

Predicting Wheat Grain Yields Based on Available Water

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William F. Schillinger, Steven E. Schofstoll, and J. Richard Alldredge

OVERVIEW

Wheat is the principal crop grown in many Mediterranean-like climate zones around the world, including the 8.3 million acre dryland cropping region of the U. S. Inland Pacific Northwest (PNW). Farmers in the low and intermediate precipitation areas of this region know that planting spring wheat (SW) will help them control winter-annual grass weeds and that SW production can be profitable with adequate available water. However, farmers are often reluctant to plant spring wheat (SW) because grain yields are highly variable compared to winter wheat (WW) after summer fallow (SF). Our research had three objectives: (1) assess the relationship between available water and wheat grain yield based on dryland field experiments conducted from 1953 to 1957 and comparing it to findings in studies carried out from 1993 to 2005, (2) assess the relative importance of stored soil water and spring rainfall for both WW and SW during the 1993–2005 period, and (3) provide a tool for predicting SW grain yield that uses stored soil water at time of planting and expected rainfall during the individual months of April, May, and June. The results of statistical analysis in the 1953–1957 study of 90 replicated plots have shown that 4.0 inches of available water is required just for vegetative growth (before wheat reproductive development begins), whereas in the 1993–2005 study of 175 replicated plots, only 2.3 inches of available water were needed. In addition to water required for vegetative growth, statistical analysis showed that from 1953 to 1957 each inch of available stored soil water and spring rainfall produced 5.3 and 6.9 bushels per acre (bu/ac), respectively, compared to 5.7 and 6.6 bu/ac respectively, for the 1993–2005 study. Further statistical analysis done in the 1993–2005 studies showed 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 than SW did. Data reveal that modern semi-dwarf wheat varieties begin grain production with 1.7 inches less available water than the standard-height varieties of the 1950s. This, along with improved agronomic management, is a major contributor to the ever increasing wheat grain yields of the past 50 years.

INTRODUCTION

This paper focuses on our research into the relationship between available water and wheat grain yield under the Mediterranean-like climatic conditions of the U.S. Inland PNW. Our research had three objectives: (1) assess the relationship between available water and wheat grain yield based on dryland field experiments conducted from 1953 to 1957 and comparing it to findings in studies carried out from 1993 to 2005, (2) assess the relative importance of stored soil water and spring rainfall for both WW and SW during the 1993–2005 period, and (3) provide a tool for predicting SW grain yield that uses stored soil water at time of planting and expected rainfall during the individual months of April, May, and June.

Dryland wheat farming is widely practiced in Mediterranean-like climates, which include numerous countries surrounding the Mediterranean Sea, the U.S. Inland Pacific Northwest, 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 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 in these areas ranges from 6-24 inches, with 60%-70% of it occurring from October through March. About 25% of the annual precipitation occurs from April through June, when most wheat growth occurs. Due to wide differences in the amount of precipitation, the Inland PNW can be divided into three annual precipitation zones: (1) low (<12 inches of precipitation), (2) intermediate (12 to 18 inches of precipitation), and (3) high (18 to 24 inches of precipitation).

In the low-precipitation zone, the dominant crop rotation is WW–SF, where only one crop is produced every other year. In the intermediate-precipitation zone, a 3-year WW–SW–SF rotation is commonly practiced, with spring barley sometimes substituted for SW. In the high-precipitation zone, annual crop-

ping is practiced, with WW mostly grown every third year in rotation with SW, spring barley, lentils, peas, and other spring-sown crops. Further details on crop rotations, soils, and climate in the Inland PNW can be found in Schillinger et al. (2006).

Increased cropping intensity (i.e., less SF) provides environmental benefits by reducing wind (Papendick 2004) and water erosion (Papendick et al. 1983). However, most farmers in the low and intermediate precipitation zones are reluctant to plant SW in lieu of SF because SW is riskier and grain yields less reliable compared to WW after SF (Schillinger et al. 2007). Of all the factors affecting crop growth, 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, and safflower. 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 relationship between WW grain yield and available soil water at planting and suggested that this relationship could be used for crop planning purposes, as well as to assess the risks to profitable production prior to planting.

