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Cropping frequency and N fertilizer effects on soil water distribution from spring to fall in the semiarid Canadian prairies

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ABSTRACT

In the semiarid Canadian prairies, water is the most limiting and nitrogen (N) the second most limiting factor influencing spring wheat (*Triticum aestivum* L.) production. The efficiency of water- and nitrogen use needs to be assessed in order to maintain this production system. The effects of cropping frequency and N fertilization on trends in soil water distribution and water use were quantified for an 18-yr (1967-1984) field experiment conducted on a medium textured Orthic Brown Chernozem (Aridic Haploboroll) in southwestern Saskatchewan, Canada. Soil water contents were measured eight times each year and plant samples were taken at five phenological growth stages. The treatments studied were continuous wheat (Cont W), summer fallow - wheat, F-(W) and summer fallow - wheat - wheat, F-W-(W) each receiving recommended rates of N and phosphorus (P) fertilizer, and (F)-W-W and (Cont W) each receiving only P fertilizer, with the examined rotation phase shown in parentheses. Soil water conserved under fallow during the summer months averaged 25 mm in the root zone, and was related to the initial water content of the soil, the amount of precipitation received, its distribution over time, and potential evapotranspiration. Under a wheat crop grown on fallow, soil water contents between spring and the five-leaf stage remained relatively constant at about 250 mm, but those under a stubble crop, with 40 mm lower spring soil water reserves, increased slightly until about the three-leaf stage. During the period of expansive crop growth (from the five-leaf to the soft dough stage) soil water was rapidly lost from all cropped phases at rates of 1.87 mm·day^{-1} for F-(W) (N+P), 1.23 mm·day^{-1} for Cont W (N+P) and 1.17 mm·day^{-1} for Cont W (+P). The initial loss was from the 0 - 0.3 m depth, but during the latter half of the growing season from deeper depths, although rarely from the 0.9 - 1.2 m depth. In very dry years (e.g., 1973, with 87 mm precipitation between spring and fall) summer fallow treatments lost water. In wet years with poor precipitation distribution (e.g., 1970, with 287 mm precipitation between spring and fall but 142 mm of this in one week between the three- and five-leaf stages) even cropped treatments showed evidence of leaching. The above-ground biomass water use efficiency for Cont W was 19.2 and 16.7 kg·ha^{-1}·mm^{-1}, respectively, for crops receiving (N+P) and P fertilizer only. Grain yield water use efficiency (8.91 kg·ha^{-1}·mm^{-1}) was not significantly influenced by cropping frequency or N fertilizer. The 18 years of detailed measurements of plant and soil parameters under various crop management systems provide an invaluable source of information for developing and testing simulation models.

Keywords: Fallow Frequency; Water Use; Plant Biomass; Spring Wheat; Soil Water

1. INTRODUCTION

In the semiarid region of the northern Great Plains (*i.e.*, the Brown Chernozemic soil zone), water is the main factor influencing wheat (Triticum aestivum L.) production [1,2]. Potential evapotranspiration (PET) always exceeds precipitation (PPT) during the growing season, and consequently farmers in this area often practice summer fallowing (F) to conserve water for the next crop. This practice also serves to control weeds and to increase mineral nitrogen (N) in the soil, thereby helping to alleviate the second greatest restriction to production in this region (*i.e.*, soil N deficiency) [1]. Although the area devoted to summer fallow on the Canadian prairies has been decreasing steadily in recent years, the rate of decrease is lowest in the Brown soil zone (1.3% yr^{-1}) [3]; thus, summer fallowing is still an important management tool in this region.

The efficiency of soil water storage from precipitation in the prairies is generally low and varies greatly depending on soil texture, type of cultural practice, the amount of crop residues left standing to trap snow, and the amount and distribution of precipitation received in the non-crop-growing period [4,5]. We recently assessed the effects of cropping frequency and N fertilization on soil water conservation based on the results from a 40-yr experiment conducted on a medium-textured Orthic Brown Chernozem (Aridic Haploboroll) at Swift Current, Saskatchewan [6]. We examined three treatments: continuous wheat (Cont W) and fallow-wheat (F-W) each receiving N and phosphorus (P) fertilizer, and Cont W receiving only P fertilizer. The results showed that at harvest, F-W and Cont W (N+P) had similar amounts of water in the soil profile, but Cont W (+P) had more because of less growth and reduced water use. However by the following spring, soil water recharge, being proportional to the amount of crop residues produced, had conserved an extra 64, 55 and 40 mm of water in treatments F-W, Cont W (N+P) and Cont W (+P), respectively [6].

Numerous studies (see review articles [7,8]) have been conducted in which the relationships between crop yield and water use on the prairies have been assessed. The effects of fertilization rates [9-11], tillage practices [12-14], cropping frequency [15,16] and soil- and weather-conditions [17] on water use efficiency have been documented extensively. However, less is known about the seasonal changes in crop water use and in water use efficiency of the plant biomass.

Agro-ecosystem models are being increasingly used for site specific analyses and the development of site adapted agricultural production systems [18,19]. On a regional and/or national scale these models are used for the evaluation of current land use and potential remediation measures through scenario simulations [20-22]. However, testing and validation of the models should be done using independently measured data from field experiments such as those described in this manuscript.

During the first 18 years (1967-1984) of the Swift Current long-term crop rotation experiment, detailed measurements of soil water and plant biomass were made, with eight samplings between spring and fall on selected treatments. Although some assessments of these data were made [23,24], seasonal changes in soil water content and its distribution within the profile were not examined.

The objectives of this paper were to determine the effect of cropping frequency and N fertilizer on 1) soil water trends and its depth distribution from spring to fall, and to assess how these patterns were influenced by weather conditions, and 2) the efficiency of water use to produce above-ground biomass and grain of spring wheat. Furthermore, we want to alert agricultural system modellers to the unique nature of these long term experimental results.

2. MATERIALS AND METHODS

The Swift Current crop rotation experiment was initiated in 1967 on a flat (slope < 2%) Swinton loam [25], an Orthic Brown Chernozem [26]. Swift Current (50˚17′ N, 107˚48′ W, elevation 883 m) is located in the driest portion of the Canadian Prairies, with long cold winters and short growing seasons [27]. The soils are frozen from mid October until March/April. Rainfall is marginal for many agricultural activities (on average 197 mm is received during the growing season) and timing of rainfall is as important as total amount. Over the 18-yr study period, the annual average precipitation was 324 mm, of which 108 mm was in the form of snow. A substantial proportion of the latter can disappear as sublimtion, snow blowoff and, after melting, as surface runoff. No runoff from rainfall was observed during the growing season. The 18-yr mean PET (calculation method described in Section 2.2 below) was 661 mm.

The rotation experiment consisted of 12 cropping systems, of which we discuss five of the special plots. Special plots (0.04 ha each) were sampled for soil water and above-ground plant dry matter eight times between spring and fall of each year between 1967 and 1984 [28, 29]. The experiment has been described in numerous publications [23,24,30,31], thus we only present information required to assess the factors examined.

The treatments examined were summer fallow-wheat F-(W), summer fallow-wheat-wheat-F-W-(W), and continuous wheat (Cont W) each receiving N and P fertilizer, and (F)-W-W and (Cont W) each receiving only P fertilizer. The rotation phase shown in parentheses was the special plot treatment. Fertilizer N and P were applied in accordance with the soil NO_3-N (0 - 0.6 m depth) and soil P (0 - 0.15 m depth) levels in individual plots, measured the previous fall (mid-October) [30]. Fertilizer

N, as ammonium nitrate, was applied by broadcasting it in spring prior to seedbed preparation. We used N rates recommended by the soil testing laboratory at the University of Saskatchewan [32]. Wheat grown on summer fallow received about 9 $kg \cdot N \cdot ha^{-1} \cdot yr^{-1}$ and wheat grown on stubble received an average of 30 $kg \cdot N \cdot ha^{-1} \cdot yr^{-1}$ during the 18-yr period. Phosphorus fertilizer (monoammonium phosphate) was applied with the seed, with the designated treatments receiving 9 to 10 $kg \cdot N \cdot ha^{-1} \cdot yr^{-1}$ in accordance with the general recommendations for the area and crop [33]. Nitrogen in the P source was accounted for in the N rates. All phases of each rotation were present each year. There were three replicates.

Full-sized farm equipment was used for all field operations. Tillage on summer fallow was performed two to five times with a heavy-duty cultivator and/or rod weeder. Late fall application of 2,4-D ester to control broadleaf weeds was customary and other herbicides were applied to cropped areas as required [31]. No fall tillage was performed on the plots. The field management operations (*i.e.*, seedbed preparation, in-crop herbicide application, seeding, harvesting, and tillage of summer fallow areas) were generally similar to those discussed previously [34].

Seeding dates ranged from May 3 to June 5 (average May 17) and harvest dates ranged from August 16 to September 23 (average September 1).

