WATER USE AND EFFICIENCY IN A 12-YEAR ROTATION STUDY IN SOUTHWESTERN SASKATCHEWAN

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INTRODUCTION

Crops require water for growth and maturation. Practically all the water enters a crop through the roots and moves to the atmosphere via leaf and stem stoma. It is generally agreed that the processes of photosynthate production and transpiration are closely linked. Photosynthetic activity diminishes when water stress occurs due mainly to the closing of stoma (Boyer and McPherson, 1975). Recounting historical developments, Hanks and Rasmussen (1982) referred to this link between transpiration, T, and CO_2-O_2 exchange through the stoma as evidence supporting the conclusion that dry matter yield, Y, could be analyzed from transpiration ratios, T/Y.

Unfortunately, transpiration rates and quantities are difficult to measure and depend heavily on climate. The root-zone of the soil, while providing practically all the water for transpiration by the crop, also looses this vital fluid by evaporation from surfaces exposed to the atmosphere, by transpiration through weeds, and by natural drainage. Consequently, transpiration ratios were obtained from plants grown in containers where evaporation and drainage could be controlled; this deviation from field conditions led to the criticism that T/Y ratios were unrealistic.

Approximate relationships to predict crop yield from measured water use have been developed for semiarid climates. These estimates depend on field measurements to estimate soil evaporation, E, and evapotranspiration, ET, and generally follow the form:

$$Y = a + b(ET) + c(ET)^2 \qquad (1)$$

where the constants a,b and c tend to vary with location and duration of the experiment. de Wit (1958), as reported by de Jong and Rennie (1967), proposed a relation for total dry matter production, DMY, in semiarid environments based on the ratio of transpiration, T, to free water evaporation, E_o, and a crop factor, m:

$$DMY = m\ T/E_o \qquad (2)$$

Although de Wit's model is less site specific, the basic difficulty of measuring T in the field remains. Many workers have approached the problem (Hanks and Rasmussen, 1982) and a number of good models have been proposed. One redefines de Wit's relation using two constants, a and b:

$$Y = a + b(WU/PWU) \qquad (3)$$

where Y = harvested grain yield, WU = water used by the crop, and PWU = potential water used when not limiting (de Jong and Cameron, 1980). If for a specific location and time period a = 0 and

PWU remains constant, rearrangement of the terms results in

$$b' = Y/WU \qquad (4)$$

where b' has been called the "water use efficiency", WUE.

The simplicity of equation (4) permits its adaptation to various yield and water data. Davis and Pallesen (1940) compared WUE's for continuously-cropped spring wheat in North Dakota based on WU equalling growing season precipitation, GSPR. de Jong and Rennie (1969) combined GSPR with the growing season change in soil water volumes, SW, (usually confined to the upper 122 cm of the profile) between spring, SP, seeding and summer harvest, HA:

$$WUE = Y / (GSPR + SPSW - HASW) \qquad (5)$$

Bolton (1981) simply divided yield by the harvest-to-harvest precipitation measured during one year for annual crops and two years for fallowed production.

The WUE's for spring wheat grown on summerfallowed and on annually-cropped soil are most easily compared using growing season precipitation and soil water depletion, ie., Equ. (5). In these comparisons, the summerfallow wheat generally exhibits a greater WUE, reflecting the greater yields following fallow. Warder et al. (1963) reviewed grain yields and the growing season water used for two comparable years, 1957 and 1960, for fallow and stubble crops grown near Swift Current, Saskatchewan, on Sceptre heavy clay and Wood Mountain loam. Calculated water use efficiencies on the clay averaged 8.9 and 7.7 kg ha^{-1} of grain per mm of water for fallow and stubble, respectively, compared to 9.3 and 8.0 kg ha^{-1} mm^{-1} on the loam. Similar average differences in WUE between fallow and stubble wheat were reported from the Dark Brown and Black Soil Zones by de Jong and Rennie (1969), and by de Jong and Cameron (1980). These authors also emphasized that WUE's would decrease significantly if water use during the fallow year were included in the calculation.

The inefficiency of summerfallow to conserve and utilize precipitation during the storage period has often been noted. The major water losses during the fallow period are: evaporation, deep drainage, runoff and redistribution of wind-blown snow. In summerizing soil moisture data at Mandan, North Dakota, Haas and Willis (1962) calculated an average summerfallow water conservation of 19% for the period 1915 to 1954. In reviewing findings from eight studies, de Jong and Cameron (1980) listed conservation values ranging from 6% in the Gray Soil Zone to 21-24% in the Dark Brown and Brown Zones. The relative retention and use of precipitation for crop production decreased with rotation length in a test at Brandon, Manitoba. Ferguson (1963) showed four-year average water use/precipitation ratios of .617 for the spring wheat-fallow, .477 for the W-W-F, .412 for the W-W-W-F and .215 for the continuous wheat rotations. The resulting WUE's equalled 11.0, 9.8 and 9.5 kg $ha^{-1}mm^{-1}$ for the wheat on fallow, wheat second crop and wheat third crop, respectively.

