Nitrogen effects on water use efficiency in the semi-arid Canadian Prairies

R. Kröbel[1], R.L. Lemke[2], C.A. Campbell[1], R.P. Zentner[3], H. Steppuhn[3], R.L. Desjardins[1], and R. De Jong[1]

[1] Eastern Cereal and Oilseed Research Center, Agriculture and Agri-Food, Canada
[2] Saskatoon Research Centre, Agriculture and Agri-Food, Canada
[3] Semiarid Prairie Agricultural Research Centre, Agriculture and Agri-Food, Canada

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Abstract

In the semiarid environment of the Canadian prairies, water is the main constraint to crop production. Few studies have examined the influence of fertilizer on water use efficiency (WUE) and fewer still have made comparisons on a cropping system basis. We assessed the impact of fertilizer N on WUE in a 39-year crop rotation experiment conducted on a Brown Chernozemic soil at Swift Current, Saskatchewan. The cropping systems included continuous wheat (Cont W) with N+P and P fertilizer alone, and a fallow-wheat-wheat (F-W-W) system with N+P and P only. All cropping systems were managed using conventional tillage practices. We developed an equation to asses WUE of the cropping systems that included water use during the fallow year. We also calculated precipitation use efficiency (PUE, i.e., yield/harvest-to-harvest precipitation). WUE and PUE values and fertilizer effects were greatest in the later third of the study period, due to the increase in recommended fertilizer N rates applied and the more favorable moisture conditions that prevailed. We converted PUE results into net return values (\$ ha^{-1} mm^{-1} water) by assuming an average price over the 39-yr period and found that N fertilizer in the Cont W system earned an average return above fertilizer cost of \$36.39 ha^{-1} yr^{-1} and \$9.81 ha^{-1} yr^{-1} in the F-W-W system.

Introduction

In the semi-arid Canadian Prairie, water is the most and nitrogen the second most limiting factor influencing crop production (Campbell et al. 1997). There is a positive interaction between these two factors. If either factor is deficient the efficiency of the other will also be impaired. Quantifying and understanding the efficiency with which cropping systems utilize available water and nutrients is of critical importance for the sustainability of cropping systems on the Canadian prairies.

Under field conditions, approximate relationships have been developed and employed in models to allow estimates of crop yield from measured water use under semi-arid climates. For example, Hanks and Rasmussen (1982) proposed:

$$Y = a + b\left(WU / PWU\right)$$

where, WU is the water used by the crop, PWU is the potential water used when water is not limiting, and a and b are the y-intercept and slope of the regression line of Y vs. WU / PWU, respectively.

With a few convenient assumptions, this equation can be simplified to give:

$$b' = Y / WU$$

where, b' is referred to as the water use efficiency.

De Jong and Rennie (1969) estimated WU as the sum of the growing season precipitation (GSP) plus the growing season change in soil water volumes (seeding to harvest) in the rooting zone. Thus:

$$WUE = \frac{Y}{\left(W_p - W_h\right) + GSP}$$

where, Y is the grain yield (kg ha^{-1}), W_p is the soil water at planting (mm 120 cm^{-1}), W_h is the soil water at harvest (mm 120 cm^{-1}), and GSP is the growing season precipitation (mm rainfall from May 1 – Aug. 31).

Only a few studies are available in which the WUE of complete cropping systems have been investigated. Here we utilize an ongoing long-term crop rotation experiment at Swift Current to determine the influence of N fertilizer on WUE and PUE for fallow containing and for continuously cropped treatments.

Materials & Methods

The "Old rotation experiment" was established in 1967. The soil is classified as Swinton loam to silt loam. Three replicates are arranged in a randomized complete block design. All phases of each rotation were present every year and each rotation was cycled on its assigned plots. Four treatments were evaluated:

1) Fallow-wheat-wheat with N + P fertilizer [F-W-W (N+P)],
2) Fallow-wheat-wheat with P only fertilizer [F-W-W (P)],
3) Continuous wheat with N + P fertilizer [Cont W (N+P)]
4) Continuous wheat with P only fertilizer [Cont W (P)]

Commercial farm equipment was used to perform all cultural and tillage operations. Weed control was achieved by a combination of stubble mulch tillage (mainly cultivator and rodweeder), and herbicides (as required) using recommended methods and rates. On average, summer fallow plots received four tillage operations for weed control. Plots were soil sampled in early spring and shortly after harvest to determine soil water content and nutrient status.

