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Water and Nutrient Crop Sufficiency Models for Potato, Wheat, Canola, Oats, Alfalfa, and Corn

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ABSTRACT

Crop water and nutrient efficiency is very important for optimal economic and environmental productivity. Functional models relating crop yields to water and nutrient requirements are integral to many modeling studies forecasting climate change impacts on crop production and environmental footprints. The objective of this paper was to collect data, and identify or develop statistical models relating water and nutrient requirements to yield for some major crops grown in western Canada through a review of studies conducted in the Great Plains. Statistical models developed to predict water, nitrogen, and phosphorus rates for potato, wheat, canola, oats, alfalfa, and corns were reviewed and compared in terms of optimal yield achievements. Water and nutrient requirements depend on crop species, and varies among regions and models. Based on statistical models reviewed or developed in this study, the optimal growing season water requirement for wheat, oats, canola, alfalfa, and corn was 350, 450, 350, 500-600, and 425 mm, respectively. Average water use of potato for Manitoba was in the range of 375 to 400 mm but could go as high as 696 mm. Optimal nitrogen sufficiency for potato was reported to be 200 kg N ha^{-1}. Nitrogen requirements for wheat, oats, canola, alfalfa, and corn were 105, 100-110, 150-220, 0 or 35-55, and 160 kg N ha^{-1}, respectively. Optimal phosphorus sufficiency for potato was reported to be about 50 kg P ha^{-1} for Manitoba. Phosphorus sufficiency for wheat, oats, canola, alfalfa, and corn were about 15-50, 25-29, 26-36, 36-60, and 33-64 kg P ha^{-1}.

Keywords: crop response, nitrogen, phosphorus, water

CONTENTS

INTRODUCTION

Water and nutrient deficiency may result in significant yield loss in crop production systems. Estimates of crop water use are of increasing interest because of climate change and its potential impacts on crop production. Canada has a short growing season and climatic conditions that vary widely across years and regions. The prospect of changing weather patterns has created concern regarding potential water deficits in drier regions of Canada. In summer 2009, some areas of Saskatchewan and Alberta saw record dry conditions, while other areas were described as extremely low in moisture. About 80% to 90% of Saskatchewan, Alberta and the Peace River area of British Columbia experienced extremely dry conditions (Agriculture and Agri-Food Canada's 2009). Drought has caused significant yield losses in these regions. Climate change and a recent upward trend in drought-related yield losses across Canada would suggest that the potential for crop losses due to droughts is increasing. Understanding crop water needs is important for the development of optimal crop production practices that minimize impacts of drought by either meeting the crop water requirement or avoiding crop water stress during critical periods. Knowledge of crop water responses and requirements is essential for efficient water management and to optimize crop yield and profits.

Not all water received by fields during the growing season is available to the crop planted (Nadler 2003). Some water will be lost to drainage until the soil reaches field capacity and, under intense rainfall, some water will be lost due to runoff. If water is deficient and crops are stressed, yield losses can result. The amount of water available to the crop is dependent upon several factors (Field Crops Branch 1985; Cassel and Nielsen 1986; Alberta Agriculture), with one important factor being evapotranspiration rate. For the crop to have sufficient water, available, soil moisture must exceed the evaporative demand of the atmosphere.

Evapotranspiration (ET), or water use, is affected by several factors including crop type, soil water content, temperature, relative humidity, solar radiation, wind velocity, and canopy size (Curwen 1993; King and Stark 1997; Shaykewich *et al.* 2002). As many of these factors vary from day to day, so will evapotranspiration. Each crop has differing responses to moisture, or lack thereof, and also to the timing of moisture deficits during the growing season. As such, water sufficiency for a given crop is a function of

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both the amount of water available to the crop and when that water is available. In the case of potato, for example, yield can be increased by 41-60% if adequate water is supplied to meet its potential water requirement (USDA 2007).

Estimating the nutrient requirements of crops is of also interest because of growing economic concerns related to energy use in agriculture and also environmental concerns related to the accumulation of nutrients in the environment. The loss of N into the atmosphere in the form of greenhouse gases may contribute to climate change (Snyder *et al.* 2009), while N accumulations in surface and groundwater may result in reduced water quality (Glozier *et al.* 2006). Similarly, accumulations of P in water bodies may give rise to reduced water quality and eutrophication (Glozier *et al.* 2006). Optimizing nutrient use efficiency in cropping systems has the potential not only to improve energy use efficiency in agricultural systems, but also to reduce environmental impacts.

One of the key tools available for growers making fertilizer decisions is soil testing in combination with regionally-developed fertilizer recommendations. These fertilizer recommendations are typically developed based on field trials that determine the crop response to various fertilizer rates across a range of conditions. The development of statistical relationships that describe crop response to fertilizer application is important in that it helps to identify nutrient levels that optimize crop yield and profit. Further, a better understanding of nutrient requirements has the potential to minimize nutrient losses into the environment by avoiding over-application, and thereby to increase nutrient use efficiency.

Statistical models of crop responses to water and nutrients exist, but a detailed review of these relationships is not available and, for some crops, information is very limited. These crop response functions are very important in modeling integrated crop biophysical, environmental, and economic relationships, or simply for explaining climate impacts on crop production. The main objective of this paper was to collect existing data from scientific, popular and unpublished sources, and to identify or develop statistical models relating water, nitrogen, and phosphorus to crop yield for some of the major crops grown in Canada including potato, wheat, canola, oats, alfalfa, and corn. This review evaluated and compared input requirements in terms of optimal yield achievements for each crop.

METHODS

A large body of studies and data, mainly from the Great Plains, were used to identify or develop water and nutrient sufficiency response functions for potato, wheat, canola, oats, alfalfa, and corn. Water and fertilizer requirements can be determined by fitting statistical models to yield data collected from field experiments. Data from water and fertilizer management studies are usually fitted to several statistical models to determine optimum water and nutrient use. Many functional forms were reported in the literature and the advantage of one form over another was not obvious (Bock and Sikora 1990; Angus *et al.* 1993; Bullock and Bullock 1994). Model selection has considerable effects on estimating optimal water and nutrient use (Cerrato and Blackmer 1990; Isfan *et al.* 1995). Functional forms reviewed or developed in this study are provided with no discussion on choice of one model over another although the most common type of model used was mentioned. Functional forms and data reviewed or estimated were linear, quadratic, and Mitscherlich-Bray exponential equations and represented water and nutrient management studies for many different regions within the Great Plains. The quadratic functional form was more common among the data and studies reviewed. The nutrient requirements associated with optimal yield varied among regions and models. Crop yields reported herein are either actual yields or based on a normalized yield function where normalized was defined as taking the inverse of the peak yield and multiplying it by the calculated yield as a function of either water or nutrient use. In the normalized relation, yield is equal to 1 when it is maximized.

