anthesis in wheat as affected by nitrogen fertilizer: Relationship to kernels per spike. *Field Crops Research*, 64(3), 249–259.
- Evans, L. T., & Fischer, R. A. (1999). Yield potential: Its definition, measurement, and significance. *Crop Science*, 39(6), 1544–1551.
- Fanning, B. (2012). Setting yield goals. South Dakota State University Extension. <http://igrow.org/agronomy/wheat/settings-yield-goals/>. Accessed 1 Oct. 2015.
- Ferris, R., Ellis, R. H., Wheeler, T. R., & Hadley, P. (1998). Effect of high temperature stress at anthesis on grain yield and biomass of field-grown crops of wheat. *Annals of Botany*, 82(5), 631–639.
- Geisseler, D., & Horwath, W.R. (2013). Determining yield goals. California Department of Food and Agriculture. [http://apps.cdfa.ca.gov/frep/docs/Yield\\_Goals.pdf](http://apps.cdfa.ca.gov/frep/docs/Yield_Goals.pdf). Accessed 1 Oct. 2015.
- Girma, K., Holtz, S. L., Arnall, D. B., Fultz, L. M., Hanks, T. L., Lawles, K. D., et al. (2007). Weather, fertilizer, previous year yield, and fertilizer levels affect ensuing year fertilizer response of wheat. *Agronomy Journal*, 99(6), 1607–1614.
- Girma, K., Martin, K. L., Anderson, R. H., Arnall, D. B., Brixey, K. D., Casillas, M. A., et al. (2006). Mid-season prediction of wheat-grain yield potential using plant, soil, and sensor measurements. *Journal of Plant Nutrition*, 29(5), 873–897.
- Howell, T. A., Steiner, J. L., Schneider, A. D., Evett, S. R., & Tolk, J. A. (1997). Seasonal and maximum daily evapotranspiration of irrigated winter wheat, sorghum, and corn—Southern High Plains. *Transactions of the ASAE*, 40(3), 623–634.
- Hunt, L. A., & Pararajasingham, S. (1995). CROPISM-Wheat: A model describing the growth and development of wheat. *Canadian Journal of Plant Science*, 75(4), 619–632.
- Illston, B. G., Basara, J. B., Fisher, D. K., Elliot, R., Fiebrich, C. A., Crawford, K. C., et al. (2008). Mesoscale monitoring of soil moisture across a statewide network. *Journal of Atmospheric and Oceanic Technology*, 25(2), 167–182.

- Large, E. C. (1954). Growth stages in cereals: Illustration of the Feekes Scale. *Plant Pathology*, 3(4), 128–129.
- Liu, C., Zhang, X., & Zhang, Q. (2002). Determination of daily evaporation and evapotranspiration of winter wheat and maize by large-scale weighing lysimeter and micro-lysimeter. *Agricultural and Forest Meteorology*, 111(2), 109–120.
- McMaster, G. S., & Wilhelm, W. W. (1997). Growing degree-days: One equation, two interpretations. *Agricultural and Forest Meteorology*, 87(4), 291–300.
- Oklahoma Mesonet. (2015). Daily data retrieval. University of Oklahoma. [http://www.mesonet.org/index.php/weather/category/past\\_data\\_files](http://www.mesonet.org/index.php/weather/category/past_data_files). Accessed 1 Oct. 2015.
- Nix, H. A., & Fitzpatrick, E. A. (1969). An index of crop water stress related to wheat and grain sorghum yields. *Agricultural Meteorology*, 6(5), 321–337.
- Porter, J. R., & Gawith, M. (1999). Temperatures and the growth and development of wheat: A review. *European Journal of Agronomy*, 10(1), 23–36.
- Porter, J.R., & Moot, D.J. (1998). Research beyond the means: Climatic variability and plant growth. In N.R. Dalezios (Ed.), *International symposium on applied agrometeorology and agroclimatology* (pp 13–25). Office for Official Publication of the European Commission, Luxembourg
- Raun, W. R., Solie, J. B., Johnson, G. V., Stone, M. L., Lukina, E. V., Thomason, W. E., et al. (2001). In-season prediction of potential grain yield in winter wheat using canopy reflectance. *Agronomy Journal*, 93(1), 131–138.
