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Available water and wheat grain yield relations in a Mediterranean climate

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ABSTRACT

Wheat (*Triticum aestivum* L.) is the principle crop grown in many Mediterranean climate zones around the world, including the 3.35 million hectare dryland cropping region of the Inland Pacific Northwest (PNW) of the United States. Farmers in the low- and intermediate-precipitation areas of the region are often reluctant to plant spring wheat (SW) because grain yields are highly variable compared to winter wheat (WW) after summer fallow (SF). Our objectives were to: (i) assess available water and wheat grain yield relations from well-fertilized dryland field experiments conducted from 1953 to 1957 versus related studies from 1993 to 2005, (ii) compare and compartmentalize available water-use efficiency of WW compared to SW during the 1993–2005 period, and (iii) provide a tool to allow farmers to predict SW grain yield based on stored soil water at time of planting plus expected spring (April, May, June) rainfall. Simple linear regression showed that 10.1 cm of available water was required just for vegetative growth (before wheat reproductive development begins) in the 1953–1957 study ($n = 90$ replicated treatments), whereas only 5.9 cm of available water was needed in the 1993–2005 experiment ($n = 175$ replicated treatments). In addition to water required for vegetative growth, multiple regression analysis showed that from 1953 to 1957 each centimeter of available stored soil water and spring rainfall (SR) produced 140 and 183 kg grain ha^{-1}, respectively, compared to 150 and 174 kg grain ha^{-1}, respectively, for the 1993–2005 study. Multiple regression further demonstrated in the 1993–2005 studies that April rainfall contributed much less to grain yield than rainfall in May and June for both SW and WW. Winter wheat always produced more grain per unit of available water compared to SW. Data reveal that modern semi-dwarf wheat cultivars begin grain production with 4.2 cm less available water than standard-height cultivars of the 1950s. This, along with improved agronomic management, is a major contributor to ever increasing wheat grain yields during the past 50 years.

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1. Introduction

Dryland wheat farming is widely practiced in Mediterranean-like climates including numerous countries surrounding the Mediterranean Sea, the Inland PNW of the United States, parts of western and southwestern Australia, and central Chile. The Mediterranean climate is characterized by cool, wet winters and warm, dry summers. Dryland wheat production in these climates is generally heavily dependent on water stored in the soil during the winter in addition to spring rainfall (Arnon, 1972).

The dryland cropping region of the Inland PNW includes eastern Washington, north-central Oregon, and northern Idaho. Average annual precipitation ranges from 150 to 600 mm with 60–70% occurring from October through March. About 25% of annual precipitation occurs from April through June when most wheat growth occurs. Due to wide differences in the quantity of precipitation, the Inland PNW is divided into three annual precipitation zones: (i) low <300 mm of precipitation, (ii) intermediate 300–450 mm of precipitation, and (iii) high 450–600 mm of precipitation.

In the low-precipitation zone, the dominant crop rotation is WW–SF where only one crop is produced every other year. A 3-year WW–SW–SF rotation is commonly practiced in the intermediate-precipitation zone, with spring barley (*Hordeum vulgare* L.) sometimes substituted for SW. Annual cropping is practiced in the high-precipitation zone with WW mostly grown every third year in rotation with SW, spring barley, lentil (*Lens culinaris*

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Abbreviations: OWG, over-winter soil water gain; PNW, Pacific Northwest of the United States; r^2, coefficient of simple determination; R^2, coefficient of multiple determination; SF, summer fallow; SFW, summer fallow available soil water; SR, spring rainfall; SW, spring wheat; WW, winter wheat.

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Medik.), pea (*Pisum sativum* L.) and other spring-sown crops. Further details on crop rotations, soils, and climate in the Inland PNW are found in Schillinger et al. (2006).

Increased cropping intensity (i.e., less SF) provides environmental benefits by reducing wind (Papendick, 2004) and water (Papendick et al., 1983) erosion. However, most farmers in the low- and intermediate-precipitation zones are reluctant to plant SW in lieu of SF because SW is more risky and grain yields more variable compared to WW after SF (Schillinger et al., 2007).

The complex theoretical framework of crop growth as related to biomass water productivity, solar radiation, precipitation timing, evapotranspiration, nitrogen nutrition, and other factors has been presented by Stockle et al. (2003), Steduto et al. (2007), Rodriguez and Sadras (2007), and others. Brown et al. (1981) suggested using grain yield response to soil water at planting and expected growing season precipitation to help guide crop choices in flexible cropping systems in Montana and North Dakota that included SW, WW, barley, oats (*Avena sativa* L.) and safflower (*Carthamus tinctorius* L.). Nielsen and Halvorson (1991) defined a linear relationship between WW grain yield and the combination of soil water use and rainfall from April through June in Colorado. Nielsen et al. (2002) reported a similar linear response of WW grain yield to available soil water at planting and suggested that the relationship could be used for crop planning purposes and to assess risk of profitable production prior to planting.