Water use efficiency, if not water use, apparently varies with fertilizer management. Campbell et al. (1977) noted a positive correlation between WUE and increasingly greater additions of N fertilizer to spring wheat grown on stubble in field lysimeters near Swift Current. These results agree with those of Viets (1962), Bauer and Young (1966), de Jong and Rennie (1969), and many others. Reporting on unpublished data from the University of Saskatchewan, Department of Soil Science, de Jong and Cameron (1980) indicated that very moderate amounts of fertilizer increased WUE by 10 to 20% on fallow and at least 20% on stubble in the Dark Brown, Black, and Gray Soil Zones. In addition to observing increases in WUE with fertilization, Warder et al. (1963) in southwest Saskatchewan and Bond et al. (1971) near Mandan, North Dakota, also measured greater depletions in soil water with applications of N when growing spring wheat.

Water use efficiency tends to vary widely from season to season. These variations stem mainly from climatic influences and occur regardless of the measure used to quantify water use. Such wide fluctuations reflect changes in crop-production factors other than water use. Significant year to year deviations must be expected even under consistent, attentive cultural management.

Comparisons of the water used and the resultant production efficiencies occurring under selected dryland rotations form the objective of this paper. A twelve-year study at Swift Current provide the data.

MATERIALS AND METHODS

The rotation plots are located on gently sloping land at the Agriculture Canada Research Station near Swift Current. The soil was described by Mitchell et al. (1944) as a Wood Mountain loam to clay loam belonging to the Orthic Brown Chernozemic Group. Prior to the study the land had been cropped in a fallow-wheat rotation since 1922.

The twelve rotations vary in length, fertilization, and crop substitutes for spring wheat. Campbell et al. (1983) presented a complete description and plan of the study. Six of the rotations were suitable for water use comparisons (Table 1). These include rotations with cycles of one (continuous), two and three years in length. Plots, 10.5 m wide and 40m long, represent each year of each rotation cycle. Thus, every year two plots are assigned to the two-year rotation, three plots to each three-year rotation, and one plot each to the continuous rotations; each rotation is cycled on its assigned plot. By convention, each rotation year in the two or three-year cycle is numbered such that 1 represents the fallowed year, 2 the first cropped year, etc. This permits reference to each rotation (ROT) and each year of the cycle (RY) by numbers in a ROT-RY format (eg. Rot. 1-3 refers to the second crop year of Rotation 1 proceeding in a fallow-wheat-wheat cycle). The study is replicated three times which over the twelve years reported here resulted in 36 plots for each ROT-RY.

Table 1. Description of the crop rotations selected for water use study from 1967-1978

Rotation No.	Rotation Length (yrs)	No. of rot. cycles	Crop[+] & Rot. year 1	2	3	Fertilizer applied
1	3	4	(F)[#]	W	(W)	Phosphorus as required
2	3	4	F	W	(W)	P & Nitrogen as required
3	3	4	F	Fa	(W)	P & N as required
8	1	12	(W)	(W)	(W)	P as required
11	2	6	F	(W)	F	P & N as required
12	1	12	(W)	(W)	(W)	P & N as required

[+] W = spring-seeded wheat, variety Chinook 1967-74, Canuck 1975-78
F = summerfallow
Fa = flax, varieties: Norland 1967-1969, Noralta 1970-1974, Redwood 1975-1978

[#] Soil water samples were taken in the spring and fall on all plots; in addition, selected plots were further sampled at harvest in the rotation year indicated by parentheses.

Commercial farm equipment is used to perform cultural and tillage operations. Weed control is achieved by a combination of tillage and recommended herbicide application. The plots are seeded at 67 kg ha^{-1} for spring wheat and 31 kg ha^{-1} for flax usually in early May. The varieties used are listed in footnotes to Table 1. No innovative technologies such as snow management or direct seeding were utilized.

Soil cores were obtained in early May just prior to seeding and at harvest usually in August. Core samples representing the 0-15cm, 15-30cm, 30-61cm, 61-91cm, and 91-122cm depths were analyzed for water gravimetrically. In the spring three cores taken along the centre axis of each plot were bulked to provide one sample set. At harvest, sample cores were extracted from positions near a designated cornor of each plot. Fertilizer was applied according to rotation specifications and fertility tests based on soil samples obtained in mid-October. The N fertilizer (34-0-0) was broadcast prior to seeding and the P fertilizer (11-48-0) was placed with seed.

Plots were harvested at the full-ripe stage. The grain was combined by cutting a 5-m wide swath 40m long through the middle of each cropped plot. The grain was weighed for yield determination. The straw was distributed on the plots by a paddle-type spreader attached to the combine.

