WATER STRESS IN MONTANA CROPPING SYSTEMS: EFFECTS OF CULTIVAR, MANAGEMENT, AND ENVIRONMENT ON CROP PRODUCTION IN DRYLAND SYSTEMS

by

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DEDICATION

Everything herein is dedicated to eastern Montana. For my first 25 years, I only saw you from The Front. For the past five years, I explored you. You have much more to offer than I realized…..except for rattlesnakes.

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ABSTRACT

Crop productivity—defined as yield, protein, and economic returns—hinge on crop water use. Crop water use is a function of genetic, environment, and management factors. This thesis addresses how these factors interact with crop water use and productivity in Montana.

In chapter 2, a two-year (2014-2015) study compared winter wheat yield and protein following fallow and three intensive sequences on deep and shallow soils. Water extraction was measured on deep soils, and kriged soil depth estimates served as a surrogate for stored soil moisture on shallow soils. On deep soils, yields ranged from 72-84% of fallow-wheat from 20.5 mm less water extracted below 45 cm, while protein was ~0.63% greater in intensified sequences. On shallow soils, sequence did not affect yield or protein. Yields increased with soil depth while protein decreased in 2014, but no trends were observed in 2015 due to 47 mm greater precipitation from joint to heading. Intensive sequences diminish wheat productivity on deep soils, whereas soil depth and precipitation timing control productivity on shallow soils.

In chapter 3, state-wide cultivar testing, soils, and climate data was used to quantify four general drought patterns in winter wheat and five in pea. Cultivar had little impact on yield compared to drought pattern with winter wheat yields ranging from 4421 kg ha^{-1} to 2539 kg ha^{-1} and pea yields ranging from 2877 kg ha^{-1} to 975 kg ha^{-1}. Yields negatively correlated with drought intensity at heading in wheat (r^2=-0.79) and flowering in pea (r^2=-0.76). Quantifying drought patterns provides a physical interpretation to improve management and breeding efforts.

In chapter 4, yield-evapotranspiration (ET) functions were derived for spring wheat, pea, and chickpea from a three-year (2002-2004) seeding date trial. Yield-ET functions were coupled with ten-year (2005-2015) climate records to predict yields at four staggered seeding dates. Yield predictions were converted to marginal revenues based on high, medium, and low markets and fixed production costs. Across seeding dates and markets, simulated returns were highest for chickpea (~601 \$ ha^{-1}) followed by wheat (372 \$ ha^{-1}) and pea (202 \$ ha^{-1}). This indicates chickpea should be seeded before wheat and pea.

CHAPTER 1

INTRODUCTION

Background

Montana’s landscape and climate are diverse. The Rocky Mountains dominate the western half of the state where the climate is characterized by mild winters, moderate wind, high humidity, and evenly distributed annual precipitation (WRCC, 2015). East of the Rocky Mountains, the landscape abruptly transitions to expansive plains and constitutes Montana’s predominate dryland agricultural region and a sizeable portion of Northern Great Plains (NGP) (Figure 1.). The climate in the NGP has been described as:

> “continental,with long cold winters; short, but warm summers; large, diurnal fluctuations in temperature; frequent strong winds; and from an agricultural perspective, most importantly highly variable and unpredictable precipitation”
>
> (Padbury et al., 2002)

Notably annual precipitation ranges from 280 to 410 mm with approximately 50-55 % falling between the April to July growing season, with precipitation generally peaking in May or June, followed by terminal drought beginning in July.

The NGP climate has implications on Montana dryland agricultural production. Specifically, the dominant cropping system is fallow-wheat, in which wheat (*Triticum aestivium* L.) is planted following an extended idle or fallow period to ensure stored soil moisture and stabilize wheat yields from drought (Tanaka et al., 2010). Nearly 1.3 million ha of agricultural land is fallowed annually (NASS, 2014), but recent adoption of no-till farming has enhanced soil moisture storage. Namely, standing stubbles trap more snow (Lafond et al., 1991) and reduce soil evaporation via wind protection (Caprio et al., 1985) and the need for an extended fallow period is declining across the state.

Such management has enabled producers to replace summer fallow with alternative crops. In particular, pulse crops such as pea (*Pisium sativum* L.), chickpea (*Cicer arietinum* L.), and lentil (*Lens culinaris* L) has expanded from 6,900 ha in 1995 to over 353,900 ha in 2015 (Tanaka et al. 2010, Long et al. 2015) (Figure 2.), with most pulse production replacing summer fallow (Lee, 2011).

This transition has been brought on by potential economic benefits to producers. Most notably, mineralized nitrogen (N) from pulse residues can reduce fertilizer nitrogen (N) costs to the succeeding crop (Miller et al., 2015; O'Dea et al., 2015), and pulse markets have been strong due to rising global demand (Lee, 2011).

Additional benefits of eliminating summer fallow include increased soil organic matter, reduced nutrient leaching, and less saline seepage (Linfield L.B., 1902; Miller et al., 2015). Diversified crop rotations can further depress pest and weed pressures thereby reducing dependence on pesticides and herbicides (Kirkegaard et al., 2008). Given the economic and environmental benefits of intensified systems, much work has been directed at replacing summer fallow with pulses and other rotational crops throughout Montana (Miller and Holmes, 2005; Lenssen et al., 2007; Burgess et al., 2012; Chen et al., 2012; Lin and Chen, 2014; Miller et al., 2015).

Ideal fallow replacement crops in Montana are cool short-season crops that can be seeded and harvested early. Such crops boost profits while leaving ample time for soil moisture recharge before subsequent water demand is high. In addition to pulses, oilseeds such as canola (*Braissica napus* L.), mustard (*Sinapsis arevensis* L.), and camelina (*Camelina sativa* L.) have potential to meet these requirements (Johnston et al., 2002; Mcvay and Lamb, 2008), but cropping systems studies throughout Montana have shown mixed results. For instance, Chen et al. (2012) found that a wheat-lentil sequence had a 114 \$ ha^{-1} advantage on net returns compared to wheat fallow in Central Montana. The economic gain was due to fertilizer N savings through decomposition and mineralization of N in lentil residues, profit gained by harvesting lentil in place of fallow, and similar wheat yields following both lentil and fallow. Alternatively Chen et al. (2015) observed that wheat-fallow was superior to a wheat-camelina rotation by nearly 100 \$ ha^{-1}. In this study, production costs of camelina outweighed the marginal returns of harvesting camelina for grain, whereas wheat yields were greatly reduced following camelina compared to fallow.

Maintaining recropped wheat yields is critical to eliminating summer fallow. Past estimates from the Canadian Prairies suggest recropped wheat yields must fall within 67 to 84 % of a wheat-fallow control for net economic returns to be equivalent among systems (Zentner and Campbell, 1987). Meeting this threshold, however, depends greatly on site and season. For instance Miller et al. (2006) observed spring wheat yields following pea and mustard were similar to wheat-fallow at a site with shallow soils in Central Montana. However respective yields following each crop diminished to 56% and 36 % of the wheat-fallow control in Northern Montana on deep soils. Yield differences across sites were influenced by environmental factors. The shallow soil profile in central Montana had fully recharged by spring seeding and resulted in similar water availability across sequences. Conversely, the deep soil profile in northern Montana had not fully recharged under recropped wheat, and marginal June rainfall gave the wheat-fallow sequence an advantage due to deep stored soil moisture compared to continuous sequences.

This study highlights how soil depth can help evaluate risk from continuous cropping on a site-specific basis, but management factors also play a role on crop productivity. Too much early applied fertilizer N can cause excessive vegetative growth and deplete soil water reserves before the crop reaches reproductive growth stages, and this may reduce yield if the crop is not relieved by rainfall during reproductive growth (van Herwaarden et al., 1998). Coincidentally early seeding dates in spring sown crops increases the likelihood that critical growth stages will be better-timed with peak May-June rainfall in Montana (Black and Siddoway, 1977).

Plant genetics further impact crop productivity. For instance, early flowering cultivars may be best adapted to sites where precipitation is expected to peak early. Likewise plant traits such as high root length density to maximize soil water extraction may be best-adapted to Montana’s driest regions (Bueckert and Clarke, 2013).

Thesis Objective and Outline

Crop productivity greatly hinges on crop water use in Montana’s dryland agroecosystems. Crop water use is ultimately a function of genetic, environment, and management interactions. The overarching theme of this thesis is to address how crop water use and hence crop productivity is affected by these interactions. Specifically chapter 2 compares how crop sequence affects winter wheat yields at two contrasting sites with similar precipitation patterns but different soil water holding capacities from variable soil depths. In chapter 3, a dynamic simulation procedure is developed to quantify the long-term drought patterns for winter wheat and pea across four sites, and addresses how breeding and management can be improved on a site-specific basis. In chapter 4, the simulation procedure is extended to develop grain yield vs. evapotranspiration functions and evaluate economic tradeoffs from delayed seeding of spring wheat, pea, and chickpea under contrasting market scenarios over a ten-year time frame at a site in Southwest Montana.

Figure 1. The transition from the mountainous western Montana landscape to the expansive eastern prairies as seen from the Continental Divide near Marias Pass in early March. The area east of the Rocky Mountains (right side of image) constitutes Montana’s predominate dryland wheat production regions and is characterized by a continental climate with terminal drought beginning in July.

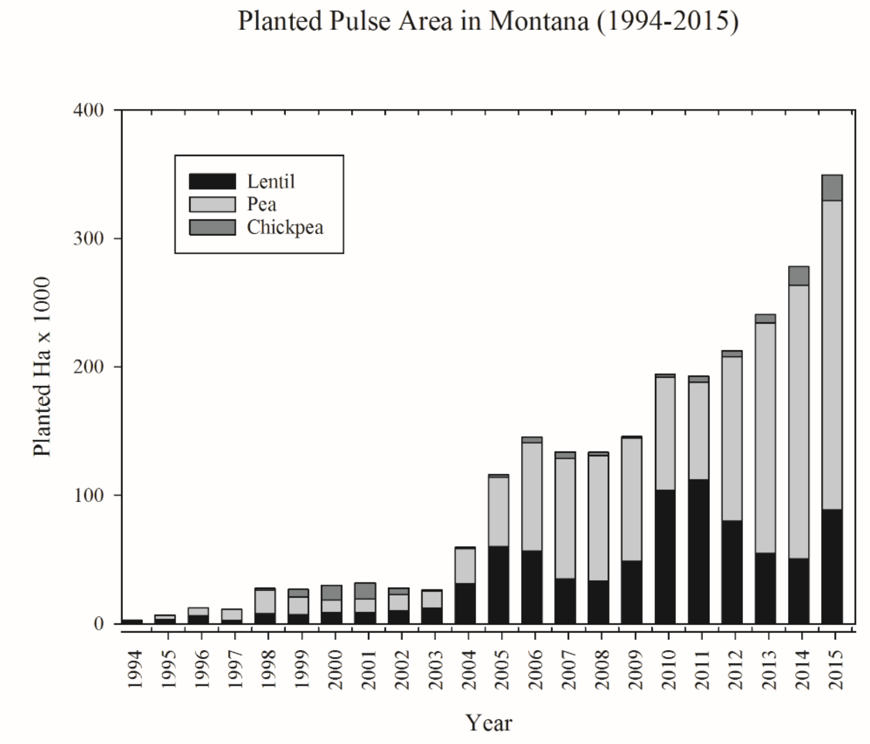

Figure 2. Planted pulse area has exponentially increased from 1994 to 2015.

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CHAPTER TWO

CROP SEQUENCE AFFECTS WINTER WHEAT YIELDS, BIOMASS AND PROTEIN ON DEEP AND SHALLOW SOILS

Abstract

Summer fallow conserves deep soil moisture to protect wheat productivity from untimely precipitation but may not benefit wheat grown on shallow soils. This study compared crop sequence effects on winter wheat yields and protein at two Montana locations with varying soil depths (NARC, deep soils; CARC, shallow soils) and precipitation patterns over two growing seasons (2014-2015). Sequences were fallow-winter wheat (FAL-WW), camelina-winter wheat (CAM-WW), camelina-pea-winter wheat (CAM-PEA-WW) and pea-camelina-winter wheat(PEA-CAM-WW). Changes in soil moisture were monitored at NARC and block kriged soil depth estimates were used as a surrogate for stored soil moisture on shallow soils at CARC. At NARC, yields in intensified sequences ranged from 72% to 84% relative to FAL-WW due to less water (~20.5 mm) extracted below 45 cm, while protein was ~0.63% greater in intensified sequences. Despite similar growing season precipitation (~63 mm in 2014; ~ 68 mm in 2015) yields were higher in 2015 due to 40.7 mm greater precipitation received between joint and heading stages highlighting the significance of precipitation timing on wheat yield. At CARC, yield and protein were unaffected by sequence, but respective yield and protein averaged 2514 kg ha^{-1} and 13.9% in 2014 compared to 3662 kg ha^{-1} and 10.3 % in 2015. Moderate linear relationships between kriged soil depth and yield (R^2=0.45) and

protein (R^2=-0.68) suggested stored soil moisture influenced yield and protein in 2014 when 67.5 mm of precipitation fell between joint and heading stages. Alternatively no relationships were observed in 2015 with 147.5 mm of precipitation from joint to heading stages. These results suggest that both crop sequence and precipitation timing control wheat productivity at NARC, whereas precipitation timing and soil depth control wheat productivity at CARC.

Introduction

Water limits wheat productivity (*Triticum aestivum* L.*)* in Montana's dryland cropping systems (Nielsen et al., 2005). Consequently, wheat is sequenced with fallow or an idle period to guarantee deep soil moisture. While wheat-fallow is a conservative practice for stabilizing yields, there are disadvantages associated with the summer-fallow period. First, the soil profile is often recharged before wheat seeding (Peterson et al., 1996), and drainage below the root zone can occur. Drainage represents poor water use efficiency since less water is allotted to crop productivity and can also cause environmental hazards from nutrient leaching. Second, summer fallow reduces harvest frequency, whereas by continuous cropping, producers may benefit economically if monetary gains from rotational crops outweigh losses from diminished wheat yields (Zentner et al., 2008).

Given these disadvantages, considerable research in Montana has been directed at replacing fallow with crops that provide diverse and intensive crop rotations (Aase and Pikul, 2000; Miller and Holmes, 2005; Miller et al., 2006; Lenssen et al., 2014; Lin and

Chen, 2014). Diversified rotations help mitigate weed and disease risk (Kirkegaard et al., 2008) and improve soil health through reduced wind erosion and increased organic matter (O'Dea et al., 2015). Cool, short-season crops are compatible with Montana's climate since they can be seeded and harvested early. This provides a larger window for soil-moisture recharge before subsequent wheat water demand is high. Pulse crops (Miller et al., 2002) and oilseeds (Johnston et al., 2002) show potential to meet these requirements, yet mixed results regarding cropping sequence effects on wheat yields have been observed throughout the state. For instance, Miller et al. (2006) observed spring similar wheat yields following pea and mustard compared to wheat-fallow at a site in central Montana, but respective yields following each crop diminished to 56% and 36 % relative to the wheat-fallow control in Northern Montana. Differences between the two sites were due to soil depth and precipitation patterns. The shallow soil profile in Central Montana had recharged by spring seeding time and resulted in similar stored soil moisture and yield. Conversely, the deep soil profile in Northern Montana had not fully recharged under recropped wheat, and marginal June rainfall gave the wheat-fallow sequence a yield advantage due to greater soil water extraction from deeper in the soil profile. A similar study in Northern Montana showed that wheat yields in intensified systems ranged from as little as 4% to greater than 100 % of a wheat fallow control under low and high June precipitation respectively (Lenssen et al., 2007).

Crop sequence and environmental conditions may also impact wheat protein. In a Montana study conducted on shallow soils, wheat protein following pea was found to be lower than fallow where pea residue decomposition and N mineralization slowed by drought conditions John (2015). Conversely studies on deep soils generally show higher protein in continuous systems relative to wheat-fallow (Miller et al., 2006; Selles et al., 2006). The latter result is often attributed to greater crop water use following fallow (Selles et al., 2006) which can increase kernel number and size leading to diluted protein content (Brown et al., 2005).

These studies highlight that subsequent wheat yield and protein hinge on water availability. Water availability is a function of crop sequence, precipitation timing, and stored soil moisture. Importantly stored soil moisture depends on soil depth which is highly variable throughout Montana. This means specific sequences may be better adapted on a site specific basis. The objective of this study was to contrast winter wheat yield and protein from a fallow-wheat rotation against more intensified crop rotations at two field sites with deep and shallow soils.

Materials and Methods

Site Descriptions, Experimental Design, and Management

The study was conducted over the 2014 and 2015 growing seasons at two Montana State University agricultural research stations. The Northern Agricultural Research Center (NARC; 48^o 29’ 08” N: 109^o 48’ 08” W; Elev: 826 m) is located in north-central Montana and is characterized by deep soils classified as Telstad clay loam (fine-loamy, mixed *Aridic Argiboroll*) and variable precipitation patterns generally peaking in late May and extending into early June. The Central Agricultural Research Center (CARC; 47^o 03’ 32” N: 109^o 57’ 03” W; Elev: 1293 m) is located near the geographical center of Montana and is characterized by shallow soils classified as Judith clay loam (fine-loamy, carbonatic *Typic Calciborolls*) with depths ranging from 20 cm to greater than 100 cm (Figure 1.). The ten-year (2006-2015) average annual precipitation at NARC and CARC are 288 and 352 mm respectively. Table 1 shows 2006-2015 climate trends and 2014 and 2015 departures from normal taken from on-site weather stations. Table 2 details soils information for each site.

The experiment consisted of four cropping sequences—fallow-winter wheat (FAL-WW), camelina (*Camelina sativa L.)* -winter wheat (CAM-WW), camelina-pea (*Pisum sativum L.*)-winter wheat (CAM-PEA-WW) and pea-cam-winter wheat (PEA-CAM-WW) with all phases present. Both sites were managed under no-till and row spacing was 30 cm. The experimental layout at NARC was a randomized complete block design with three replications, and plot dimensions were 3.7 m x 19.5 m. Experimental plots at CARC constituted a subset of a larger cropping systems study setup in grid formations on two separate fields (Figure 3.) with four replications, and plot dimensions were 7.2 x 9.1. Starter fertilizer was fall band-applied in a 20-20-20-10 blend at 112 kg ha^{-1}, and 90 kg ha^{-1} was spring applied as urea broadcast. Additional herbicide and fungicide applications were determined on a per-site basis. Further experiment and seeding date details are shown in Table 3.

Field Measurements at NARC

Field measurements at NARC were soil moisture, grain yield, and grain protein. Soil moisture readings were taken at five growth stages corresponding to joint (Feekes 6), flag leaf (Feekes 8), heading (Feekes 10.3), milk (Feekes 11.1), and physiological maturity (Feekes 11.3) using a CPN 503DR hydroprobe (Cambell Pacific Nuclear, 1998) and access tubes at 0-15, 15-45, 45-75, and 75-105 cm depth increments. The neutron probe was calibrated gravimetrically by depth, and moisture measurements were converted to equivalent depths by multiplying volumetric water content to each sample depth increment. Hand-harvested yields were determined by cutting biomass samples from 3 inner rows at 1 m row lengths at physiological maturity, drying samples at 60 ^{o}C, and threshing the samples for dry seed weights. Six inner rows were subsequently harvested via a plot combine at 5 m lengths, and grain yields were taken as the average of hand-harvested and combine yields to better account for within plot variability. Sub-samples of harvested grain were separated and analyzed for protein at 12 % moisture using near infrared-transmittance spectrophotometry.

Field Measurements at CARC

All field measurements at CARC were identical to NARC except soil moisture. Due to shallow and variable soil depths, moisture readings could not be made to a consistent depth. Instead, soil depth was assumed to be the primary limitation on stored soil moisture, and soil depth measurements were made by removing soil cores from all plot centers in a grid formation with a tractor mounted hydraulic probe and measuring core depths (Figure 3.). Mean soil depths within each treatment plot were then estimated by block kriging (*see statistical analysis).*

Statistical Analysis at NARC

Primary response variables at NARC were grain yield, protein, growing season evapotranspiration (ET), and water use efficiency. Crop ET was defined as the difference in soil moisture between joint and maturity plus intermittent precipitation. Muddy field conditions limited field access prior to joint stage, so crop ET prior to joint stage could not be measured. Water use efficiency was defined as the ratio of grain yield to crop ET. ANOVA was used to evaluate cropping sequence effect given by the model:

$$Y_{ijkl} = \mu + \alpha_i + \tau_j + \gamma_k + \tau\gamma_{jk} + \varepsilon_{ijkl} \qquad \text{Eq 1.}$$

where μ is the grand mean of all response variables, α_i is the random block effect, τ_j is the fixed crop sequence effect, γ_k is the fixed year effect, and ε_{ijkl} is the error term with residuals distributed by $N(0,\sigma)$. Homogeneity of variance assumptions were validated via Levene's tests, and post-hoc multiple comparisons were conducted via Fisher tests with treatment effects considered significant at the $\alpha=0.05$ level.

Simple linear regression relating yield and protein to cumulative ET was used to evaluate the impacts of ET on wheat productivity at heading and maturity. Pearson correlation analysis relating cumulative ET to yield and protein referenced from joint to each subsequent growth stage (e.g. joint-flag leaf, joint-heading, etc.) at cumulative depth increments (0-15 cm, 0-45 cm, 0-75 cm, 0-105 cm) was further performed to gain insight into the phenological and depth integrated impacts of ET on grain yield and protein.