METHODS USED

Overview and Study Description

In the years from 1953 to 1957, G.E. Leggett, a soil scientist at Washington State University, conducted a series of field experiments in eastern Washington to determine the optimum nitrogen fertility for dryland wheat based on available water in the soil 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 permanent wilting point. The working definition for “available water” in this paper is total water potentially obtainable by the wheat plant minus the water remaining in the 6-ft soil profile at grain harvest in early August. Water remaining in the 6-ft soil profile at wheat harvest is considered “unavailable.” We consider available water in three phases: (1) Over-winter gain (OWG) is the net increase in soil water from the previous wheat crop harvest (or end of the SF period in the WW-SF rotation) to late March, (2) spring rainfall (SR) is the amount of rain in April, May, and June,

all of which is considered available to the wheat plant, and (3) summer fallow water (SFW) is the gain in soil water after 13 months of SF that is used to establish WW in late August planting. All spring rainfall is considered “available” because runoff from rainfall on planted wheat fields in the spring is negligible (Papendick and McCool 1994).

Leggett (1959) obtained gravimetric soil water measurements in late March and again following grain harvest in early August. Over the course of 90 replicated plots (Figure 1), data consisted of WW grown after SF, recrop WW (i.e., no SF), and recrop SW, which were combined in his report (Leggett 1959). Leggett 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 system experiments conducted from 1993 to 2005, volumetric soil water content, wheat grain yield, and precipitation data were collected from 175 replicated plots. Of these, 49 data points were for WW after SF, 33 for recrop WW, 85 for recrop SW, and 8 for SW after SF. Volumetric water content in the 0- to 1-ft depth was determined from two 6-inch cores using gravimetric procedures as described by Topp and Ferre (2002). Volumetric soil water content in the 1- to 6-ft depth was measured in 6-inch increments by using a neutron hydroprobe (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 within 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 nitrogen prior to planting in all experiments conducted from 1953 to 1957 and from 1993 to 2005. Four nitrogen fertilizer rates (0, 20, 40, and 80 lb of nitrogen per acre) were used for the 1953 to 1957 experiments (Leggett et al. 1959). For the 1993 to 2005 experiments, the nitrogen fertilizer rate was based on available soil water and soil residual nitrogen needed to achieve 2.3 lb of total nitrogen for each expected bushel of grain. In our study, an average of 10 lb/ac of phosphorus and 8 lb/ac of 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 6 to 24 inches, but the majority of sites were in the 9.5- to 13.8-inch average precipitation zone in Adams, Lincoln, and Whitman Counties. Soil depth at all sites for both the Leggett (1959) and recent study was more than 6 ft. The three main soil types on which experiments were conducted were Shano silt loam, Ritzville silt loam, and Walla Walla silt loam. All soil types are well drained and formed in loess overlying basalt bedrock.

The main SW varieties used in the 1953–1957 experiments were Baart, Marfed, and Brevor, and the only WW variety used was Elmar (Leggett et al. 1959). These were standard height (i.e., no reduced-height genes), soft-white varieties that were widely planted by regional farmers from 1953 to 1957 (USDA 1959). In the early 1960s, PNW wheat breeders began incorporating reduced-height genes into different varieties 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 varieties released since the early 1960s are semi-dwarfs that carry these reduced-height genes. The SW variety Alpowa and WW variety Eltan, both semi-dwarfs of the soft-white class, were the predominant wheat varieties 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 since the cooperating farmers' equipment was used for most of the 1953–1957 experiments. Plot length for the 1993–2005 experiments ranged from 200 to 500 ft.