2.1. Plant and Soil Sampling

At the three-leaf, five-leaf, shot blade (also known as flag leaf complete) and soft dough growth stages, which on the Feekes scale [35] correspond approximately to stages 1, 2, 10 and 10.5.3, respectively, and at harvest, plant samples were taken from two plant rows, each 3 m long and located 1 m from the edge of the plot (sampled area = 1.115 m^2). Plant samples were dried at 70˚C and the mass of the above-ground parts determined. The soil was sampled at the aforementioned growth stages, as well as prior to spring seeding in early May, at plant emergence, at harvest, and in the fall, just prior to freeze-up. The fallow plots of rotation (F)-W-W (+P) were sampled at the same time as the cropped plots and therefore its sampling times will also be referred to as spring, emergence, three-leaf, *etc.* Over the 18-yr period most sampling stages occurred within a 2- to 4-wk range. Soil samples were taken (three cores per plot were bulked) from the 0 - 0.15, 0.15 - 0.3, 0.3 - 0.6, 0.6 - 0.9 and 0.9 - 1.2 m depths. These samples were analyzed for gravimetric soil water content, which was converted to volumetric units using measured bulk densities of 1.20, 1.22, 1.26, 1.49 and 1.67 $Mg \cdot m^{-3}$ for the five depths, respectively [28]. The lower limits of available water, *i.e.* the permanent wilting point, as determined from field measurements [36] were 27, 28, 28, and 31 mm for the 0 - 0.3, 0.3 - 0.6, 0.6 - 0.9 and 0.9 - 1.2 m depths respectively, for a total of 114 mm for the 1.2-m depth. Water contents at –0.03 MPa (*i.e.*, field capacity) were 88, 87, 97 and 109 mm for the same depth intervals, for a total of 381 mm for the 1.2-m profile [37].

2.2. Weather Data

Daily maximum and minimum air temperatures and precipitation were measured at a meteorological site located 1 km west of the experimental site. Potential evapotranspiration was estimated from a regression equation relating latent evaporation (*i.e.*, evaporation from Bellani plate atmometers) to meteorological information [38]. Although equations using a number of weather elements were developed, the most common one, using daily maximum and minimum air temperature data, was used:

$$LE = 0.928\ Tmax + 0.933\ Trange + 0.0486\ Qo - 87.03$$

where, LE is latent evaporation from a Bellani plate surface ($cm^3 \cdot day^{-1}$), Tmax is daily maximum temperature (˚F), Trange is the difference between daily maximum and daily minimum temperature (˚F), and Qo is the daily amount of solar radiation at the top of the atmosphere ($cal \cdot cm^{-2}$). The latter can be calculated for a given latitude and day of the year. LE is multiplied by a factor of 0.096 to obtain PET in $mm \cdot day^{-1}$ [39]. The empirical Baier-Robertson equation, which has been calibrated and validated for Canadian conditions, was chosen over the more physically based Penman-Monteith formulation, because net radiation, windspeed and humidity data were not continuously available during the 18-yr study period.

2.3. Data Analysis

Grain yields and above-ground plant biomass at the various stages of growth were related by regression analysis to water use (WU) and relative water use, WU/PET. Water use was defined as: (spring soil water - soil water at a later stage) + precipitation received during that period.

3. RESULTS

3.1. Soil Water under Summer Fallow

3.1.1. Eighteen-yr Mean Soil Water Contents

Producers use summer fallow to conserve extra water for the next crop. The main portion of the 20-mo fallow period in which water is conserved in the semiarid prai-

Table 1. 18-yr (1967-1984) mean soil water (0 - 1.2 m depth), above-ground dry matter, and precipitation (PPT) received between sampling times in five crop rotation phases at Swift Current, Saskatchewan[a].

Average calendar day	Stage sampled	Rotation Phase Sampled										
		(F)-W-W(+P)	F-(W) (N+P)		F-W-(W) (N+P)		Cont W (N+P)		Cont W (+P)			
		Soil water (mm)	Soil water (mm)	Dry matter (kg·ha^{-1})	Soil water (mm)	Dry matter (kg·ha^{-1})	Soil water (mm)	Dry matter (kg·ha^{-1})	Soil water (mm)	Dry matter (kg·ha^{-1})	Period	Period PPT (mm)
123	Spring (Sp)	213	251	-	211	-	210	-	203	-	Sp to Em	29.2
151	Emergence (Em)	217	248	-	218	-	211	-	210	-	Em to 3L	17.5
162	Three-leaf (3L)	222	252	90	217	87	214	87	211	78	3L to 5L	29.8
177	Five-leaf (5L)	225	246	503	214	422	211	424	213	365	5L to SB	28.1
188	Shot blade (SB)	224	215	1792	192	1343	190	1428	188	1176	SB to Do	52.1
224	Soft dough (Do)	230	158	5130	157	3808	152	3788	158	3102	Do to Ha	11.1
238	Harvest (Ha)	233	154	4957	150	3706	150	3463	154	2877	Ha to Fa	40.9
290	Fall (Fa)	238	161	-	160	-	160	-	162	-	Sp to Fa	208.7

[a]Soil water and dry matter are for rotation phases shown in parentheses.

rie is the 5.5-mo period from May to mid-October [5]. Thus we observed an 18-yr average gain in soil water in the 0 - 1.2 m depth of 25 mm (*i.e.*, 0.15 mm·day^{-1}) during this period (**Table 1**). On average, the 0 - 0.3 m depth starts in spring close to 70% of field capacity with a little over 60 mm of water stored from the first eight months of the fallow period (**Figure 1**). Between spring and fall, the water content in this segment stayed fairly constant as gains from precipitation were balanced by evaporation and drainage losses. Water in the 0.3 - 0.6 m depth at the spring sampling time was slightly over 50 mm and the amount gradually increased to as much as that in the 0 - 0.3 m depth by the shot blade stage (Calendar day 188), and thereafter remained constant at slightly over 60 mm (like in the 0 - 0.3 m depth) until fall. Water in the 0.6 - 0.9 m and 0.9 - 1.2 m depths was about the same (45 mm) at the spring sampling. The water contents in these two depths increased gradually until the end of August, when it reached about 55 mm, *i.e.*, slightly above 50% of field capacity.

3.1.2. Soil Water Contents under Summer Fallow during Selected Years

As might be expected, the amount of water stored and the pattern of gain over time were quite variable, depending primarily on the rainfall frequency, the amount years (1970 and 1982) (**Figure 2**).

In 1968, 177 mm precipitation that was well distributed throughout the season was received between spring and fall (**Figure 2(a)**). The PET during this period was calculated to be 579 mm, and as a result the soil profile only gained 25 mm of water, or 14.1% of the precipitation. The early increases of about 28 mm of water in the 0.3 - 0.9 m depth between spring and emergence was received, and also on the temperature and wind which control evaporation in the southern prairies. We present examples of trends in water storage under fallow [(F)-W-W (+P)], in two dry years (1968 and 1973) and two wet peculiar because there was little precipitation received in this period (15 mm). We suspect that this anomaly might be due to spatial variability because the coefficient of variation of the sampled spring soil water content was high, *i.e.*, 39%. From emergence to fall, the soil water contents of all depths remained fairly constant, except between harvest and fall when the 0 - 0.6 m depth reflected the substantial precipitation (91 mm) received during this period.

With only 87 mm precipitation and PET totalling 626 mm between spring and fall, 1973 represented a very dry year (**Figure 2(b)**). The 0 - 0.3 and 0.3 - 0.6 m depths gradually lost water throughout the spring to harvest period, while the water content in the 0.6 - 0.9 m depth remained fairly constant. On the other hand, the 0.9 - 1.2 m depth gained 12 mm water from spring to the five-leaf stage, and then remained relatively constant. Thus there was evidence of water moving from upper to lower depths prior to the five-leaf stage. Overall, 21 mm of water was lost from the soil profile under summer fallow conditions due to evaporation exceeding the well distributed, but small occurrences of precipitation events in this dry year.

During the very wet years of 1970 and 1982, when summer fallow started in the spring with a modest amount of water in the profile (220 mm and 170 mm, respectively), large amounts of precipitation received in May and/or June, before evaporative demands were very