Statistical Analysis at CARC

Because soil depth was assumed to be the limiting factor on stored soil moisture, block kriging was used to estimate mean soil depths for each treatment plot. Two separate empirical semivariograms were generated for each field from soil depth measurements (Figure 2.), and spherical semivarigarams were fit to each empirical semivariogram using weighted least squares (Fig 3). Block kriged soil depth predictions were made by:

$$Z(B) = \frac{1}{|B|}\int_B Z(s)ds \qquad \text{Eq 2.}$$

were *Z(B)* is the mean soil depth (cm) within a given treatment plot, *B*, |*B*| is the fixed plot area, and the integral represents cumulative point-kriged soil depth predictions within a plot derived from spherical semivariogram fits. More detailed descriptions regarding the theory of block kriging can be found in (Schabenberger and Gotway, 2004), but for this study, it is important to recognize that *Z(B)* is an estimate of the spatially averaged soil depth within each treatment plot at CARC.

To control for confounding effects of variable soil depth on yield and protein responses, analysis of covariance (ANCOVA) was used to evaluate cropping sequence effects. The specific model was:

$$y_{ijk} = \mu + \beta_i[Z(B)_i - \overline{Z(B)}] + \tau_j + \varepsilon_{ijk} \qquad \text{Eq 3.}$$

where β_i is the regression coefficient for soil depth, $Z(B)_i$ is the estimated soil depth within a given plot derived from block kriging and $\overline{Z(B)}$ is the mean of all soil depth estimates. Years were analyzed separately since differences in precipitation timing and amount can confound crop dependence on stored soil moisture (Lilley and Kirkegaard, 2007). Homogeneity of variance assumptions were tested via Brown Forsythe tests, and homogeneity of slopes assumptions were tested by checking that no significant soil depth by crop sequence interactions existed at the α=0.05 level. F-ratios were calculated using type III sums of squares and post-hoc multiple comparison procedures were conducted via Fisher tests. Treatment effects were considered significant at the alpha=0.05 level.

The SAS/GLM procedure (SAS Institute Inc., 2012) was used to conduct ANOVA and ANCOVA analysis, and block kriging was carried out using the R packages geoR (Paulo and Diggle, 2015) and gstat (Pebesma, 2004).

Results and Discussion

Climatic Context at NARC

The ten year (2006-2015) average growing season (April-July) precipitation at NARC was 186 mm. In 2014, growing season precipitation was well below average at 105 mm and only 63.2 mm falling between joint and maturity. Conversely, 2015 growing season precipitation was near average with 170 mm, but only 68.3 mm of effective rain was received between joint and maturity. In summary, wheat growth and grain production in 2014 and 2015 were severely affected by drought.

Effects of Crop Sequence on Winter Wheat Productivity at NARC

Cropping sequence affected grain yields, protein, and ET, while year affected yield and water use efficiency (Table 4). FAL-WW had greater yields and ET yet lower protein compared to intensified sequences. Both yields and water use efficiency were significantly greater in 2015 compared to 2014.

Yields were linearly related to ET. From joint to heading, there was a moderate linear fit between cumulative ET and yield ($R^2 = 0.50$), and from joint to maturity, the fit was stronger ($R^2 = 0.82$) (Fig 4.). Across years, FAL-WW and the intensified sequences extracted 45.3 mm and 34.6 mm, from the 0-45 cm soil depth and extracted 50.7 mm and 30.2 mm from the 45-105 cm soil depth respectively. This means that the primary differences in ET and hence yield were due to 20.5 mm more soil water extraction in FAL-WW below the 45 cm. Further, most water extracted below the 45-cm depth occurred after heading, and is why cumulative ET from joint to maturity better explained variation in the yield responses compared to cumulative ET between joint and heading.

Greater yields and water use efficiency in 2015 compared 2014 was likely due to differences in precipitation timing. In 2014, only 3.81 mm of precipitation fell between joint and heading compared to 50.3 mm of precipitation in 2015. Specifically in 2014, cumulative ET throughout the entire soil profile (0-105 cm) was 42.5 mm from joint to flag leaf stage and 62.5 mm from joint to heading in FAL-WW compared to 26.0 and 39.8 mm in the intensified sequences (CAM-WW, CAM-PEA-WW, PEA-CAM-WW) (Fig 5. Left). Correlation analysis (Fig 6. Left) showed moderate to strong trends between cumulative ET and yield from joint to flag leaf at the 0-15 cm ($r^2 = 0.59$) and 0-45 cm (r^2

= 0.71) depth intervals, but correlations from the 0-75 cm and 0-105 cm depth intervals were strong at 0.80 and 0.81 respectively. This indicates that less available water below 45 cm in intensified sequences negatively impact yields by flag leaf stage relative to FAL-WW in 2014. Alternatively correlations from joint to flag leaf and joint to heading generally did not exceed 0.50 (Fig. 6 Right) in 2015. Strong correlations between cumulative ET and yield were only apparent over the 0-105 cm depth interval from joint to milk (r^2 = 0.87) and joint to maturity (r^2 = 0.88). This suggests that yield variation was due to differences in soil water extraction from the 75-105 cm depth after heading in 2015.

Physiologically water stress from joint to heading/anthesis reduces seed number per head, whereas water stress from heading/anthesis to maturity reduces seed size (Savin et al., 2015). Numerous deficit irrigation studies have linked higher yields and water use efficiency to greater seed number per head from applied irrigation between jointing and anthesis compared to post-anthesis irrigation (Xue et al., 2003, 2006). Seed number per head and seed size were not measured in this study, but given that precipitation was 47 mm greater in 2015 from joint to heading, it is likely that greater seed number, spiked yields and water use efficiency.

Yield was negatively related to protein (R^2=0.40) and explains why FAL-WW had lower protein compared to intensive sequences (Table 4.). Protein was also related to ET over different growth stages. Notably linear fits between protein and ET were stronger between joint and heading (R^2 = 0.60) compared to ET from heading to maturity (R^2 = 0.01) (Fig 6). Further, the strongest negative correlations between cumulative ET by depth and protein occurred before heading in both years. Specifically in 2014 the strongest negative correlation between ET and protein was observed between joint and heading over the 0-105 cm depth increment ($r^2 = 0.88$), and in 2015 at the 0-15 cm and 0-45 cm depths between joint and flag leaf in ($r^2 \sim 0.79$) (Fig 7.). Results from this study suggest that greater crop ET from joint to diminished protein more so than ET from heading to maturity.

Based on two years data, CAM-PEA-WW, CAM-WW, and PEA-CAM-WW produced respective yields of 82 %, 72%, and 84 % of FAL-WW. Past estimates from the Canadian Prairies suggest that wheat yields should fall between 67 to 84 % to economically justify eliminating summer fallow (Zentner and Campbell, 1987). All intensified sequences fell within this range despite below average growing season precipitation, indicating that camellia and pea could be suitable rotational crops depending on markets for rotational crops. Further grain protein increased by ~0.63 % in intensified sequences, meaning there is less risk for diminished protein premiums compared to FAL-WW.

Climatic Context at CARC

The ten-year (2006-2015) average growing season (April-July) precipitation at CARC was 249 mm. In 2014, growing season precipitation was 140 mm, and in 2015, growing season precipitation was 258. Hence the 2015 growing season was notably better than 2014 due to substantially more precipitation.

Effects of Crop Sequence on Winter Wheat Productivity at CARC

Intensified sequences resulted in similar yield, and protein compared to FAL-WW in both 2014 and 2015 at CARC (Table 5.). These results support that there is marginal risk of diminished winter wheat productivity from intensifying sequences with pea and camelina.

Soil depth impacted yield and protein in 2014, but not in 2015 (Table 5). Yield increased by 40.5 kg ha^{-1} for each additional cm of block kriged soil depth (R^2=0.45) while protein decreased by 0.16 % in 2014 ($R^2 = 0.68$) (Fig. 7). Regressions were flat and variable in 2015 with yield only increasing by 17.1 kg ha^{-1} (R^2=0.07) for each additional cm of block kriged soil depth, and protein decreased by 0.09 % (R^2=0.26).

Rainfall amount and timing can explain the differences among yield, protein, and influence of block kriged soil depth on yield and protein for each year. Approximately 60 mm more rainfall fell in 2015 over the active crop cycle (Table 6.), which led to approximately 1100 kg ha^{-1} greater yields and 3.7% less protein than in 2014. Further, most precipitation fell between joint and heading in both seasons, but nearly 2.5 times more precipitation fell between joint and heading in 2015 (Table 6.). Greater precipitation between joint and heading likely led to greater water use efficiency and less dependency on deep stored soil moisture similar to wheat grown at NARC in 2015. Less dependency on deep soil moisture explains the weak trends between block kriged soil depth and protein and yield in 2015.

Summary and Conclusion

Winter wheat yield and protein responded differently to crop sequence at two contrasting sites with deep and shallow soils. At NARC, where soils were deep, the primary limitation on wheat yield was soil moisture below 45 cm. On average, intensified sequences extracted ~20.5 mm less water extracted below this depth compared to FAL-WW. Consequently yields in intensified systems ranged from72% to 84% (or 16% to 28% yield reduction) of FAL-WW yield. Alternatively, protein increased by ~0.63% in intensified sequences resulting from drought stress.

On shallow soils at CARC, cropping sequence did not impact wheat yield or protein. Block kriged soil depth showed respective positive and negative trends with yield and protein in 2014 when precipitation was 40 mm below average. No trends were observed in 2015, which likely resulted from 121 mm of precipitation that fell between joint and heading. Thus soil depth only influenced yield and protein in the low precipitation year at CARC.

Table 1. Growing season weather summary for the Northern Agricultural Research Station (NARC) Havre, MT and the Central Agricultural Research Center (CARC) Moccasin, MT described as 10-year (2006-2015) normals and 2014-2015 departures from normal.

	2006-2015	2014	2015	2006-2015	2014	2015	2006-2015	2014	2015
	Precipitation			Mean Monthly Maximum Temperature			Mean Monthly Minimum Temperature		
NARC	mm			°C			°C		
March	13.1	3.4	-1.7	8.0	-6.7	4.5	-4.9	-3.9	2.5
April	30.7	-9.3	-20.0	11.6	1.7	4.1	-1.6	0.7	1.5
May	72.5	-59.5	-19.9	16.7	2.2	2.1	3.4	0.4	0.4
June	53.4	3.0	-37.6	21.8	-0.7	5.9	7.5	-0.1	3.1
July	29.7	-15.2	61.0	28.9	0.6	0.0	11.4	0.6	1.6
Total/Avg.	199.3	-77.6	-18.2	--	--	--	--	--	--
CARC									
March	14.1	14.4	-5.3	8.0	-3.9	4.6	-2.0	-1.6	2.6
April	32.1	-15.1	-2.8	11.6	0.8	1.7	-1.3	0.3	0.5
May	78.5	-44.0	13.3	16.7	0.6	-1.5	3.0	0.3	-0.3
June	55.9	-0.5	-14.3	21.8	-1.9	3.3	9.0	-0.9	1.8
July	26.5	7.0	13.3	28.9	0.1	-2.4	10.1	0.0	-0.9
Total/Avg.	207.0	-38.3	4.2	--	--	--	--	--	--

Table 2. Soil physical properties for the Northern Agricultural Research Center (NARC) and the Central Agricultural Research Center (CARC).

		NARC			
Horizon	Depth Increment	Bulk Density	Texture	Plant Available Water	Stones
	cm	g cm^{-3}		mm	Percent Volume
A	0-13	1.36	Loam	21.21	1
Bt	13-33	1.45	Clay-Loam	40.6	0
Btk	33-48	1.5	Loam	36	1
Bk	48-84	1.65	Loam	83.16	5
Bky	84-122	1.63	Loam	105.3	1
		CARC¶			
A	0-15	1.46	Clay-Loam	24.1	13
Bk1	15-48	1.3	Clay	47.2	27
Bk2	48-91	NA	Coarse Sandy Loam	NA	88
Bk3	91-117	NA	Silt Loam	NA	85
C	117-160	NA	Silt Loam	NA	84

Soils information is taken from on-site soils characterization reports provided by the National Resource Conservation Service (NRCS). See (USDA, 1992) for more detailed information at NARC and (USDA, 2007) for CARC.

¶ Soil depths and properties vary spatially at CARC. Particularly the bottom depths for the Bk1 horizon may range from 20 cm to greater than 100 cm (Fig 1).

Table 3. Agronomic and management factors at the Central Agricultural Research Center (CARC) and the Northern Agricultural Research Center (NARC).

Agronomic Factors	CARC (Moccasin, MT)	NARC (Havre, MT)
Crop cultivars		
Wheat	Yellowstone	Genou
Seeding Rate (kg ha-1)		
Wheat	65	65
<u>2014 Growing Season</u>		
Wheat seeding date	Oct 2.	Oct 2.
Wheat flower date	Jun 22.	10 Jun.
Wheat maturity date	Jul 25.	18 Jul.
First moisture reading §	--	5 May.
<u>2015 Growing Season</u>		
Wheat seeding date	20 Sep.	23 Sept.
Wheat flower date	8 Jun.	5 Jun.
Wheat maturity date	10 Jul.	29 Jun.
First moisture reading §	--	17 Apr.

§ Soil moisture was only monitored at NARC since shallow and variable soil depths limited moisture to be monitored to a consistent depth CARC. Soil depth was assumed to be the limiting factor on stored soil moisture at CARC.

Table 4. Effects of Cropping Sequence on wheat productivity at Northern Agricultural Research Center (NARC) for the 2014 and 2015 growing seasons.

Crop Sequence	Yield kg ha^{-1}	Protein %	ET mm	WUE mm kg^{-1} ha^{-1}
			2014-2015¶	
FAL-WW	2895 B	14.0 B	168 B	17.3
CAM-PEA-WW	2375 A	14.7 A	131 A	17.9
CAM-WW	2090 A	14.6 A	131 A	16.0
PEA-CAM-WW	2441 A	14.6 A	147 A	16.7
Year				
2014	2260 a	14.8	151	14.7 a
2015	2641 b	14.8	140	18.9 b
			P-Values from F-tests	
Sequence	<0.01	<0.01	<0.001	NS
Year	<0.05	NS	NS	<0.01
Year x Sequence	NS	NS	NS	NS

Different letters indicate statistical differences among treatments or years at the 0.05 level by Fishers (LSD) test.

¶ Responses means are pooled across years since no significant interactions were detected.

Table 5. Effects of cropping sequence and soil depth on annual wheat productivity at Central Agricultural Research Center (CARC) for the 2014 and 2015 growing seasons.

Sequence	Yield kg ha-1	Protein %
	2014	
CAM-WW	2505	14.2
CAM-PEA-WW	2579	13.3
FAL-WW	2472	14.5
PEA-CAM-WW	2501	13.5
	P-Values from F-tests	
Soil Depth	<0.01	<0.01
Sequence	NS	NS
	2015	
CAM-WW	3834	9.9
CAM-PEA-WW	3519	10.3
FAL-WW	3644	9.7
PEA-CAM-WW	3650	10.2
	P-Values from F-tests	
Soil Depth	NS	¶
Sequence	NS	NS

¶ Homogeneity of slopes assumption was not met for protein responses in 2015, so sequence effects were evaluated using ANOVA.

Table 6. Cumulative precipitation from joint to distinct growth stages at the Central Agricultural Research Center (CARC) in 2014 and 2015.

	Precipitation			
	------------------------------------mm------------------------------------			
Year	Joint to Flag Leaf	Joint to Heading	Joint to Milk	Joint to Maturity
2014	22.2	60.9	68.9	98.4
2015	26.4	147.5	149.8	160.0

Figure 1. Image of the shallow and variable soil depths from a soil pit at the Central Agricultural Research Center (CARC). Fine textured soils are underlain by a quaternary gravel layer. Fine textured soils range in depth from 20 to greater than 100 cm and limit stored soil moisture. Orange line shows interphase between the fine-textured soils and gravel layer.

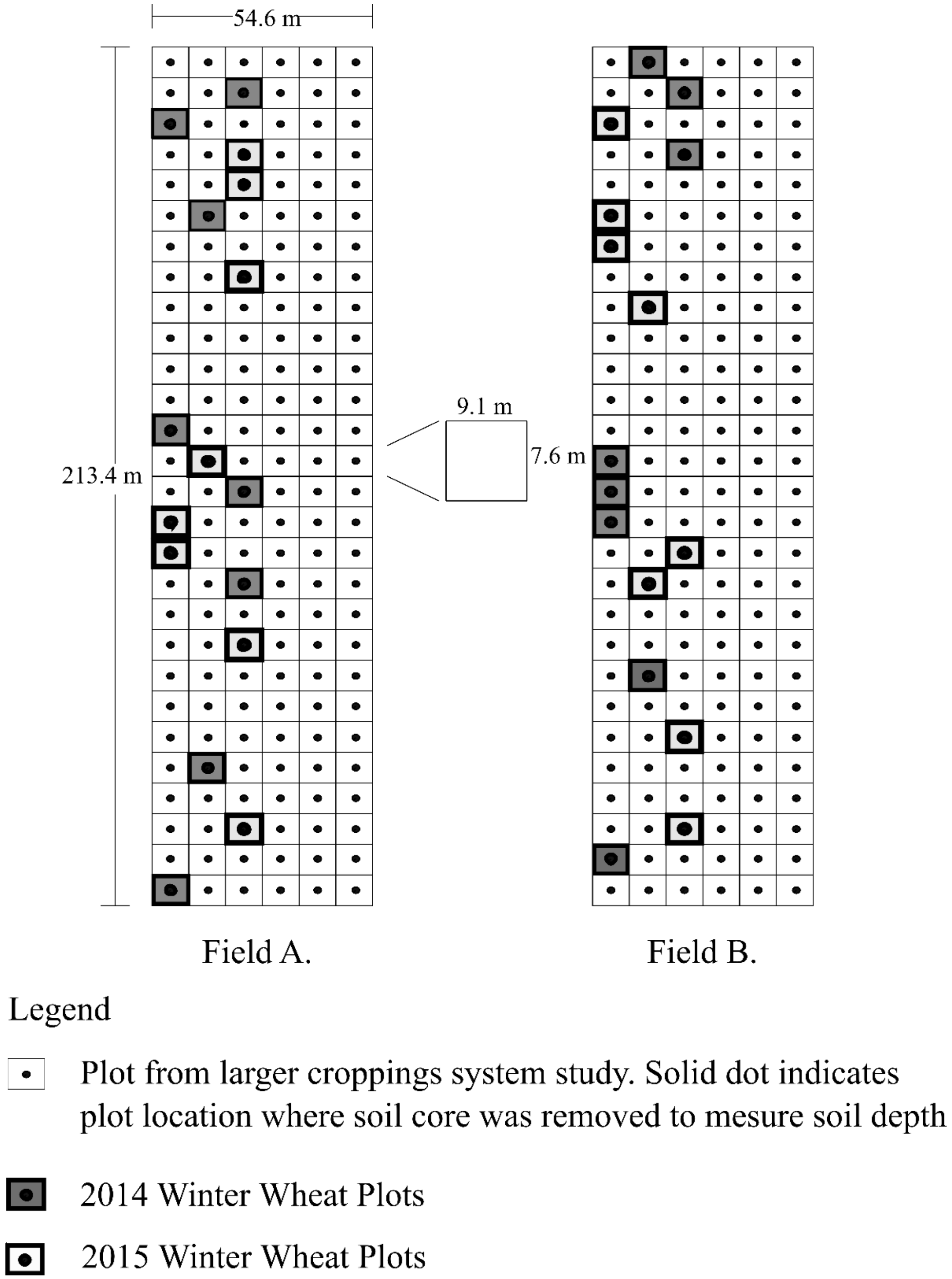

Figure 2. Field layout at the Central Agricultural Research Center (CARC). Soil cores were removed from plot centers as indicated by solid circles in a grid formation, and soil depths were recorded. Soil depth measurements were then used to generate semivariograms for each field.

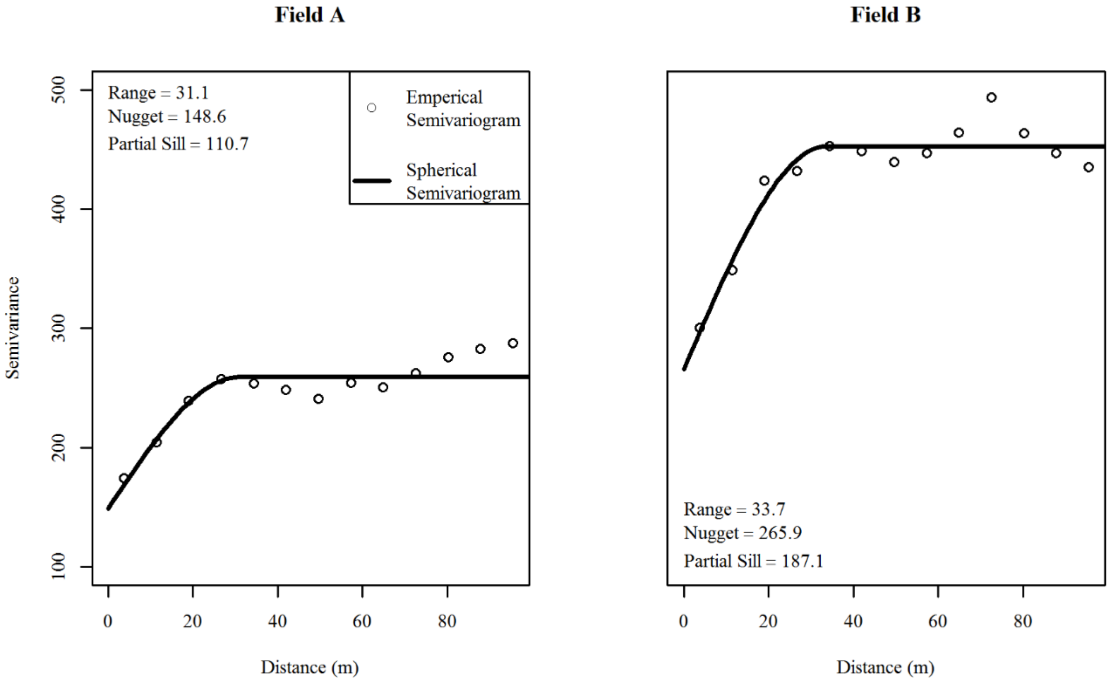

Figure 3. Empirical semivariograms (hollow circles) and weighted least squares spherical semivariogram fits (dark lines) used to generate block kriged soil depth estimates at the Central Agricultural Research Center (CARC). Range, nugget, and partial sill are the parameter estimates which define the shape of each spherical semivariogram fit.