Water sufficiency

While insufficient water can reduce crop yields, flooding and excessive moisture in the soil reduces gaseous exchanges, resulting in an oxygen deficient soil, which ultimately leads to reduced water and nutrient uptake and damaged crops (Shaykewich *et al.* 1997; Canola Council of Canada 2001a). Therefore, crop yield potential can be reduced both by water deficiency and water excess.

1. Water sufficiency – potato

Potato crops are very sensitive to water stress, with yield reductions occurring with as little as a 10% deviation from optimal soil moisture conditions (King and Stark 1997). This deviation can be a water shortage which can limit transpiration and plant growth, or excess, which can reduce yields through reduced soil aeration, increased disease, and reduced N availability due to leaching losses from the root

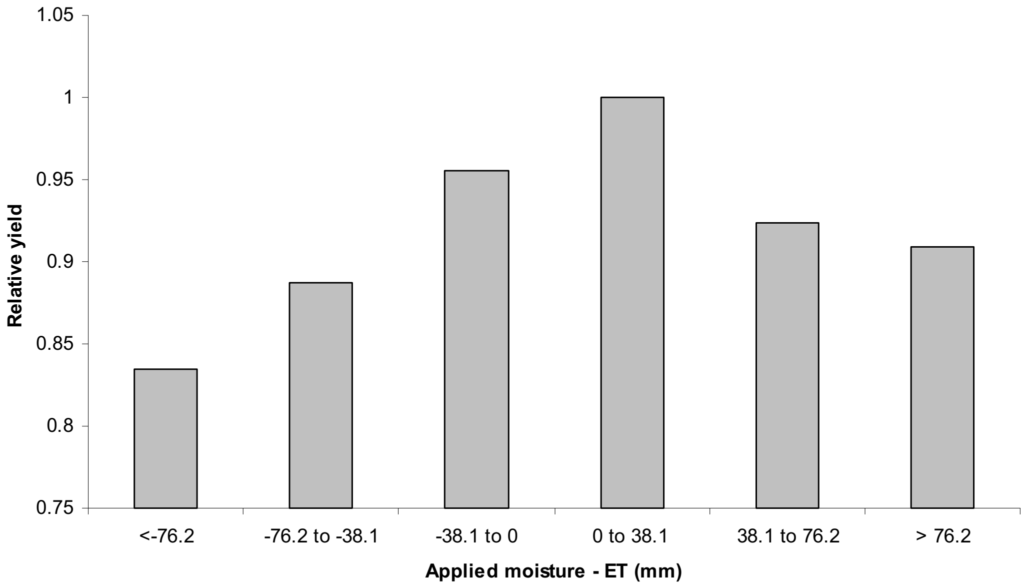

Fig. 1 Response of 'Russet Burbank' potatoes to differences between applied moisture and evapotranspiration. Source: Modified from King and Stark (1997).

Table 1 Water sufficiency response equations for potato.

Reference	Response to Water W is water use in mm Y is yield in t ha^{-1}	R^2	Comments	Optimum Water mm
Ojala *et al.* 1990	Y = 0.0341W + 5.6455	0.99	Russet Burbank	N/A
Wright and Stark 1990	Y = -0.000614 W^2 + 0.704052W - 154.061122	1.00	Russet Burbank; seasonal water	573
Wright and Stark 1990	Y = -0.000372 W^2 + 0.446011W - 73.225594	1.00	Kennebec; seasonal water	599
Wright and Stark 1990	Y = -0.000347 W^2 + 0.408391W - 73.773520	1.00	Lemhi Russet; seasonal water	588
Stark and McCann 1992[b]	Y = 26.2W + 6.0059	0.96	Russet Burbank; effect of water stress timing on yield reductions	N/A
Shaykewich 2000	Y = 0.1062W + 6.4788	0.89	1996 data; SWE not included	N/A
Shaykewich 2000	Y = -0.00032 W^2 + 0.25996W - 11.94848	0.94	1997 data; SWE not included	406
Shaykewich 2000	Y = 0.0403W + 16.736	0.49	1998 data; SWE not included	N/A
Shock and Feibert 2000	Y =0.0484W + 15.28	N/A	W is irrigation plus precipitation	N/A
Shaykewich *et al.* 2002	Y = -0.00028W^2 + 0.23172W - 9.51464	0.54	Russet Burbank; P days unaccounted; unsure if SWE is accounted	414
Shaykewich *et al.* 2002[a]	Y = -0.0001014 W^2 + 0.1410665W - 1.3877148	1.00	Russet Burbank; 800 P days; unsure if SWE is accounted	70
Shaykewich *et al.* 2002[a]	Y = -0.0001334 W^2 + 0.1617221W - 1.4997995	1.00	Russet Burbank; 850 P days; unsure if SWE is accounted	606
Shaykewich *et al.* 2002[a]	Y = -0.0001665 W^2 + 0.1807765W - 1.4250763	1.00	Russet Burbank; 900 P days; unsure if SWE is accounted	543
Shaykewich *et al.* 2002[a]	Y = -0.0002044 W^2 + 0.2002312W - 1.4224077	1.00	Russet Burbank; 950 P days; unsure if SWE is accounted	490

[a] For this data set, W refers to water x P-days.
[b] For this data set W refers to fraction of optimum water.

Table 2 Water sufficiency response equations for wheat.

Reference	Response to Water W is water use in mm Y is yield in t ha^{-1}	R^2	Comments	Optimum Water mm
de Jong and Rennie 1969	Y = 0.0063*W + 0.4185	0.71	On summer fallow	N/A
de Jong and Rennie 1969	Y = 0.00496*W + 0.43574	0.73	On stubble	N/A
de Jong and Rennie 1969	Y = -0.0000130*W^2 + 0.0140000*W - 0.5540000	N/A	On summer fallow; fertilized	538
de Jong and Rennie 1969	Y = -0.0000230* W^2 + 0.0159000*W - 0.674000	N/A	On stubble; fertilized	346
de Jong and Rennie 1969	Y = -0.0000030* W^2 + 0.0071000*W + 0.0280000	N/A	On summer fallow; unfertilized	1183
de Jong and Rennie 1969	Y = -0.0000130* W^2 + 0.0098000*W - 0.1920000	N/A	On stubble; unfertilized	377
Karamanos and Henry 1991	Y = 0.0092668*W - 0.5884398	N/A	Dry Brown; water use (WU) is GS precipitation plus stored water	N/A
Karamanos and Henry 1991	Y = 0.0099287*W - 0.5674241	N/A	Brown; water use (WU) is GS precipitation plus stored water	N/A
Karamanos and Henry 1991	Y = 0.0105906*W - 0.5380021	N/A	Dark Brown; water use (WU) is GS precipitation plus stored water	N/A
Karamanos and Henry 1991	Y = 0.0112525*W - 0.5001738	N/A	Thin Black; water use (WU) is GS precipitation plus stored water	N/A
Karamanos and Henry 1991	Y = 0.0119144*W - 0.4539393	N/A	Thick/Gray Black; water use (WU) is GS precipitation plus stored water	N/A
Karamanos and Henry 1991	Y = 0.0125763*W - 0.3992984	N/A	Gray; water use (WU) is GS precipitation plus stored water	N/A
Engel *et al.* 2001	Y = 0.01297W - 1.33156	N/A	Water includes stored soil water, GS precipitation and irrigation	N/A
Belcher *et al.* 2003[a]	Y = -0.000016*AW^2 + 0.011149*AW - 0.915733	0.99	AW is available water	348