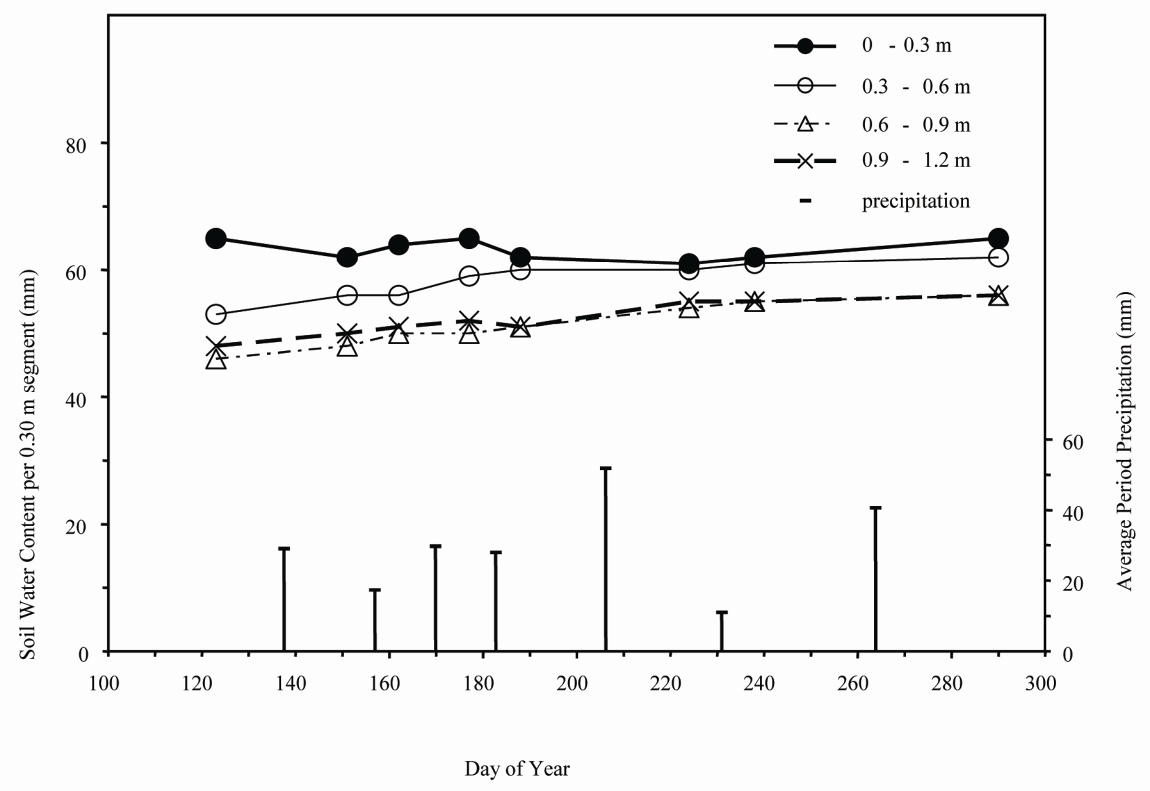

Figure 1. 18-yr mean trend in soil water content under summer fallow [(F)-W-W (+P)] as a function of time of sampling, precipitation received during the sampling periods, and depth (successive sampling times are spring, emergence, three-leaf, five-leaf, shot blade, soft dough, harvest and fall).

high, resulted in marked gains in soil water, *i.e.*, 53 mm, or 18.5% of the precipitation, in 1970 and 105 mm, or 31.6% of the precipitation in 1982 (**Figures 2(c)-(d)**). About half (142 mm) of the total precipitation received in 1970 fell in a one week period between the three- and five- leaf stage, causing wetting of all depths to 1.2 m and possible deeper. After the five-leaf stage small rainfall events were balanced by evaporation and thus, barring the anomalous water contents in the 0.9 - 1.2 m depth at the soft dough stage and the one in the 0 - 0.3 m depth at harvest, the soil water contents of all depths remained constant till fall. In 1982, when the precipitation was better distributed throughout the season than in 1970, soil water contents in the upper two depths reached almost field capacity at the five-leaf stage and stayed constant and high till harvest before increasing slightly till fall. The steady gains in water in the 0.6 - 1.2 m depth were 84% of those in the 0 - 0.6 m depth.

Water draining beyond the 1.2 m depth during wet years has also been demonstrated in several soil water simulation studies [37,40,41]. Thus, the amount of water conserved during the summer months under summer fallow depends on the complex combination of amount and time-distribution of precipitation received, the initial soil water content in spring, and the evaporative demands during the season.

3.2. Soil Water under a Crop

3.2.1. Eighteen-yr Mean Soil Water Contents for 0 - 1.2 m Depth

Soil water conditions under cropped systems in the semiarid prairies reflect the net balance between precipitation received and water lost via evaporation and transpiration. Drainage through the root zone should be rare except when very wet conditions occur in the early part of the growing season, before the crop is well established. The 18-yr mean amount of soil water in 0 - 1.2 m depth under wheat being grown on fallow [F-(W) (N+P)] was approximately 250 mm from spring to the five-leaf stage; thereafter, soil water decreased rapidly to 158 mm at the soft dough stage (*i.e.*, at a rate of 1.87 mm·day^{-1}) (**Table 1**). Between harvest and fall there was an average gain of about 7 mm of water in response to an average precipitation of 41 mm received in this 52-day period.

The 18-yr mean soil water content in the 0 - 1.2 m depth at spring sampling under well-fertilized stubble crop wheat systems [e.g. F-W-(W) (N+P) and Cont W

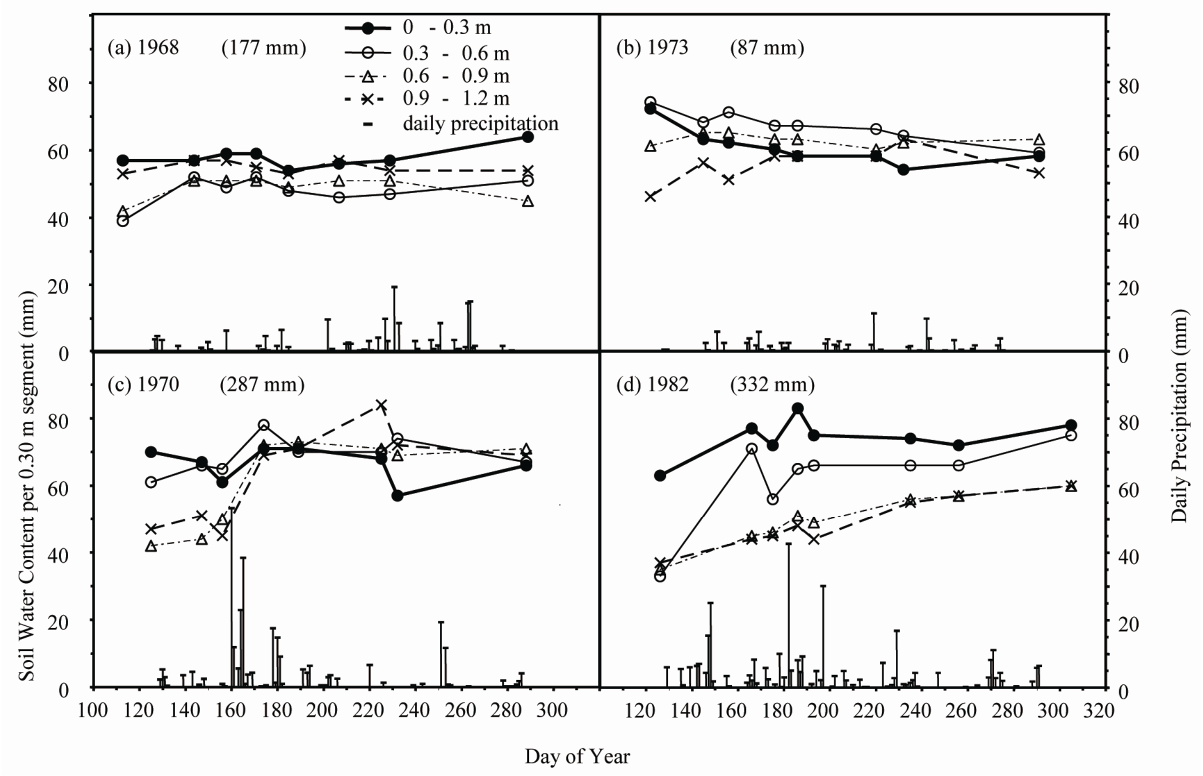

Figure 2. Examples of soil water contents under summer fallow [(F)-W-W (+P)] as a function of time of sampling, daily precipitation, and depth for four selected years (values in brackets are precipitation totals between spring and fall).

(N+P)] was 210 mm (**Table 1**). Generally, these drier systems gained a few mm of water by the three-leaf stage, as gains from precipitation exceeded losses due to low evapotranspiration rates related to minimal dry matter production and generally cool spring conditions. Here too, as was the case for wheat grown on fallow [F-(W) (N+P)], soil water in the profile decreased rapidly between the five-leaf and soft dough stage to about 155 mm in 1.2 m depth (at about 1.23 mm·day^{-1}). Between harvest and fall these well fertilized, stubble cropped systems then gained on average 10 mm of water from the 41 mm of precipitation received in this period.

As discussed by [6], Cont W (+P), because it had less standing stubble than Cont W (N+P), trapped less snow over winter; thus in spring, on average, it started with about 7 mm less water in the profile (**Table 1**). Like well-fertilized systems of wheat grown on stubble, Cont W (+P) gained a small amount of water (10 mm) between the spring sampling and the five-leaf stage, then, like the other cropped systems, it lost water rapidly at a rate of 1.17 mm·day^{-1} until the soft dough stage, before regaining about 8 mm between harvest and fall. Note that the rates of decrease in soil water during the period of rapid growth (*i.e.* the five-leaf to soft dough stage) were proportional to the rate of above-ground dry matter production (**Table 1**). This suggests that transpiration was mainly responsible for the water loss in that period.