Calculations

To estimate the WUE for a crop rotation the equation was expanded to include all phases of the rotation:

$$WUE = \frac{Y_1 + Y_2 + \ldots + Y_n}{\left[\left(W_{p1} - W_{h1}\right) + GSP_1\right] + \left[\left(W_{p2} - W_{h2}\right) + GSP_2\right] + \ldots + \left[\left(W_{pn} - W_{hn}\right) + GSP_n\right]}$$

where Y_n is the grain yield of the nth year in the crop rotation (kg ha^{-1}), and $[(W_{pn}-W_{hn})+GSP_n]$ is the water used in the nth year of the crop rotation (mm). Note that for a F-W-W treatment, both grain yield and water used in the first year would in this case be given a value of zero.

The above equation was modified to account for the inefficient use of the water received during the summer fallow phase. A crop was assumed to be growing in the fallow period but no yield produced – resulting in a water storage term similar to normal cropping years:

$$WUE(FWW) = \frac{Y_2 + Y_3}{\left[\left(W_{pf} - 154\right) + GSP_f\right] + \left[\left(W_{p2\,corr} - W_{h2}\right) + GSP_2\right] + \left[\left(W_{p3} - W_{h3}\right) + GSP_3\right]}$$

$$where:$$

$$W_{p2\,corr} = W_{p2} - \left(W_{p2} - W_{p3}\right)$$

$$W_{p2\,corr} = W_{p3}$$

so that:

$$WUE(FWW) = \frac{\sum_{i=1}^{n} Y}{\sum_{i=1}^{n} GSP + \left[\left(W_{pf} - 154\right) + \left(W_{p3} - W_{h2}\right) + \left(W_{p3} - W_{h3}\right)\right]}$$

where *f*, *2* and *3* refer to the fallow, wheat on fallow, and wheat on stubble phases of the F-W-W rotation, respectively; and $W_{p2\,corr}$ is the spring soil water of the crop following fallow, corrected for double counting.

Precipitation use efficiency (PUE) was calculated as:

$$PUE = \frac{\sum_{n=1}^{n} Y_n}{\sum_{n=1}^{n} P_n}$$

where Y is the grain yield (kg ha^{-1}), and P is the precipitation (mm) from harvest to harvest (Sept. – Aug).

The 1967–2005 average farm price for wheat (\$138.36 Mg^{-1}) and fertilizer-N (\$533.16 Mg^{-1}), was used to make calculations indicating the economic impact of N fertilizer and PUE on net returns. Multiplying PUE by the average price of wheat and deducting the cost of the fertilizer gives the economic benefit per mm of water. Multiplying these results by the precipitation input amount used in the PUE calculation gives the net revenue from fertilizer application in dollars per hectare.

Results and Discussion

Water use efficiency for Cont W (N+P) averaged 5.7 kg grain ha^{-1} mm^{-1} water over the 1967 to 2005 period (Table 1) compared to 4.5 kg grain ha^{-1} mm^{-1} water for Cont W (P), with the greatest difference being in the 1994 – 2005 period when fertilizer N rates were higher and water deficits lower. The trend in WUE for Cont W (N+P) was similar to that for Cont W (P) during the drier years, but the positive influence of fertilizer N application on WUE was most apparent in the wetter years between 1994 and 2005.

The average WUE for the F-W-W system over this same period was 6.0 kg grain ha^{-1} mm^{-1} water for the system receiving N+P, 5.6 kg grain ha^{-1} mm^{-1} water for the system receiving P only (Table 1). The trends in WUE for F-W-W showed little effect of N up to 1990 when soil moisture conditions improved. This emphasizes the need for adequate soil moisture as well as nutrients to ensure a positive synergistic expression of these input factors.

Table 1. Water Use Efficiencies (WUE) calculated for a continuous wheat (Cont.W) and a fallow-wheat-wheat (F-W-W) treatment for three time periods on a long-term study at Swift Current.