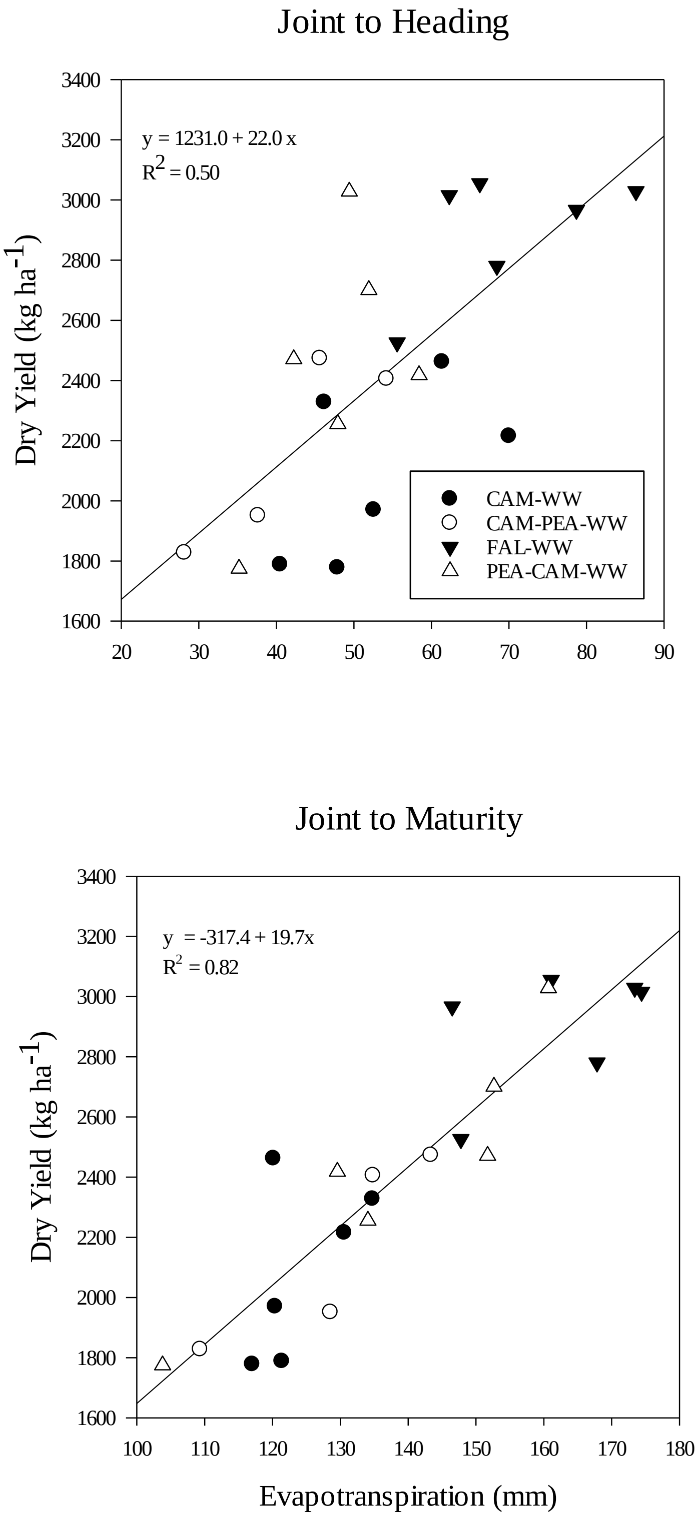

Figure 4. Linear regressions of yield and protein vs cumulative evapotranspiration (ET) from joint to heading (top) and joint to maturity (bottom) within the 1.05 cm soil profile at the Northern Agricultural Research Center (NARC).

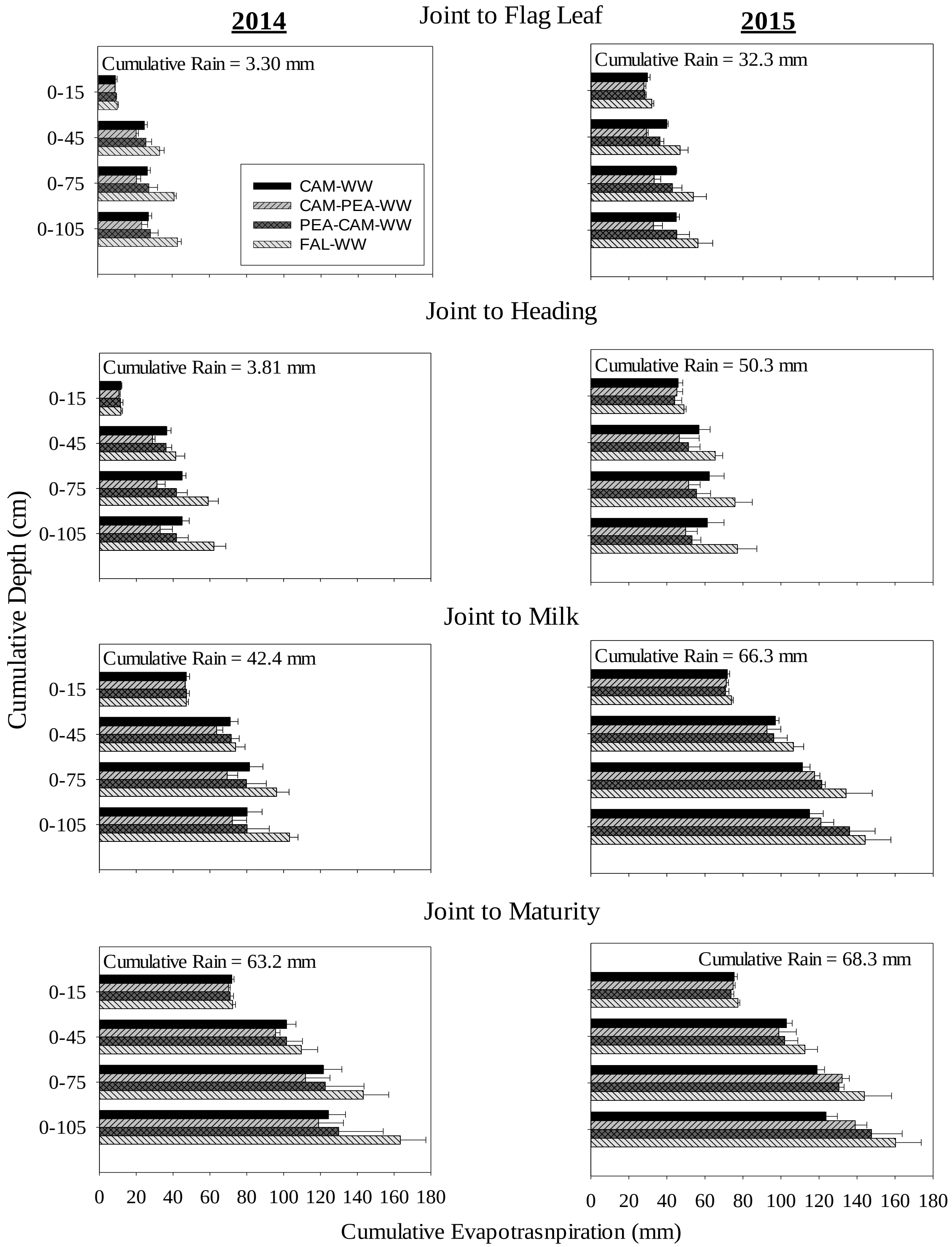

Figure 5. Cumulative evapotranspiration (ET) (e.g. cumulative rain + change in soil moisture) over increasing depth increments from joint to subsequent growth stages over the 2014 (left) and 2015 (right) growing seasons at the Northern Agricultural Research Center (NARC). Error bars are standard deviations on means.

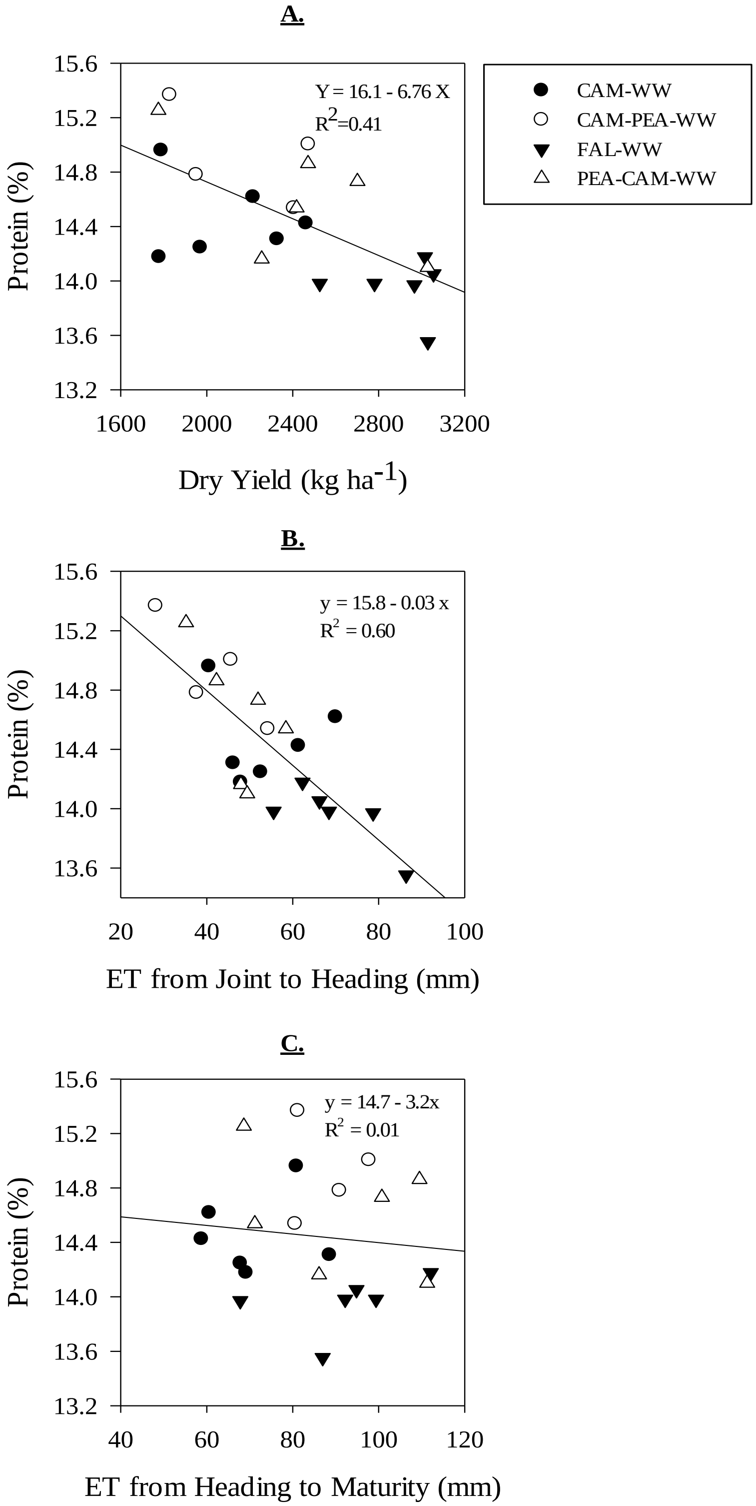

Figure 6. Linear relationships of protein vs. yield (A), protein vs. evapotranspiration (ET) from joint to heading (B), and protein vs. ET from heading to maturity (C) at the Northern Agricultural Research Center (NARC) for the 2014-2015 growing seasons.

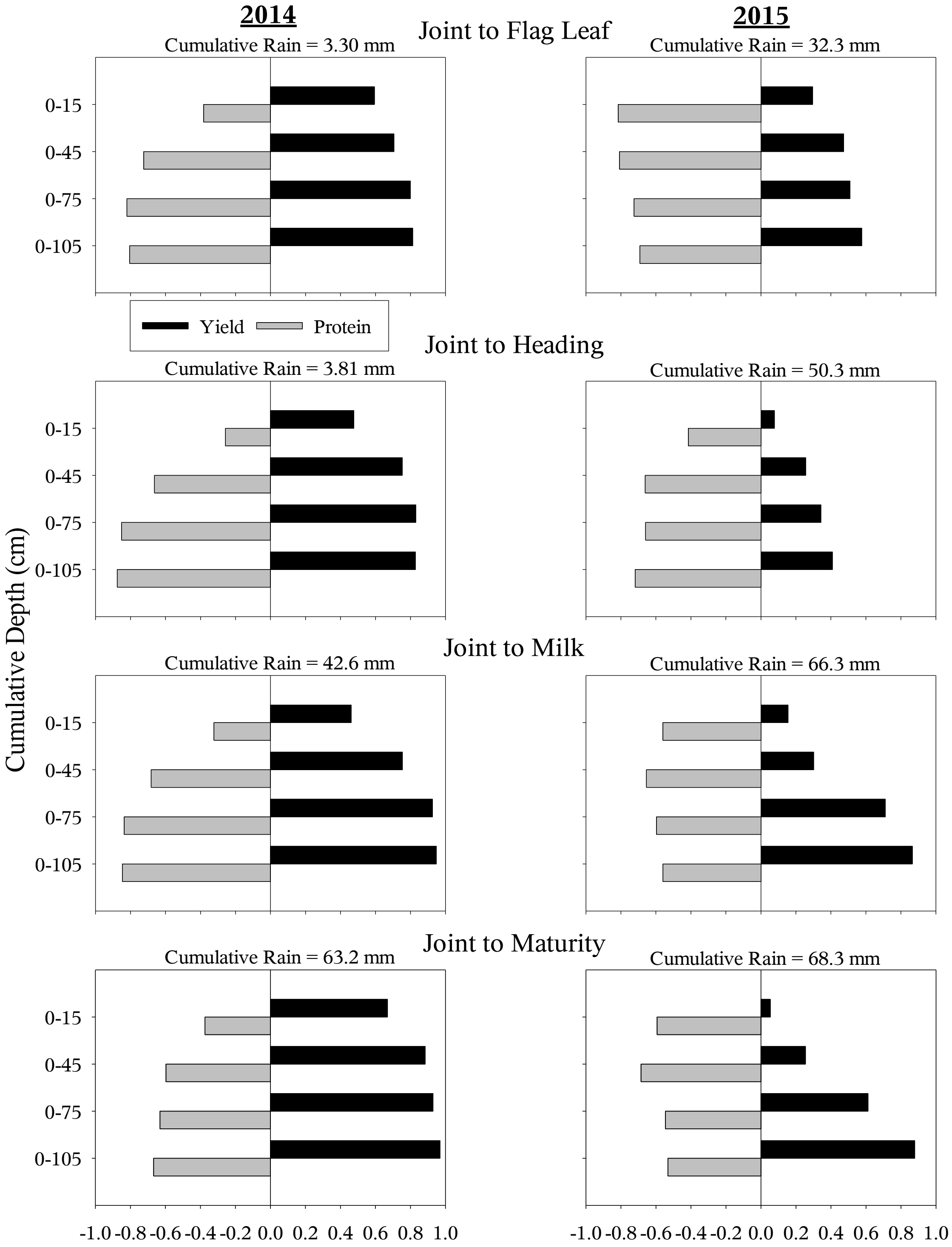

Figure 7. Pearson correlations between cumulative evapotranspiration (ET), yield and protein over increasing depth from joint to subsequent growth stages over the 2014 (left) and 2015 (right) growing seasons at the Northern Agricultural Research Center (NARC).

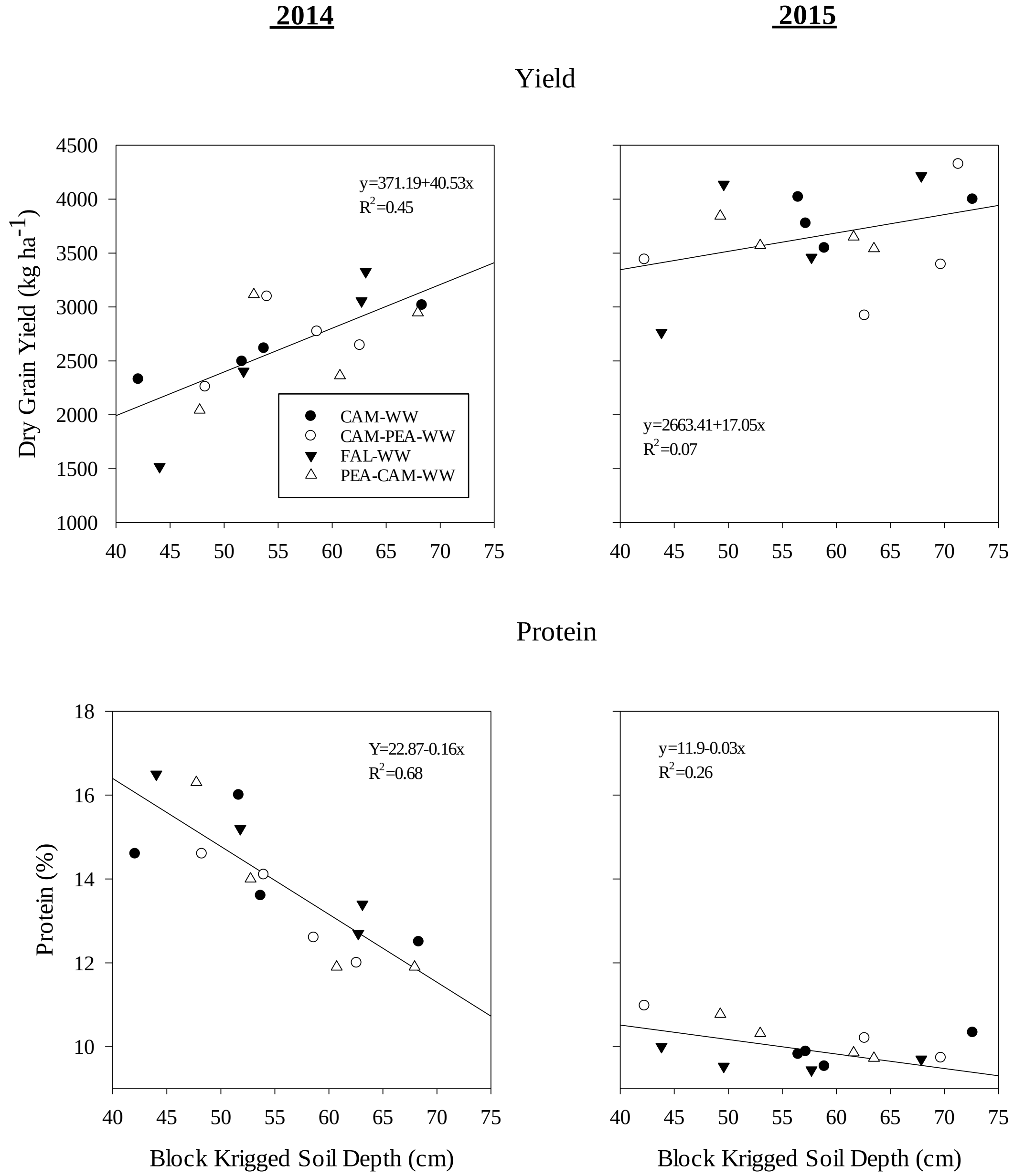

Figure 8. Linear regressions between yield and protein versus block kriged soil depth at the Central Agricultural Research Center (CARC) over the 2014 (left) and 2015 (right) growing seasons.

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CHAPTER THREE

ENIVIRONMENTAL CHARACTERIZATION USING DROUGHT STRESS PATTERNS TO IMPORVE WINTER WHEAT AND FIELD PEA YIELDS IN MONTANA

Abstract

Terminal drought is common in Montana's agroecosystems. The objective of this study was to characterize drought stress patterns in winter wheat (*Triticum aestivum* L.) and field pea (*Pisum sativum* L.) using a dynamic simulation approach. The FAO-56 and ARID water balance models were coupled with daily weather, soils, and cultivar testing data across 3 sites x 9 years x 9 cultivar combinations in winter wheat and 4 sites x 7 years x 6 cultivar combinations in field pea. Four drought patterns in wheat (DPW-1 to -4) and five drought patterns in pea (DPP-1 to -5) with increasing drought intensity (e.g. ARID indices) were characterized. Average winter wheat yields and standard errors were (4421 ± 80 kg ha^{-1}), (3342 ± 71 kg ha^{-1}), (2777 ± 141 kg ha^{-1}), and (2539 ± 113 kg ha^{-1}) for DPW-1, DWP-2, DPW-3, and DPW-4, respectively. Average pea yields and standard errors were (2877 ± 101 kg ha^{-1}), (2364 ± 125.7 kg ha^{-1}), (2213 ± 126 kg ha^{-1}), (1585 ± 76.9 kg ha^{-1}), (974.7 ± 30.2 kg ha^{-1}) and for DPP-1, DPP-2, DPP-3, DPP-4, and DPP-5 respectively. Yields were most negatively correlated with drought intensity at heading in wheat (r^2=-0.79) and at flowering in pea (r^2=-0.76). Probability of occurrence indicated the southern Montana site was mainly associated with the least stressed (highest yielding) winter wheat drought pattern whereas no single site was associated with the least-stressed

pea drought pattern. Interpreting dynamic drought stress patterns in conjunction with probability of occurrence may help accelerate breeding and management efforts in winter wheat and field pea on a site-specific basis.