Precipitation and pan-water evaporation was measured at a climate station within one km of the plots. The Canadian standard raingauge and pan were used in the summer, the Nipher-shielded gauge during the winter.

During the study, annual precipitation was slightly less than the long-term average, while pan evaporation was about the same. The average harvest-to-harvest precipitation between 1966 and 1978 was 12% less than the 96-year average, although annual accumulations in five of the twelve years exceeded the long-term value (Table 2). The large growing season precipitation recorded in 1970 was the result of heavy rains which occurred mainly during a short period in June. Average seasonal pan evaporation for the twelve years about equalled the 22-year average.

Table 2. Accumulated daily precipitation measured in standard and Nipher-shielded gauges and daily evaporation from a standard pan located within 1km of the rotation plots. Precipitation periods include: harvest, HA, to spring, SP (overwinter); spring to harvest; harvest to harvest (annual).

	Precipitation (mm)			Growing Season Pan
Period	HA to SP	SP to HA	HA to HA	Evaporation (mm)
1966 to 1967	222	55	277	789
1967 to 1968	147	86	233	801
1968 to 1969	233	135	368	677
1969 to 1970	170	244	414	669
1970 to 1971	152	122	274	751
1971 to 1972	98	155	253	707
1972 to 1973	180	64	244	838
1973 to 1974	219	257	476	735
1974 to 1975	162	210	372	670
1975 to 1976	152	222	374	792
1976 to 1977	71	227	298	693
1977 to 1978	150	123	273	687
Total	1956	1900	3857	8810
12-Yr. Mean± Stand. Dev.	163±48	158±72	321±77	734±59
Long-term Mean			360 (96 yr)	727 (22 yr)

RESULTS AND DISCUSSION

Comparative Utilization of Precipitation

The water accumulated in the upper 122cm of soil between harvest and spring-seeding calculated as a percentage of available precipitation differed between rotations (Table 3). Rot.11 proved to be the least efficient in each of the ten comparative periods primarily because of its long 21 months of fallow compared to only 9 months for recropped wheat. The three-year rotations exhibited a slightly greater conservation of over-winter precipitation than that recorded for continuous cropping and probably reflects a more effective snow-trap by a taller, stiffer stubble from a fallow crop. A similar argument might explain the slightly better soil water retentions noted in the N-fertilized rotation, although statistically these differences were not consistently significant. A comparison of the standard deviations in Table 3 reveals a low value for the F-W rotation indicating a reason for its popularity for reducing the risk of crop failure from drought.

Table 3. Average percentage of the precipitation occurring after harvest measured[+] as soil-water recharge available for the next crop, 1967-1978

Rot.-Rot.Yr.*	1-3	2-3	11-2	12-1	8-1
Mean %	38.2c	40.7c	18.9a	28.6b	35,8bc
Stan. Dev.	±25	±28	±4	±16	±23
No. of storage periods	11	11	10	11	11

[+] Harvest soil water volumes for rotations 1 and 2 were approximated by those in Rot. 11, Rot. Yr. 2

[*] Rotation year, RY, of the next crop

The amount of water conserved from precipitation by summerfallowing in southwest Saskatchewan has not improved since the 1940's. Staple and Lehane (1952) observed soil water enrichment on 6 to 10 farms following 21 months of fallow during the period 1939-1950. Soil water accumulations ranged from 16 to 29% of the period precipitation and averaged 21%. The twelve-year 1967-1978 soil water recharge for the fallow-wheat Rot. 11 ranged from 7 to 33% and averaged 19%. Summerfallowing increased soil water reserves on average by 93mm, 60% of which occurred during the first fall and winter, 26% during the fallow summer, and 14% from the second fall and winter.

Water Used and Water Use Efficiency Compared

The quantity of soil water extracted to grow spring wheat at Swift Current relates primarily to the frequency of summerfallow in the rotation. Mean 12-year differencies in soil water volumes between spring and harvest for the last rotation year in each cycle equalled: 66,66 and 68mm for Rotations 1,2 and 3; 101mm for the fallow-wheat rotation; 53mm for Rot. 12; 62mm for Rot. 8. The cultivation of spring wheat in southwest Saskatchewan tends to extract all the seasonal soil water available. Consequently, the average quantities of spring soil water above 168mm (the 1520 kPa "wilting point" value) are generally indicative of soil water use: 54mm each for Rotations 1,2 and 3; 90mm for the W-F; 45 and 52mm for the continuous wheat without and with N-fertilizer additions. Harvest soil water contents averaged well below 168mm and exceeded that amount in only 4 years out of 12 in the F-W Rotation and in 3 years out of 12 in the stubble years of the other rotations. These results agreed with those of an earlier period observed by Staple and Lehane (1954).