3.2.2. Eighteen-yr Mean Soil Water Contents at Individual Depths

The 18-yr mean soil water content in the 0 - 0.3 m and 0.3 - 0.6 m depths at spring sampling under wheat being grown on summer fallow [F-(W) (N+P)] was about 64 mm (**Figure 3(a)**). Soil water remained almost constant till the three-leaf stage (five-leaf stage for the 0.3 - 0.6 m depth), then decreased sharply to about 35 mm at the soft dough stage as evapotranspiration markedly exceeded precipitation. The soil water contents then remained constant for a short time until harvest. Between harvest and fall (with no transpiration) the water content of the 0 - 0.3 m depth was recharged with precipitation to reach about 46 mm of water by the fall sampling. The water content of the second depth remained constant till fall, as excess precipitation between harvest and fall was insufficient to wet the soil beyond the 0.3 m depth. Both the 0.6 - 0.9 m and 0.9 - 1.2 m depths had about 59 mm of soil water at the spring sampling, and water levels in these two depths remained almost constant till the five-leaf stage before decreasing slightly in both depths till the shot blade stage. Thereafter, soil water in both of these segments decreased sharply, though faster in the 0.6 - 0.9 m depth, till harvest, and then remained con-

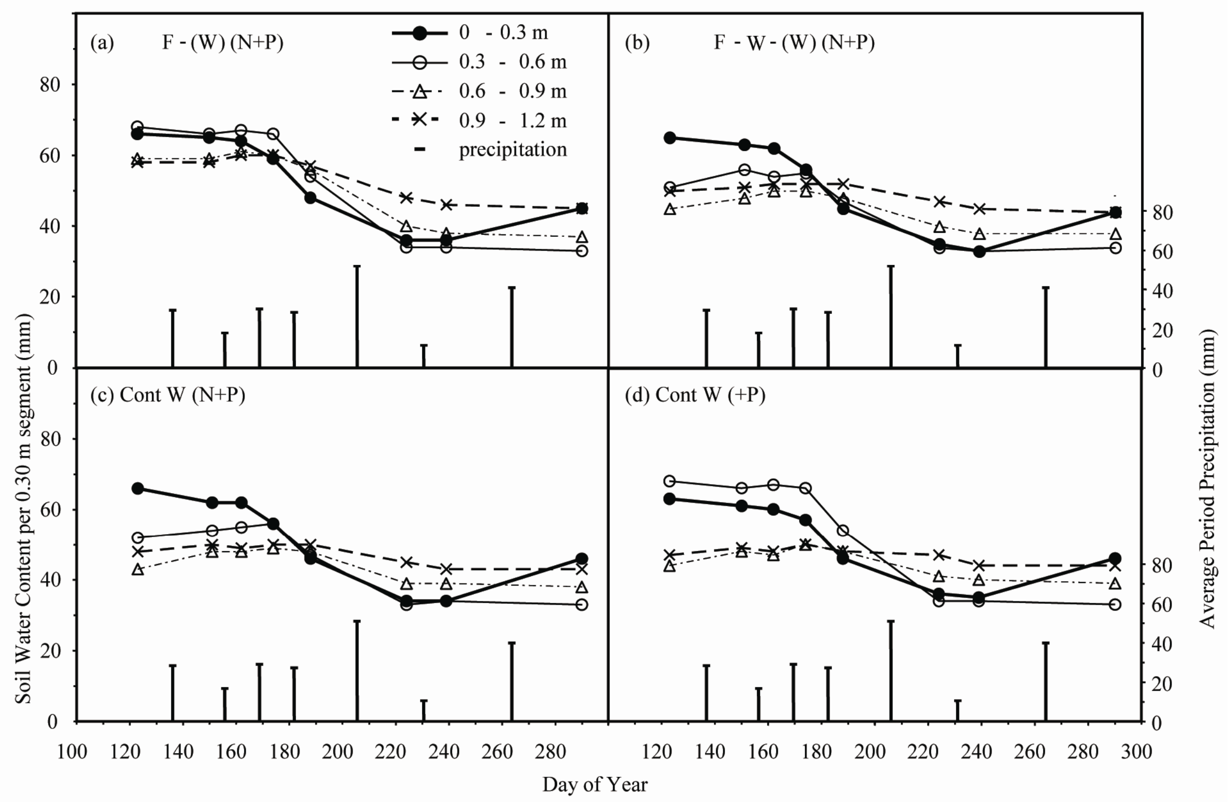

Figure 3. 18-yr mean trend in soil water content under spring wheat as a function of time of sampling, precipitation received during the sampling periods, and depth (successive sampling times are spring, emergence, three-leaf, five-leaf, shot blade, soft dough, harvest and fall).

stant till fall when the 0.6 - 0.9 m depth had about 38 mm and the 0.9 - 1.2 m depth had about 46 mm of water.

Thus, in the F-(W) (N+P) system most of the water was used between the five-leaf and soft dough stage, and mainly from the top 0.6 m of soil. This was related to the period of greatest growth (**Table 2**) and evapotranspiration. Water was used more slowly from the 0.6 - 0.9 m depth and even more slowly from the 0.9 - 1.2 m depth. After harvest there was generally only sufficient extra water to recharge the 0 - 0.3 m depth by the fall.

Soil water distribution with depth and changes from spring to fall were similar for the stubble crop systems F-W-(W) (N+P) and Cont W (N+P) (**Figures 3(b)-(c)**); therefore, we will only discuss the results for Cont W (N+P). Soil water content and response in the 0 - 0.3 m depth between spring and fall in this system were almost identical to that of a summer fallow crop system F-(W) (N+P) (**Figure 3(a)**). The stubble crop system, with much less time for soil water to be recharged (8 mo vs 20 mo), had only about 51 mm of water in the 0.3 - 0.6 m depth in spring. There was sufficient precipitation and maybe some drainage from the 0 - 0.3 m depth to slightly increase the soil water content in the 0 - 0.6 m depth to about 55 mm by the five-leaf stage. From the five-leaf to the soft dough stage, soil water in both the 0 - 0.3 and 0.3 - 0.6 m depths decreased sharply and linearly at the same rate to about 35 mm, which is similar to that for the F-(W) (N+P) system. Thereafter, as for F-(W) (N+P), soil water in the 0 - 0.3 m depth increased, and that of the 0.3 - 0.6 m depth remained constant, until fall. Soil water in the 0.6 - 0.9 m and 0.9 - 1.2 m depths, like in the 0.3 - 0.6 m depth, started the spring with much less water than in F-(W) (N+P). Although this pattern of water loss from these two lower depths mimicked those for the respective depths in F-(W) (N+P), the lower rate of water use by the lower-yielding stubble crop compared to the fallow crop (**Table 2**), resulted in less water being taken-up from these two depths under the stubble crops. Consequently, the soil water contents in these lower depths were generally similar in Cont W (N+P), F-W-(W) (N+P) and F-(W) (N+P) by fall.

Soil water content in the 0 - 0.3 m depth under Cont W receiving only P [(Cont W (+P)] (**Figure 3(d)**) was similar in amounts and distribution with depth as Cont W (N+P) from spring to fall. However, soil water in the 0.3 - 0.6 m depth under Cont W (+P) exceeded that in the 0 - 0.3 m depth from spring to the five-leaf stage (constant at about 66 mm). This may be related to the

Table 2. Effect of cropping frequency and N fertilizer on above-ground dry matter accumulation at Swift Current, Saskatchewan (1967-1984)[a].

Year	Stage	Dry matter (kg·ha^{-1})				PPT[b] (mm) (Spring to harvest)	PET[c] (mm) (Spring to harvest)
		F-(W) (N+P)	F-W-(W) (N+P)	Cont W (N+P)	Cont W (+P)		
1967	Three-leaf	161	128	111	67	54	450
	Five-leaf	606	522	566	345		
	Shot blade	1474	1329	1376	1032		
	Soft dough	2984	2960	2489	2210		
	Harvest	3401	3834	3345	2687		
1968	Three-leaf	84	101	121	91	87	466
	Five-leaf	432	432	502	358		
	Shot blade	1072	917	1169	764		
	Soft dough	2237	1198	1306	1346		
	Harvest	3044	1243	1261	1315		
1969	Three-leaf	101	104	108	101	135	464
	Five-leaf	355	348	318	237		
	Shot blade	911	897	917	794		
	Soft dough	2013	2083	2076	2023		
	Harvest	4379	3992	4302	3694		
1970	Three-leaf	37	44	54	57	244	460
	Five-leaf	348	311	429	452		
	Shot blade	2060	1256	1742	1882		
	Soft dough	5107	3633	4202	3473		
	Harvest	3410	3107	3310	2486		
1971	Three-leaf	50	57	67	71	124	522
	Five-leaf	419	375	476	372		
	Shot blade	3536	2267	2930	1762		
	Soft dough	7059	3667	3490	3051		
	Harvest	5491	3405	3709	2976		
1972	Three-leaf	50	64	60	60	155	536
	Five-leaf	177	281	214	224		
	Shot blade	897	1075	884	961		
	Soft dough	4082	4116	3606	3832		
	Harvest	3360	3730	2337	2379		
1973	Three-leaf	50	47	37	34	64	503
	Five-leaf	991	532	535	465		
	Shot blade	1799	1156	1178	991		
	Soft dough	3596	3064	3473	2505		
	Harvest	2888	2418	2588	2251		
1974	Three-leaf	104	104	111	114	258	464
	Five-leaf	917	717	791	724		
	Shot blade	2019	1956	1979	1711		
	Soft dough	4488	3231	3483	3366		
	Harvest	5435	3896	3778	3643		
1975	Three-leaf	111	101	101	84	210	457
	Five-leaf	1215	853	747	687		
	Shot blade	3128	2144	2164	1861		
	Soft dough	5486	4357	4756	3985		
	Harvest	3489	3375	3870	3468		
1976	Three-leaf	134	141	148	101	223	479
	Five-leaf	515	603	556	489		
	Shot blade	3610	3074	3295	2368		
	Soft dough	9417	6343	6772	5486		
	Harvest	8053	5563	5100	5030		
1977	Three-leaf	134	74	84	71	227	551
	Five-leaf	429	180	221	207		
	Shot blade	2063	964	1142	1175		
	Soft dough	8774	7090	6480	5419		