RESULTS AND DISCUSSION

Leggett vs. 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 relationships. He plotted a line that showed 4.0 inches of available water was required just for vegetative growth of wheat and, for every additional inch of water, 5.6 bu/ac of wheat could be expected, as shown by the dotted line in (Figure 1). A statistical analysis of his data produced Equation 1:

$$Y = 5.3 \text{ OWG} + 6.9 \text{ SR} - 23.8$$

where Y is grain yield in bu/ac, OWG is over-winter soil water gain in inches (i.e., gain from time of previous crop harvest until planting of SW, or gain since

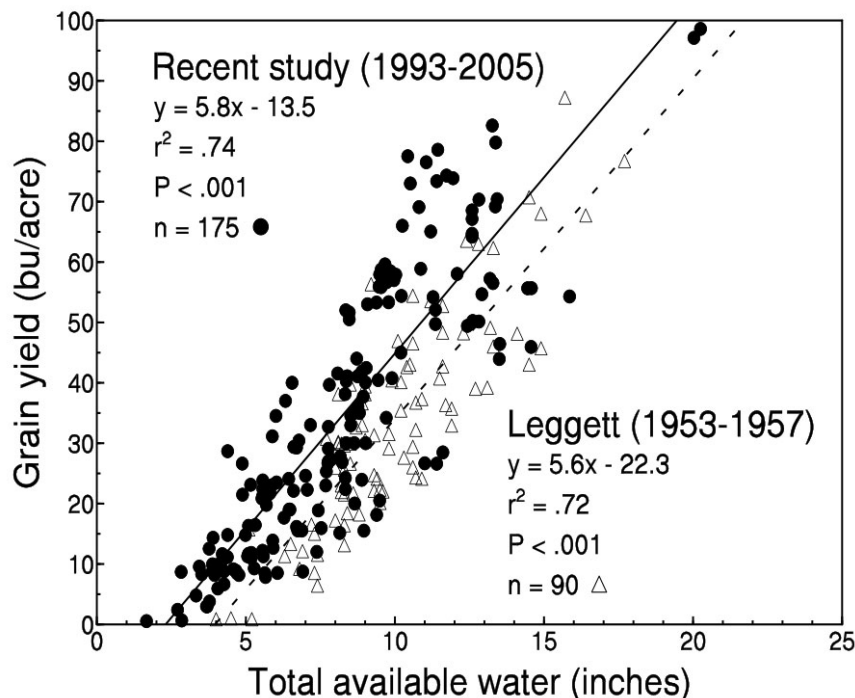


Figure 1. The relationship between available water in the soil profile plus spring rainfall and grain yield of dryland wheat in eastern Washington. Data were collected from 1953 to 1957 (dotted line, open triangles) and from 1993 to 2005 (solid line, filled circles). Grain yield data are from a combination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

planting into SF for WW), and SR is spring rainfall in inches that occurred in April, May, and June. The analysis also showed that 73% of the variability in the data can be explained by this equation. The average OWG during the 5-year Leggett (1959) study was 7.1 inches, and average total spring rainfall was 2.8 inches. (They did not report rainfall by individual months.) The 5-year average grain yield for combined WW (57 replicated plots) and SW (33 replicated plots) was 33.5 bu/ac.

Combining WW after SF, recrop WW, recrop SW, and SW after SF data from the more recent (1993–2005) study, statistical analysis (Figure 1, solid line) showed that wheat requires 2.3 inches of available water for vegetative growth, with 5.8 bu/ac produced per each additional inch of water. Analysis of data resulted in Equation 2:

$$Y = 5.7 \text{ OWG} + 6.6 \text{ SR} - 14.7$$

As with the Leggett study, this equation accounts for 73% of the variability in the data for the 1993–2005 study. Over the 13-year period, available soil water content averaged 6.4 inches in late March with an additional 2.3 inches of spring rain. Our average grain yield was 44.1 bu/ac for WW and 26.3 bu/ac for SW, with an overall average (including recrop WW and SW after SF) of 34.7 bu/ac.

We can conclude from both the 1953–1957 and 1993–2005 studies that spring rainfall was more effective than stored soil water for increasing wheat yield, as shown in Equation 1 and Equation 2. However, because less than 30% of the annual precipitation occurs during the spring, the amount of rainfall at this time was less important overall than was stored water for determining wheat yield. When treated as separate variables statistically, stored water accounts for 67% of the variability in the data, while spring rainfall only accounts for 26%. The slopes of the plotted lines are almost identical for the Leggett (1959) and the more recent study (Figure 1). However, because we show wheat grain production beginning at 2.3 inches of available water compared to 4.0 inches found in Leggett (1959), a greater predicted grain yield will result, according to our statistical equation. There was no statistical difference in the slope between the two lines in Figure 1, but the difference in intercept was highly significant.