Introduction

Terminal drought beginning in June to early July is a trademark of Montana’s dryland cropping environments (Padbury et al., 2002). High yielding environments are associated with timely precipitation and favorable temperatures lasting into the grain fill period, whereas early onset of drought constitutes low yielding environments. A common goal for both breeders and producers is to minimize terminal drought impacts to optimize productivity. Breeders adapt plant traits such as increased root length density to maximize soil water extraction (Bueckert and Clarke, 2013) or develop early-maturing breeds for late-season drought avoidance. Early seeding generally improves yield for spring-sown crops (Black and Siddoway, 1977; Miller et al., 2006a) since critical growth stages are better timed with seasonal rainfall patterns, and responsible nitrogen (N) application rates and timing can keep the crop from ‘haying off’ in the absence of late-season rainfall (van Herwaarden, 1998; Savin et al., 2015). Hence environment, genetic, and management factors impact crop productivity.

Environmental characterization is an important component to improving crop productivity in Montana. Past environmental characterization has been based on pedo-climatic variables (Padbury et al., 2002) where regions with similar soils, precipitation, and temperature are grouped into a single agroecosystem. The predominant agroecosystems in Montana are characterized by well-drained soils and annual precipitation ranging from 300-475 mm with most precipitation received during the April through July growing season (Padbury et al., 2002). Results from small-scale variety testing or field experiments conducted within a defined agroecosystem could hypothetically be extrapolated to the entire agroecosystem, but Montana’s highly-variable continental climate make such extrapolations crude. More recently Mohammed et al. (2016) utilized yield performance from multi-location cultivar trials to characterize mega-environments for field pea (*Pisum sativum* L.) using bi-plot analysis. While bi-plot analysis can be useful for identifying cultivars well-adapted to certain regions, it does not provide a physiological framework as to why different cultivars perform better in certain regions (Baker, 1996).

Dynamic environmental characterizations provides an alternative to overcome the broadness of pedo-climatic environmental characterization and the black-box nature of mega-environments derived from biplot analysis. Specifically, in water limited regions, crop drought stress indices simulated from crop models can quantitatively evaluative the timing and severity of water stress a crop experiences over its growth cycle (Muchow et al., 1996; Chapman et al., 2000). By combining long-term weather, management, crop phenology, and soils information, crop-specific drought patterns are simulated across multiple years and locations. Environmental characterization based on similar drought patterns are then generated through clustering methods (Chauhan et al., 2013; Chauhan and Rachaputi, 2014). This approach quantifies the timing and severity of drought stress a crop will likely undergo given a specific location and seeding date. A quantitative interpretation of drought stress can help breeders adapt specific plant traits for drought avoidance on a per-site basis (Chenu, 2015). Likewise, risk management such as the decision to foliar apply N to boost grain yield or quality can better be evaluated based on the level of drought stress a crop is likely to experience during critical growth stages.

Environmental characterization from drought patterns have been applied widely in Australia (Chenu et al., 2011; Sadras et al., 2012, 2013). For instance, Sadras et al. (2013) showed the primary drought patterns for field pea were characterized by drought stress over flowering and could informatively recommend breeding for low pod wall ratio to boost yields. Drought characterizations have not been applied in Montana but will be particularly important for wheat and pea. That is, wheat is Montana’s predominant cash crop, and pea production is rapidly expanding due to rising global demand (Lee, 2011). Further crop production is nearly always water-limited, making drought-based environmental characterizations appropriate for Montana agriculture. The primary objectives of this study were a) to characterize drought stress patterns for winter wheat and pea by coupling a simulation procedure with cultivar testing data collected from four regions in Montana and b) to evaluate effects of characterized drought patterns and cultivar on winter wheat and pea yields.

Materials and Methods

Site Description and Agronomy Data

Winter wheat (*Triticum aestivum* L.) (2005-2013) and pea (*Pisum sativum* L.) (2008-2014) cultivar yield data were compiled from four Montana State University

(MSU) research centers. The centers included the Central, Eastern, Northern and Southern Agricultural Research Centers (CARC, EARC, NARC, SARC) and represent the general range of climate patterns and soil types across Montana's dryland production regions (Figure 1., Table 1.). Agronomic data comprised nine and seven cropping seasons for winter wheat and pea, respectively. Cultivar trial data included seeding dates, heading or flowering dates, harvest dates and final grain yields. Only common cultivars across years were considered, and incidences where storm, animal, and pest damage was reported were omitted. For wheat, heading dates were determined as the time when 50 percent of the heads in a plot had extended above the flag-leaf collar, and for pea, flowering was recorded as the time when 50 percent of plants in each plot had reached first flower. Wheat was planted on no-till fallow ground at 23-30 cm row spacing (depending on site), and in general pea was seeded into cereal stubble at 30 cm row spacing—although in some cases pea was planted on fallow. Fertilizer rates were applied according to Montana State University recommendations based on targeted yield potential for wheat, and pea seed was inoculated according to local recommendations. Additional herbicide and fungicide management was adapted on a site-specific basis. Agronomic and site details are summarized in Tables 1 and 1 for pea and wheat respectively.

Model Description for Simulating Drought Patterns and Assumptions

Crop evapotranspiration was simulated by combining the FAO-56 Penman-Monteith model (Allen et al., 1998) with the Agricultural Reference Index for Drought

(ARID) water balance model (Woli et al., 2012). The FAO crop coefficient method simulates potential evapotranspiration (PET) by multiplying daily crop coefficients (Kc) by reference evapotranspiration (ET_o) of a well-watered grass at peak growth. Mathematically PET is given as

$$PET_i = Kc_i \, x \, ET_{oi} \qquad \text{Eq 1.}$$

where the subscript *i* denotes daily values for each variable. Daily ET_o values were derived from daily temperature, humidity, wind speed measurements taken from on-site weather stations. Daily crop coefficients were estimated from a crop coefficient vs. phenological growth stage curve where the initial (Kc_{ini}), maximum (Kc_{max}), and final crop coefficients define points on the curve corresponding to specific phenological stages (Fig 2.).

For this analysis, it was assumed that Kc_{ini}, Kc_{max}, and Kc_{end} corresponded to emergence, heading, and physiological maturity in wheat, and to two-leaf stage, flowering and physiological maturity in pea. Daily crop coefficients were interpolated linearly between all points, and Kc_{max} remained constant form heading to seedfill in wheat, and durring flowering in pea. All crop growth stages except observed heading dates were approximated based on growing-degree day (base temp=0°C) estimates published by (Miller et al., 2001). $Kc_{ini,}$ Kc_{max} and Kc_{end} were taken from (Allen et al., 1998).

The ARID water balance model assumes a uniform soil profile within a specified rooting depth (z) of a given crop. Runoff is estimated by the Natural Resource

Conservation Service (NRCS) curve number (CN) method, and drainage below the root zone (z) is specified by an empirical drainage coefficient (β) (Suleiman and Ritchie, 2004) specifying the fraction of daily soil-water that can be drained when the soil profile exceeds field capacity (θ_{fc}). Root water extraction is assumed to be constant throughout the profile, and actual evapotranspiration (ET_a) is a function of soil water availability and evaporative demand. With sufficient soil water, ET_a is equal to PET, but as soil water diminishes ET_a is reduced. Mathematically ET_a is given by:

$$ET_{ai} = min\begin{cases} PET_i \\ \alpha\ x\ \theta_{a,i-1}^{ad} \end{cases} \qquad \text{Eq 2.}$$

where α is and empirically derived root water uptake constant (Dardanelli et al., 2004) controlling the maximum daily fraction of water above wilting point (θ_{wp}) that can be extracted by roots, and $\theta_{a,i-1}^{ad}$ (cm^3 cm^{-3}) is the plant available water from the previous day. Daily drought stress index, or the ARID index, is given as:

$$ARID_i = 1 - \frac{ET_{ai}}{PET_i}\,. \qquad \text{Eq .3}$$

When PET_i equals ET_{ai} , there is no drought stress, but when PET_i exceeds $ET_{a,}$ the ARID index asymptotically approaches one. Hence larger ARID indices indicate greater drought stress.

Initial soil moisture inputs (θ_{ini}) are lastly required to initiate the model. Since winter wheat was planted following a 14 month fallow period, it was assumed that θ_{ini} was at field capacity to 120 cm or the effective rooting depth of wheat. Similarly, given pea’s shallow root zone (~60 cm), it was assumed the soil profile had recharged between harvest of the previous crop and spring seeding. Altogether, fifteen inputs are needed to generate ARID indices using the described method. A description of each input, value and source or reference is provided in Table 2.

Simulations and Statistical Analysis

Model simulations were run for each site x crop x cultivar combination beginning at reported planting dates and lasting to physiological maturity. A total of 231 simulations were run for wheat (3 sites x 9 years x 9 cultivars – incidences of crop damage), and a total of total of 111 simulations were run for pea (4 sites x 7 years x 6 cultivars – incidences of crop damage). Daily ARID drought indices generated from each simulation were then averaged at discrete 100 degree-day intervals referenced from reported heading or flowering dates to produce 231 and 117 individual drought patterns for wheat and pea respectively. Similar drought patterns were then grouped into fixed classes using K-means clustering , where the number of clusters (e.g. fixed classes) were determined using the scree plot method (Gatell, 1966) on within clusters sums of squares. Fixed drought patterns were established by taking marginal means on 100 degree-day ARID intervals grouped within the same cluster.

To assess the effect of fixed drought patterns and cultivar on yield, two-way ANOVA given by the model:

$$Yield_{ijkl} = \mu + G_i + E_k + GE_{ijk} + \varepsilon_{ijkl} \qquad \text{Eq 5.}$$

was run where G_i is cultivar and E_k is the fixed drought pattern derived from the K-means clustering. Type II sums of squares was used to test for treatment effects due to the unbalanced grouping of cultivar within fixed drought patterns (Langsrud, 2003), and homogeneity of variance assumptions were tested via Levene’s test. Post-hoc multiple comparisons on weighted mean yields were conducted via Tukey tests. Because unbalanced groupings of cultivar within fixed drought patterns unavoidable, differences were considered significant at the α=0.10 level. Additionally, Pearson correlation analysis relating individual yield observations to ARID drought indices were interpreted in conjunction with the number of occurrences each fixed drought pattern was observed at each site to help discuss and interpret how breeding and management efforts can be improved on a per-site basis.

All analyses were conducted in R statistical programming software (R Core Team, 2014), and model simulations were generated by combining custom R-code with the ARID water balance model implemented in the R-package ZeBook (Brun et al., 2013).

Results and Discussion

Drought Pattern Characterization and Effects of Fixed Drought Pattern and Cultivar on Winter Wheat Yields

K-means clustering distinguished four discrete classes, and thereby four fixed drought patterns for winter wheat (Figure 3 A). Fixed drought patterns were the result of 231 site x crop x cultivar model simulations which depend on seeding dates, heading dates, daily climate and soils inputs as well as assumptions relating crop water demand to crop growth stages (*see model description section*). From a mechanistic standpoint, each drought pattern and their corresponding ARID drought indices have been quantified through soil-plant-atmosphere interactions and represent the four general yet dynamic drought patterns that winter wheat cultivars experienced over 2005 to 2013 growing seasons at CARC, NARC and SARC.

The least stressed drought pattern (DPW-1) was characterized by no drought stress until 200 degree-days after heading and reached a maximum ARID index of 0.24 by physiological maturity, whereas drought stress began between 600 and 300 degree-days before heading and asymptotically approached ARID indices exceeding 0.80 by maturity for the remaining fixed drought patterns (DPW-2,DPW-3 and DPW-4). The main difference among all fixed drought patterns were the ARID indices at heading, with respective values of 0.00, 0.32, 0.52, and 0.74 for DPW-1, DPW-2, DPW-3 and DPW-4. Accordingly, mean yields associated with DPW-1, DPW-2, DPW-3 and DPW-4 were 4421 kg ha^{-1}, 3343 kg ha^{-1}, 2777 kg ha^{-1}, and 2539 respectively, with all yield comparisons differing significantly except DPW-2 and DPW-3 and DPW-3 and DPW-4 (Figure 3 B.). Genotype did influence yield, but in only one case. Mean yields for cv. Yellowstone were 3698 kg ha^{-1} compared with 2787 kg ha^{-1} for cv. Bynum (*data not shown*). This result is expected though because Bynum is specifically bred for high grain protein as opposed to yield, whereas cv. Yellowstone is bred for yield. These results coupled with no significant G x E interaction (data not shown) indicate that cultivar has a generally low impact on yield compared to fixed drought pattern and that drought severity—specifically at heading—is an important factor for determining yields.

Implications on Winter Wheat Breeding. The trend in decreasing yields with increasing ARID indices at heading is best illustrated by correlations shown in Figure 3 C. The strongest negative correlations among observed yields and ARID values occurred from 50 (r= -0.79) to 150 degree-days after heading (r= -0.72). Physiologically heading to shortly after flowering is a critical period for determining seed per head in wheat. It has been suggested that adapting plant traits to reduce stress at heading stage will benefit yields more so than reducing stress during grain fill when seed size is set (Savin et al., 2015). By this logic, correlations agree that seeds per head is *generally* a more critical yield component than seed size, but this does not imply adapting traits to mitigate drought at heading is the best strategy to increase yields for all sites. For example, DPW-1 is characterized by no stress until 250 degree-days after heading, and the number of occurrences based on 10-year data (Figure 3 D.) show that wheat grown at SARC was associated with DPW-1 nearly 80 % of the time. This implies that winter wheat cultivars at SARC typically underwent drought during grain-fill but not at heading. This could mean targeting traits to increase seed-size could benefit yields at SARC. Alternatively CARC and SARC were associated with DPW-2, DPW-3, and DPW-4 which were characterized by drought stress well-before heading. Targeting traits to mitigate drought stress at heading may increase seeds per head and could be an effective strategy to increase yield at these sites.

Implications on Winter Wheat Management. Interpreting fixed drought patterns in conjunction with number of occurrences can also aid in management decisions. Timing of fertilizer N application has received considerable attention in Montana (Burgess et al., 2014; Chen, 2014). One management option is to apply additional N at heading to boost protein yields (Westcott et al., 1997; Chen et al., 2008), but the overall effectiveness of this strategy depends on seeds per head. Lower grain protein is associated with higher seeds per head since plant N reserves are distributed to more ‘sinks’ for protein synthesis (Brown et al., 2005). If wheat has undergone considerable drought stress by heading, seed number per head will be low, and plant N reserves will likely be sufficient to meet protein premiums. Alternatively, low drought stress at heading is indicative of high seeds per head, so applying more N may be a good strategy to achieve targeted protein levels. Because ARID indices were generally low over heading at SARC, a second application of N would more likely spike protein levels at SARC more so than at CARC and NARC.

Drought Pattern Characterizations and Effects of Fixed Drought Pattern and Cultivar on Field Pea Yield

Five fixed drought patterns were established for pea (Figure 4 A.) and were the result of 111 site x crop x cultivar model simulations experienced at CARC, EARC, NARC, and SARC over the 2008-2014 growing seasons. The least stressed drought pattern was DPP-1 and was characterized by modest (<0.10) ARID values from emergence to flowering. Thereafter, the ARID index rose sharply to a maximum of 0.57 at 350 degree days after flowering. Following the peak, ARID values steadily fell to 0.35 at maturity. The moderately stressed fixed drought patterns—DPP-2 and DPP-3—had similar drought patterns characterized by increasing ARID indices from 150 degree-days before flowering and reached respective ARID indices of 0.65 and 0.69 at 50 degree-days after flowering. The difference between DPP-2 and DPP-3 were the ARID values over the last 150 degree-days as a result of 10 mm greater precipitation in DPP-2 after flowering. The highest stressed fixed drought patterns were DPP-4 and DPP-5 with ARID indices beginning to increase 350 degree days before flowering and asymptotically reaching maxima of approximately 0.70 by maturity.

Notably mean pea yields for fixed drought patterns were negatively associated with ARID indices at flowering, and followed in the order of DPP-1>DPP-2>DPP-3>DPP-4>DPP-5, and were 2877 kg ha^{-1}, 2364 kg ha^{-1}, 2212 kg ha^{-1}, 1585 kg ha^{-1}, and 975 kg ha^{-1} respectively (Figure 4 B.). No significant yield differences were found between DPP-1 and DPP-2, DPP-2 and DPP-3, or DPP-4 and DPP-5 while remaining comparisons differed significantly. Further cultivar had no significant effect on yield. Similar to winter wheat, these results indicate that fixed drought patterns, and particularly drought severity at flowering, have a larger impact on yield compared to cultivar.

Implications on Pea Breeding. The strongest negative correlations between ARID indices and yield were observed from 50 degree days before flowering to (r= -0.76) to 50 degree-days after observed flowering dates (r=-0.75) (Figure 4 C.). These correlations are expected since seed number is set over the flowering window in pea, and drought stress incurred during flowering often results in the largest yield reductions in field pea relative to other growth stages (Guilioni et al., 2003; Sadras et al., 2012, 2013). Possible adaptive traits to reduce yield loss over flowering include increased growth rates (Guilioni et al., 2003) or more explicitly low pod to wall ratio (Sadras et al., 2013). Importantly these traits may benefit pea yields at all sites since the number of occurrences are somewhat uniform across all fixed patterns (Figure 4 D.).

Earlier flowering dates could also mitigate drought stress in pea. Averaged across cultivars, observed flower dates for pea were July 1st (Julian day=182), June 23rd (Julian day=174), June 21st (Julian Day=172) and June 14th (Julian day=165) at CARC, EARC, NARC, and SARC respectively. This means that pea reached its critical growth phase (e.g. early flower) in the latter half of June, yet the latter half of June extending into July is generally characterized by diminishing precipitation and increasing evaporative demand. Further, considering pea's shallow rooting depth (60 cm), stored soil moisture is quickly exhausted during extended periods with no rainfall.

<u>Implications on Pea Management.</u> From a management standpoint, pea offers benefits as a rotational crop. Specifically, replacing the summer fallow period with pea can increase producer economic returns through greater harvest frequency and fertilizer N savings from N mineralized in pea residues to the succeeding crop (Chen et al., 2012; Miller et al., 2015). The primary disadvantage, alternatively, is that, during drought cycles, pea may deplete water reserves, and the following crop may suffer substantial yield reductions (Miller and Holmes, 2005a). To alleviate this risk, producers could early-terminate pea as hay or green manure at early flower and conserves soil moisture while providing mineral N benefits to the next crop (Miller et al., 2006c). The decision to early-terminate pea will depend on market values and pea yield potential—low market values will provide more incentive to early terminate a low-yielding crop and vice versa.

Early yield predictions at flowering could provide decision support for producers considering early-terminating pea. Because generating ARID indices requires simulating a daily water balance (Eq 3.), simulated stored soil moisture at the time of pea flowering could provide a mid-season estimate of pea yield potential. Figure 5. shows the relationship between observed yields and simulated plant available water at observed flowering dates. The reasonable relationship (R^2=0.61) can be explained on two accounts. First plant available water is indicative of the drought severity pea has undergone and is currently experiencing at flowering (Eq. 3), and second, plant available water acts as a buffer against increasing evaporative demand and diminishing rainfall (Guilioni et al., 2003) which frequently occurs near flowering in Montana. While this model remains coarse, it requires basic soils and weather inputs that could rapidly be obtained and could ultimately serve as a functional tool (Ritchie, 1991) to address the economic tradeoffs of early terminating pea.

Summary and Conclusion

Combining the FAO-56 Penman-Monteith and the ARID water balance models provides a method for characterizing drought patterns for wheat and pea yields. Four drought patterns were characterized for winter wheat cultivars grown at CARC, NARC and SARC from 2005-2013, and five patterns were characterized for pea grown at CARC, NARC, SARC, and EARC from 2008-2014. Yields were most negatively correlated with ARID values at heading in wheat and flowering in pea. SARC was generally associated with the least stressed drought patterns for wheat, whereas no clear associations between location and drought stress patterns were evident in pea. In general, cultivar had a marginal effect on yield relative to drought patterns for both crops, but quantitative drought pattern characterization provides deeper insights into the complexities that govern crop yields compared to nominal or pedo-climatic based environmental characterizations. Such insights may accelerate breeding and management efforts.

Table 1. Summary data from state-wide cultivar trial testing for pea at the Central Agricultural Research Center (CARC), Northern Agricultural Research Center (NARC), Eastern Agricultural Research Center (EARC), and the Southern Agricultural Research Center (SARC). Pea data pertains to 2008-2014 growing seasons.