	Harvest	7719	5796	5337	4725		
1978	Three-leaf	57	77	64	67	135	510
	Five-leaf	261	626	483	355		
	Shot blade	680	1122	1089	754		
	Soft dough	3211	3014	2388	1953		
	Harvest	5602	3021	2892	1902		
1979	Three-leaf	-	-	-	-	131	487
	Five-leaf	214	161	177	207		
	Shot blade	1018	995	1105	724		
	Soft dough	4601	2746	3543	2270		
	Harvest	4565	3521	3491	2535		
1980	Three-leaf	-	-	-	-	189	550
	Five-leaf	321	174	108	148		
	Shot blade	840	442	399	442		
	Soft dough	5579	3643	2689	1725		
	Harvest	5184	2827	2418	2027		
1981	Three-leaf	-	-	-	-	211	484
	Five-leaf	-	-	-	-		
	Shot blade	-	-	-	-		
	Soft dough	-	-	-	-		
	Harvest	6284	4282	3670	2573		
1982	Three-leaf	60	64	77	57	285	466
	Five-leaf	416	368	355	315		
	Shot blade	1185	1105	1068	646		
	Soft dough	9353	6339	6627	5392		
	Harvest	8742	6166	4967	4237		
1983	Three-leaf	-	87	84	-	150	441
	Five-leaf	-	375	375	-		
	Shot blade	-	890	512	-		
	Soft dough	-	5914	5639	-		
	Harvest	-	5787	5220	-		
1984	Three-leaf	124	114	94	121	113	494
	Five-leaf	436	311	355	261		
	Shot blade	2384	1239	1333	958		
	Soft dough	4082	1333	1373	1604		
	Harvest	3220	757	757	990		
Mean	Three-leaf	90	87	87	78	167	488
	Five-leaf	503	422	424	365		
	Shot blade	1792	1343	1428	1176		
	Soft dough	5130	3808	3788	3102		
	Harvest	4957	3706	3463	2877		

[a]Some data, especially in 1981 and 1983, were missing; [b]PPT = precipitation; [c]PET = potential evapotranspiration.

reduced water uptake by a crop whose early growth is partly restricted by inadequate nitrogen fertility [6]. The pattern of water response in the 0.3 - 0.6 m depth under Cont W (+P) was similar to that of the other cropped systems. Soil water patterns and contents in the 0.6 - 0.9 m and 0.9 - 1.2 m depths under Cont W (+P) were generally similar to those under Cont W (N+P). There was about 45 mm of water in each of these two depths between spring and the shot blade growth stage. Thereafter, water was slowly and gradually lost from these two depths till harvest, but from the 0.6 - 0.9 m depth moreso than from the 0.9 - 1.2 m depth (**Figure 3(d)**). No water gains occurred in these lower depths between harvest and fall.

3.2.3. Soil Water Contents during Selected Years

In four selected years of varying precipitation, soil water contents in the profile varied from the 18-yr mean pattern (**Figure 4**). In the period prior to the five-leaf stage and after harvest, the 0 - 1.2 m depth soil water content was mainly related to precipitation. For example, in 1970 the very wet month of June caused the soil water content to increase from 261 mm at the spring sampling to 308 mm at the five-leaf stage (**Figure 4(a)**). However, in 1976, when spring precipitation was only moderate (see **Figure 4(b)**); the soil water content was fairly con-

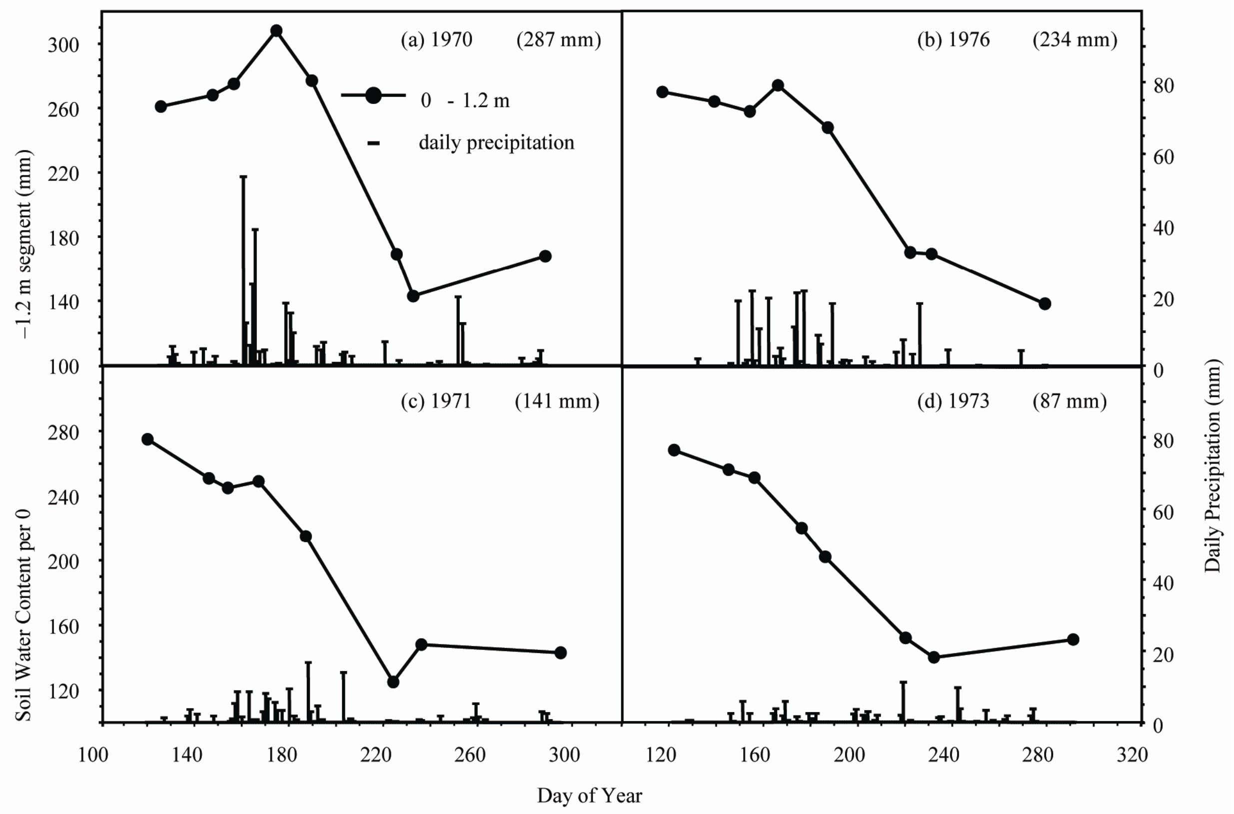

Figure 4. Examples of trends in soil water content in the 0 - 1.2 m depth under spring wheat grown on fallow [F-(W) (N+P)] for four typical years (values in brackets are the precipitation totals between spring and fall).

stant to the five-leaf stage (**Figure 4(b)**). Transpiration during this early part of the growing season was generally low. Similarly, precipitation dictated the pattern of soil water trends after the soft dough stage when the crop was no longer withdrawing soil water. In dry years such as 1971 and 1973 when little precipitation fell before the five-leaf stage, the soil water content decreased rapidly from early spring onwards (**Figures 4(c)-(d)**). In all systems the rapid growth between the five-leaf and soft dough stages (**Table 2**) was accompanied by a rapid decrease of soil water, irrespective of the amount of precipitation received, as evapotranspiration far exceeded precipitation.