[a]Normalized response function.

zone. King and Stark (1997) noted that the variety Russet Burbank was very sensitive to moisture stress, which corresponded with the findings from Shock and Feibert (2000) that tolerance to water stress varied between potato varieties. The response of Russet Burbank to water deficit, as expressed as the difference between applied soil moisture and evapotranspiration (ET), is shown in **Fig. 1**. As applied soil moisture approaches ET, the yield increases; the larger the difference, whether positive or negative, the greater the loss of potential yield. Continuous high moisture results in undersized tubers, which results in a reduced marketable yield (Stark *et al.* 1993).

In general, potatoes require substantial amounts of water during the growing season. Water use can range from 300 to 800 mm per year (Haverkort 1982; Dimitrov 1983; Wolfe *et al.* 1983; Hess *et al.* 1997; Shock and Feibert 2000; Tomasiewicz *et al.* 2004) and can be seen in **Table 1**. The response of yield to irrigation level indicates that at moisture levels below the optimal, yields would be reduced ~20% if moisture is 20% below optimal, and by 33% if soil moisture is 40% below optimal (Stark and McCann 1992).

Shaykewich *et al.* (2002) suggested that, for Russet Burbank potatoes, yield response was more accurate if the number of P-days were included in the determination of the potato water response curve. This study conducted in Manitoba by Shaykewich *et al.* (2002) suggested that optimal water use levels by potato were in the range of 375 to 400 mm of water to avoid water stress; however, the quadratic regression analysis of their reported data suggests that optimal conditions may be as high as 696 mm (**Table 1**), when accounting for P-days. It was not clear from their report whether soil moisture at planting was taken into account in their analysis.

2. Water sufficiency – wheat

The water demand of wheat depends upon stage of development, and ranges from 30 to 100% of PET (potential evapotranspiration) through development (MAFRI 2003). On average, the water demand for wheat 275 to 325 mm per year in Manitoba (Shaykewich *et al.* 1997; MAFRI 2003). From **Table 2**, wheat response curves are either linear or quadratic in nature, with optimal moisture in the 350 mm range (excluding the summer fallow data from de Jong and Rennie 1969). Inadequate water reduces yield and quality, while excess water can also reduce yield through increased

Table 3 Water sufficiency response equations for oat.

Reference	Response to Water W is water use in mm Y is yield in t ha^{-1}	R^2	Comments	Optimum Water mm
Engel 1997	Y = 0.02138W - 2.81242	0.99	GS precipitation only	N/A
Heyland and Werner 1992	Y = 0.01380W - 3.11000	0.97	Plant available water; linear regression	N/A
Heyland and Werner 1992	Y = -0.000016W^2 + 0.031086W - 7.549286	0.99	Plant available water; quadratic regression	971

Table 4 Water sufficiency response equations for canola.

Reference	Response to Water W is water use in mm Y is yield in t ha^{-1}	R^2	Comments	Optimum Water mm
Karamanos and Henry 1991	Y = 0.00441W - 0.28021	N/A	Dry Brown soil; included stored water plus GS precipitation	N/A
Karamanos and Henry 1991	Y = 0.00552W - 0.31524	N/A	Brown soil; included stored water plus GS precipitation	N/A
Karamanos and Henry 1991	Y = 0.00662W - 0.33626	N/A	Dark Brown soil; included stored water plus GS precipitation	N/A
Karamanos and Henry 1991	Y = 0.00728W - 0.32365	N/A	Thin Black soil; included stored water plus GS precipitation	N/A
Karamanos and Henry 1991	Y = 0.00794W - 0.30263	N/A	ThickBlack/Gray Black soil; included stored water plus GS precipitation	N/A
Karamanos and Henry 1991	Y = 0.00883W - 0.28021	N/A	Gray soil; included stored water plus GS precipitation	N/A
Nielsen 1997	Y = 0.00773W - 1.22172	N/A	Cumulative water use	N/A
Sidlauskas and Bernotas 2003	Y = -0.00003W^2 + 0.01920W - 0.52000	N/A	Precipitation; unsure if SWE was included	320

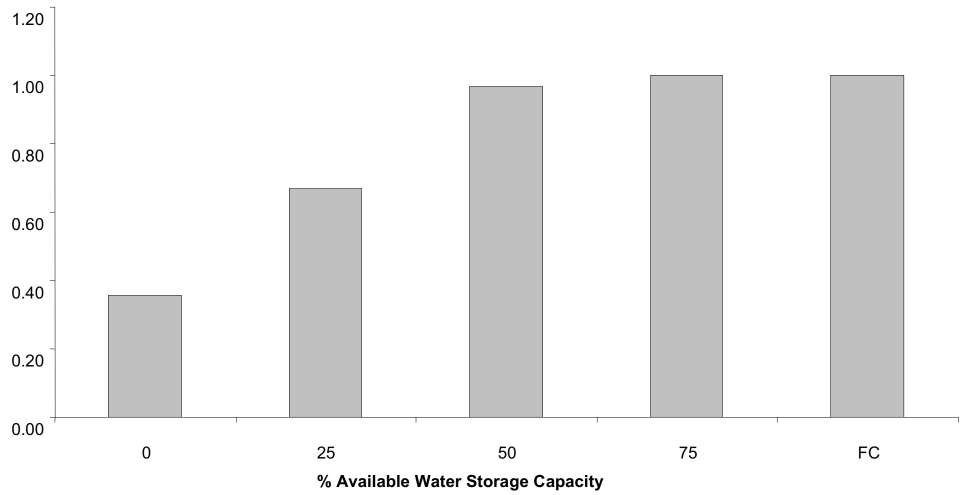

Fig. 2 Effect of maintaining adequate soil moisture on canola yield. Source: Modified from Canola Council of Canada (2001a).

incidence of disease (Ashley *et al.* 1998).