Our focus in this paper is the relationship of water and wheat grain yield under the Mediterranean-like climatic conditions of the Inland PNW. The study had three objectives. These were to: (i) assess available water and wheat grain yield relations from dryland field experiments conducted from 1953 to 1957 compared to studies carried out from 1993 to 2005, (ii) assess the relative importance of stored soil water and SR for both WW and SW during the 1993–2005 period, and (iii) provide a tool to predict SW grain yield based on stored soil water at time of planting plus expected SR during the individual months of April, May, and June.

2. Materials and methods

2.1. Overview and study description

In the years 1953–1957, G.E. Leggett, soil scientist at Washington State University, conducted a series of field experiments in eastern Washington to determine optimum nitrogen fertility for dryland wheat based on available water in the soil profile in mid-to-late March plus spring (i.e., April, May, and June) rainfall. From 1993 to 2005, the authors conducted a series of related dryland wheat-related cropping systems experiments in eastern Washington.

Available soil water is most commonly described in the literature as the difference between the water content values at field capacity and the permanent wilting point of −1.5 MPa (Romano and Santini, 2002). The working definition of "available water" in this paper is total water potentially obtainable by the wheat plant minus water remaining in the 180 cm soil profile at grain harvest in early August. Water remaining in the 180 cm soil profile at wheat harvest is considered "unavailable". We consider available water in three phases: (i) over-winter gain (OWG) is the net increase in soil water from harvest of the previous wheat crop (or end of SF period in the WW–SF rotation) to late March; (ii) spring rainfall (SR) is rain in April, May, and June—all of which is considered available to the wheat plant; and (iii) summer fallow water (SFW) is the gain in soil water after 13 months of SF used for establishment of WW in late August planting. All SR is considered "available" because runoff from rainfall events on planted wheat fields in the spring is negligible (Papendick and McCool, 1994).

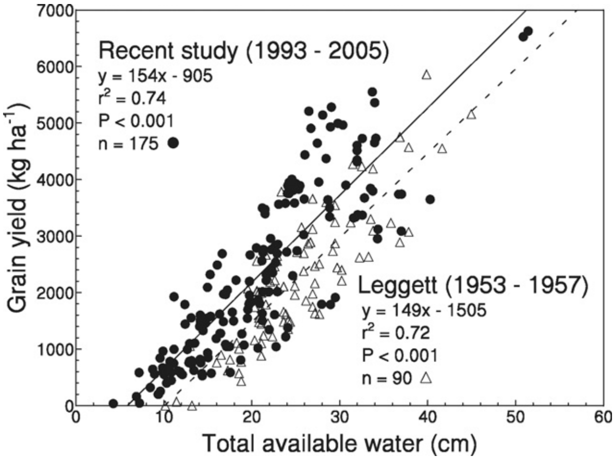

Fig. 1. The relationship between available water in the soil profile plus spring rainfall and grain yield of dryland wheat in eastern Washington. Data were collected from 1953 to 1957 (dotted line, open triangles) and from 1993 to 2005 (solid line, filled circles). Grain yield data are from a combination of winter wheat and spring wheat.

Leggett (1959) obtained gravimetric soil water measurements in late March and again following grain harvest in early August. Over the course of 90 treatments with each having 3–6 replications (Fig. 1), data consisted of WW grown after SF, recrop WW (i.e., no SF), and recrop SW, combining all the grain yield data together in his report (Leggett, 1959). He used known soil bulk density values for various soil types at each experiment site to convert gravimetric water content values to volumetric water content (Topp and Ferre, 2002). The cooperating farmers measured spring rainfall.

For the dryland wheat-related cropping systems experiments conducted from 1993 to 2005, volumetric soil water content, wheat grain yield, and precipitation data were collected from 175 replicated treatments. Each data point in Fig. 1 represents from four to six replications. Of these, 49 data points are for WW after SF, 33 for recrop WW, 85 for recrop SW, and 8 for SW after SF. Volumetric water content in the 0–30-cm depth was determined from two 15 cm cores using gravimetric procedures as described by Topp and Ferre (2002). Volumetric soil water content in the 30–180-cm depth was measured in 15 cm increments by neutron thermalization (Hignett and Evett, 2002). For recrop WW and recrop SW, volumetric soil water was measured in late March and again following grain harvest in early August. In the WW–SF rotation, soil water content in SF was measured just before planting in late August and again in the growing WW crop in late March, i.e., the same dates as the other spring soil water measurements. Year-round precipitation was measured at all sites with either an official U.S. Weather bureau monitor or small computerized weather stations.