- Raun, W. R., Solie, J. B., Stone, M. L., Martin, K. L., Freeman, K. W., Mullen, R. W., et al. (2005). Optical sensor-based algorithm for crop nitrogen fertilization. *Communications in Soil Science and Plant Analysis*, 36(19–20), 2759–2781.
- Rehm, G., & Schmitt, M. (1989). Setting realistic crop yield goals. Minnesota Ext. Serv. AG-FS-3873. University of Minnesota.
- Robinson, J. B., Freebairn, D. M., Dimes, J. P., Dalal, R. C., Thomas, G. A., & Weston, E. J. (1999). Modeling wheat production from low-rainfall farming systems in northern Australia. *Environmental International*, 25(6–7), 861–870.
- SAS Institute Inc. (2011). *SAS/STAT® 9.3 User's Guide*. Cary, NC: SAS Institute Inc.
- Sharma, L. K., & Franzen, D. W. (2013). Use of corn height to improve relationship between active optical sensor readings and yield estimates. *Precision Agriculture*,. doi:10.1007/s11119-013-9330-9.
- Singandhupe, R. B., & Sethi, R. R. (2005). Estimation of reference evapotranspiration and crop coefficient in wheat under semi-arid environment in India. *Archives of Agronomy and Soil Science*, 51(6), 619–631.
- Soil Survey Staff. 2012a. Official soil series description. USDA-NRCS. <http://soils.usda.gov/technical/classification/osd/index.html>. Accessed 1 April 2012.
- Soil Survey Staff. 2012b. Web soil survey: Soil data mart. USDA-NRCS. <http://websoilsurvey.nrcs.usda.gov>. Accessed 1 April 2012.
- Solie, J. B., Raun, W. R., Whitney, R. W., Stone, M. L., & Ringer, J. D. (1996). Optical sensor based field element size and sensing strategy for nitrogen application. *Transactions of the ASAE*, 39(6), 1983–1992.
- Soltani, A., & Sinclair, T. R. (2012). *Modeling Physiology of Crop Development*. Cambridge, MA: Growth and Yield. CAB International.
- Stephens, D. J., Lyons, T. J., & Lamond, M. H. (1989). A simple model to forecast wheat yield in Western Australia. *Journal of the Royal Society of Western Australia*, 71(2–3), 77–81.
- Stone, P. J., & Nicolas, M. E. (1994). Wheat cultivars vary widely in their responses of grain yield and quality to short periods of post-anthesis heat stress. *Australian Journal of Plant Physiology*, 21(6), 887–900.
- Stone, M. L., Solie, J. B., Raun, W. R., Whitney, R. W., Taylor, S. L., & Ringer, J. D. (1996). Use of spectral radiance for correcting in-season fertilizer nitrogen deficiencies in winter wheat. *Transactions of the ASAE*, 39(5), 1623–1631.
- Thakur, P., Kumar, S., Malik, J. A., Berger, J. D., & Nayyar, H. (2010). Cold stress effects on reproductive development in grain crops: An overview. *Environmental and Experimental Botany*, 67(3), 429–443.
- Walsh, O. S., Klatt, A. R., Solie, J. B., Godsey, C. B., & Raun, W. R. (2013). Use of soil moisture data for refined Greenseeker sensor based nitrogen recommendations in winter wheat (*Triticum aestivum* L.). *Precision Agriculture*, 14(3), 343–356.
- Wheeler, T. R., Batts, G. R., Ellis, R. H., Hadley, P., & Morison, J. I. L. (1996). Growth and yield of winter wheat (*Triticum aestivum*) crops in response to CO<sub>2</sub> and temperature. *Journal of Agricultural Science, Cambridge*, 127(1), 37–48.