3. Water sufficiency – oat

With the exception of rice, oat requires the most water of any other cereal crop (Tamm 2003; CUDCSS 2004). As evident in **Table 3**, very little work has been done on the response of oat to water. Sandhu and Horton (1977) found that water stress during different stages of crop development had significant effects on grain yield.

The data in **Table 3** shows that optimal water for oat is almost 1000 mm (Heyland and Werner 1992 quadratic response), significantly higher than the peak for wheat of about 350 mm. This would suggest that water requirements of oats are significantly greater than those of potato. This high water requirement may not be applicable in western Canada, however. In field studies conducted in Manitoba, de Rocquigny *et al.* (2004) found that average evapotranspiration for two oat varieties ranged from 266 to 311 mm based on two site-years of data. Due to this discrepancy, a quadratic regression was approximated for oat with a peak at about 450 mm, using the equation (1):

$$Y = -0.0000050 \times AW^2 + 0.0045915 \times AW - 0.0501856 \quad (1)$$

where Y is relative yield and AW is available water in mm.

4. Water sufficiency – canola

For optimal yields, canola requires about 350 mm of water in Black soils (Alberta Agriculture, Field Crops Branch, 1985), producing 6.17 kg of yield per ha per mm of water. As with all crops, highest canola yield is obtained when adequate moisture is present throughout the growing season. For canola, as long as soil moisture is kept above 50% of available water storage capacity (AWSC), yields should not be limited by moisture (**Fig. 2**). If soil moisture exceeds AWSC, water logging or flooding will occur and canola yields will be reduced as canola can only tolerate short periods of flooding (Canola Council of Canada 2001a).

As shown in **Table 4**, response of canola to water is considered linear in most cases although Sidlauskas and Bernotas (2003) found a quadratic response with optimal yield at 320 mm of moisture. Given that canola has limited tolerance to flooding, the linear responses to water reported may simply reflect studies where excess water did not occur. Yield responses from Karamanos and Henry (1991) and Nielsen (1997) are between 4.4 and 8.8 kg ha^{-1} mm^{-1} of water.

5. Water sufficiency – alfalfa

Limited response data was available for alfalfa. According to MAFRI (2003), alfalfa in Manitoba requires 400 to 450 mm of water per year, approximately equal to PET (potential evapotranspiration). For a second cut of alfalfa, an additional 110 to 210 mm (MAFRI 2003) is required to avoid moisture stress, thus total crop demand is about 500 to 650 mm yr^{-1}. Shaykewich *et al.* (1997) found crop water demand of alfalfa to be 500 to 600 mm yr^{-1}.

Table 5 Suggested values for the weighing factor as determined by the stage of crop growth.

Growth stage	Weighing factor, W_i
Vegetative	0
Late vegetative	1
Silking and pollination	1.3
Blister kernel	1
Maturity	0

Source: Timlin *et al.* 2001

As no response data was found, a quadratic function was developed using the crop water demands published by MAFRI (2003) and Shaykewich *et al.* (1997). Using a peak, or optimal, water of 575 mm for two cuts of alfalfa in Manitoba, the following normalized response equation was developed:

$$Y = -0.0000031 \times AW^2 + 0.0036131 \times AW - 0.0394912 \quad (2)$$

where Y is relative yield and AW is available water in mm.

6. Water sufficiency – corn

Limited data was found on the response of corn to soil moisture. Timlin *et al.* (2001) developed a relation between water stress and yield, taking corn heat units into account. The relation suggests that water stress could be related to yield through a seasonal water stress, as shown in equation 3.

$$S_s = \sum_{i=1}^{n} [(S_{Di})(W_i)] \quad (3)$$

where n is the number of days from planting to harvest; W_i is the stage-of-growth dependent weighing factor that accounts for sensitivity of yield to water stress on that day; and S_{Di} is the daily stress index for day i. The daily stress index is calculated from daily and actual transpiration values:

$$SD_i = 1 - T_a/T_p \quad (4)$$

where T_a is actual transpiration and T_p is potential transpiration. Values of the weighting factor, W_i, are shown in **Table 5**.

Yield of corn is then calculated as:

$$Y = Y_p - 198 \times S_s \quad (5)$$

where the value of 198 is known as the water stress response coefficient in tonnes ha^{-1} $unit^{-1}$ of seasonal water stress and Y_p is potential yield where water is not limiting in tonnes ha^{-1}. The potential yield is temperature dependent, and can be evaluated using an equation related to corn heat units (CHU):

$$Y_p = 7.51 \times CHU - 4441 \quad (6)$$

Shaw and Newman (1984) reported that, in most cases, average precipitation was not sufficient for corn production without water stress. While this may apply to areas such as the Great Plains, this may not be true for moister climates such as the eastern seaboard and Pacific Northwest. Under conditions of excess moisture, corn may also be subject to stress.

A response function for corn was developed from the water demand reported for Manitoba conditions by MAFRI (2003). Assuming a peak water of 425 mm, the following normalized equation was developed:

$$Y = -0.0000053 \times AW^2 + 0.0044743 \times AW + 0.0489045 \quad (7)$$

where Y is relative yield and AW is available water in mm.

Nitrogen sufficiency

Yield responses to nitrogen (N) fertilizer are influenced by the levels of soil NO_3-N in the rooting zone as well as N mineralization during the growing season (Oberle and Keeney 1990). In the current paper, most response functions were derived from studies conducted in the Great Plains.

1. Nitrogen sufficiency – potato

Potatoes require relatively large quantities of N for optimal yields (Racz 1995), with yields and tuber size increasing with increased N rates (Rykbost *et al.* 1993; Tomasiewicz 1995). N-deficient conditions result in lower yields due to reductions in tuber numbers and tuber size (Griffin and Hestermann 1991; Belanger *et al.* 2000; Khiari *et al.* 2001) and the creation of favourable conditions for certain diseases such as early blight and Verticillium wilt (Rosen 1991).

N is often over-applied to potatoes to protect against yield loss (Waddell *et al.* 1999); however, excess N in potato production can reduce yields through increased weed growth, delayed maturity, delayed tuber growth and initiation, and increased vine growth which can increase disease incidence (Kleinkopf *et al.* 1981; Alberta Agriculture, Field Crops Branch 1985; Kleinkopf 1985; Westermann and Kleinkopf 1985; Griffin and Hestermann 1991; Rosen 1991; Westermann *et al.* 1994; Belanger *et al.* 2000). Tuber quality, such as specific gravity, can also be affected by excess N, thus reducing net returns.