Site Description	Year	Seeding Date	Flower Date	Harvest Date	Grain Yield
CARC	------	------	--------	------	kg ha^{-1}
Lat: 47^{o} 03' 32" N	2008	--	--	--	--
Lon: 109^{o} 57' 03" W	2009	Apr 13.	Jun 27.	Aug 06.	975
Elevation: 1293 m	2010	Apr 09.	Jun 29.	Aug 07.	2615
Soils: Judith C-L	2011	Apr 27.	Jul 08.	Aug 09.	914
PAW$_{600}$: 87 mm	2012	Apr 11.	Jun 26.	Jul 12.	1156
	2013	Apr 19.	Jun 29.	Jul 30.	1645
	2014	Apr 09.	Jul 03.	Aug 01.	2008
NARC					
Lat: 48^{o} 29' 08" N	2008	Apr 14.	Jun 22.	Aug 01.	3667
Lon: 109^{o} 48' 08" W	2009	Apr 13.	Jun 18.	Jul 28.	2249
Elevation: 826 m	2010	Apr 20.	Jun 26.	Aug 06.	3271
Soils: Joplin C-L	2011	--	--	--	--
PAW$_{600}$: 98 mm	2012	Apr 13.	Jun 17.	Jul 20.	1831
	2013	--	--	--	--
	2014	Apr 20.	Jun 21.	Jul 28.	2044
EARC					
Lat: 47^{o} 43' 35" N	2008	Apr 18.	Jun 22.	Jul 30.	1204
Lon: 104^{o} 09' 01" W	2009	Apr 22.	Jun 21.	Aug 13.	1791
Elevation: 899 m	2010	Apr 22.	Jun 24.	Aug 13.	3139
Soils: Williams C-L	2011	Apr 28.	Jul 02.	Aug 05.	2344
PAW$_{600}$: 112 mm	2012	Apr 17.	Jun 18.	Jul 30.	1275
	2013	--	--	--	--
	2014	Apr 23.	Jun 21.	Jul 31.	2662
SARC					
Lat: 45^{o} 55' 25" N	2008	Mar 20.	Jun 16.	Aug 01.	1814
Lon: 108' 14" 37' W	2009	Mar 23.	Jun 09.	Jul 21.	2116
Elevation: 919 m	2010	Mar 27.	Jun 11.	Jul 29.	2614
Soils: Fort Collins C-L	2011	--	--	--	--
PAW$_{600}$: 98 mm	2012	Apr 05.	Jun 11.	Jul 23.	1367
	2013	--	--	--	--
	2014	May 05.	Jun 21.	Aug 04.	1068

Pea Cultivars were CDC Striker, Cruiser, Delta, DS Admiral, Majoret, SW Midas

-- Data is not relevant or available due to storm, pest or animal damage.

PAW—Plant available water taken from web soil survey (Soil Survey Staff, 2015). Subscripts indicates a 600 mm rooting depth (z) for pea.

Table 2. Summary data from state-wide cultivar trial testing for winter wheat at the Central Agricultural Research Center (CARC), Northern Agricultural Research Center (NARC) during the 2005-2014 growing seasons. Winter wheat is not grown at the Eastern Agriculture Research Center (EARC) due to winterkill.

Site Description	Year	Seeding Date	Heading Date	Harvest Date	Grain Yield
CARC	------	------	------------	---------	kg ha^{-1}
Lat: 47° 03' 32" N	2005	Sep 29.	Jun 21.	Aug 04.	2311
Lon: 109° 57' 03" W	2006	Sep 29.	Jun 05.	Jul 18.	3144
Elevation: 1293 m	2007	Sep 26.	Jun 11.	Jul 25.	4375
Soils: Judith C-L	2008	Sep 18.	Jun 23.	Aug 12.	2777
PAW$_{1200}$: 133 mm	2009	Sep 24.	Jun 20.	Aug 08.	2594
	2010	Oct 17.	Jun 26.	Aug 12.	3430
	2011	Sep 29.	Jun 30.	Aug 08.	2590
	2012	Sep 27.	Jun 16.	Jul 26.	1880
	2013	Sep 27.	Jun 20.	Aug 08.	3167
	2014	--	--	--	--
NARC					
	2005	Sep 28.	Jun 13.	Aug 14.	3514
Lat: 48° 29' 08" N	2006	Sep 20.	Jun 01.	Jul 25.	3270
Lon: 109° 48' 08" W	2007	Sep 29.	Jun 08.	Jul 25.	3311
Elevation: 826 m	2008	Sep 21.	Jun 16.	Aug 06.	3796
Soils: Joplin C-L	2009	Sep 18.	Jun 18.	Aug 12.	2353
PAW$_{1200}$: 186 mm	2010	Sep 17.	Jun 20.	Aug 07.	4083
	2011	--	--	--	--
	2012	Sep 30.	Jun 14.	Aug 02.	2949
	2013	Sep 19.	Jun 12.	Aug 10.	3824
	2014	--	--	--	--
SARC					
Lat: 45° 55' 25" N	2005	Sep 23.	Jun 06.	Jul 20.	3984
Lon: 108' 14" 37' W	2006	Sep 26.	May 30.	Jul 14.	4810
Elevation: 919 m	2007	Sep 28.	Jun 03.	Jul 19.	5247
Soils: Fort Collins C-L	2008	Sep 26.	Jun 17.	Jul 29.	4623
PAW$_{1200}$: 199 mm	2009	Oct 18.	Jun 10.	Aug 05.	5074
	2010	Oct 28.	Jun 12.	Aug 02.	4930
	2011	Sep 30.	Jun 20.	Aug 04.	4231
	2012	Sep 26.	Jun 04.	Jul 18.	3563
	2013	Oct 17.	Jun 10.	Jul 24.	3639
	2014	--	--	--	--

Winter Wheat Cultivars were Bynum, Carter, CDC Falcon, Genou, Jerry, Ledger, Norris, Pryor, and Yellowstone

-- Data is not relevant or available due to storm, pest or animal damage.

PAW—Plant available water taken from web soil survey (Soil Survey Staff, 2015). Subscripts indicates a 1200 mm rooting depth (z) for wheat.

Table 2. Model Inputs, symbols, description and sources used for simulating Agricultural Reference Index for Drought (ARID) stress indicies. Values in parenthesis are standard deviations on the mean observed field values.

Input	Symbol	Description	Units	Wheat	Pea	Source or Reference
Reference Evapotranspiration	ET_o	Daily water transpired of a reference grass under well water conditions.	mm	--	--	Derived from meteorological measurement from on-site weather stations. (Allen et al., 1998)
Initial Crop Coefficient	Kc_{ini}	Initial crop coefficient defining initial point crop coefficient vs. phenology curve. Coincides with emergence in wheat and two-leaf stage in pea	---	0.4	0	(Allen et al., 1998)
Maximum Crop Coefficient	Kc_{max}	Maximum crop coefficient defining maximum point on crop coefficient vs. phenology curve. Initiates at heading in wheat and lasts to seed-fill and lasts from beginning to end of flowering in pea.	---	1.15	1.15	(Allen et al., 1998)
Final Crop Coefficient	Kc_{end}	Final crop coefficient defining final point on crop coefficient curve. Coincides with physiological maturity with base temp=0 °C	---	0.5	0.4	(Allen et al., 1998)
Degree-days from sowing to joint or two-leaf	---	Accumulated growing degree days from seeding to joint in wheat or two leaf stage in pea with base temp=0 °C	°C	600	200	(Miller et al., 2001)
Degree-days to heading or flower	---	Accumulated growing degree-days from joint or two-leaf stage to heading or flowering in wheat and pea respectively with base temp=0 °C	° C	250* (28)	608* (46)	*Heading and flowering dates were field observed and values represent back-calculated degree-days for all site x year x cultivar combinations. Parentheses are standard deviations on back calculated means.
Degree-days over flowering	---	Accumulated growing-degree days from heading to seed fill in wheat, and over flowering in pea with base temp=0° C	° C	270	300	(Miller et al., 2001)
Degree-days to maturity	--	Accumulated growing degree-days from end of flowering in pea and chickpea and seed-fill in wheat to physiological maturity	° C	500	300	(Miller et al., 2001)
Rooting Depth	z	Effective rooting depth to which soil water is uniformly extracted	mm	1200	600	Field observed from separate 2014-2015 study conducted at NARC and SARC.
Field Capacity	θ_{fc}	Volumetric water content at field capacity to effective rooting depth (z)	%	Site-specific	Site-specific	Taken from web soil survey. (Soil Survey Staff, 2015) See Table 1.
Wilting Point	θ_{wp}	Volumetric water content at wilting point to effective rooting depth (z)	%	Site-specific	Site-specific	Taken from web soil survey.(Soil Survey Staff, 2015) See Table 1.
Initial Soil Water	θ_{ini}	Initial spring volumetric water content	%	Site-specific **	Site-specific **	** Initial soil water was set to field capacity for both crops since wheat was planted after fallow, and
Drainaige Coefficient	β	Daily fraction of water that can drain when soil profile exceeds field capacity	---	0.55	0.55	(Suleiman and Ritchie, 2004)
Root water uptake coefficient	α	Daily fraction of remaining plant available water that can be extracted by roots under supply limited conditions.	---	0.096	0.082	*Field calibrated for wheat and pea from separate 2014-2015 following (Dardanelli et al., 2004) at NARC and SARC (See Appendix B).
Curve Number	CN	Runoff curve number	---	83	82	(National Resource Conservation Service, 2007)

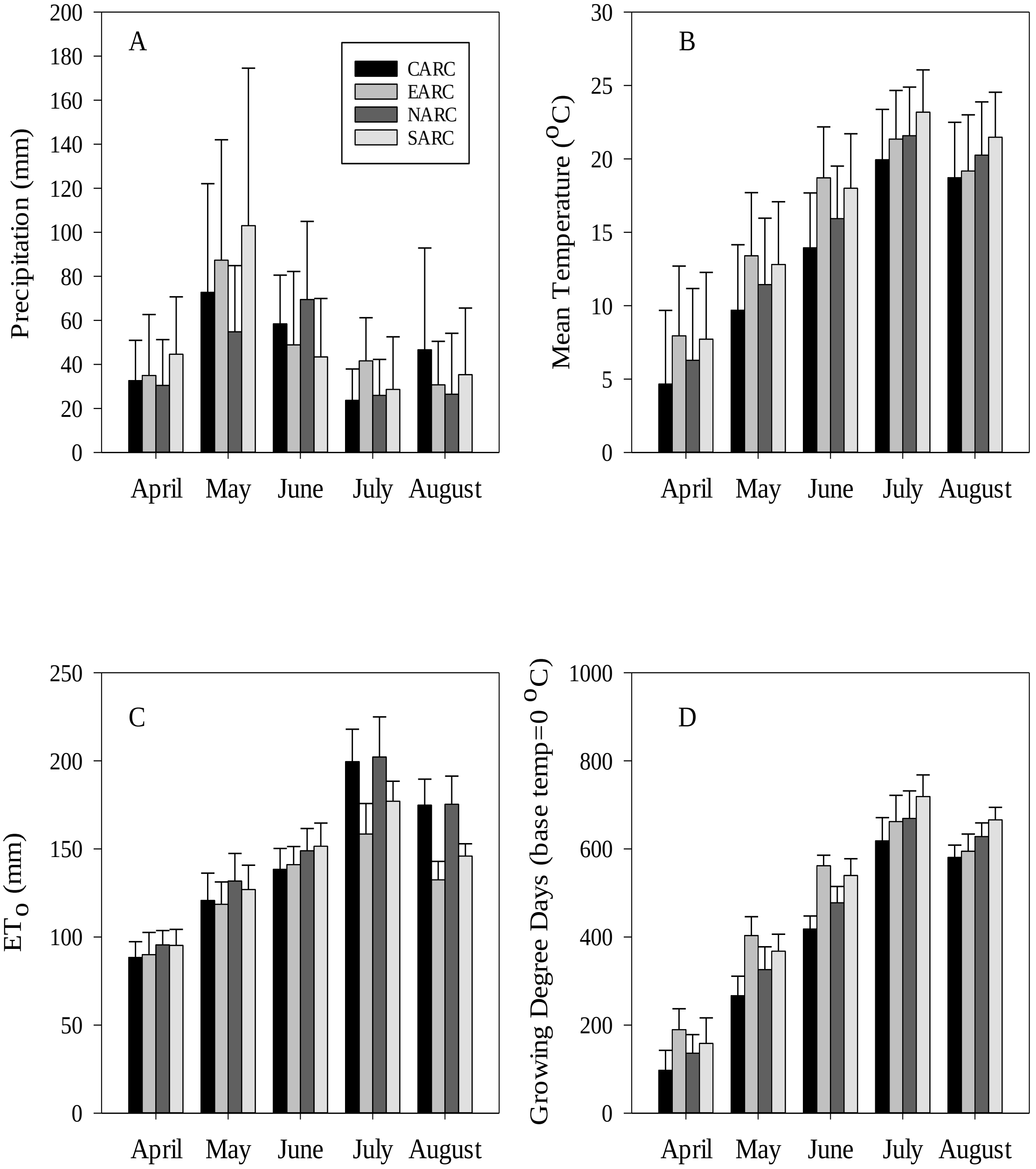

Figure 1. Average 10-year (2005-2014) growing season (May-July) climate trends derived from on-site weather stations at the Central, Eastern, Northern, and Southern Agricultural Research Centers (CARC, EARC, NARC, and SARC). Error bars are standard deviations on 10-year monthly means.

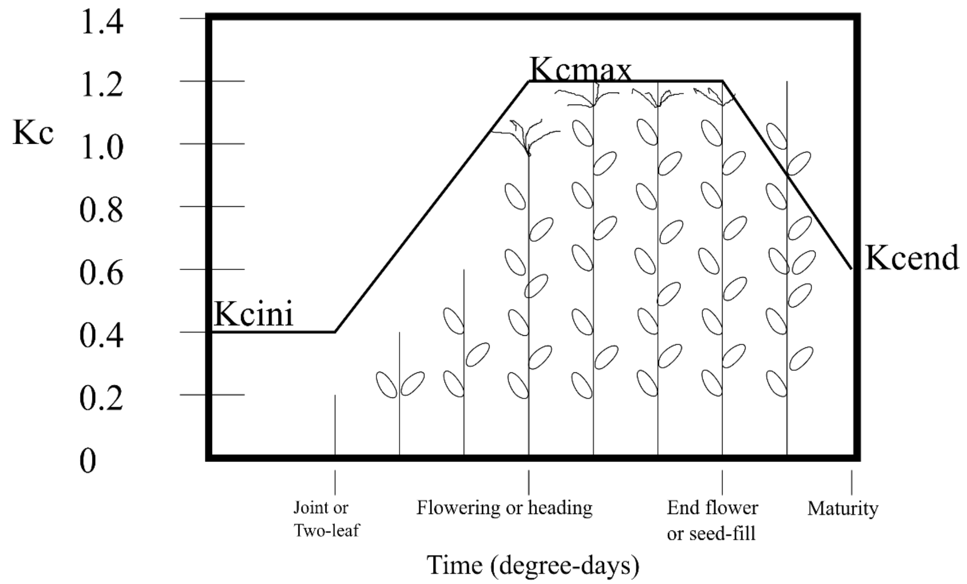

Figure 2. Physical depiction of daily crop coefficient vs. growth stage curve. The initial (Kc_{ini}), maximum (Kc_{max}), and final (Kc_{end}) define points on the curve corresponding to specific growth stages. Specific Kc values and their associated degree-day separations are given in Table 2.

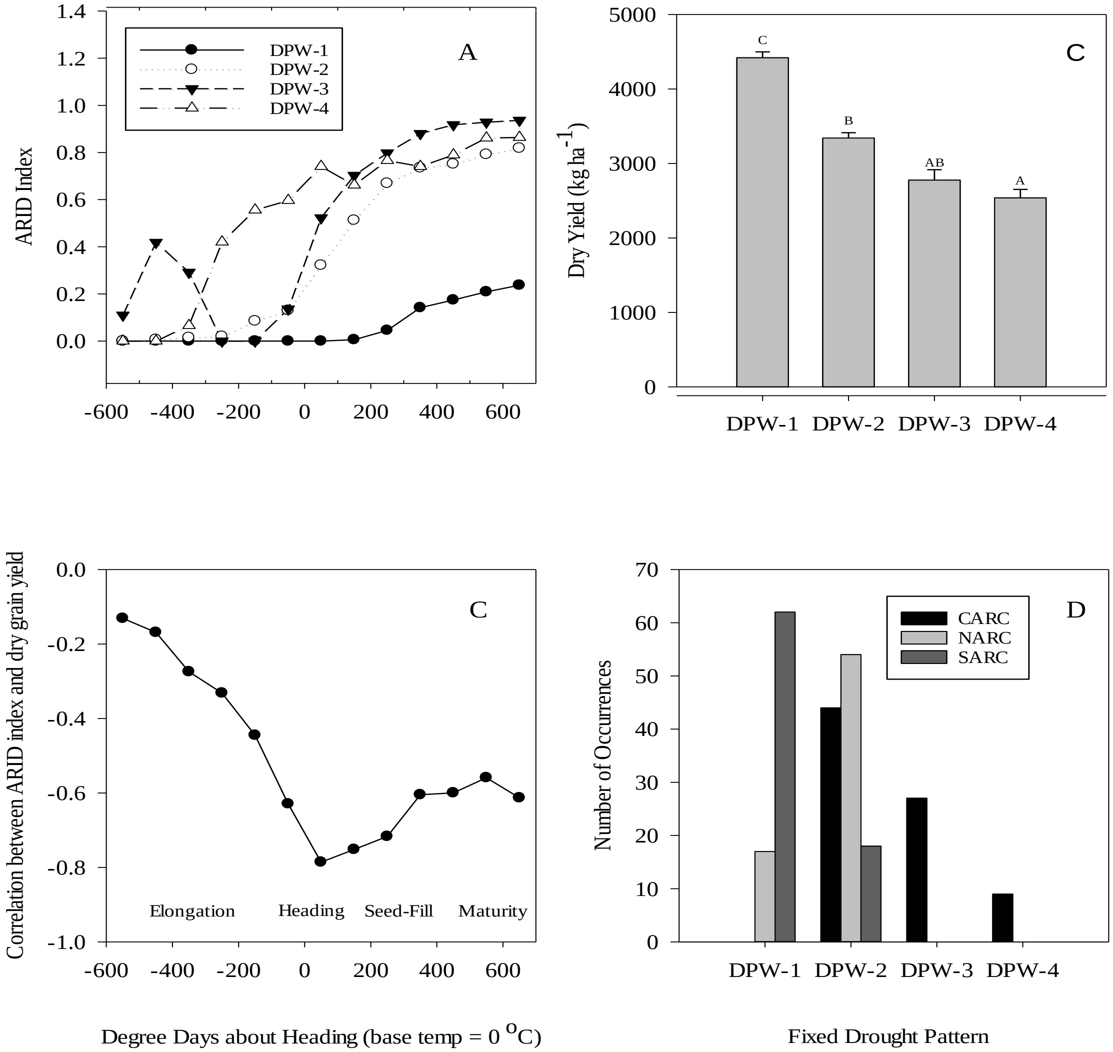

Figure 3. A. Fixed drought patterns for wheat (DPW) depicted as average ARID indices (e.g. drought stress) plotted against degree-days centered on heading observations. Negative values on x-axis indicate degree-days before heading, and positive values indicate degree-days after heading. B. Mean grain yields associated with each fixed drought pattern. Different letters indicate significant differences at p-value<0.10, and error bars are standard errors on within group means. C. Pearson correlation coefficient between average ARID index and yield vs. degree-days based on site x year x cultivar simulations and yield observations. D. Number of occurrences each fixed drought pattern was realized at each site from 2005-2013. Not shown—c.v.Yellowstone significantly out yielded c.v. Bynum with respective mean yields of 3626 kg ha^{-1} and 2726 kg ha^{-1} atvalue<0.10. No additional yield differences among cultivars were detected, and no significant genotype by environment (G x E) interactions were detected.

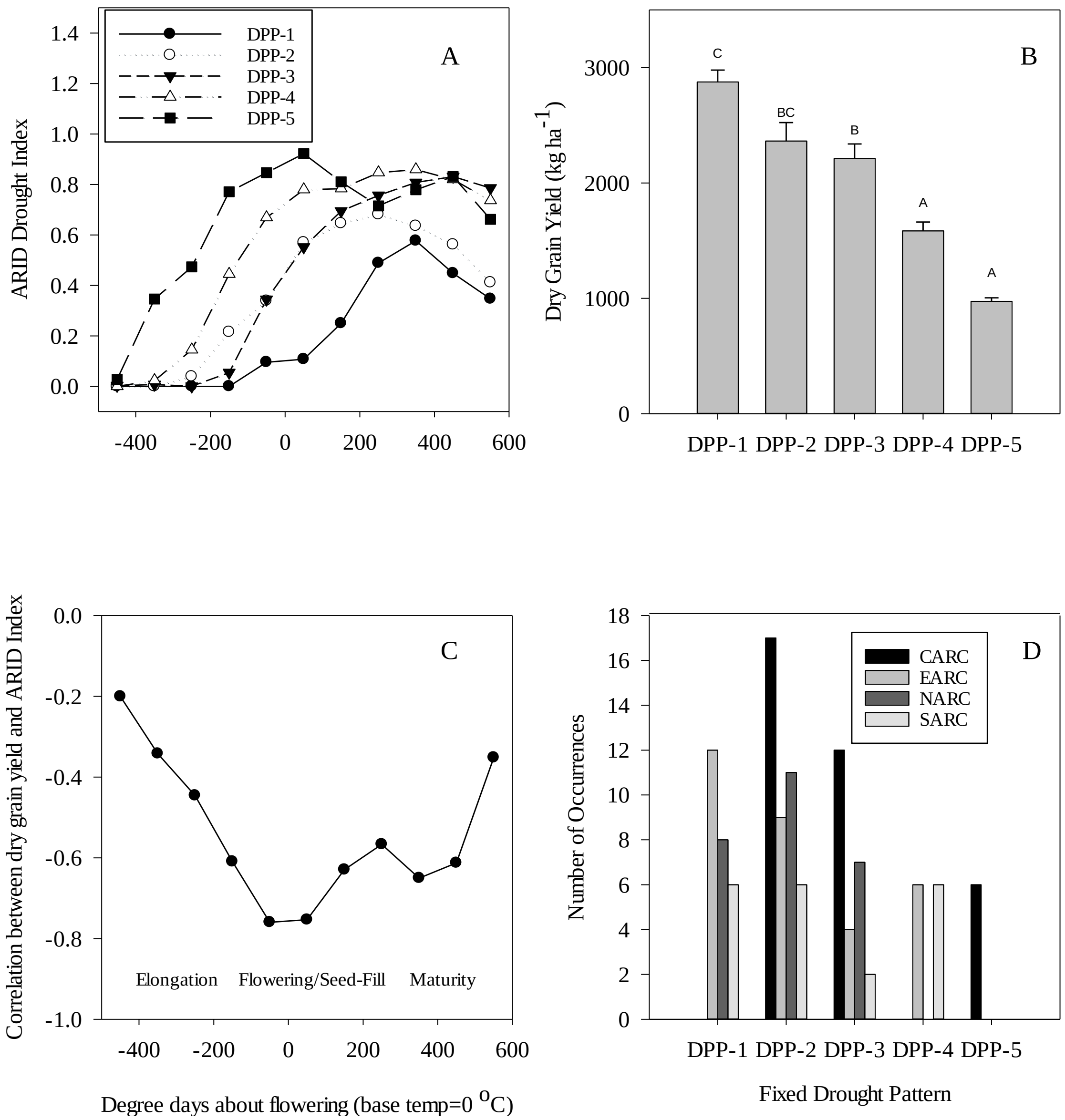

Figure 4. A. Fixed drought patterns for pea (DPP) depicted as average ARID indices (e.g. drought stress) plotted against degree-days centered on flowering observations. Negative values on x-axis indicate degree-days before flowering, and positive values indicate degree-days after flowering. B. Mean dry grain yields associated with each fixed drought pattern. Different letters indicate significant differences at p-value<0.10, and error bars are standard errors on within group means. C. Pearson correlation coefficient between average ARID index and yield vs. degree-days based on cultivar x site x year simulations and yield observations. D. Number of occurrences each fixed drought pattern was realized at each site from 2008-2014. Not shown—No statistical differences among pea cultivars were detected. No cultivar differences or significant genotype by environment (G x E) interactions were detected.