Soil water distribution in the profile from spring to fall under a crop, was similar under F-(W) (N+P) as under Cont W (N+P), therefore we show only a couple of examples for Cont W (N+P) for two dry years (1968 and 1973), and for two wet ones (1970 and 1982) (**Figure 5**). In 1968, 177 mm of precipitation fell between spring and fall, of which almost 90 mm was received outside the growing season, between harvest and fall. (**Figure 5(a)**). Most of the changes in soil water content occurred in the 0 - 0.3 m depth; after an initial slow decrease from spring to the three-leaf stage, the water content rapidly decreased to near the wilting point by the shot blade stage, remained constant till the soft dough stage and then increased till fall to about 60 mm in response to the 121 mm precipitation received in this late period. The low spring soil water contents in the 0 - 0.3 m and 0.3 - 0.6 m depths reflect the dry conditions of the previous year and the small amount of overwinter precipitation (74 mm between fall and spring) that did not wet the soil beyond the 0.3 m depth. All depths below 0.3 m gradually lost small amounts of water till the shot blade stage, as water use by the crop slightly exceeded the rainfall replenishment. The small amount of water uptake by the crop (133 mm) was reflected in the low total dry matter production [maximum at the soft dough stage, 1306 kg·ha^{-1} (**Table 2**)]. The increase in soil water content at the 0.6 - 0.9 m depth between the three- and five- leaf stage may be a sampling error because there was no precipitation during this period.

The year 1973 was even drier than 1968, with only 64 mm precipitation well-distributed between spring and harvest (**Figure 5(b)**). The soil water content in the 0 - 0.3 m depth decreased almost linearly from spring to harvest, and then increased slightly from harvest to fall in response to the late small precipitation events. The

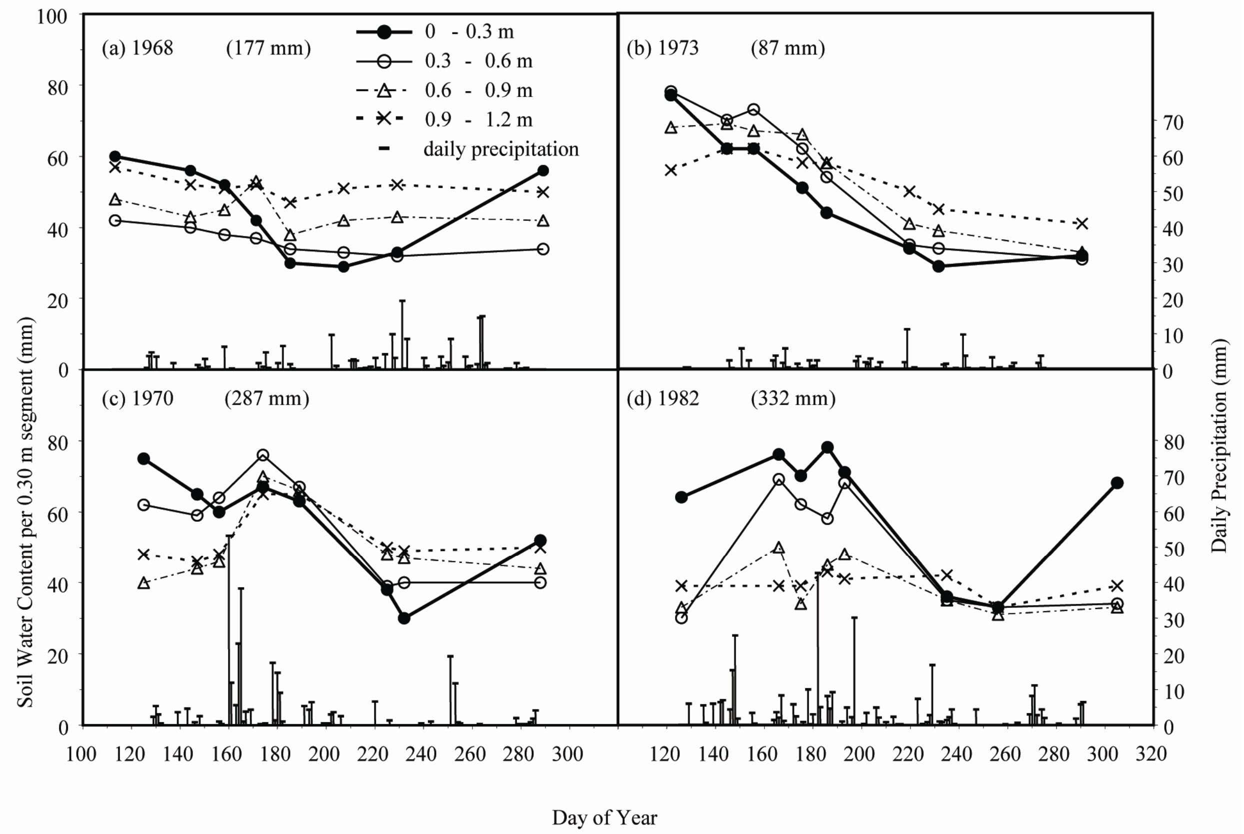

Figure 5. Soil water distribution with depth (spring to fall) under stubble wheat [Cont W (N+P)] for two dry (1968 and 1973) and two wet (1970 and 1982) years (values in brackets are the precipitation totals between spring and fall).

water content of the 0.3 - 0.6 m depth decreased slowly from spring to the three-leaf stage, then rapidly to the soft dough stage before levelling off at maturity. This pattern reflects plant growth and crop water uptake. Because of low rainfall, the soil water content of the 0.6 - 0.9 m depth remained constant till the five-leaf stage, reflecting the time it takes for roots to reach this depth. Thereafter, water loss was linear to the soft dough stage and more slowly till the fall sampling date. Generally, between the five-leaf stage and harvest, water losses from the 0.3 - 0.6 m depth and from the 0.6 - 0.9 m depth were parallel to each other. In the 0.9 - 1.2 m depth the soil water content remained relatively constant from emergence to the shot blade stage, then decreased slowly, but linearly to harvest and even more slowly till fall. The marked loss of soil water from all four depths from spring to harvest, a total of 194 mm, was reflected in a dry matter production of 3473 kg·ha^{-1} at the soft dough stage (**Table 2**), almost three times higher than in 1968.

The two wet years shown as examples differed in that 50% (142 mm) of the period precipitation received in 1970 occurred during a single week in June (**Figure 5(c)**) while the 332 mm of precipitation received in 1982 was well-distributed throughout the period (**Figure 5(d)**). Thus, plant dry matter production was much greater in 1982 than in 1970 [6627 kg·ha^{-1} vs 4202 kg·ha^{-1} at the soft dough stage (**Table 2**)] and presumably evapotranspiration would also have been much greater in 1982. The balance between evapotranspiration and precipitation favoured drainage in 1970 as was evidenced by a rare occurrence under crop when all soil segments to 1.2 m depth (and probably beyond) showed an increase in water content between the three- and five- leaf stage (**Figure 5(c)**). All soil depths then lost water rapidly between the five-leaf and soft dough stage in 1970, then they remained constant, except for the 0 - 0.3 m depth which gained water between harvest and fall, reflecting the 40 mm of rainfall received in this period.

In 1982, the low spring soil water contents in the 0.3 - 1.2 m depth reflect the lower than normal fall soil water contents in 1981 and the small amount of overwinter precipitation (95 mm between fall and spring) that did not wet the soil beyond the 0.3 m depth. Large amounts of precipitation received prior to the five-leaf stage (177 mm) markedly increased the soil water content in the 0 - 0.6 m depth and to a lesser extent that in the 0.6 - 0.9 m depth. However the 80 mm of precipitation received between the shot blade and soft dough stage was more than counter-balanced by high evapotranspiration, and consequently the 0 - 0.9 m depth lost significant amounts of water (82 mm). Between the harvest and fall sampling, when there is no transpiration, the 50 mm precipitation received increased the water content in the 0 - 0.3 m depth by 35 mm, with no wetting below this depth. The soil water content in the 0.9 - 1.2 m depth remained relatively constant throughout the growing season, suggesting that sufficient water was available for good crop growth in the upper three depths.

3.3. Dry Matter Production and Water Use (WU)

We calculated WU and total above-ground dry matter production between spring and each sampling time for Cont W (N+P) and Cont W (+P), in order to assess the influence of N fertilizer on this parameter (**Table 3** and **Figure 6**). A regression of dry matter accumulated to each growth stage vs WU was linear for both treatments (**Figure 6**). The y-intercepts were not significantly different ($P < 0.05$), but the regression slopes were signifi-

Table 3. Effect of N fertilizer on relationship between total dry matter (TDM) accumulation versus water use (WU), potential evapotranspiration (PET) and relative water use (WU/PET) at Swift Current, Saskatchewan. The values are 18-yr means ρ standard deviation.

Period	Treatment	Change in soil water (0 - 1.2 m depth) (Spring to period)	Precipitation (Spring to period)	WU[a] (Spring to period)	PET (Spring to period)	WU/PET	TDM (kg·ha^{-1})
			(mm)				
Spring to three-leaf	Cont W (N+P)	–1 ρ22	48 ρ35	47 ρ26	143 ρ24	0.329 ρ0.157	87.0 ρ29.2
	Cont W (+P)	–5 ρ21	48 ρ35	43 ρ28	143 ρ24	0.301 ρ0.178	78.3 ρ24.6
Spring to five-leaf	Cont W (N+P)	–2 ρ34	75 ρ48	73 ρ33	199 ρ24	0.367 ρ0.176	424 ρ189
	Cont W (+P)	–11 ρ29	75 ρ48	64 ρ34	199 ρ24	0.322 ρ0.179	365 ρ166
Spring to shot blade	Cont W (N+P)	20 ρ37	103 ρ52	123 ρ39	264 ρ23	0.467 ρ0.141	1428 ρ780
	Cont W (+P)	14 ρ34	103 ρ52	117 ρ37	264 ρ23	0.443 ρ0.141	1176 ρ559
Spring to soft dough	Cont W (N+ P)	58 ρ30	155 ρ68	213 ρ57	429 ρ34	0.497 ρ0.132	3788 ρ1748
	Cont W (+P)	44 ρ28	155 ρ68	199 ρ51	429 ρ34	0.464 ρ0.119	3102 ρ1399
Spring to harvest	Cont W (N+P)	60 ρ31	166 ρ67	226 ρ55	488 ρ34	0.463 ρ0.126	3463 ρ1289
	Cont W (+P)	48 ρ28	166 ρ67	215 ρ52	488 ρ34	0.440 ρ0.115	2877 ρ1124

[a]WU = (Increase in soil water between spring and a later period) + precipitation received in the period.