The response of potato to N is often determined through a quadratic regression curve (Belanger *et al.* 2000). **Table 6** shows the regression of data collected through a literature review of potato response to N. As can be seen in the table (for cases were soil N values were reported), optimal N levels for peak yield vary considerable from as low as 194 kg N ha^{-1} to higher than 500 kg N ha^{-1} depending on yield potential, or geographic location.

For a recent potato rotation modeling study (Khakbazan *et al.* 2009), the N response curve described by Mohr (2003), with an optimal N level at 200 kg N ha^{-1} was assumed. Optimal N levels ranging from 226 to 291 kg ha^{-1} (Racz 1995; Tomasiewicz 1995) have been reported for the same region, but were based on a smaller dataset.

2. Nitrogen sufficiency – wheat

Wheat response to N on the Great Plains is highly moisture dependent because moisture supply is a major yield-limiting factor. In dry years response to N is low, while in wet years increased N increases yield to a greater degree, reflecting the higher N demand to support the higher yield potential (McKenzie *et al.* 2000). Soil N levels influence the likelihood of crop response to applied N fertilizer (McKenzie 2001). Many studies have looked at the response of wheat to N levels. As shown in **Table 7**, optimum levels of total N are generally between 100 and 220 kg N ha^{-1}. The study by Lawrence *et al.* 2002 included residual soil N, N fertilizer and N mineralized during the growing season, resulting in a linear relation indicating that for every kg of N 21 kg of yield is produced.

Wheat response to N was shown to be water dependent as described by McKenzie *et al.* (2000). Soil moisture, taken as growing season precipitation and snow water equivalent, was incorporated into the sufficiency calculation, making N sufficiency water dependent. In general, based on the equations reported by McKenzie *et al.* (2000), as listed in **Table 7**, the optimal N level for wheat is around 105 kg N ha^{-1}, regardless of water levels.

3. Nitrogen sufficiency – oat

Limited data was found for oat response to N. Overall, oat yield was optimized at total N levels (soil test N plus fertilizer N) between 100 and 110 kg N ha^{-1} (**Table 8**). When

Table 6 Nitrogen sufficiency response equations for potato.

Reference	Response to Nitrogen N is available N in kg ha^{-1} Y is yield in t ha^{-1}	R^2	Comments	Optimum N kg ha^{-1}
Kleinkopf *et al*. 1981	$y = -0.000129*N^2 + 0.138596*N + 5.962308$	1.00	Available N includes preplant soil N, mineralized N during growing season and N fertilizer; Russet Burbank	537
Kleinkopf *et al*. 1981	$y = -0.000241*N^2 + 0.198964*N + 7.945812$	1.00	Available N includes preplant soil N, mineralized N during growing season and N fertilizer; Lemhi Russet	413
Kleinkopf *et al*. 1981	$y = -0.000269*N^2 + 0.207717*N + 6.458547$	1.00	Available N includes preplant soil N, mineralized N during growing season and N fertilizer; Centennial Russet	386
Kleinkopf *et al*. 1981	$y = -0.000007*N^2 + 0.034454*N + 26.236239$	1.00	Available N includes preplant soil N, mineralized N during growing season and N fertilizer; Norgold Russet	2461
Kleinkopf *et al*. 1981	$y = -0.000216*N^2 + 0.200925*N + 12.898205$	1.00	Available N includes preplant soil N, mineralized N during growing season and N fertilizer; Pioneer	465
Westermann and Kleinkopf 1985	$y = -0.000214*N^2 + 0.145211*N + 11.541243$	0.90	Soil N included; Russet Burbank;1978 data	339
Westermann and Kleinkopf 1985	$y = -0.00051*N^2 + 0.39407*N - 35.78367$	0.28	Soil N included; Russet Burbank;1980 data	386
Westermann *et al*. 1988	$y = -0.0002*N^2 + 0.1499*N + 8.6867$	0.98	1978 & 1980 data; residual N and mineralizable N included	375
Ojala *et al*. 1990	$y = -0.0000015*N^2 + 0.0082256*N + 5.6608029$	0.70	Soil N included; Russet Burbank; seasonal water of 161 mm	2742
Ojala *et al*. 1990	$y = 0.0000569*N^2 - 0.0049668*N + 13.6006018$	0.90	Soil N included; Russet Burbank; seasonal water of 273 mm	N/A