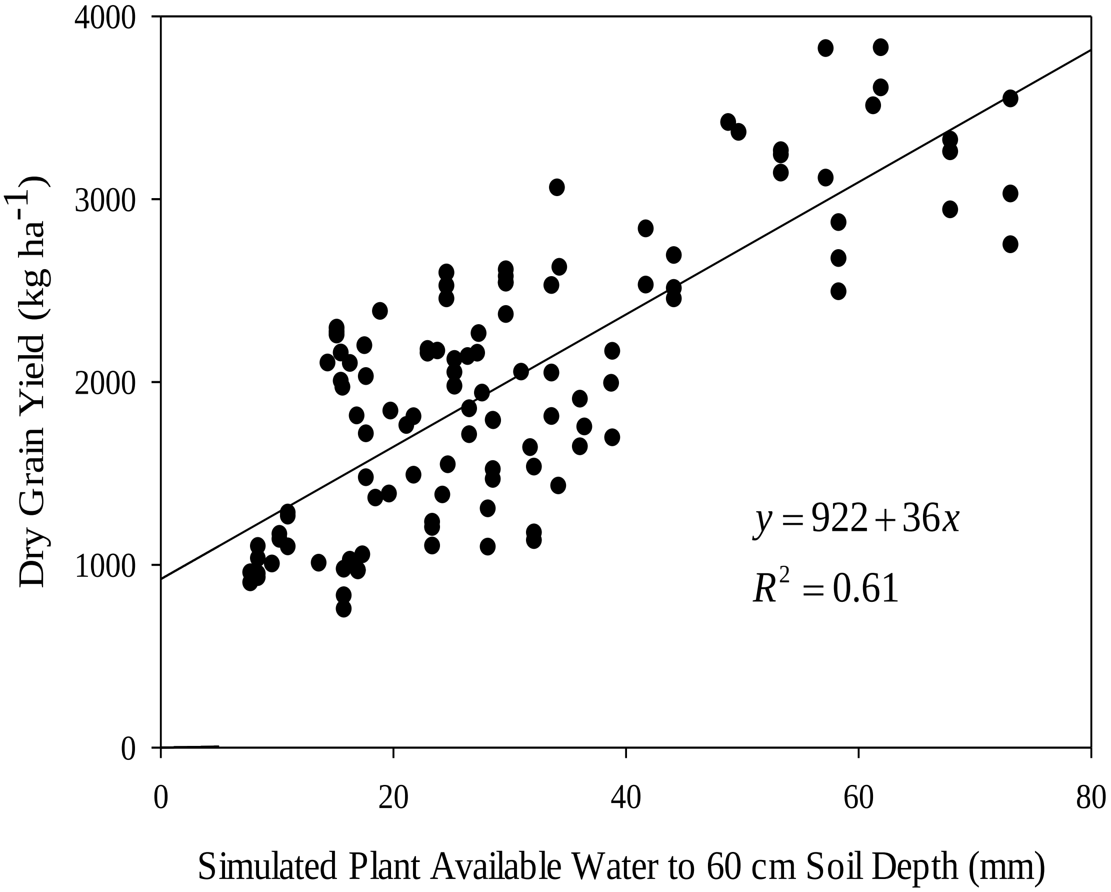

Figure 5. Pea grain yield vs. simulated plant available water (PAW) at flowering stages

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CHAPTER FOUR

WATER USE PRODUCTION FUNCTIONS TO SIMULATE ECONOMIC TRADEOFFS FROM DELYAED SEEDING OF SPRING WHEAT, PEA, AND CHICKPEA

Abstract

Early spring seeding increases crop yields and revenues in Montana, yet producers growing multiple species must prioritize which to seed first. The objective of this study was to assess marginal returns from staggered seeding of spring wheat, pea, and chickpea under changing markets. Weather and field data taken from a three-year seeding date study in Amsterdam MT were used to generate yield versus ET production functions for each crop by combining the FAO-56 and ARID water balance models. Production functions were then used to forecast yields at four seeding dates over the 2005-2014 growing seasons, and mean marginal returns were determined at the maximum, median, and minimum market values based on 10-yr prices received and production costs for each crop. The chickpea production function had the best fit with R^2=0.75, relative root means square error (RRMSE) of 0.19, mean absolute error (MAE) of 171 kg ha^{-1}, and model efficiency (EF) of 0.77, while pea and wheat had respective R^2 values of 0.66 and 0.70, RRMSE of 0.25 and 0.22, MAE of 331 and 387 kg ha^{-1}, EF of 0.69 and 0.72. Simulated mean marginal returns were highest for chickpea (~601 \$ ha^{-1}) followed by wheat (372 \$ ha^{-1}) and pea (202 \$ ha^{-1}) despite chickpea having the lowest simulated yields. Simulated marginal return ratios for chickpea/wheat declined from 1.7

to 1.4 whereas ratios for pea/wheat declined from 0.6 to 0.4 from the earliest to latest seeding dates. These results support that early-seeded chickpea has a greater economic advantage relative to wheat and pea.

Introduction

Terminal drought beginning in June or July characterizes much of Montana’s dryland cropping environments (Padbury et al. 2002). Consequently higher yields are associated with early-seeding dates for most spring-sown crops since the crop’s critical growth-stages are better-timed with favorable precipitation patterns (Black and Siddoway, 1977; Miller et al., 2006). Heavy seeding machinery often has limited access to fields in early spring due to high soil moisture from snowmelt and precipitation, and given the right seeding conditions, producers growing multiple crops must prioritize which to seed first. Consequently spring-seeding may span over several weeks in April and May in Montana.

From 1995 to 2015, planted pulse area has expanded from 6,900 to over 353,900 hectares, with the majority of pulses replacing summer fallow, an idle growing season traditionally used to ensure stored soil moisture for the following year’s cereal cash crop (Tanaka et al. 2010, Long et al. 2015). The shift to intensified cereal-pulse systems has been brought on by potential economic benefits for producers. Specifically mineralized nitrogen (N) from pulse residues can reduce fertilizer N costs to the succeeding crop (Burgess et al., 2012; Miller et al., 2015), and market values have been strong due to rising global pulse demand (Lee, 2011). For these reasons, Montana producers assume less risk by intensifying their rotations (Lawrence 2015; Miller et al. 2015) but must now consider how staggered seeding among cereals and pulses will affect yields and profits.

Two pulse species that will likely compete with spring cereals for early seeding are dry pea (*Pisum sativum* L.) and chickpea (*Cicer arietinum* L.*)*. Seeding date trials in the neighboring Canadian Prairies showed 44 and 31 % yield reductions from delayed seeding of two to four weeks for chickpea and pea, respectively (Miller et al., 2006). Statewide variety testing indicates pea and chickpea yields range from ~3000 kg ha^{-1} to ~500 kg ha^{-1} (Mohammed and Chen, 2014) suggesting the combination of seeding date and precipitation greatly affects yield. Such yield variability will clearly impact profits, and profits will further be confounded by changing market prices for each crop. Hence optimal seeding will remain a moving target depending on both economic and climatic factors.

While growing season conditions cannot be reliably projected in advance, basic weather, soils, and crop inputs can be used to simulate growing season evapotranspiration (ET) probabilities (Raes et al., 2006). There is often a strong linear relationships between growing season ET and yield in water limited environments (de Witt, 1958), and these relationships, or production functions, are practical tools for yield forecasting (Brown and Carlson, 1990; Ritchie, 1991). Yield forecasts can then be combined with different economic scenarios to address how profits are impacted from staggered seeding. The objectives of this study were to a) generate production functions for spring wheat (*Triticum aestivum* L.*),* pea, and chickpea from simulated growing season ET and b) use yield forecasts from the production functions to address how marginal returns could be impacted from delayed seeding of each crop under contrasting market scenarios.

Materials and Methods

Initial Experiment,
Management, and Field Measurements

A field experiment was conducted over three growing seasons (2002-2004) on two adjacent fields located near Amsterdam, MT (45^o 45’ 43” N 111^o 25’ 37” W; Elev: 1490 m). Fields were established on cereal stubble under no-till management, and soils were classified as Amsterdam silt loam (frigid Typic Haplustoll). Weather measurements were daily maximum and minimum temperatures (^{o}C), windspeed (km day^{-1}), precipitation (mm), and relative humidity (%) and were taken from the nearest meteorological weather station (Belgrade, Montana airport, Western Regional Climate Center) located 20 km from the site. The experimental layout was a randomized complete block design with four replications. Main plot factors were crop species (pea *cv. Mozart*, chickpea *cv. Dwelley* and wheat *cv. McNeal*) and seeding date staggered at approximately two-week intervals from late March to early June, but based on similar growing degree day accumulation among seeding dates (next seeding date was planted on the day (+/- 1 d) 50% of the plant from the previous seeding had emerged). Crops were seeded using a low-disturbance 1.8-m wide disc seeder with 7 rows and independent disc coulters for side-banding fertilizer. Chickpea and pea were treated with recommended rates of *Allegiance* fungicide to prevent Pythium seed rot and wheat was treated with recommended rates of *Raxil MD*. Commercial herbicides were used at recommended rates and supplemented with hand weeding to achieve weed control. Specific seeding date, herbicide, and fertilizer details appear in Table 1 below.

Field measurements were crop growth stages, grain yield, and soil moisture. Specific growth stage observations were emergence, flowering, end of flowering, and physiological maturity. Crop emergence was defined when greater than 50% of seedlings were visible. Flowering was determined when 50% of plants had reached first bloom for pea and chickpea and when anthers were first visible on heads for wheat. End of flowering was monitored for only chickpea and pea in 2002 and 2004 and was determined when 50% of the plants in a plot had an open flower. Physiological maturity was estimated based on 95% change in pod color to yellow in pea and chickpea and when 95% of wheat kernels were in the firm dough stage (~30-40% grain moisture). Grain yields were collected by harvesting four center rows at 12 meter lengths with a plot combine and were converted to dry grain weights. Soil moisture was measured in 2002 and 2004. Initial spring soil moisture was measured by grid sampling each treatment block and an adjacent fallow field. Soil cores were collected to 1.2 m, split into 0.3-m segments, and dried at 50 °C. Soil moisture was converted to equivalent water depth by multiplying bulk density by gravimetric water content. Post-harvest soil moisture was determined by the same method, but cores were collected from all plots.

Model Description for Simulating Crop Evapotranspiration and Assumptions

Crop evapotranspiration was simulated by combining the FAO-56 Penman-Monteith model (Allen et al., 1998) with the Agricultural Reference Index for Drought

(ARID) water balance model (Woli et al., 2012). The FAO crop coefficient method simulates potential evapotranspiration (PET) by multiplying daily crop coefficients (Kc_i) by reference evapotranspiration (ET_o) of a well-watered grass at peak growth derived from daily meteorological parameters. Potential evapotranspiration is given by:

$$PET_i = Kc_i\ x\ ET_{oi} \qquad \text{Eq 1.}$$

where the subscript *i* denotes daily values for each variable. Daily crop coefficients are estimated from a crop coefficient vs. phenological growth stage curve (Figure 1.) where the initial (Kc_{ini}), maximum (Kc_{max}), and final (Kc_{end}) crop coefficients define points on the curve corresponding to specific crop growth stages.

For modeling PET, it was assumed that Kc_{ini}, Kc_{max}, and Kc_{end}, corresponded to emergence, flowering, and physiological maturity, and daily crop coefficients were linearly interpolated between these points. Kc_{max} remained constant during flowering in pea and chickpea, and from flower to seed-fill in wheat. Values for Kc were taken from (Allen et al., 1998). All crop growth stages were monitored over the field study except seed-fill for wheat and end of flowering in pea in chickpea in 2003. Flowering to seed-fill in wheat was estimated based on growing degree day (base temperature = 0^oC) recommendations by (Miller et al., 2001), and end of flowering for pea and chickpea in 2003 were approximated from degree-day averages from 2002 and 2004 field observations.

The ARID water balance model assumes a uniform soil profile within a specified rooting depth (z) of a given crop. Runoff is estimated by the Natural Resource

Conservation Service (NRCS) curve number (CN) method, and drainage below the root zone (z) is approximated by an empirical drainage coefficient (β) (Suleiman and Ritchie, 2004) specifying the fraction of water that can be drained in a day when the soil profile exceeds field capacity (θ_{fc}). Root water extraction is assumed to be constant throughout the profile, and actual evapotranspiration (ET_a) is a function of soil water availability and evaporative demand. With sufficient soil water, ET_a is equal to PET, but as soil water diminishes ET_a is reduced. Mathematically ET_a is given by:

$$ET_{ai} = min\begin{cases} PET_i \\ \alpha\ x\ \theta_{a,i-1}^{ad} \end{cases} \qquad \text{Eq 2.}$$

where α is an empirically derived root water uptake constant (Dardanelli et al., 2004) controlling the maximum daily fraction of water above wilting point (θ_{wp}) that can be extracted by roots, and $\theta_{a,i-1}^{ad}$ ($cm^3\ cm^{-3}$) is the plant available water from the previous day.

The most sensitive parameters in many water balance models are field capacity (θ_{fc}) and wilting point (θ_{wp}) (Gijsman et al., 2002; Woli et al., 2013), and initial soil moisture inputs are required to run simulations. Field capacity was therefore estimated based on spring soil sampling an adjacent fallow field, and wilting point was estimated from harvest soil measurements for crop species. Initial spring soil moisture was based on field measurements in 2002 and 2004, but in 2003 when moisture was not recorded, the average of 2002 and 2004 were taken as initial soil water conditions. A summary of specific model inputs and sources are shown in Table 2.

Production Functions and Evaluation

For each seeding date x year for each crop (pea, chickpea, or wheat) , measured grain yield was regressed linearly against simulated growing season ET (de Witt, 1958; Brown and Carlson, 1990; Nielsen, 2001) to generate production functions given by:

$$\overline{Yield} = \hat{\alpha} + \widehat{\beta_1}\overline{ET} + \epsilon \qquad \text{Eq. 3}$$

Where $\overline{Yield}$ is mean dry grain yield (kg ha^{-1}) and $\overline{ET}$ is mean simulated growing season ET for each treatment combination. Production functions were evaluated on the relative root means square error (RRMSE), mean absolute error (MAE), and model efficiency (EF). The RRMSE is given as:

$$RRMSE = \sqrt{\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{n}}\frac{1}{\bar{O}} \qquad \text{Eq 4.}$$

where O_i is measured yield, P_i is predicted yield by Eq 3, n is the number of mean yield observations, and $\bar{O}$ is the mean of all yield measurements. The RRMSE expresses model error as a fraction of averaged measured yield, and generically RRMSE values from 0-0.10 are considered excellent, 0.10-0.20 good, 0.20-0.30 fair, and values above 0.30 are considered poor (Jamieson et al., 1991). The MAE error represents the average absolute difference from observed and predicted values and is given by:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|O_i - P_i| \;. \qquad \text{Eq 5.}$$

Lastly model efficiency or EF (Nash and Sutcliffe, 1970) is a skill score that ranges from -∞ to 1. A score of 0 indicates that the production functions yield predictions are equivalent to the mean of all yield observations, values less than zero indicate that production functions perform worse than the mean of all yield observations, and a value of one indicates the production functions predict yield perfectly. Model efficiency is calculated as:

$$EF = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \qquad \text{Eq 6.}$$

Assessing Net Marginal Returns form Delayed Seeding and Changing Markets

Simulated ET and production functions (Eq 3.) were used to forecast yields from staggered seeding from 2005 to 2014 weather inputs. Four seeding dates were set at 2-wk intervals beginning 15 April, and initial spring soil moisture was fixed at 80 % field capacity to 120 cm. Predicted yields were then converted to marginal returns by:

$$Marginal\ Returns = Marginal\ Cost\ x\ Prices\ Recieved - Marginal\ Production\ Cost \qquad \text{Eq.7.}$$

Market variation was generated by setting prices received for each crop to the minimum, median, and maximum of observed September prices received from 2005-2014 (NASS, 2014). Marginal production costs were machinery, seed, and fertilizer costs (Table. 3).

A total of three crops x 10 yr x four seeding dates x three prices received resulted in 360 simulated marginal return responses. The effects of crop, seeding date, and prices received on simulated marginal returns were then evaluated using ANOVA given by the model:

$$y_{ijklm} = \mu + \tau_i + \ \alpha_j + \beta_k + \gamma_l + \sum(\alpha\beta\gamma)_{jkl} + \varepsilon_{ijklm} \qquad \text{Eq. 8}$$

where y_{ijkl} is a simulated marginal return observation, μ is the grand mean of all marginal return observations, τ_i is the fixed year (2005-2014) or block effect controlling for year-to-year variations in weather, α_j is the fixed effect of prices received, β_k is the fixed seeding date effect, γ_l is the fixed crop effect, $\sum(\alpha\beta\gamma)_{jk}$ are all possible combinations of two- and three-way main-effect interactions, and ε_{ijkl} is the residual error term assuming model residuals are independent and identically distributed with a mean of zero and constant variance.

The primary intent of Eq 8. is to compare marginal returns for any crop x seeding date x prices received combination to help prioritize spring seeding. For instance, if at spring seeding, pea was projected to have a market value near its ten-year maximum, and wheat was projected to retain its median value, comparing projected differences in marginal returns across seeding dates could help producers decide which crop to seed first. Results are therefore presented in tabular format with projected mean net returns of the three crop x four seeding date x three prices received combinations, and least significant differences determined by a Tukey test at the alpha=0.10 level.

All analyses were conducted using R software (R Core Team, 2014), and ET was simulated by combining custom R code with the ARID water balance model implemented in the R package ZeBook (Brun et al., 2013).

Results and Discussion

Precipitation and Reference Evapotranspiration at the Field Site

The 12-yr average annual precipitation (2002-2014) at Amsterdam was 380 mm with 45% or 172 mm occurring during the growing season (1-May to 31-Aug). (Figure 2.). Cumulative precipitation for the 2002 and 2004 growing season was above normal at 194 mm and 224 mm, respectively. Conversely, cumulative precipitation for the 2003 growing season was 109 mm, or 63 mm below the 12-yr. average. Average growing season reference evapotranspiration was (ET_o) was 685 mm. Cumulative ET_o in 2002 and 2004 were below average at 659 mm and 618 mm respectively. In 2003, conversely, cumulative reference ET_o was 717mm or 32 mm above the 12-yr average. Thus the 2002 and 2004 growing seasons experienced more favorable growing conditions compared to 2003.

Grain Yield vs. ET Functions

Dry grain yield vs. simulated growing season ET were well modeled by linear production functions for all three crop species (Figure 3). Using relative root mean square error (RRMSE) and model efficiency (EF) as surrogates for predictive performance, the chickpea production function performed the best, followed by the wheat and pea. The production functions do not explicitly account for heat stress, which may partially explain the lower R^2 values associated with pea (R^2=0.66) and wheat (R^2=0.70) relative to chickpea (R^2=0.75). Numerous greenhouse and field studies have shown that temperatures exceeding 26°C over the flowering and pod fill window reduces pea yield through pod abortion (Jeuffroy et al., 1990) and fewer pods per plant (Lambert and Linck, 1958; Pumphrey and Ramig, 1990; Guilioni et al., 1997). Similarly, temperature shock after flowering may prematurely stop grain-fill in spring wheat leading to reduced seed-size and yield (Brukner and Frohberg, 1987). For chickpea, alternatively, (Awasthi et al., 2014) found a greater reduction in photosynthetic activity resulting from drought compared to heat stress and concluded that drought had the greater impact on yield loss. By this logic, higher R^2 values would be expected from chickpea because the production functions emphasize growing season water stress (e.g. growing season ET) as opposed to temperature stress, but in general, all ET-yield production functions fit well.