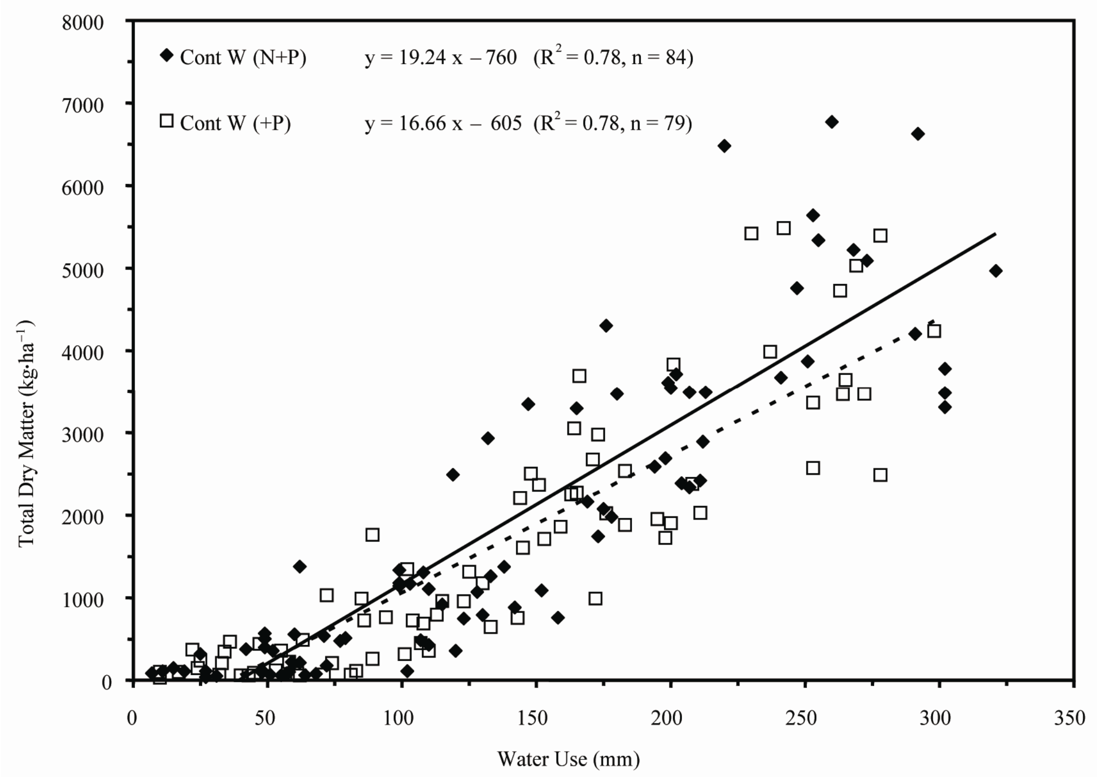

Figure 6. Effect of N fertilizer on the relationship between dry matter accumulation and water use.

cantly different at P < 0.10. The equations indicated early season evaporation (WU intercept) was 39 mm for Cont W (N+P) and 36 mm for Cont W (+P). The later season evapotranspiration (WU) efficiency (slope of the regression line) was 19.2 kg·ha^{-1}·mm^{-1} for Cont W (N+P) compared to 16.7 kg·ha^{-1}·mm^{-1} for Cont W (+P). These slopes are much lower than the 33.0 kg·ha^{-1}·mm^{-1} slope reported by [42] for winter triticale (xTriticosecale Wittmack) grown in Colorado, but similar to values 21.3 and 18.9 kg·ha^{-1}·mm^{-1} reported in [43] from a study done by [44] which showed a positive effect of P fertilizer on water use efficiency of wheat. They observed the greatest difference in evapotranpiration at any growth stage to be 12 mm for P treatments, while we observed a mean maximum difference in WU of 14 mm during the spring to soft dough stage (**Table 3**). The early-season evaporation in the [44] study was 32 mm, while in our study it averaged 38 mm. We also determined the relationship between total dry matter produced and WU relative to potential evapotranspiration (WU/PET) (**Table 3**), but found no significant effect of N fertilizer in this case.

3.4. Grain Yield, Water Use and Relative Water Use

The annual grain yields, water use and relative water use (WU/PET) for each treatment (**Table 4**) were used to construct regression equations (**Figure 7**). The relationships between wheat yield and water use were significant ($P < 0.05$) for all treatments (**Figure 7(a)**). The water use efficiency (*i.e.*, the slope of the regression line) was slightly greater for well-fertilized wheat grown on fallow [F-(W) (N+P)] than for well-fertilized wheat grown on stubble [F-W-(W) (N+P) and Cont W (N+P)], and the latter slightly greater than for stubble wheat without N fertilizer [Cont W (+P)]. However, the regressions were not significantly different ($P < 0.05$), and therefore we pooled the data and derived a single regression: $Y = 8.91X - 648$ (**Figure 7(a)**). This equation suggests a yield increase of nearly 9 kg·ha^{-1}·mm^{-1} water used, and 73 mm of evapotranspiration required before the first kg·ha^{-1} of grain is produced in this semiarid region. These values are generally similar to those reported previously by [24,45,46] for systems in southern Saskatchewan and Alberta, but lower than the slope (12.49 kg·ha^{-1}·mm^{-1}) and intercept (132 mm) reported by [47] for winter wheat in Colorado. A regression of yield against water use normalized per unit of PET did not improve the relationship compared to that with water use alone (**Figure 7(b)**).

4. DISCUSSION

This rotation study has been ongoing for 40 yr, during which the first 18 yr discussed in this paper were much drier than the subsequent 22 years [6]. Thus, it is not surprising to find that the 18-yr mean amount of water conserved under summer fallow during the 5.5 mo. summer period (25 mm) was 16% less than the 31 mm 40-yr average observed for this period by [6]. Annual analysis of soil water conserved under summer fallow throughout the summer months showed that the pattern of soil water accumulation throughout the soil profile

Table 4. Growing season precipitation (GSP), potential evapotranspiration (PET), water use (WU)[a], relative water use (WU/PET) and grain yields - effect of cropping frequency and N fertilizer at Swift Current, Saskatchewan (1967-1984)[b].

Year	GSP (mm)	PET (mm)	Cont W (N+P)			Cont W (+P)			F-W-(W) (N+P)			F-(W) (N+P)		
			Yield (kg·ha^{-1})	WU (mm)	WU/PET	Yield (kg·ha^{-1})	WU (mm)	WU/PET	Yield (kg·ha^{-1})	WU (mm)	WU/PET	Yield (kg·ha^{-1})	WU (mm)	WU/PET
1967	54	450	1017	147	0.33	820	172	0.38	1139	158	0.35	987	171	0.38
1968	87	466	468	134	0.29	554	124	0.27	429	123	0.26	1264	179	0.38
1969	135	464	1070	177	0.38	1145	166	0.36	1091	181	0.39	1005	216	0.47
1970	244	460	1100	302	0.66	974	278	0.60	1160	296	0.64	1306	361	0.78
1971	124	522	1279	202	0.39	1109	172	0.33	1148	178	0.34	1842	251	0.48
1972	55	536	1038	207	0.39	983	207	0.39	1381	229	0.43	1342	221	0.41
1973	64	503	918	194	0.39	811	162	0.32	802	180	0.36	978	192	0.32
1974	258	464	1413	301	0.65	422	264	0.57	1419	297	0.64	1920	330	0.71
1975	210	457	1750	251	0.55	1636	263	0.58	1607	266	0.58	1539	280	0.61
1976	223	479	1652	273	0.57	1896	269	0.56	2004	300	0.62	2668	322	0.67
1977	227	551	1995	255	0.46	2060	263	0.48	2126	262	0.48	2752	326	0.59
1978	135	510	1017	212	0.42	754	200	0.39	1163	241	0.47	2060	253	0.50
1979	131	487	1529	212	0.44	1285	182	0.37	1618	233	0.48	1923	248	0.51
1980	189	550	960	212	0.38	9412	211	0.38	1279	202	0.37	2013	274	0.50
1981	211	484	1491	241	0.50	1160	253	0.52	1107	250	0.52	2140	297	0.61
1982	285	466	2087	321	0.69	1618	298	0.64	2275	317	0.68	2707	337	0.72
1983	150	441	1804	268	0.61	-	-	-	1929	241	0.55	-	-	-
1984	113	494	265	158	0.32	411	171	0.35	2412	147	0.30	1216	227	0.46
Mean	166	488	1270	226	0.47	1151	215	0.44	1328	228	0.47	1745	264	0.54
SD[c]	68	34	492	54	0.13	456	52	0.12	543	58	0.13	603	59	0.13

[a]WU = [spring soil water - harvest soil water (0 - 1.2 m depth)] + GSP; [b]Data missing for CONT W (+P) and F-(W) (N+P) in 1983; [c]ρ = standard deviation.