Ojala *et al*. 1990	$y = -0.0002446*N^2 + 0.1255929*N + 4.5829713$	0.86	Soil N included; Russet Burbank; seasonal water of 379 mm	257
Ojala *et al*. 1990	$y = -0.0002747*N^2 + 0.1396437*N + 12.4519215$	0.97	Soil N included; Russet Burbank; seasonal water of 433 mm	253
Ojala *et al*. 1990	$y = -0.0001401*N^2 + 0.0870770*N + 22.9484651$	0.92	Soil N included; Russet Burbank; seasonal water of 493 mm	311
Ojala *et al*. 1990	$y = -0.0001040*N^2 + 0.0748498*N + 31.3537310$	0.86	Soil N included; Russet Burbank; seasonal water of 586 mm	360
Griffin and Hestermann 1991	$y = -0.000089*N^2 + 0.040000*N + 13.750000$	0.91	Soil N not included	225
Griffin and Hestermann 1991	$y = -0.000044*N^2 + 0.014000*N + 13.300000$	0.28	Soil N not included	159
Griffin and Hestermann 1991	$y = -0.000468*N^2 + 0.123513*N + 22.215873$	0.90	Soil N not included; after corn	132
Griffin and Hestermann 1991	$y = -0.000062*N^2 + 0.018878*N + 26.304762$	0.57	Soil N not included; after other crops	152
Gavlak *et al*. 1993	$y = -0.00013*N^2 + 0.09144*N + 28.99002$	0.99	1990 data; Allagah Russet, includes soil N	352
Gavlak *et al*. 1993	$y = -0.00030*N^2 + 0.15616*N + 20.79908$	0.88	1990 data; Frontier Russet, includes soil N	260
Gavlak *et al*. 1993	$y = -0.00059*N^2 + 0.25019*N + 17.79120$	0.52	1990 data; Russet Burbank, includes soil N	212
Gavlak *et al*. 1993	$y = -0.00073*N^2 + 0.34030*N - 3.56146$	0.97	1990 data; BelRus, includes soil N	233
Gavlak *et al*. 1993	$y = -0.00002*N^2 + 0.02047*N + 29.66591$	0.79	1990 data; Norkotah Russet, includes soil N	512
Gavlak *et al*. 1993	$y = -0.00032*N^2 + 0.18391*N + 17.51477$	0.86	1990 data; HiLite Russet, includes soil N	303
Gavlak *et al*. 1993	$y = -0.00019*N^2 + 0.10853*N + 17.64849$	1.00	1991 data; Allagah Russet, includes soil N	286
Gavlak *et al*. 1993	$y = 0.00001*N^2 + 0.04668*N + 18.36570$	0.93	1991 data; Frontier Russet, includes soil N	N/A
Gavlak *et al*. 1993	$y = -0.00041*N^2 + 0.12547*N + 10.16835$	0.81	1991 data; Russet Burbank, includes soil N	153
Gavlak *et al*. 1993	$y = -0.00014*N^2 + 0.07836*N + 16.09686$	0.94	1991 data; BelRus, includes soil N	280
Gavlak *et al*. 1993	$y = -0.00004*N^2 + 0.05795*N + 14.90679$	0.99	1991 data; Norkotah Russet, includes soil N	724
Gavlak *et al*. 1993	$y = -0.00011*N^2 + 0.07378*N + 17.05546$	0.81	1991 data; HiLite Russet, includes soil N	335
Westermann *et al*. 1994	$y = -0.0003627*N^2 + 0.1705692*N + 18.2939141$	1.00	Soil N included; Russet Burbank; K rate of 112 kg/ha as KCl; 1988 data	235
Westermann *et al*. 1994	$y = -0.000461*N^2 + 0.208064*N + 30.097715$	1.00	Soil N included; Russet Burbank; K rate of 112 kg/ha as KCl; 1989 data	226
Westermann *et al*. 1994	$y = 0.0388393*N + 26.1056250$	1.00	Soil N included; Russet Burbank; K rate of 224 kg/ha as KCl; 1988 data	N/A
Westermann *et al*. 1994	$y = 0.068750*N + 32.422500$	1.00	Soil N included; Russet Burbank; K rate of 224 kg/ha as KCl; 1989 data	N/A
Westermann *et al*. 1994	$y = -0.0003747*N^2 + 0.1855134*N + 17.6290156$	1.00	Soil N included; Russet Burbank; K rate of 448 kg/ha as KCl; 1988 data	247
Westermann *et al*. 1994	$y = -0.000585*N^2 + 0.277934*N + 28.466471$	1.00	Soil N included; Russet Burbank; K rate of 448 kg/ha as KCl; 1989 data	237
Westermann *et al*. 1994	$y = -0.0004145*N^2 + 0.1999107*N + 17.0489375$	1.00	Soil N included; Russet Burbank; K rate of 112 kg/ha as K_2SO_4; 1988 data	241
Westermann *et al*. 1994	$y = -0.000267*N^2 + 0.156336*N + 31.244396$	1.00	Soil N included; Russet Burbank; K rate of 112 kg/ha as K_2SO_4; 1989 data	293
Westermann *et al*. 1994	$y = 0.0107143*N + 28.3050000$	1.00	Soil N included; Russet Burbank; K rate of 224 kg/ha as K_2SO_4; 1988 data	N/A
Westermann *et al*. 1994	$y = 0.050000*N + 39.180000$	1.00	Soil N included; Russet Burbank; K rate of 224 kg/ha as K_2SO_4; 1989 data	N/A
Westermann *et al*. 1994	$y = -0.0003694*N^2 + 0.1879985*N + 17.5028594$	1.00	Soil N included; Russet Burbank; K rate of 448 kg/ha as K_2SO_4; 1988 data	254