Meaningful comparisons of water use efficiency, WUE, between rotations was not easily arranged. Initial comparisons using Equ. (5)[+] for the final year in each rotation cycle resulted in

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[+] WUE = Grain Yield/ (Spring-Harvest Soil Water + Growing Season Precipitation) the average efficiencies shown by the solid bars in Figure 1. The 12-year mean WUE for Rot.11 indicated by (e) exceeds all others. If, however, some measure* of the water available during the fallow period is included, the mean fallow-wheat WUE drops below all others as shown by the (i)-bar in Figure 1.

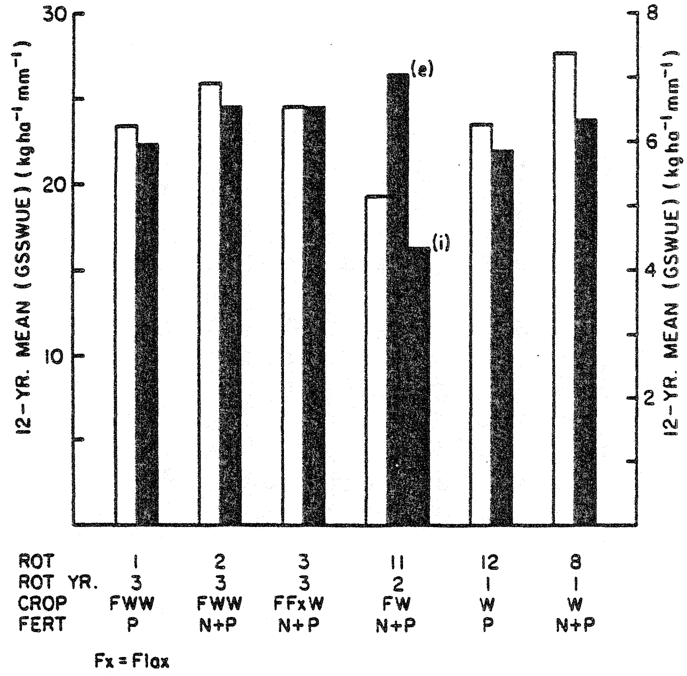


Fig. 1. Mean spring wheat yield efficiencies in the last year of six rotations produced yearly 1967 thru 1978 based on growing season soil water used (GSSWUE) and soil water plus precipitation used (GSWUE) including (i) and excluding (e) a measure of fallow soil water.

It is well known that only part of the growing season precipitation is transpired by the crop. Significant quantities either fail to enter the soil because of runoff and evaporation or pass through the soil root zone as drainage. The development of the general WUE Equ. (4) replaces transpiration with water use, WU, to simplify measurement. Thus, precipitation as a measure of WU inherently includes error caused by evaporation and drainage.

$$^{*}WUF = GSPR + SFPR + (SPSW\,1_{Rot1-1} - HASW_{11-2}) + (SPSW_{Rot8-1} - HASW_{8-1})$$

where WUF is the water used including the fallow period and equals the precipitation; PR, measured during the growing season, GS, and the summerfallow period, SF, plus the soil water difference between the first spring, SPSW 1, and the end of the growing year, HASW, plus the soil water enrichment lost the second fall and winter as estimated by Rot. 8-1.

To evaluate this error with the data measured, we computed WUE's based on growing season spring minus harvest soil water contents (GSSWU) without adding precipitation. The open bars in Figure 1 present these WUE's and clearly show the F-W Rot. 11 as the least efficient. Although it is illogical to assume that growing season precipitation does not contribute water used by the crop, the calculated WUE's with and without precipitation demonstrate the inadequacy of annually-based Equ. (5) for comparing rotations.

The most direct method of comparing water use data between the rotations utilizes the total quantities summed for the twelve test years (Table 4). This approach excluded the flax Rot. 3 from comparison. Spring-wheat grain totals were computed from plot averages for each rotation cycle multiplied times the number of cycles in each rotation. These totals demonstrate the advantage of N-fertilizer additions in both the three-year and the continuous rotations. They also show that total production decreased with frequency of summerfallow in the rotation. Naturally, WUE's based on the total 12-year precipitation (3857mm) followed a ranking equal to that for grain yield. The total soil water used during the growing season (GSSWU) was lowest for the F-W rotation because only six years were cropped. The GSSWU for the N-fed continuous Rot. 8 was greatest because withdrawal was relatively high for twelve consecutive years. The WUE's for totals calculated by Equ. (5) are given under the GSWUE column and clearly favor the continuous rotations and those where nitrogen was supplemented.

Table 4. Comparative 12-year spring wheat grain production efficiencies (E) based on total precipitation (PRWU = 3857mm) from harvest to harvest, total growing season soil water used (GSSWU) measured between spring and harvest, and total growing season water used (GSWU) which equals total growing season precipitation plus GSSWU.