Soil samples were collected and analyzed for No_3^- nitrogen prior to planting all experiments conducted from 1953 to 1957 and from 1993 to 2005. Four nitrogen fertilizer rates (0, 22, 44, and 88 kg N ha^{-1}) were used for the 1953–1957 experiments (Leggett et al., 1959). For the 1993–2005 experiments, the nitrogen fertilizer rate was based on available soil water and soil residual nitrogen to achieve 23 kg of total nitrogen for each expected 1000 kg of grain yield. In our study, an average of 10 kg ha^{-1} phosphorus and 8 kg ha^{-1} sulfur were also applied (to recrop WW and SW only) based on soil test results for these nutrients.

The 1953–1957 and 1993–2005 field experiments were conducted throughout eastern Washington where average annual precipitation ranges from 150 to 600 mm, but the majority of sites were in the 240–350 mm average precipitation-zone in Adams, Lincoln, and Whitman Counties. Depth of soil at all sites for the Leggett (1959) and recent study was >180 cm. The three main soil types on which experiments were conducted are Shano silt loam (coarse-silty, mixed, superactive, mesic Xeric Haplocambids), Ritzville silt loam (coarse-silty, mixed, superactive, mesic Calcidic Haploxerolls), and Walla Walla silt loam (coarse-silty, mixed, mesic Typic Haploxerolls). All soil types are well drained and formed in loess overlying basalt bedrock.

The main SW cultivars in the 1953–1957 experiments were Baart, Marfed, and Brevor, and the only WW cultivar used was Elmar (Leggett et al., 1959). These were standard-height (i.e., no reduced-height genes) soft-white cultivars that were widely planted by regional farmers from 1953 to 1957 (USDA, 1959). In the early 1960s, PNW wheat breeders began incorporating *Rht₁* and *Rht₂* reduced-height genes into cultivars for superior straw strength and the ability to tolerate high levels of nitrogen fertilizer without lodging (Jones, 2002). All but two PNW soft-white wheat cultivars released since the early 1960s are semi-dwarfs that carry either *Rht₁* or *Rht₂* reduced-height genes. The SW cultivar Alpowa and WW cultivar Eltan, both semi-dwarfs of the soft-white class, were the predominant wheat cultivars used for the 1993–2005 experiments.

Wheat grain yield for the 1953–1957 experiments was determined by harvesting two or more samples by hand within each plot if the plots were small; otherwise a commercial-size combine was used and grain augured into a weigh wagon (Leggett et al., 1959). For the 1993–2005 experiments, either a Hege 140 plot combine or a commercial-size combine with weigh wagon were used to measure wheat grain yield. No information on plot size is provided in either the Leggett (1959) or Leggett et al. (1959) reports, although we assume that most plots were quite long as the cooperating farmer's equipment was used for most of the 1953–1957 experiments. Plot length for the 1993–2005 experiments ranged from 60 to 150 m.

2.2. Statistical analysis

We analyzed our own as well as Leggett (1959) data through simple and multiple regression procedures using SAS Proc Reg (Version 9.1.3). Normality and homogeneity of variance of residuals were checked using normal probability plots and plots of residuals versus predicted values, respectively. Variance inflation factors were used to check for multicollinearity among predictor variables in the multiple regression analyses. Small, but relatively inconsequential, errors were found in the original Leggett (1959) regression analyses—this is not surprising given the volume of data and the fact that all statistics were done with a slide rule and hand calculations in the 1950s.

3. Results and discussion

3.1. Leggett versus recent study

Leggett (1959) used the greatest wheat grain yield obtained from the four nitrogen fertilizer rate treatments in his experiments (Leggett et al., 1959) to plot available water and grain yield relations. He fitted a simple linear regression line that showed 10.1 cm of available water was required just for vegetative growth of wheat and, for every additional centimeter of water, 149 kg ha^{-1} of wheat could be expected (Fig. 1, dotted line). Using multiple regression, his data produced the equation:

$$Y = 140\,\mathrm{OWG} + 183\,\mathrm{SR} - 1599 \qquad (1)$$

where Y is the grain yield in kg ha^{-1}, OWG is the over-winter soil water gain in centimeters (i.e., gain from time of harvest of the previous crop until planting of SW, or gain since planting into SF for WW), and SR is the spring rainfall in centimeters that occurred in April, May, and June. The coefficient of multiple determination (R^2) for Eq. (1) is 0.73 with $P < 0.001$. The average OWG during the 5-year Leggett (1959) study was 18.0 cm, and average total SR was 7.1 cm (he did not report rainfall by individual months). The 5-year average grain yield for combined WW ($n = 57$) and SW ($n = 33$) was 2251 kg ha^{-1}.