Table 6 (Cont.)

Reference	**Response to Nitrogen** **N is available N in kg ha^{-1}** **Y is yield in t ha^{-1}**	**R^2**	**Comments**	**Optimum N kg ha^{-1}**
Westermann *et al*. 1994	$y = -0.000429*N^2 + 0.208294*N + 30.073129$	1.00	Soil N included; Russet Burbank; K rate of 448 kg/ha as K_2SO_4; 1989 data	243
Racz 1995	$y = -0.00010*N^2 + 0.05817*N + 23.66612$	0.98	Soil test N included to 60 cm, Russet Burbank	291
Racz 1995	$y = -0.00013*N^2 + 0.07194*N + 30.05236$	0.92	Soil test N included to 60 cm, Shepody	277
Tomasiewicz 1995	$y = -0.000225*N^2 + 0.101727*N + 19.542204$	0.60	Russet Burbank, Soil test included to 60 cm	226
Honeycutt *et al*. 1996	$y = -0.000046*N^2 + 0.018361*N + 3.987631$	0.97	Potato alfalfa rotation; no soil test levels	199
Honeycutt *et al*. 1996	$y = -0.000088*N^2 + 0.032064*N + 2.761087$	0.95	Potato potato rotation; no soil test levels	182
Honeycutt *et al*. 1996	$y = -0.000026*N^2 + 0.018948*N + 3.116323$	0.93	Potato oat rotation; no soil test levels	364
Boswell 1998	$y = -0.000448*N^2 + 0.198028*N + 7.830685$	0.99	Soil N not included; Russet Burbank; 30 cm row spacing	221
Boswell 1998	$y = -0.000550*N^2 + 0.208921*N + 8.975822$	0.99	Soil N not included; Russet Burbank; 35 cm row spacing	190
Boswell 1998	$y = -0.000302*N^2 + 0.156424*N + 9.989632$	0.99	Soil N not included; Russet Burbank; 40 cm row spacing	259
Mohammad *et al*. 1999	$y = -0.00015*N^2 + 0.09929*N + 22.67308$	0.99	No soil test levels, 1995 data	331
Mohammad *et al*. 1999	$y = -0.00043*N^2 + 0.21429*N + 35.20588$	0.99	No soil test levels, 1996 data	249
Belanger *et al*. 2000	$y = -0.00010*N^2 + 0.04540*N + 18.78960$	N/A	Non-irrigated; includes soil N level	227
Belanger *et al*. 2000	$y = -0.000070*N^2 + 0.036500*N + 20.696250$	N/A	Non-irrigated; includes soil N level	261
Belanger *et al*. 2000	$y = -0.00020*N^2 + 0.09200*N + 12.91500$	N/A	Non-irrigated; includes soil N level	230
Belanger *et al*. 2000	$y = -0.00009*N^2 + 0.05126*N + 15.41559$	N/A	Non-irrigated; includes soil N level	285
Belanger *et al*. 2000	$y = -0.00030*N^2 + 0.11780*N + 16.36930$	N/A	Non-irrigated; includes soil N level	196
Belanger *et al*. 2000	$y = -0.00001*N^2 + 0.01108*N + 36.51084$	N/A	Non-irrigated; includes soil N level	554
Belanger *et al*. 2000	$y = -0.00005*N^2 + 0.47070*N + 19.60755$	N/A	Non-irrigated; includes soil N level	471
Belanger *et al*. 2000	$y = -0.00020*N^2 + 0.09840*N + 25.17680$	N/A	Non-irrigated; includes soil N level	246
Belanger *et al*. 2000	$y = -0.00010*N^2 + 0.05700*N + 28.99750$	N/A	Non-irrigated; includes soil N level	285
Belanger *et al*. 2000	$y = -0.00010*N^2 + 0.04260*N + 15.74560$	N/A	Non-irrigated; includes soil N level	213
Belanger *et al*. 2000	$y = -0.00030*N^2 + 0.15020*N + 17.45080$	N/A	Irrigated; includes soil N level	250
Belanger *et al*. 2000	$y = -0.00030*N^2 + 0.16800*N + 15.02750$	N/A	Irrigated; includes soil N level	280
Belanger *et al*. 2000	$y = -0.00040*N^2 + 0.17300*N + 7.50500$	N/A	Irrigated; includes soil N level	216
Belanger *et al*. 2000	$y = -0.00006*N^2 + 0.03184*N + 22.57006$	N/A	Irrigated; includes soil N level	265
Belanger *et al*. 2000	$y = -0.00020*N^2 + 0.12180*N + 10.72720$	N/A	Irrigated; includes soil N level	304
Belanger *et al*. 2000	$y = -0.00020*N^2 + 0.09520*N + 16.43620$	N/A	Irrigated; includes soil N level	238
Belanger *et al*. 2000	$y = -0.00010*N^2 + 0.04680*N + 33.62440$	N/A	Irrigated; includes soil N level	234
Belanger *et al*. 2000	$y = -0.00020*N^2 + 0.09680*N + 17.67220$	N/A	Irrigated; includes soil N level	242
Belanger *et al*. 2000	$y = -0.00050*N^2 + 0.19400*N + 11.75200$	N/A	Irrigated; includes soil N level	194
Belanger *et al*. 2000	$y = -0.00020*N^2 + 0.09340*N + 32.65680$	N/A	Irrigated; includes soil N level	233
Belanger *et al*. 2000	$y = -0.00001*N^2 + 0.00650*N + 36.55375$	N/A	Irrigated; includes soil N level	325
Belanger *et al*. 2000	$y = -0.00030*N^2 + 0.12280*N + 23.72680$	N/A	Irrigated; includes soil N level	213
Khiari *et al*. 2001	$y = -0.00050*N^2 + 0.15494*N + 32.71786$	0.94	No soil test levels, 1993 data; Superior cv.	155
Khiari *et al*. 2001	$y = -0.00042*N^2 + 0.14808*N + 21.97381$	0.97	No soil test levels, 1994 data; Superior cv.	176
Khiari *et al*. 2001	$y = -0.00052*N^2 + 0.18253*N + 24.25833$	0.91	No soil test levels, 1994 data; Kennebec cv.	176
Mohr 2003[a]	$y = -0.000010*N^2 + 0.003994*N + 0.578271$	N/A	Irrigated; includes soil N level	199
Sincik, Turan and Goksoy 2008	$Y = -0.00014*N^2 + .063*N + 22.0$	0.984	No soil N; potato following common vetch	225
Sincik, Turan and Goksoy 2008	$Y = -0.00018*N^2 + 0.096*N + 16.2$	0.995	No soil N; potato following winter wheat	267
Sincik, Turan and Goksoy 2008	$Y = -0.00016*N^2 + 0.067*N + 21.89$	0.994	No soil N; potato following faba bean	210
Shillito *et al*. 2009	$Y = -0.0002*N^2 + 0.09*N + 14.3$	N/A	No soil N levels; 2003 data	225
Shillito *et al*. 2009	$Y = -0.0005*N^2 + 0.16*N + 19.5$	N/A	No soil N levels; 2004 data	160

[a] Normalized response equation.

total N exceeds 112 kg N ha^{-1}, yield increases do not occur and yield losses are possible due to lodging (Mohr *et al.* 2007).

4. Nitrogen sufficiency – canola

Nitrogen requirements of canola are quite high (Soper *et al.* 1971; Alberta Agriculture, Field Crops Branch 1985; Lewis and Knight 1987; Bailey 1990; Nuttall *et al.* 1992; Grant and Bailey 1993) and yield responses have been seen with the application of as much as 269 kg N ha^{-1} (Henry and MacDonald 1978; Ukrainetz *et al.* 1975). From **Table 9** the collected response data suggests that the quadratic function peaks at total N levels ranging from 150 to more than 300 kg N ha^{-1}. These values are comparatively higher than most other crops included in this study. Karamanos *et al.* (2005) assumed an optimal N level of 219 kg N ha^{-1} for hybrid canola.

5. Nitrogen sufficiency – alfalfa

Few studies were available to describe the yield response of alfalfa to N fertilizer. Given the N-fixing capabilities of this legume crop, it would be expected that a pure alfalfa stand inoculated with rhizobium and actively fixing N would not require additional fertilizer N. In the literature, quite a wide range of optimal N values are reported for alfalfa. Data from Raun *et al.* (1999) suggest a low N requirements of alfalfa (35 to 55 kg N ha^{-1}), while Eardly *et al.* (1985) suggests that alfalfa requires about 180 kg ha^{-1} total N for peak yield. The third set of data, from Nuttall (1985) suggests a wide range of N values, anywhere from 55 to 147 kg N ha^{-1}. **Table 10** shows the data collected from these papers.

Table 7 Nitrogen sufficiency response equations for wheat.