		Total[+]					
Rot.	Fert.	Grain Yield kg ha^{-1}	PRWUE kg ha^{-1} mm^{-1}	GSSWU mm	GSSWUE kg ha^{-1} mm^{-1}	GSWU mm	GSWUE kg ha^{-1} mm^{-1}
1	P	11,728	3.04	670	17.5	2570	4.56
2	P+N	13,264	3.44	669	19.8	2569	5.16
11	P+N	10,908	2.83	606	18.0	2506	4.35
12	P	14,832	3.85	670	22.1	2570	5.77
8	P+N	16,728	4.34	748	22.3	2649	6.31

[+] Averaged from 3 replicate plots per year

The data of Table 4 infer depressions in WUE's in those rotations which maximize soil water by forfeiting cropping opportunity. To verify these results, we computed differences in GSWU and annual grain yield between Rot. 11-2 and 8-1 for the twelve years; mean differences equalled 197mm and 444 kg ha^{-1}, respectively. The mean WUE for these differences is a relatively low 2.25 kg ha^{-1} per mm of water (compared to 6.3 for Rot. 8-1), and infers that the grain production obtained with the extra water from summerfallowing tends to be relatively inefficient. This result would be expected if wheat production functions for water use are curvilinear as reported by Hexem and Heady (1978) in Figure 2.

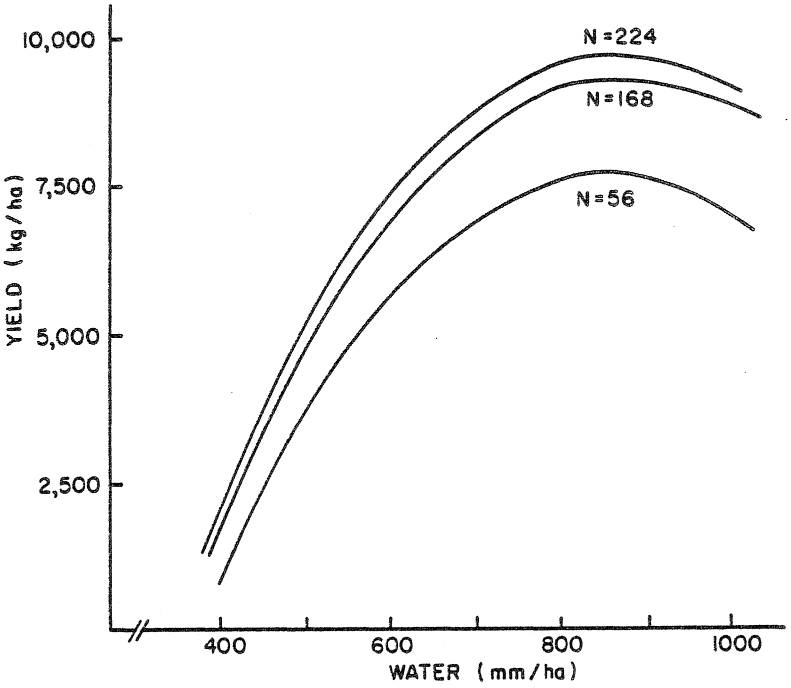


Fig. 2. Wheat production response curves to increasing inputs of irrigated water under three N-fertilizer levels, Yuma Valley, Arizona, 1971-72, (Hexem and Heady, 1978)

Crop Yield as a Function of Water-Related Variables

The correlation of spring-wheat grain yield with water use for dryland crops commonly includes considerable divergence. The 1967-1978 data for the spring wheat rotations were no exception. Grain yield plotted as a function of water used (GSPR + SP - HASW) for the three replicates per year are exemplified by Figures 3a for Rot. 8-1 and 3b for Rot. 11-2. Scatter in the data stems from error in the test, the use of annual values which sum unsteady temporal distributions, and the many factors which influence yield. Of special note is the increase in variability with greater water usage especially in the F-W rotation. Evidence exists (Aulakah et al., 1982) that denitrification by facultive organisms is enhanced in wetter environments.