Grain yield vs. ET production functions differ somewhat from those developed by others in Montana. Lenssen et al. (2007) reported yield increases of 5.8, 11.8, and 5.2 kg ha^{-1} mm^{-1} of cumulative ET in spring wheat, pea, and chickpea respectively. Their study was conducted in the driest growing region of Montana, and measured ET rarely exceeded 200 mm while crop yields remained below 1500 kg ha^{-1}. Conversely yield and simulated ET presented herein (Figure 3.) covers a wider range of values and may explain why regression slopes are greater than those developed by (Lenssen et al., 2007).

Effect of Crop, Seeding Date, and Prices Received on Marginal Returns

Table 4 summarizes ten-year (2005-2014) simulated mean yields and marginal returns. Averaged across seeding dates and prices received, chickpea had the highest marginal returns (601 \$ ha^{-1}) compared to wheat (372 \$ ha^{-1}) and pea (202 \$ ha^{-1}),yet mean simulated yields followed the order of wheat>pea>chickpea at 2054 kg ha^{-1}, 1298 kg ha^{-1}, and 1095 kg ha^{-1}. This result is mainly due to greater prices received in chickpea relative to wheat and pea despite higher chickpea seed costs (Table 3.)

Importantly the ratio of chickpea/wheat marginal returns decreased with seeding date. Simulated marginal chickpea returns were 1.7, 1.6, 1.4, and 1.4 times greater than spring wheat for 15-Apr, 29-Apr, 13-May, and 27-May seeding dates respectively. Alternatively simulated pea/wheat ratios were 0.6, 0.6, 0.5, and 0.4 of spring wheat for the same seeding date (Figure 4.).

These results highlight the economic advantage of early-seeded chickpea, but early-seeded chickpea is also at greater risk for disease. Namely ascochyta blight can reduce chickpea yields by 96 % (Chongo et al., 2003) and spreads easily with high precipitation and moderate temperatures (Trapero-Casas and Kaiser, 1992). This raises the likelihood for additional fungicide applications and increases production costs. Depending on producer risk, it may be more conservative to seed chickpea in late April or May to lower the occurrence of ascochyta blight.

Risk, notably, will depend on producer, management, and economics (Zentner et al., 2008). The primary intent of Table 4. is to provide producers with 36 possible scenarios (4 seeding dates x 3 crops x 3 prices received) that will help prioritize seeding of spring wheat, pea, and chickpea based on personal risk. While these simulations do not capture the detailed intricacies of crop growth dynamics (e.g. N-cycling, heat stress, weed and disease pressure), they provide a functional and long-term approximation of the economic tradeoffs from delayed seeding that cannot easily be accomplished in a field study.

Summary and Conclusion

Weather and field data taken from a three-year seeding date study in Amsterdam MT were used to generate yield versus ET production functions for spring wheat, pea, and chickpea by combining the FAO-56 and ARID water balance models. The chickpea production function had the best overall accuracy compared with the pea and spring wheat based on R^2, RRMSE, MAE, and EF parameters, but in general, all production functions had reasonable accuracy. Production functions were then used to simulate yield and marginal economic returns at four seeding dates and three levels of prices received over a ten-year time frame for each crop. Simulated mean marginal returns were generally highest for chickpea despite having the lowest simulated mean yields. This result suggests that chickpea should be seeded before wheat and pea, but producers should also consider the elevated risk of asochyta blight from early-seeded chickpea. Despite not capturing the detailed intricacies of plant growth dynamics, results presented herein have potential to aid producers in prioritizing spring seeding wheat, pea, and chickpea under changing markets and management.

Table 1 Seeding date, soil temperature, fertilizer N-P-K_S, and soil management for seeding date Amsterdam, MT 2002-04.

Year	Calendar	Soil temp*	Fertilizer **	NO_3-N[+]	pH[++]	SOM
		ºC	kg ha^{-1}	ppm		%
2002	9-Apr	6	11-7-24-10	11.2	8.3	1.3
	23-Apr	6				
	13-May	> 15				
	27-May	> 15				
2003	8-Apr	13	3-7-21-9	NA	NA	NA
	22-Apr	16				
	8-May	12				
	21-May	> 15				
	30-May	> 15				
2004	25-Mar	12	5-9-17-7	10.3	8.4	1.2
	13-Apr	12				
	2-May	16				
	21-May	17				
	4-June	>15				

** Fertilizer N-P-K-S applied at seeding in the seed furrow. Nitragin Soil Implant strain-specific peat granular inoculant applied in seed furrow at a rate of 6 kg ha^{-1}. In 2002 spring wheat received an additional 88 kg ha^{-1} of N (46-0-0) and in 2003 and 2004 wheat received an additional 111 kg ha^{-1} of N (46-0-0) side-banded at seeding.

[+] Average of 4 reps to 0.6-m depth

[++] Average of 4 reps to 0.3-m depth

Table 2. Model Inputs, symbols, description and sources for simulating growing season evapotranspiration (ET). Values in parenthesis are standard deviations on the mean observed field values.

Input	Symbol	Description	Units	Wheat	Pea	Chickpea	Source or Reference
Initial Crop Coefficient	Kc_{ini}	Initial crop coefficient defining initial point crop coefficient vs. phenology curve. Coincides with emergence.	---	0.4	0	0	(Allen et al., 1998)
Maximum Crop Coefficient	Kc_{max}	Maximum crop coefficient defining maximum point on crop coefficient vs. phenology curve. Initiates at flowering and lasts through flowering in pea and chickpea and through seed-fill in wheat.	---	1.15	1.15	1.00	(Allen et al., 1998)
Final Crop Coefficient	Kc_{end}	End crop coefficient defining final point on crop coefficient curve. Coincides with physiological maturity with base temp=0 ºC	---	0.5	0.4	0.35	(Allen et al., 1998)
Degree-days to emergence	---	Accumulated growing degree days from seeding to crop emergence with base temp=0 ºC	ºC	81 (28)	94 (34)	117 (31)	Field observed
Degree-days from emergence to flower	---	Accumulated growing degree-days from emergence to flowering with base temp=0 ºC	º C	788 (28)	608 (46)	621 (30)	Field observed
Degree-days over flowering	---	Accumulated growing-degree days over flowering in pea and chickpea and from flowering through seed-fill in wheat with base temp=0º C	º C	*200	*248 (57)	*407 (85)	*Field observed for pea and chickpea in 2002 and 2004 only and taken from (Miller et al., 2001) for wheat.
Degree-days from flower to maturity	--	Accumulated growing degree-days from end of flowering in pea and chickpea and seed-fill in wheat to physiological maturity	º C	*444 (45)	*264 (54)	*381 (95)	*Maturity dates were field observed in all years, so degree days to maturity was back calculated for wheat in all years and for pea in chickpea and pea in 2003.
Field Capacity	θ_{fc}	Volumetric water content at field capacity to 1200 mm	%	0.23 (0.02)	0.23 (0.02)	0.23 (0.02)	Field observed from spring soil moisture measurements taken from neighboring fallow field in 2002 and 2004.
Wilting Point	θ_{wp}	Volumetric water content at wilting point to 1200 mm	%	0.15 (0.03)	0.16 (0.03)	0.15 (0.03)	Field observed from post-harvest soil moisture measurements in 2002 and 2004.
Initial Soil Water	θ_{ini}	Initial spring volumetric water content	%	*Obs.	*Obs.	*Obs.	*Field observed in 2002 and 2004, and taken as average of 2002 and 2004 measurements for 2003.
Rooting Depth	z	Effective rooting depth (mm) to which soil water is uniformly extracted	mm	1200	1200	1200	Field observed
Drainaige Coefficient	β	Daily fraction of water that can drain when soil profile exceeds field capacity	---	0.55	0.55	0.55	(Suleiman and Ritchie, 2004)
Root water uptake coefficient	α	Daily fraction of remaining plant available water that can be extracted by roots under supply limited conditions.	---	0.096	0.082	0.082 *	*Field calibrated for wheat and pea from separate 2014-2015 (Dardanelli et al., 2004) (Data not shown). Chickpea was assumed to have same value as pea.
Curve Number	CN	Runoff curve number	---	83	82	82	(National Resource Conservation Service, 2007)

Table 3. Marginal production and absolute costs for operation, machinery, and fertilizer and four levels of prices received for each crop. Production costs are based on 2012-2014 averages, and prices received reflected the minimum, median, and maximum prices from 2005-2014.

Crop	Production Costs			Prices Received #		
	------------------$\$\text{ ha}^{-1}$-------------------			-----------------$\$\text{ kg}^{-1}$---------------		
	Operation and Machinery ¶*	Fertilizer ¶¶*	Seed §+	Minimum	Median	Maximum
Chickpea	26	0	301	0.62	0.82	1.09
Pea	26	0	147	0.14	0.29	0.43
Spring Wheat	0	143	37	0.17	0.27	0.36

*Indicates marginal cost.

+Indicates absolute cost.

¶ Higher operation and machinery costs for pea and chickpea are from land roller costs (15 $\$\text{ ha}^{-1}$) and combine maintenance (11 $\$\text{ ha}^{-1}$) (Aakre, 2014) .

¶¶.Higher fertilizer costs for wheat are from applied nitrogen as urea spring broadcast (0-0-46) at 98 kg ha^{-1}

§Seed costs were provided by local venders.

September prices received on a dry weight basis taken from (NASS, 2014)

Table 4. Simulated mean 10-year (2005-2014) yields and marginal returns in dollars per hectare for spring wheat (SW), pea (PEA) and chickpea (CP) from spring seeding dates staggered at 14 day intervals beginning 15-Apr and the minimum, median, and maximum September prices received for each crop from 2005-2014.

	Simulated Dry Grain Yield			
	----------------------kg ha^{-1}----------------------			
Seeding Date	15-Apr	29-Apr	13-May	27-May
SW	2304	2161	2089	1663
PEA	1565	1396	1291	940
CP	1292	1170	1058	941
LSD$_{.10}$¶	245			

	Simulated Marginal Returns											
	----------------------\$ ha^{-1}----------------------											
	SW	PEA	CP	SW	PEA	CP	SW	PEA	CP	SW	PEA	CP
Minimum	218	53	484	193	28	408	181	14	338	107	-36	215
Median	445	279	743	405	230	642	385	200	549	270	99	387
Maximum	656	506	1075	604	433	944	578	387	822	423	235	609
LSD$_{.10}$¶	156											

¶ Least significant difference (LSD) at the alpha=0.10 level by Tukey test. LSD applies to any two values within the table.

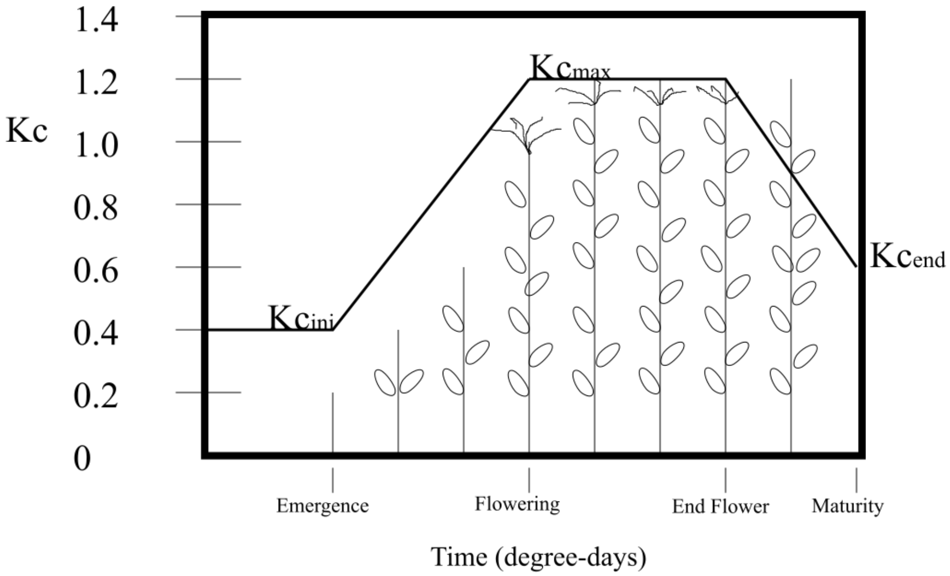

Figure 1. Daily crop coefficient vs. growth stage curve for wheat, peas, and chickpeas. Degree day accumulation between growth stage intervals are given in Table 2.

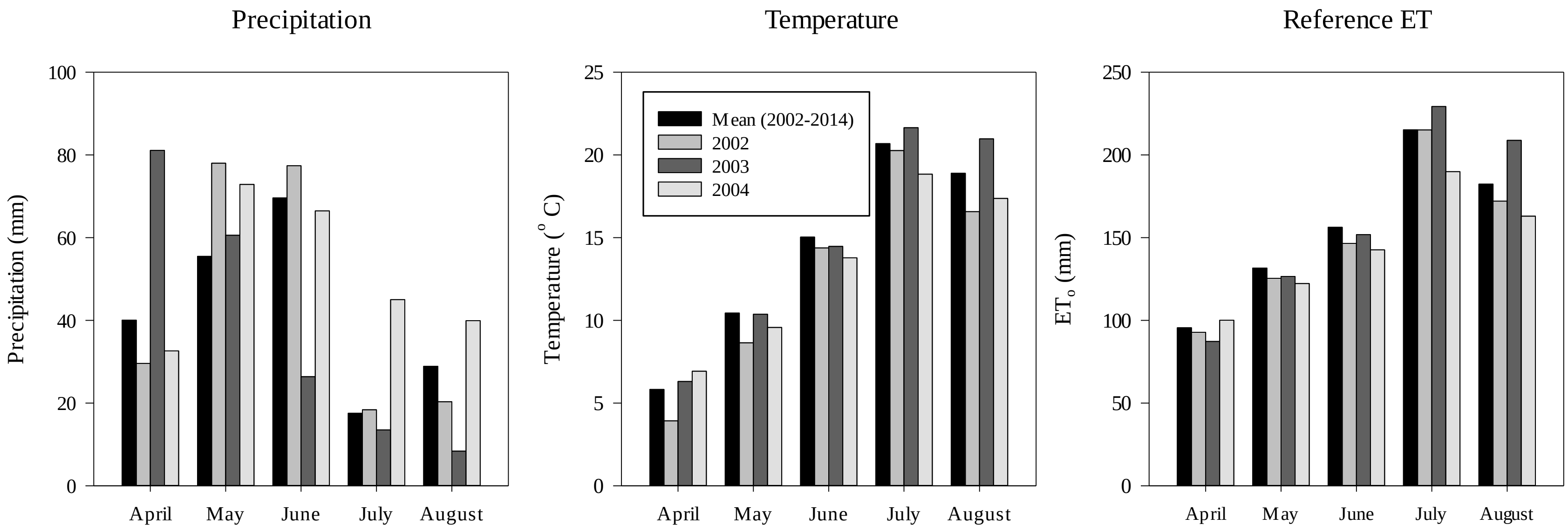

Fig 2. Mean monthly climatic variables from 2002-2014 growing seasons (April-August), and observed climatic variables over the 2002-2004 growing seasons over the field study when experimental data for production functions was collected. Climatic parameters were collected from the Belgrade airport meteorological station located 20 km from the field location.

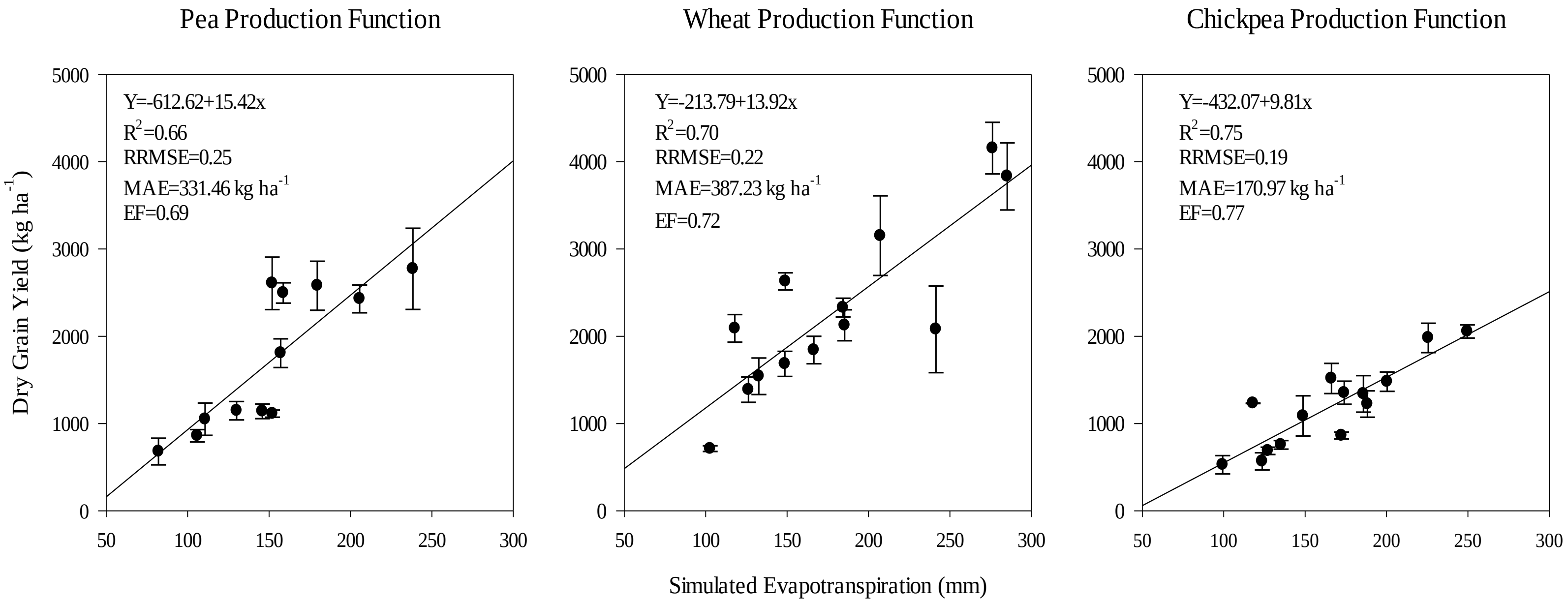

Figure 2. Yield vs. water use production functions based on simulated growing season evapotranspiration (ET) and yield measurements from the 2002-2004 seeding-date field experiment. Error bars are standard deviations on the mean of four replications.

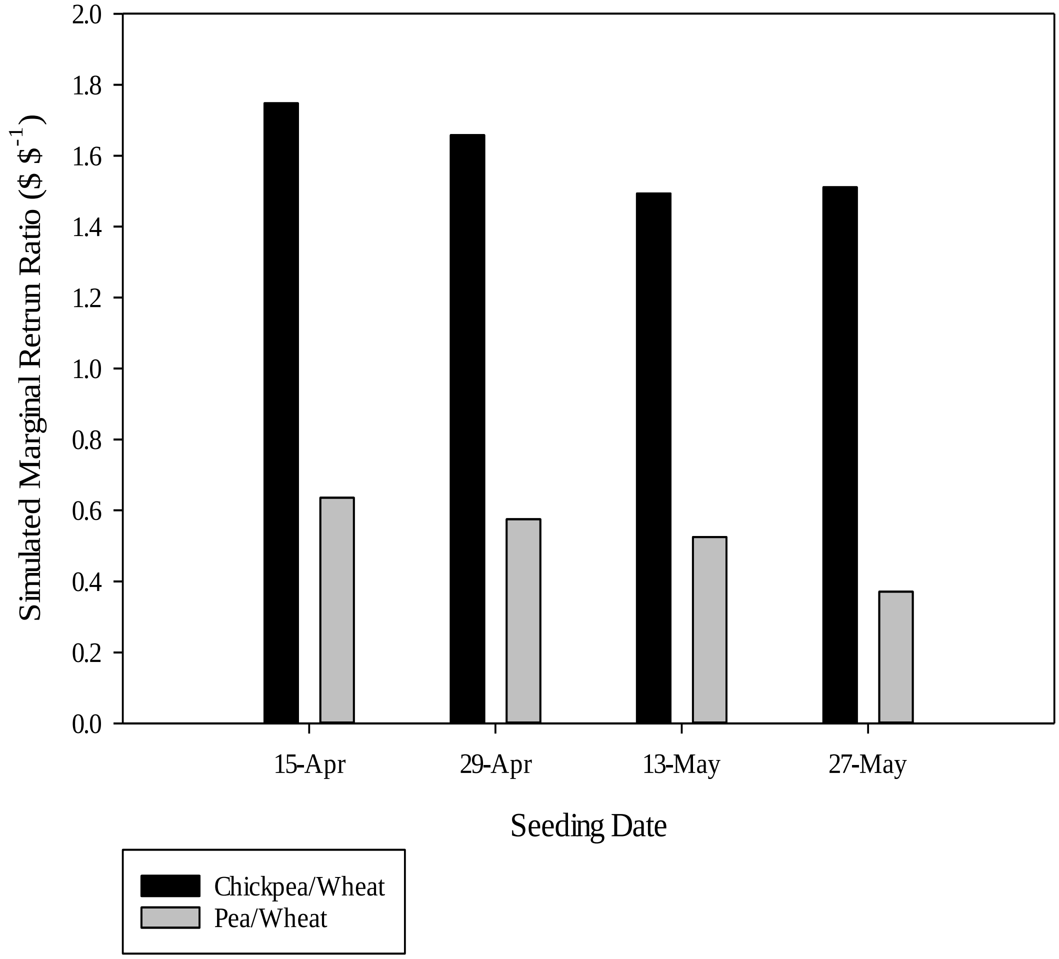

Figure 3. Simulated mean marginal return ratios of chickpea and pea relative to wheat conditioned on seeding date. Marginal return ratios are averaged across all levels of prices received.

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CHAPTER FIVE

SUMMARY

Crop productivity—defined as yield, protein content and net economic returns—hinge on crop water use. Crop water use is a function of cropping sequence, cultivar, seeding date, and environmental factors (e.g. soils and climate). Three studies were conducted to address how these factors interact with crop water use and productivity in Montana.