Combining WW after SF, recrop WW, recrop SW, and SW after SF data from the recent (1993–2005) study, simple linear regression analysis (Fig. 1, solid line) showed that wheat requires 5.9 cm of available water for vegetative growth, with 154 kg grain ha^{-1} produced per each additional centimeter of water. Multiple regression analysis of data resulted in the equation:

$$Y = 150\,\mathrm{OWG} + 174\,\mathrm{SR} - 986 \qquad (2)$$

The coefficient of multiple determination for Eq. (2) is 0.73 with $P < 0.001$. Over the 13-year period, available soil water content averaged 16.3 cm in late March with an additional 5.8 cm of SR. Our average grain yield was 2963 kg ha^{-1} for WW and 1767 kg ha^{-1} for SW, with an overall average (including recrop WW and SW after SF) of 2331 kg ha^{-1}.

For a given quantity of water, we conclude that in both the 1953–1957 and 1993–2005 studies SR was more effective than stored soil water for increasing wheat yield (Eq. (1) and Eq. (2)). However, because <30% of annual precipitation occurs during the spring, SR was less important overall than stored water for determining wheat yield. When treated as separate variables, coefficients of simple determination (r^2) of 0.67 and 0.26 were obtained for stored water and spring rainfall, respectively. The slopes of the fitted regression lines are almost identical for the Leggett (1959) and the recent study (Fig. 1). However, because we show wheat grain production beginning at 5.9 cm of available water compared to 10.1 cm for Leggett (1959), a greater predicted grain yield will result using our regression equation. There was no statistical difference in the slope between the two regression lines in Fig. 1 but the difference in intercept was highly significant ($P < 0.001$).

As an example of how to estimate wheat production based on available water on a given farm, assume that OWG is 18.3 cm and that long-term average SR at the location is 6.35 cm. Our model (Eq. (2)) predicts a SW grain yield of 2864 kg ha^{-1}. For the same quantity of stored soil water and SR, Leggett (1959) model (Eq. (1)) predicts a SW grain yield of only 2125 kg ha^{-1}. Predicted grain yield differences between the two models may likely be due to: (i) the ability of modern semi-dwarf wheat cultivars to begin grain production with less available water (Condon et al., 2004) compared to the standard-height wheat cultivars in the 1950s and (ii) improved timing of field operations and agronomic management in recent decades (Turner, 2004) that includes widespread use of phosphorus and sulfur fertilizers for SW production and nonselective herbicides for "burndown" weed control in lieu of tillage.

3.2. Spring wheat versus winter wheat in recent study

A separate analysis was conducted for available water and grain yield relations for WW after SF compared to recrop SW for data collected from 1993 to 2005. Using simple linear regression, 1 cm of available water resulted in 192 kg grain ha^{-1} for WW after SF and 142 kg grain ha^{-1} for recrop SW (Fig. 2). Brown et al. (1981) similarly reported a distinctly lower slope for the water use versus grain yield relationship for SW (135 kg ha^{-1} cm^{-1}) compared to WW (153 kg ha^{-1} cm^{-1}).

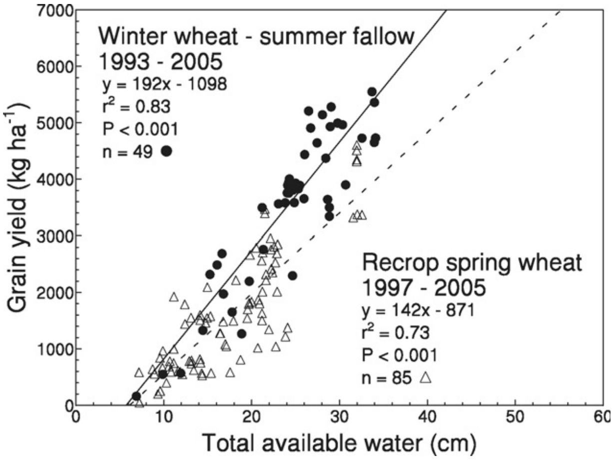

Fig. 2. The relationship between available water in the soil profile plus spring rainfall and grain yield for winter wheat after summer fallow (solid line, filled circles) and for spring wheat (dotted line, open triangles) from 1993 to 2005 in eastern Washington.