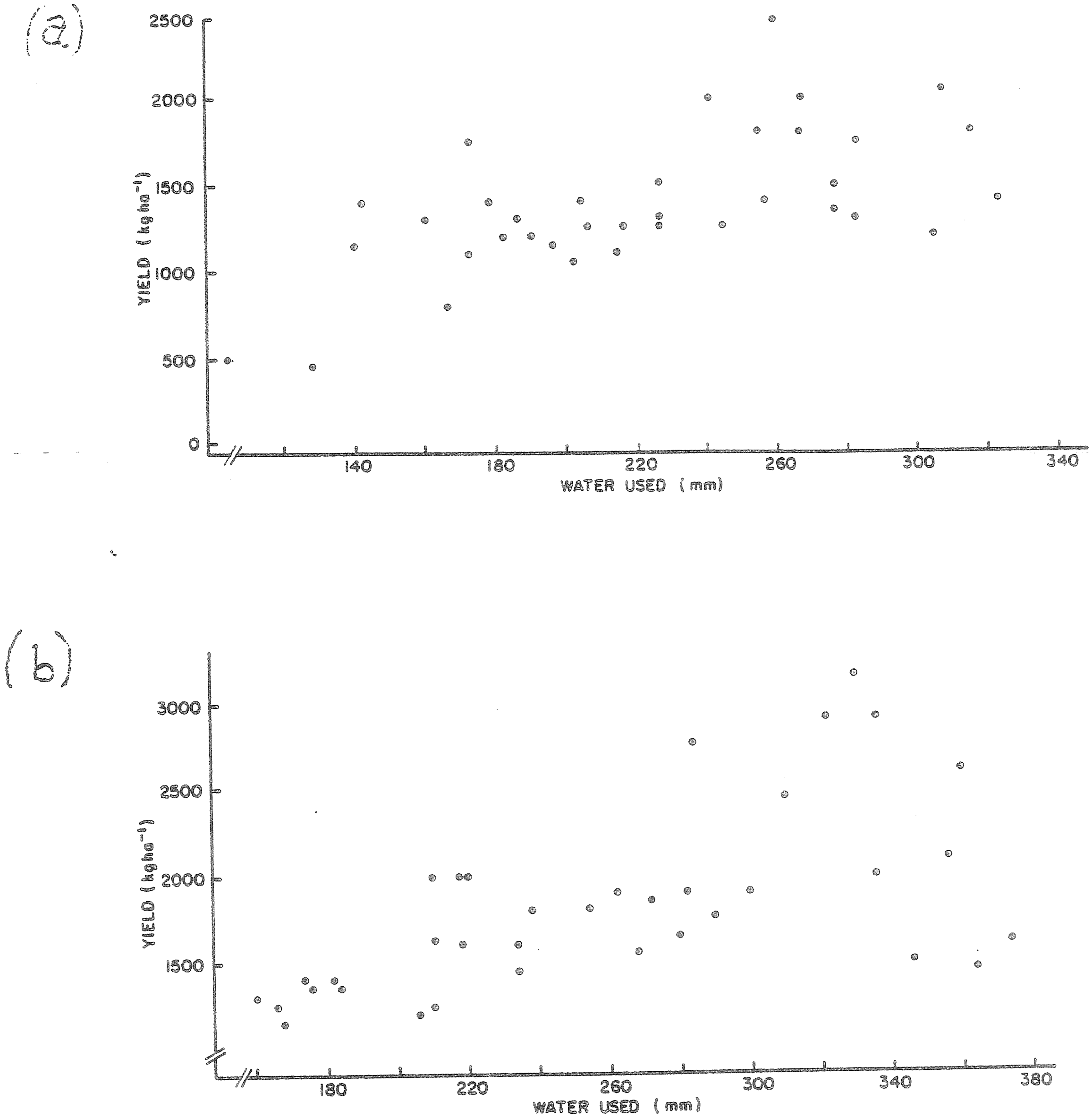


Fig. 3. Grain yield plotted as a function of growing season soil water plus precipitation used, 3 replicates, 12 years 1967-78, final year of each rotation cycle
(a) for Rot. 8-1, continuous spring wheat, N & P fertilized
(b) For Rot. 11-2, fallow-spring wheat, N & P fertilized

The wide spread in the rotation yield data might suggest that linear functions would fit as well as curvilinear models. Staple and Lehane (1954) found that linear equations described their 1938-1950 data from southwest Saskatchewan reasonably well.

Table 5 lists coefficients-of-determinations (R^2) and standard errors for various models which we applied to the measurements for the final year of each rotation cycle. Curvilinear polynomal models which included pan evaporation among the independent variables apparently gave the best fit.

Table 5. Coefficients-of-determination (R^2) and standard errors (se) for the fit of four linear and four curvilinear regression models correlating grain yield (Y) to growing-season water used (W), pan evaporation (E), and spring soil water (S) for the last year of six spring-wheat rotations, 1967-78, N = 36 observations

	Linear models$^+$							
	I		II		III		IV	
Rot-RY	R^2	se	R^2	se	R^2	se	R^2	se
1-3	.42	64	.34	69	.58	57	.58	56
2-3	.41	68	.31	74	.61	57	.51	65
3-3	.56	52	.45	58	.71	49	.67	48
11-2	.36	71	.23	77	.67	52	.47	65
12-1	.53	47	.42	52	.64	43	.59	46
8-1	.38	54	.31	57	.49	50	.56	48

	Curvilinear models #							
	V		VI		VII		VIII	
	R^2	se	R^2	se	R^2	se	R^2	se
1-3	.49	62	.58	56	.67	51	.65	52
2-3	.48	65	.57	59	.68	53	.61	59
3-3	.66	47	.69	45	.76	40	.68	47
11-2	.42	68	.51	63	.67	52	.48	67
12-1	.56	46	.58	46	.65	43	.61	45
8-1	.42	53	.48	50	.52	50	.59	47