Time period	Cont.W [N,P]	Cont.W [P]	F-W-W [N,P]	F-W-W [P]	F-W-W [N,P] (fallow year included)	F-W-W [P] (fallow year included)
	Kg grain ha^{-1} mm^{-1} water					
1967-1979	5.5	5.1	5.8	5.7	3.8	3.7
1980-1993	4.9	3.9	5.5	5.3	3.6	3.5
1994-2005*	6.7	4.6	6.7	5.8	4.4	3.7
Mean	5.7	4.5	6.0	5.6	3.9	3.6

*Nitrogen rates were increased markedly during this time period compared to the two previous time periods.

The WUE for F-W-W (N+P) system was generally higher than for Cont W (N+P) contrasting with those reported for the US Great Plains regions by Peterson et al. (1996), who suggested that WUE for systems was generally greater as cropping frequency increased. They also observed that WUE tended to be higher as they moved from south to north in the US Great Plains.

Because of the inefficiencies associated with conservation of precipitation received during the summer fallow period, and because the WUE equations usually do not account for this, the apparent water used is underestimated. When we adjusted the equation to address the inefficient conservation of water during the fallow period, the resulting trends were very similar, but the values were about 35% lower (Table 1). When calculated this way, WUE for the fallow containing systems were lower than for the treatments continuously cropped to wheat.

A preferred method of assessing the efficiency of water use for systems that include summer fallow is the calculation of PUE. This estimate of water used is an overestimate because of the various pathways of loss of moisture which can occur that are not accounted for in the procedure. Consequently, the PUE values are much lower than WUE values, but trends remain similar (Table 2).

Table 2. Precipitation Use Efficiencies (PUE) calculated for continuous wheat (Cont.W) and fallow-wheat-wheat (F-W-W) treatments for three time periods on long-term study at Swift Current.

Time period	**Cont.W [N,P]**	**Cont.W [P]**	**F-W-W [N,P]**	**F-W-W [P]**
	———— Kg grain ha^{-1} mm^{-1} water ————			
1967-1979	3.8	3.4	3.1	3.0
1980-1993	3.5	2.7	3.1	2.9
1994-2005*	4.9	3.2	4.0	3.1
Mean	4.0	3.1	3.4	3.0

*Nitrogen rates were increased markedly during this time period compared to the two previous time periods.

When comparing PUE for systems differing in fertilizer use and therefore net economic worth, it is more appropriate to estimate dollars produced (revenue minus fertilizer cost) per unit of precipitation received. The N effect in the Cont W system averaged \$36.39 ha^{-1} yr^{-1} (Table 3). This was mainly due to the high net benefit from N fertilizer in Period 3 when growing conditions were more favorable (\$76.23 ha^{-1} yr^{-1} in 1994-2005), compared to the low economic benefit from N fertilization in the dry 1967-1979 Period (\$6.25 ha^{-1} yr^{-1}). In the F-W-W system, the net benefit from N was also relatively low in Period 1 and 2 (about \$4.65 and \$3.49 ha^{-1} yr^{-1}, respectively). Although the net benefits from N fertilizer were higher in Period 3, they averaged about 30% less than that for Cont W.

Table 3. Calculated net return for the application of N fertilizer in a continuous wheat (Cont.W) and a fallow-wheat-wheat (F-W-W) treatment for three time periods at Swift Current.

Time period	Nitrogen effect for Cont.W	Nitrogen effect for F-W-W
	——— $ ha^{-1} year^{-1} ———	
1967-1979	6.25	4.65
1980-1993	30.24	3.49
1994-2005*	76.23	21.92
Mean	36.39	9.81

*Nitrogen rates were increased markedly during this time period compared to the two previous time periods.

Conclusions

The WUEs and PUEs were generally greater for systems receiving N+P than those receiving only N or P, especially for the continuous wheat treatment. Both PUE and WUE values were lower for the fallow-wheat treatment compared to the continuous wheat treatment when WUE was adjusted for the inefficient use (storage) of water during the fallow period. Using the average 1967-2005 prices for wheat and cost of N fertilizer and the PUE results, the economic profit from Cont W (N+P) over Cont W (P) averaged $36.39 ha^{-1} yr^{-1}., while the average economic profit was $9.91 for F-W-W (N+P) over F-W-W (P).

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