As an example of how to estimate wheat production based on available water on a given farm, assume that OWG is 7.2 inches and that long-term average April, May, and June rainfall at this given location is 2.5 inches. Our model (Equation 2) predicts a SW grain yield of 42.8 bu/ac. For the same quantity of stored soil water and spring rainfall, Leggett's (1959)

model (Equation 1) predicts a SW grain yield of only 31.6 bu/ac. Predicted grain yield differences between the two models may likely be due to: (1) the ability of modern semi-dwarf wheat varieties to begin grain production with less available water (Condon et al. 2004) compared to the standard-height wheat varieties of the 1950s, and (2) improved timing of field operations and agronomic management in recent decades (Turner 2004), which include widespread use of phosphorus and sulfur fertilizers for SW production and nonselective herbicides for "burndown" weed control in lieu of tillage.

Spring Wheat vs. Winter Wheat in Recent Study

For data collected from 1993 to 2005, a separate analysis was conducted on the relationship between available water and grain yield for WW after SF compared to recrop SW. The analysis showed that 1 inch of available water resulted in 7.3 bu/ac for WW after SF and 5.4 bu/ac for recrop SW (Figure 2). Brown et al. (1981) similarly reported a distinctly lower slope for the water use versus grain yield relationship when comparing SW (5.1 bu/ac/in.) to WW (5.8 bu/ac/in.).

Data were also analyzed by dividing the amount of WW after SF available water into: (1) soil water available in SF at the time of planting in late August–early September, (2) OWG, (3) April rain, (4) May rain, and (5) June rain. For recrop SW, of course, only factors (2) through (5) were used in the analysis. All April, May, and June rainfall was considered available.

The statistical models were Equation 3:

$$\text{WW after SF: } Y = 6.7 \text{ SFW} + 7.9 \text{ OWG} + 4.4 \text{ A} + 7.6 \text{ M} + 12.2 \text{ J} - 16.4$$

and Equation 4:

$$\text{Recrop SW: } Y = 5.4 \text{ OWG} + 1.4 \text{ A} + 6.4 \text{ M} + 5.7 \text{ J} - 10.6$$

where Y is grain yield in bu/ac, SFW is summer fallow available soil water in inches, OWG is net over-winter soil water gain in inches, A is April rain, M is May rain, and J is June rain in inches. Equation 3 accounted for 83% of the data variability, and Equation 4 accounted for 73% of the variability. Both equations were highly significant statistically.

Statistical analysis also revealed that about 2 inches of available water were required just for vegetative growth for both WW and SW (Figure 2). For WW (Equation 3), each inch of available SFW at time of planting produced 6.7 bu/ac. Each inch of OWG (in addition to what was present at the time of planting in late August) produced 7.9 bu/ac. Every inch of rain-