\+ I. $Y = a + bW$
II. $Y = a + b(W/E)$
III. $Y = a + bW + c(W/E) + d(1/E)$
IV. $Y = a + bP + cPS + dS + eE$

\# V. $Y = a + bW + cW^2$
VI. $Y = a + b(W/E) + c(W/E)^2$
VII. $Y = a + bW + c(W/E) + d(1/E) + eW^2 + f(1/E)^2$
VIII. $Y = a + bP + cPS + dS + eE + fP^2 + gP^2S$

Perhaps the most useful application of water-related production functions is in predicting yield before the crop is sown. Brown et al. (1981) developed yield, Y, prediction models for spring wheat grown in Montana and North Dakota using available soil water at seeding time, SM, and probable growing season precipitation, PR. We computed similar best-fit correlations for the rotation data in a function of the form:

$$Y = a + bPR + c\ SM + d\ PR\ SM \quad (6)$$

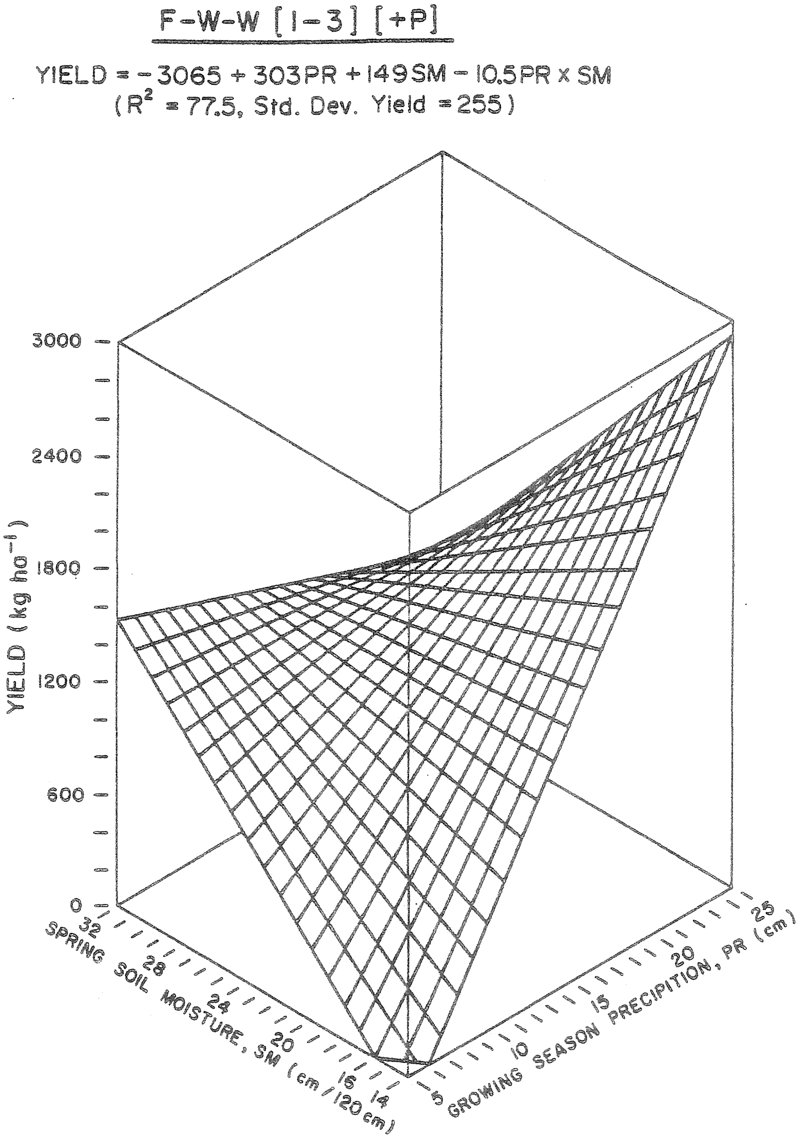
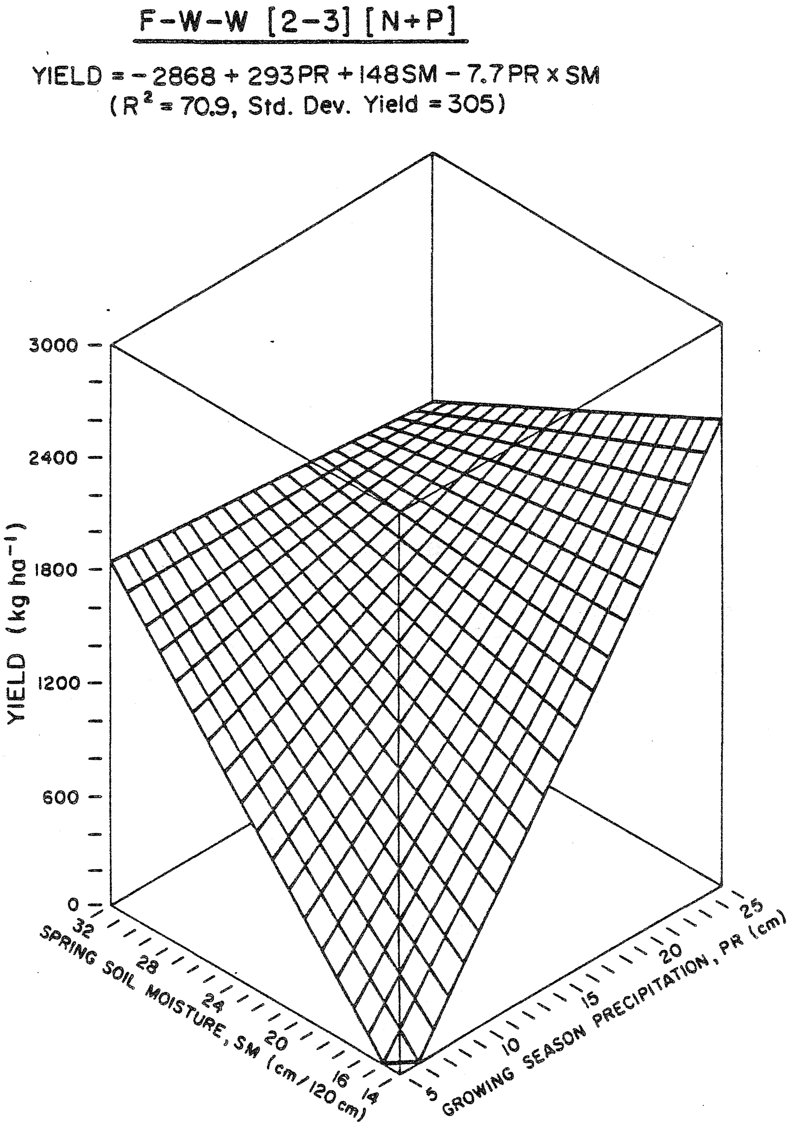