Data were also analyzed using multiple regression by partitioning the WW after SF available water into: (i) soil water available in SF at time of planting in late August–early September, (ii) OWG, (iii) April rain, (iv) May rain, and (v) June rain. For recrop SW, of course, only factors (ii) through (v) above were used in the analysis. All SR (April, May, June) was considered available.

The fitted multiple regression models were:

$$\text{WW after SF}: Y = 176\,\text{SFW} + 208\,\text{OWG} + 117\,\text{A} + 200\,\text{M} + 323\,\text{J} - 1101 \quad (3)$$

and

$$\text{Recrop SW}: Y = 143\,\text{OWG} + 38\,\text{A} + 169\,\text{M} + 150\,\text{J} - 713 \quad (4)$$

where Y is the grain yield in kg ha^{-1}, SFW is the summer fallow available soil water in centimeters, OWG is the net over-winter soil water gain in centimeters, A is the April rain, M is the May rain, and J is the June rain in centimeters. The coefficient of multiple determination was 0.83 for Eq. (3) and 0.73 for Eq. (4) with $P < 0.001$ for both equations.

Simple linear regression revealed that about 6 cm of available water was required just for vegetative growth for both WW and SW (Fig. 2). For WW (Eq. (3)), each centimeter of available SFW at time of planting produced 176 kg grain ha^{-1}. Each centimeter of OWG (in addition to what was present at time of planting in late August) produced 208 kg grain ha^{-1}. Every centimeter of rainfall in April, May, and June accounted for 117, 200, and 323 kg grain ha^{-1}, respectively. For SW (Eq. (4)), each centimeter of OWG provided 143 kg grain ha^{-1} and April, May, and June rainfall generated another 38, 169, and 150 kg grain ha^{-1}, respectively. The grain yield boost for SW from SR was only 56% of that for WW. There was no statistical difference in the intercept for WW compared to SW in Fig. 2, but the difference in slope was highly significant ($P < 0.003$).

As an example of how to predict SW yield using data from the 1993–2005 studies, assume that OWG is 13.5 cm and expected rainfall in April, May, and June is 2.3, 2.6, and 1.8 cm, respectively. Predicted SW grain yield using Eq. (4) and the above water values is 2014 kg ha^{-1}.

The analysis shows that WW makes more efficient use of both stored soil water and SR than does SW. For both WW and SW, rainfall in April is much less beneficial for grain yield compared to rainfall in May and June. This is likely because surface soils remain relatively wet during April, temperatures are generally cool, and wheat plants are not water stressed. This is particularly true for SW that is still in the seedling stage of development (Large, 1954) during April with a small leaf area index that requires and uses little water. Anthesis generally occurs in mid-to-late May for WW and early-to-mid June for SW in the Inland PNW. French and Schultz (1984), Passioura (1977), and others have emphasized the key importance of adequate available water at and after anthesis to optimize grain yield of wheat.

Ramig and Pumphrey (1977) and Payne et al. (2001) used multiple regression to predict WW grain yield based on data from a long-term winter wheat–spring pea rotation experiment conducted near Pendleton, OR. Ramig and Pumphrey (1977) reported an average of 38, −1, 148, and 307 kg grain ha^{-1} for each centimeter of stored water and April, May, June rainfall, respectively, with $R^2 = 0.64$. Payne et al. (2001), reporting on WW yield over the entire 21-year study, obtained 61, 79, 407, and 239 kg grain ha^{-1} for each centimeter of stored soil water and April, May, June rainfall, respectively, with $R^2 = 0.62$. Their studies demonstrated less benefit of stored soil water compared to Leggett (1959) and our study because they used total soil water rather than plant-available stored water in their calculations. Their findings of little or no benefit of April rainfall for WW grain yield were very similar to those in our study.

4. Conclusions

A major objective of this work was to provide farmers in the Mediterranean-like climate of the Inland PNW a decision tool, based on available soil water in late March and historic SR, to determine whether to plant SW, or instead leave the land fallow and plant WW in late summer. For the tool to be truly useful, access to long-term site-specific SR data from a location near (or representative of) a given farm is required. Long-term precipitation data are available from approximately 50 weather stations in eastern Washington and north-central Oregon. With such data, mean monthly SR and associated probability of receiving a given amount of rainfall during April, May, and June can be predicted. This tool may also be useful for farmers who produce hard red winter wheat to help determine grain yield potential and, therefore, the quantity of nitrogen to topdress in the spring to meet protein percentages to receive optimum grain price.

The next logical step to further develop the available water-wheat grain yield model into a comprehensive decision tool is to include wheat price, production costs, and site-specific yield adjustments such as weed or disease pressure. Such an all-inclusive decision tool would display the probability of different yield and profitability outcomes under numerous scenarios for both WW after SF and recrop SW.

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