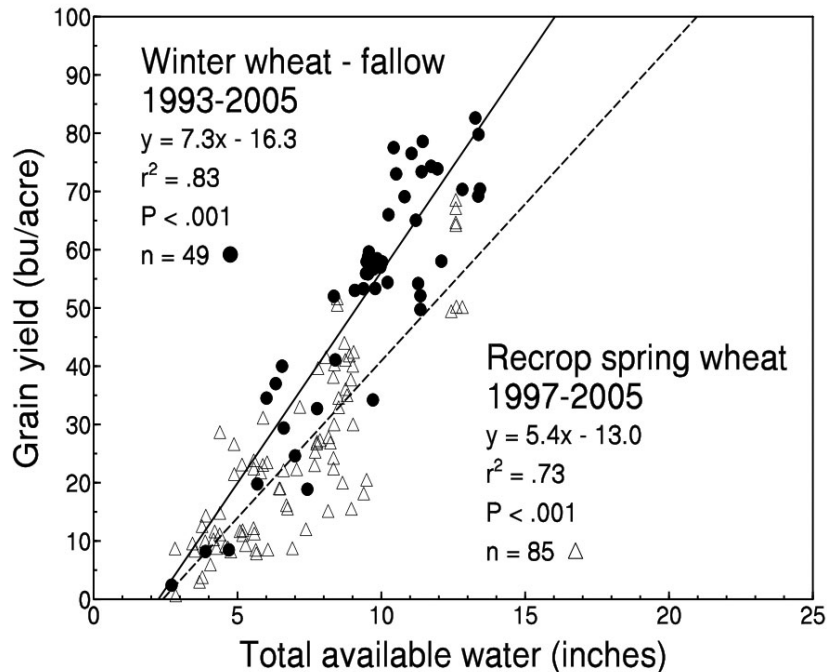


Figure 2. The relationship between available water in the soil profile plus spring rainfall and grain yield for winter wheat after summer fallow (solid line, filled circles) and for spring wheat (dotted line, open triangles) from 1993 to 2005 in eastern Washington.

fall in April, May, and June accounted for 4.4, 7.6, and 12.2 bu/ac, respectively. For SW (Equation 4), each inch of OWG provided 5.4 bu/ac, and April, May, and June rainfall generated another 1.4, 6.4, and 5.7 bu/ac, respectively. The grain yield boost for SW from spring rainfall was only 56% of that for WW. There was no statistical difference between the intercept for WW and the intercept for SW, as shown in Figure 2, but the difference in slope was highly significant.

As an example of how to predict SW yield using data from the more recent 1993–2005 studies, assume that OWG is 5.3 inches and expected rainfall in April, May, and June is 0.9, 1.0, and 0.7 inches, respectively. Predicted SW grain yield, using Equation 4 and the April, May, and June water values, is 29.7 bu/ac.

The analysis shows that WW makes more efficient use of both stored soil water and spring rainfall than does SW. For both WW and SW, rainfall in April is much less beneficial for grain yield than 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 its small leaf area index that requires little water. In the Inland PNW, flowering generally occurs in mid-to-late May for WW and early-to-mid June for SW. French and Schultz (1984), Passioura (1977), and others have emphasized the key importance of adequate available water at and after flower-

ing to optimize the grain yield of wheat.

Ramig and Pumphrey (1977) and Payne et al. (2001) predicted WW grain yield based on data from a long-term winter wheat–spring pea rotation experiment conducted near Pendleton, Oregon. Ramig and Pumphrey (1977) reported an average of 1.4, -0.1, 5.6, and 11.6 bu/ac for each inch 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 2.3, 3.0, 15.4, and 9.0 bu/ac for each inch of stored soil water and April, May, June rainfall, respectively, with their equation accounting for 62% of data variability. Their studies demonstrated less benefit of stored soil water compared to Leggett's (1959) as well as our study because they used total soil water rather than plant-available stored water in their calculations. Their findings that there was little or no benefit derived from April rainfall for WW grain yield were very similar to those in our study.

CONCLUSIONS

A major objective of this work was to provide farmers in the Inland PNW with a decision tool, based on available soil water in late March and historical spring rainfall, 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 spring rainfall 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 spring rainfall and associated probability of receiving a given amount of rainfall during April, May, and June can be predicted. This tool may also be useful to farmers who produce hard red winter wheat in that it may help them determine grain yield potential and, therefore, the quantity of nitrogen to topdress in the spring that will meet protein percentages.

The next logical step in further developing 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 could determine the probability of different yield and profitability outcomes under numerous scenarios for both WW after SF and recrop SW.

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By **William F. Schillinger** and **Steven E. Schofstoll**, Department of Crop and Soil Sciences, Washington State University, Dryland Research Station, Lind, WA; and **J. Richard Alldredge**, Department of Statistics, Washington State University, Pullman, WA.

On the Cover: (Top left photo) WSU agricultural research technician measures soil volumetric water content using a neutron probe. Photo by W.F. Schillinger. (Bottom left photo) A modern combine unloads winter wheat on the go into a bank-out wagon on the Timothy Smith farm near Lind, WA. Photo courtesy of Michelle Fode-Smith

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