Fig. 4. Grain yield from 2nd-year stubble plotted as a function of spring soil moisture, SM, and growing season precipitation, PR, under fallow-wheat-<u>wheat</u> (Rot. 1-3), phosphorus applied

The data do not completely fill an independent variable matrix. Nevertheless, Figures 4 and 5 for Rotations 1-3 and 2-3 indicate the surfaces which may result. Similar surfaces were obtained for the continuous rotations, 8-1 and 12-1. The relationships generally show a stronger yield effect for precipitation than for stored soil water. They also suggest that too much water will reduce yields. The addition of N fertilizer suppresses this effect (Figure 5). Apparently, excessive water causes N losses by leaching or denitrification which depresses yields.

These effects occurred on stubble fields with ample supplies of carbonaceous material which imply more N loss by denitrification than by deep leaching.


F-W-W [2-3] [N+P]

$$\text{YIELD} = -2868 + 293\,\text{PR} + 148\,\text{SM} - 7.7\,\text{PR} \times \text{SM}$$

($R^2 = 70.9$, Std. Dev. Yield = 305)

Fig. 5. Grain yield from 2nd-year stubble plotted as a function of spring soil moisture, SM, and growing season precipitation, PR, under fallow-wheat-wheat (Rot. 2-3) phosphorus and nitrogen applied

CONCLUSIONS

Comparisons of the water used and the grain produced summed over twelve years from 1967 to 1978 between the spring wheat rotations at Swift Current, Saskatchewan, resulted in the following conclusions:

1. The most growing season soil water extraction (to 122cm) occurred under the continuous wheat rotation supplemented with N (Rot. 8);
2. The fallow-wheat rotation (Rot. 11) removed the least water from the soil;
3. The measured precipitation accumulated between harvest 1966 and harvest 1978 equalled 3857mm;
4. The water use efficiency, WUE, calculated as growing season soil water depletion plus growing season precipitation ranged from 4.35 kg ha^{-1} mm^{-1} under the fallow-wheat rotation to 6.31 kg ha mm with the continuous wheat fertilized with N and P as required, a 45% difference;
5. The application of nitrogen fertilizer to the fallow-wheat-wheat rotation increased WUE by 13%; applied to the continuous wheat rotation N increased WUE by 9%.

Curvilinear polynomal functions which included the growing season precipitation and pan evaporation generally gave the better fit for spring-wheat grain yields during the final production year of the respective rotation cycles. The data included considerable scatter due, in part, to denitrification in excessively wet, carbonaceous soils. Combinations of excessive spring soil water and abundant growing season precipitation may even depress yields.

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