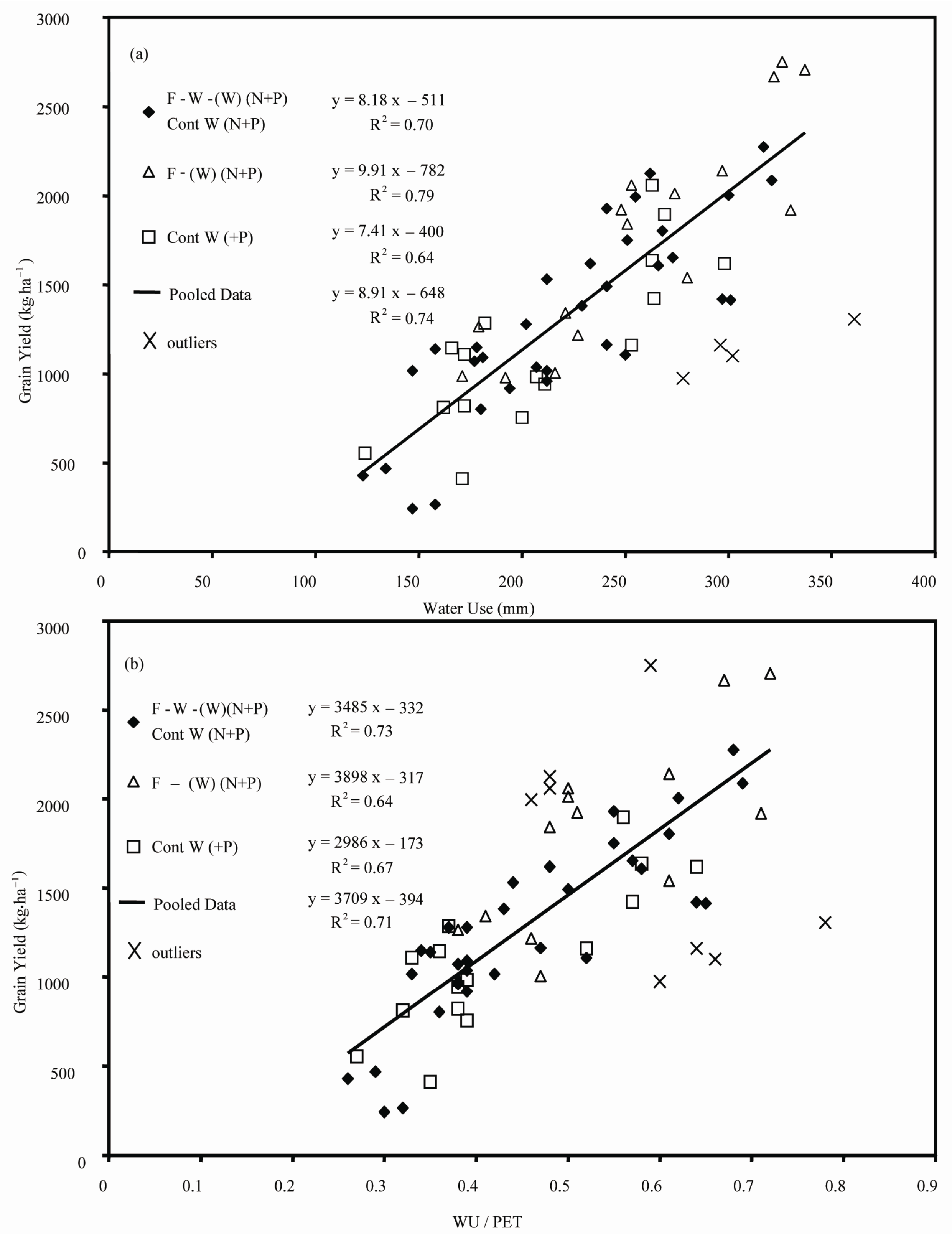

Figure 7. Relationship between grain yield and (a) water use and (b) relative water use for wheat grown on fallow or stubble receiving N and P or P only.

was related to the initial water content of the soil and the balance between the amount of precipitation received, its distribution over time, and the strength of the evaporative demands. The patterns of soil water accumulation and drying occur first in the uppermost depth and gradually moved later to lower depths, as is assumed in soil water simulation models [41,48,49].

Spring soil water contents under wheat grown on fallow were 40 mm higher than under stubble crops, and while water remained constant till the five-leaf stage for the former, the stubble crop, with lower soil water reserves in spring, gained a small amount of water till about the three-leaf stage due to low transpiration rates (caused by minimal crop growth) and low evaporation rates (as a result of low temperatures).

Soil water changes under cropped systems mainly showed the influence of precipitation during the periods prior to and after the expansive growth of the crop had occurred (five-leaf to soft dough stages). During the latter period soil water was rapidly lost in all cropped systems despite precipitation. The rate of water loss in this period was greater for F-(W) (N + P) (1.87 $mm \cdot day^{-1}$) than for Cont W (N + P) (1.23 $mm \cdot day^{-1}$) which was greater than for Cont W (+P) (1.17 $mm \cdot day^{-1}$).

Under a crop, soil water is used progressively from the uppermost depths, but rarely from the 0.09 - 1.2 m depth, which suggests that deeper rooting crops like winter wheat and/or safflower may be needed in the rotation to extract more plant available water. Water recharge between harvest and fall primarily occurs in the 0 - 0.3 m depth. On one rare occurrence when 142 mm of precipitation was received in early June, 1970, there was evidence that drainage beyond 1.2 m may have occurred under a cropped situation. This supports our findings that there has been little NO_3-N leaching from Cont W after 37 yr in this study [50].

Regression analysis showed that withholding N from Cont W was reflected in a reduced rate of above-ground plant biomass production. This supports similar findings by [44] regarding the influence of P on wheat production. Regression analysis also showed that grain yields were directly related to water use, with rates not significantly influenced by cropping frequency nor fertilizer applications, although there was a tendency for a greater water use efficiency for wheat grown on fallow than on stubble, and for well-fertilized Cont W than for Cont W receiving only P fertilizer.

In addition to the soil and plant parameters described in this paper, measurements and analyses are available for soil NO_3-N [50,51] and bicarbonate extractable P [52, 53] at the same depths and with the same frequency as the soil water content measurements. Analysis of total organic N and C in the upper two soil depths were made at irregular time intervals [54]. N and P concentrations in the above-ground biomass (grain and straw) were measured at different phenological growth stages, for both combine- and hand-harvested data [31,55]. The measured daily meteorological parameters include precipitation, maximum and minimum temperatures, global radiation and class A pan evaporation. Windspeed and relative humidity data may be obtained from a nearby weather station, located approximately 5 km NE of the experimental plots. Soil and crop management information on seedbed preparation, seeding, fertilizer and herbicide application, tillage operations and harvesting are also available [28,56].

While several investigators [40,41,57-60] have used these long term rotation data for testing and validating their models, there is a wealth of information left to be explored. For example, the measured P data have not been used in any modelling exercise. We know of no similar data sets where such detailed measurements have been made for such a lengthy period. Soil and crop modellers are therefore invited to have a look at these invaluable data sets, and start using them.

5. SUMMARY

The effects of cropping frequency and N fertilization on trends in soil water content and water use were quantified using a long-term (18-yr) field experiment in which multiple samplings were made each year. The main findings of this study were:

1) In most years precipitation increased stored soil water during non-cropping periods, (*i.e.* overwinter and during summer fallow), wetting surface soil layers first and then the lower layers. However, in very dry years summer fallow treatments actually lost soil water.

2) A growing spring wheat crop used stored soil water first from the surface layers and then gradually over time from lower depths. Rarely was water extracted from below 90 cm.

3) Soil water distribution with depth and over time was different in dry years compared to wet ones.

4) Nitrogen fertilization improved (*i.e.*, increased) the slope of the water use/dry matter function.

5) The water use/grain production function was similar to those previously reported for spring wheat in Saskatchewan and Alberta; it did not vary with cropping intensity, nor with N fertilization.

6) The 18 years of detailed measurements of soil and plant parameters under various cropping systems provide researchers with a unique and invaluable source of information for developing and testing soil-crop-management simulation models. A copy of the data, including daily weather data, can be obtained from Dr. R. P. Zentner, Semiarid Prairie Agricultural Research Centre,

Agriculture and Agri-Food Canada, Swift Current, SK, S9H 3X2, Canada (zentnerr@agr.gc.ca).

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