In the first study, winter wheat yield and protein following fallow (FAL-WW), camelina (CAM-WW), pea and camelina (PEA-CAM-WW), and camelina and pea (CAM-PEA-WW) were compared over two growing seasons (2014-2015) on deep and shallow soils at the Northern and Central Agricultural Research Centers respectively (NARC and CARC). Water extraction was measured on deep soils at NARC, and block kriged soil depth estimates served as a surrogate for stored soil moisture on shallow soils at CARC. On deep soils, yields ranged from 72-84% in continuous sequences compared to fallow-wheat since continuous sequences averaged 20.5 mm less water extracted below 45 cm. Conversely protein was ~0.63% greater in continuous sequences. On shallow soils, sequence did not affect yield or protein, but soil depth did. Yields increased with soil depth (R^2=0.47) while protein decreased (R^2=0.68) in 2014, but no trends were observed in 2015 due to 87 mm greater precipitation from joint to heading. This study suggests that on deep soils, replacing fallow will diminish winter wheat yield and boost protein, whereas soil depth and precipitation timing will govern winter wheat yield and protein on shallow soils.

In the second study, the FAO-56 and agricultural reference index for drought (ARID) water balance models were combined with 10-year (2005-2014) state-wide cultivar testing data to quantify drought stress patterns in winter wheat and field pea. Four and five drought stress patterns were characterized for winter wheat and pea respectively with varying levels of drought intensity. Winter wheat yields ranged from 4421 kg ha^{-1} in the least stressed to 2539 kg ha^{-1} in the highest stressed drought patterns, and yields were most negatively correlated with drought intensity at heading (r^2=0.79). Similarly pea yields ranged from 2877 kg ha^{-1} to 974 kg ha^{-1} in the least and most stressed drought patterns, and yields were most negatively correlated with drought intensity at flowering (r^2=0.76). The least stressed (e.g. highest yielding) drought stress pattern in winter wheat was observed to occur in south-central Montana 80 percent of the time, whereas all drought patterns were observed to occur uniformly across sites for pea. The winter wheat cultivar *Bynum* yielded significantly less than *Yellowstone*, but no yield differences were observed among pea cultivars. Quantitative drought pattern characterization provides a physical basis to assist breeders and land managers in boosting winter wheat and pea yields across Montana.

In the final study, the FAO-56 and ARID water balance model was extended to develop yield vs. water use production functions for spring wheat, pea, and kabuli chickpea. To prioritize which crop to seed first, yield predictions were used to estimate economic returns at three prices received (minimum, median, and maximum of 10-year data) and four seeding dates (15-Apr, 29-Apr, 13-May, and 27-May) based on historical weather data over a ten-year window (2006-2015) near Amsterdam, MT. The production functions predicted yields with mean absolute error (MAE) of 387, 331, and 171 for spring wheat, pea, and chickpea respectively. Simulated mean marginal returns were highest for chickpea (~601 \$ ha^{-1}) followed by wheat (372 \$ ha^{-1}) and pea (202 \$ ha^{-1}) despite chickpea having the lowest simulated yields. The simulations support that chickpea should be seeded before pea and spring wheat since higher prices received are expected from chickpea.

In conclusion, each study emphasizes different aspects of crop productivity (e.g. yield, protein, or economic return) and how each aspect ultimately depends on crop water use. Crop water use and winter wheat productivity will depend only on soil depth and precipitation timing where soils are shallow, but rotation will play an additional role on deep soils. Winter wheat is most susceptible to yield loss from drought stress near heading, but drought stress near heading is less likely to occur in Southern Montana compared with Central and Northern Montana. Similarly pea is most sensitive to yield loss from drought stress at flowering, and drought stress is equally likely to occur at flowering in North, Central, Southern, and Eastern Montana. Lastly yield loss from delayed seeding is less in chickpea compared to spring wheat and pea. However, due to higher prices received associated with chickpea, it may still be more economical to seed chickpea before pea and spring wheat.

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APPENDICES

APPENDIX A

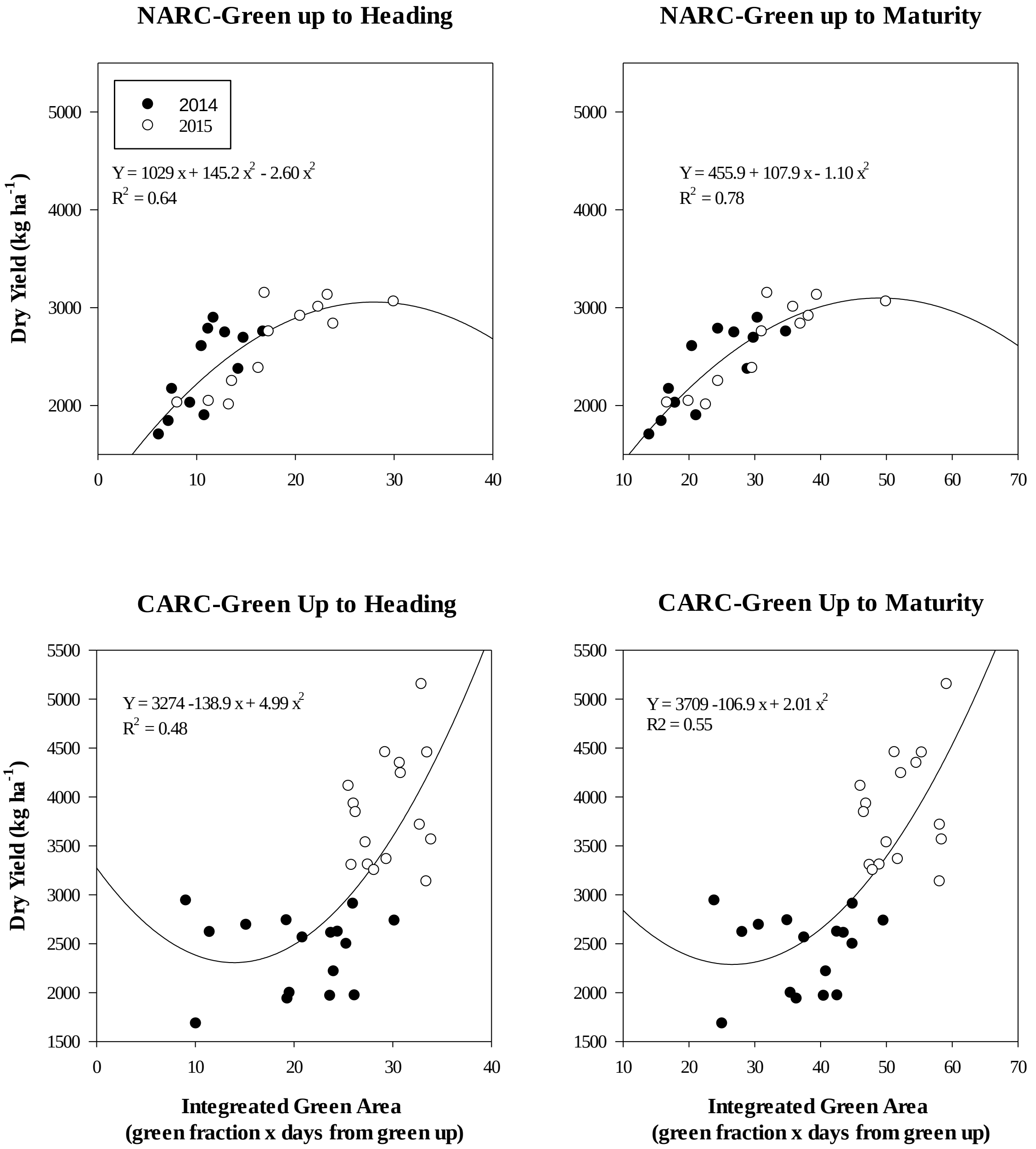
CHAPTER 2: ADDITIONAL DATA AND DETAIL

A.1.Integrated Green Canopy Coverage and Yield Relationships

A.1.1. Green Canopy Coverage and Yield Relationships

The fraction of green canopy cover was monitored weekly at the Central and Northern Agricultural Research Centers (CARC; NARC) over the 2014-2015 growing seasons. This was done by taking digital nadir images 2 meters above the canopy in a 0.6 m x 0.6 m area from fixed plot locations. Images were processed with Sigma Scan Software (SPSS Science, 1999) with hue values ranging from 60-150 and saturation values ranging from 14-100 to separate green from non-green pixels. Fraction of green canopy coverage was calculated as the ratio of green pixels to total image pixels.

Simpson’s integration between sampling dates was used to relate the integrated fraction of green area to yield from spring green-up to heading and from spring green-up to maturity. There were reasonable polynomial fits at NARC but poor and unrealistic fits at CARC. Poor fits at CARC may be due to confounding effects of soil depth and large variation in rainfall timing and amount across years the 2014 and 2015 growing seasons. The underlying figures illustrates the relationships that were observed at CARC and NARC.


NARC-Green up to Heading

NARC-Green up to Maturity

CARC-Green Up to Heading

CARC-Green Up to Maturity

Figure A.1.1. Dry yield vs. integrated green area at the Northern and Central Agricultural Research Centers over 2014-2015 growing seasons.

APPENDIX B

CHAPTER 3 AND 4: ADDITIONAL DATA AND DEAL

B.1. Root Water Uptake Parameter and Yield-ET Relationships

B.1.1 Root Water Uptake Parameter

Various root water uptake models exist. In chapters three and four, a macroscopic root water uptake model developed by (Dardanelli et al., 2004) was implemented. This model follows the equation:

$$\frac{\partial \theta_d}{\partial \theta_t} = (\theta_{d-1} - \theta_{LL})\ x\ \alpha \qquad \text{Eq 1.}$$

where θ_d is the volumetric water content on a given day, θ_{LL} is the volumetric water content at wilting point, and α is an empirical root water uptake constant representing the maximum fraction of soil water that can be extracted from the soil profile. Solving for θ_d in Eq 1.by separation of variables with lower and upper limits of integration set to θ_{LL} and θ_d respectively results in the following function:

$$\theta_d = (\theta_{d-1} - \theta_{LL})\ x\ e^{-(t\ x\ \alpha\ x\ (\theta_{d-1} - \theta_{LL}))} + \theta_{LL} \qquad \text{Eq 2.}$$

Physically this an exponential decay function where t is time (days) from beginning of rapid soil- water extraction.

In chapters 3, α was used as a parameter in the ARID water balance for simulating drought stress patterns in winter wheat and pea. The parameter α was derived from neutron measurements made at The Northern Agricultural Research Center (NARC) and the Southern Agricultural Research Centers (SARC) for wheat and pea. In chapter 4 chickpea was assumed to have the same α as pea for simulating evapotranspiration (ET).

Eq 2 was rearranged to estimate α with ordinary least squares by:

$$\log(\theta_d - \theta_{LL}) = \beta - \alpha\big(t\ x\ (\theta_{d-1} - \theta_{LL})\big) + log(\theta_{d-1} - \theta_{LL}) + \varepsilon \qquad \text{Eq 3.}$$

where β is the intercept ε is the model error term, α is the empirical root water uptake constant, and remaining values are predictor variables from field measurements. Put simply, α, is the slope of the line. The underlying figures illustrates examples of model fits to parameterize α taken from NARC in 2014.

B.1.2 Yield-ET Relationships from Chapter 3

Simulating drought stress patterns in chapter 3 required simulating evapotranspiration. There often exists strong linear relationships between yield and ET in water-limited systems (de Witt, 1958). The underlying figures illustrate the relationships between yield and simulated growing season ET for the six pea and nine winter wheat cultivars in chapter 3.

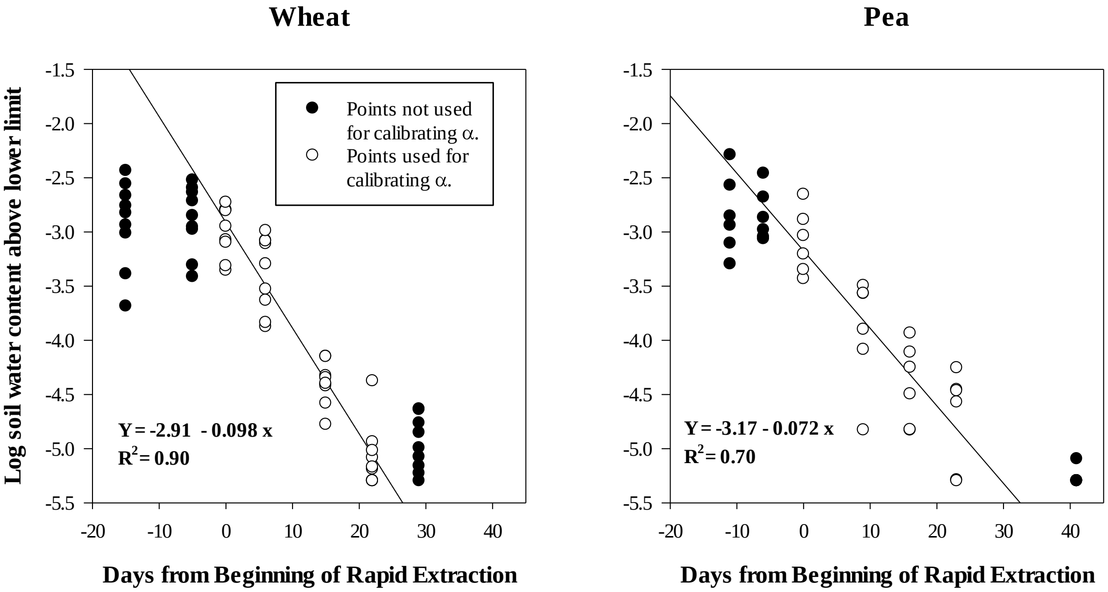


Figure B.1.1. Examples of regressions used to derive root water uptake coefficient (α) in wheat and pea from the Northern Agricultural Research Center (NARC) in 2014. The parameter α is the slope of the regression fit.

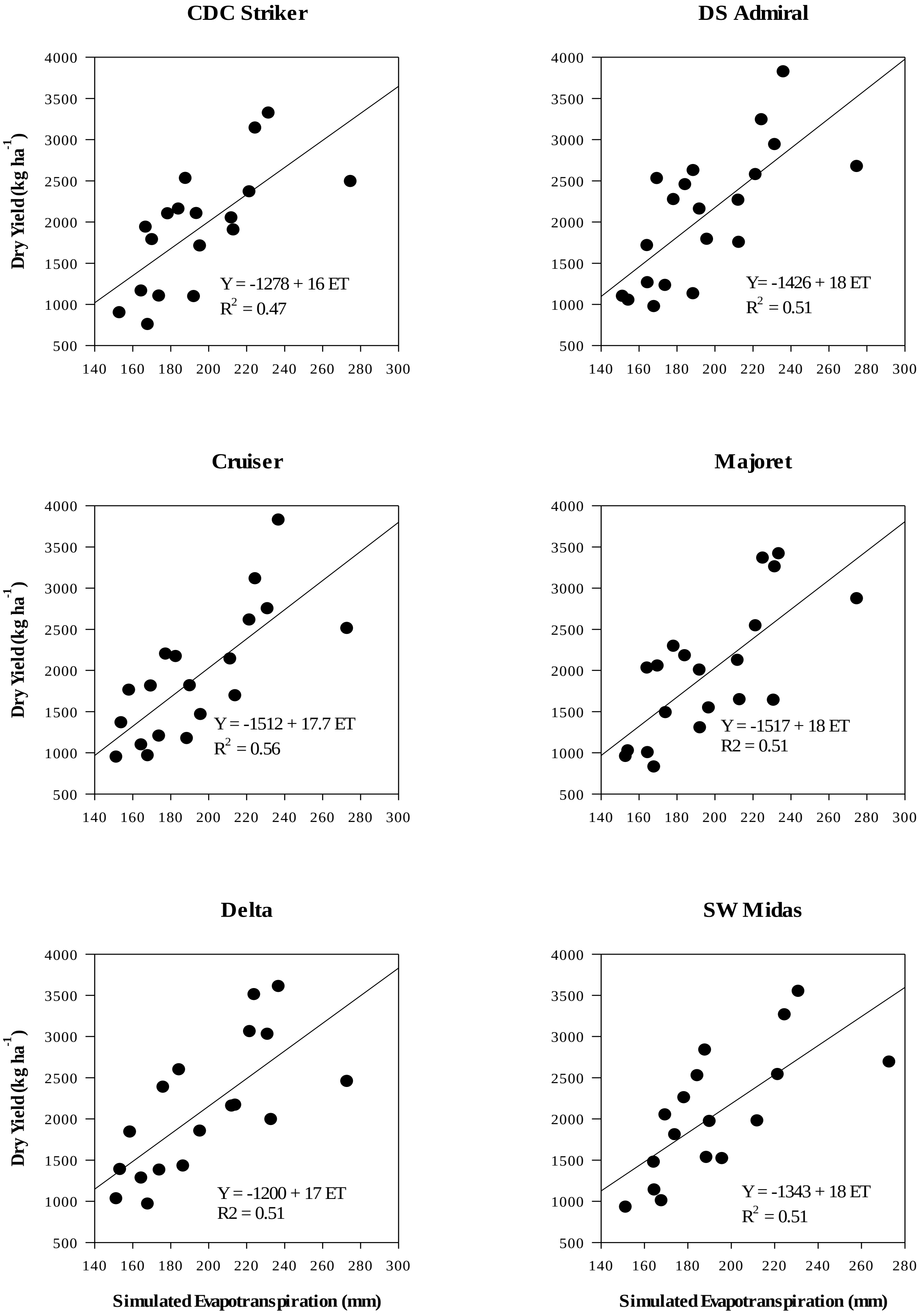


Figure B.1.2.1 Yield-ET relationships for the six pea cultivars in chapter 3.

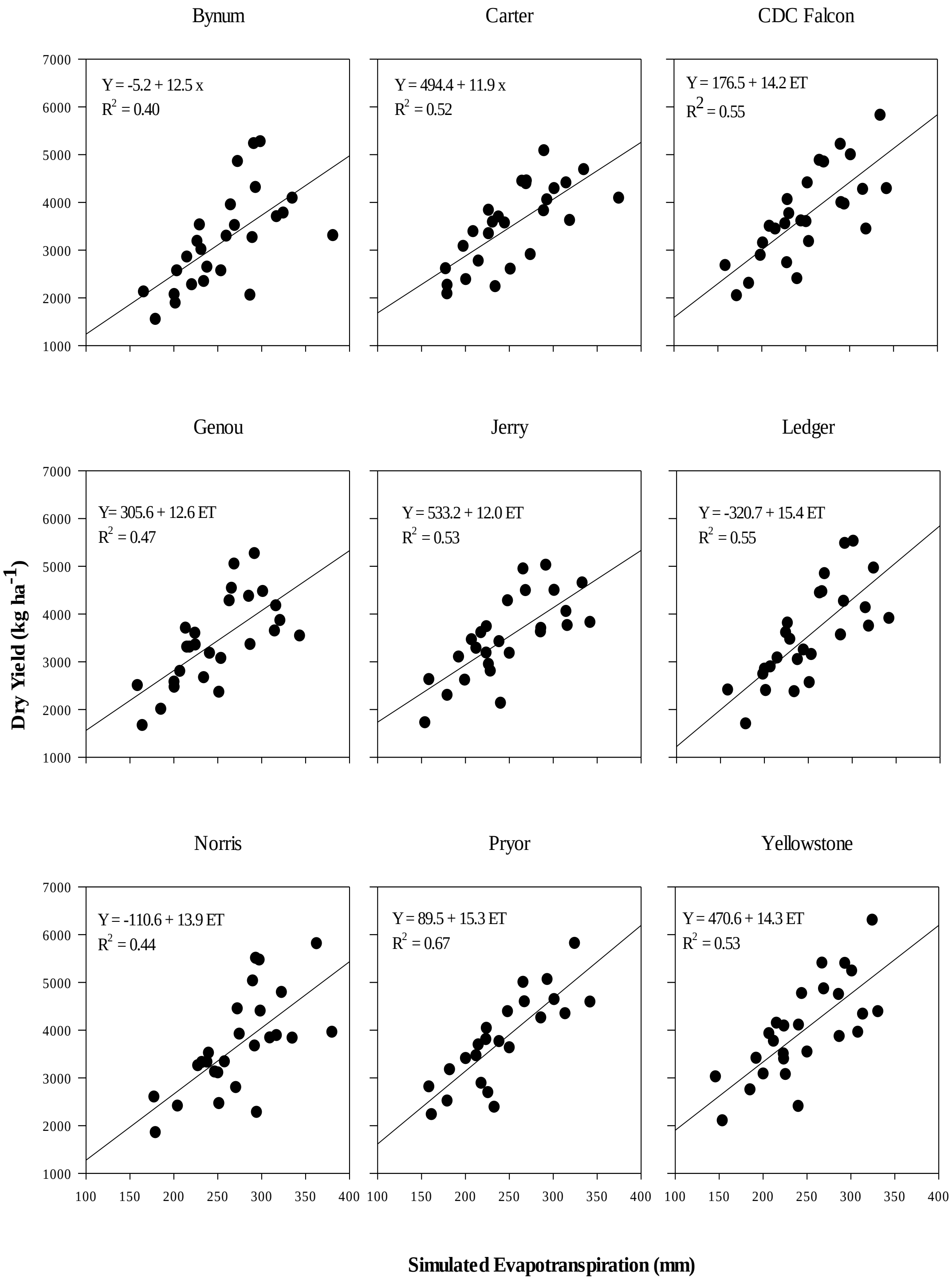


Figure B 1.2.2 Yield-ET relationships for the nine winter wheat cultivars in chapter 3.

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