Reference	Response equation y is yield in t ha^{-1} x is N in kg N ha^{-1}	R^2	Comment	Optimum N rate kg ha^{-1}
Racz *et al*. 1965	$Y = 1.58574*N - 0.37135$	1.00	Soil plus fertilizer N	N/A
Gehl *et al*. 1990	$Y = -0.000053*N^2 + 0.020688*N + 1.340816$	0.98	Minnedosa; Glenlea cultivar	195
Gehl *et al*. 1990	$Y = -0.000064*N^2 + 0.028448*N + 1.195720$	0.99	Minnedosa; HY320 cultivar	222
Gehl *et al*. 1990	$Y = -0.000065*N^2 + 0.024328*N + 1.012169$	0.98	Minnedosa; Katepwa cultivar	187
Gehl *et al*. 1990	$Y = -0.000053*N^2 + 0.020096*N + 1.313821$	0.99	Minnedosa; Len cultivar	189
Gehl *et al*. 1990	$Y = -0.000079*N^2 + 0.030616*N + 0.972698$	0.98	Minnedosa; Marshall cultivar	1934
Gehl *et al*. 1990	$Y = -0.000060*N^2 + 0.025912*N + 1.297472$	0.99	Minnedosa; Solar cultivar	216
Gehl *et al*. 1990	$Y = -0.000052*N^2 + 0.019212*N + 1.098611$	0.98	Souris; Glenlea cultivar	185
Gehl *et al*. 1990	$Y = -0.000083*N^2 + 0.029594*N + 1.209651$	0.99	Souris; HY320 cultivar	178
Gehl *et al*. 1990	$Y = -0.000048*N^2 + 0.017599*N + 1.003542$	0.97	Souris; Katepwa cultivar	183
Gehl *et al*. 1990	$Y = -0.000050*N^2 + 0.017446*N + 1.094394$	0.95	Souris; Len cultivar	174
Gehl *et al*. 1990	$Y = -0.000073*N^2 + 0.028586*N + 0.661223$	0.99	Souris; Marshall cultivar	196
Gehl *et al*. 1990	$Y = -0.000074*N^2 + 0.027966*N + 1.016587$	0.98	Souris; Solar cultivar	189
Gehl *et al*. 1990	$Y = -0.000063*N^2 + 0.018362*N + 1.862700$	0.82	Miami; Glenlea cultivar	146
Gehl *et al*. 1990	$Y = -0.000056*N^2 + 0.018373*N + 2.352285$	0.94	Miami; HY320 cultivar	164
Gehl *et al*. 1990	$Y = -0.000059*N^2 + 0.018441*N + 1.652971$	0.74	Miami; Katepwa cultivar	156
Gehl *et al*. 1990	$Y = -0.000060*N^2 + 0.018309*N + 1.737346$	0.98	Miami; Len cultivar	152
Gehl *et al*. 1990	$Y = -0.000048*N^2 + 0.019144*N + 2.084857$	0.94	Miami; Marshall cultivar	199
Gehl *et al*. 1990	$Y = -0.000059*N^2 + 0.021140*N + 1.748420$	0.96	Miami; Solar cultivar	179
Mellish 1994	$Y = -0.000080*N^2 + 0.023200*N + 1.050000$	0.99	AC Voyageur cultivar; soil levels not mentioned	145
Mellish 1994	$Y = -0.000120*N^2 + 0.045200*N + 0.750000$	0.99	Consens cultivar; soil levels not mentioned	188
Mellish 1994	$Y = -0.000090*N^2 + 0.033100*N + 0.975000$	0.99	Graidin cultivar; soil levels not mentioned	184
Mellish 1994	$Y = -0.000130*N^2 + 0.042700*N + 0.625000$	0.98	SS Maestro cultivar; soil levels not mentioned	164
Jackson 1998	$Y = -0.0000273*N^2 + 0.0107999*N + 1.4122555$	0.45	Soil plus fertilizer N; for low yield potential	198
Jackson 1998	$Y = -0.0000605*N^2 + 0.0215998*N + 1.6409064$	0.45	Soil plus fertilizer N; for medium yield potential	178
Potash and Phosphate Institute 1999a	$Y = -0.0000710*N^2 + 0.0331842*N + 1.3450053$	1.00	Soil levels not mentioned	234
Heard and Gares 2000	$Y = -0.000056*N^2 + 0.020812*N + 2.252884$	0.99	Soil N < 44.8 kg/ha	186
Heard and Gares 2000	$Y = -0.0000728*N^2 + 0.0228231*N + 2.9998421$	0.99	Soil N 44.8 to 67.3 kg/ha	157
Heard and Gares 2000	$Y = -0.0000480*N^2 + 0.0100395*N + 4.0830517$	0.66	Soil N 67.3 to 89.7 kg/ha	104
Heard and Gares 2000	$Y = -0.0000293*N^2 + 0.0053260*N + 4.3016151$	0.50	Soil N 89.7 to 112 kg/ha	91
McKenzie *et al*. 2000	$Y = -0.000204*N^2 + 0.042065*N + 0.200320$	0.98	38 cm water; includes soil test N	103
McKenzie *et al*. 2000	$Y = -0.000102*N^2 + 0.021063*N + 0.445610$	0.99	23 cm water; includes soil test N	103
McKenzie *et al*. 2000	$Y = -0.0000830*N^2 + 0.0175024*N + 0.1921436$	0.98	10 cm water; includes soil test N	105
Agrium 2001	$Y = -0.000177*N^2 + 0.039102*N + 0.632636$	0.99	Soil levels not mentioned	110
Engel *et al*. 2001	$Y = -0.0000217*N^2 + 0.0068140*N + 1.0698524$	0.78	Soil plus fertilizer N; low moisture	157
Engel *et al*. 2001	$Y = -0.0000577*N^2 + 0.0175642*N + 1.5104446$	0.82	Soil plus fertilizer N; medium moisture	152
Engel *et al*. 2001	$Y = -0.0000983*N^2 + 0.0413876*N + 1.0658273$	0.96	Soil plus fertilizer N; high moisture	210
McKenzie 2001	$Y = -0.000088*N^2 + 0.039871*N + 0.731543$	0.99	High moisture conditions	226
Eckhoff 2003	$Y = -0.000086*N^2 + 0.036707*N + 0.212259$	1.00	Soil plus fertilizer N	213
Lawrence *et al*. 2002	$Y = 0.020681*N - 0.056260$	0.99	Soil+mineralized+fertilizer N	N/A
Phillips and Mullin 2004	$Y = -0.000657*N^2 + 0.0694*N + 3.5$	N/A	No soil N; 2001 data; ammonium nitrate applied	53
Phillips and Mullin 2004	$Y = -0.000217*N^2 + 0.0280*N + 3.9$	N/A	No soil N; 2002 data; ammonium sulfate applied	65
Phillips and Mullin 2004	$Y = -0.000565*N^2 + 0.0692*N + 3.7$	N/A	No soil N; 2001 data; ammonium sulfate applied	62
Phillips and Mullin 2004	$Y = -0.000519*N^2 + 0.0706*N + 3.5$	N/A	No soil N; 2001 data; urea ammonium nitrate applied	68
MAFRI 2007	$Y = - 0.000077 *N^2 + 0.030761 *N + 2.353546$	0.99	Includes soil test N	199
MAFRI 2007	$Y = -0.000094*N^2 + 0.031444*N + 2.242713$	0.99	Includes soil test N	167
Habtegebrial and Singh 2009	$Y = -0.000123*N^2 + 0.0380*N + 1.41$	N/A	No soil N; no sulfur; black soil; improved cultivar yield	154
Habtegebrial and Singh 2009	$Y = -0.0000719*N^2 + 0.0154*N + 1.86$	N/A	No soil N; no sulfur; black soil; local cultivar yield	107
Habtegebrial and Singh 2009	$Y = -0.000115*N^2 +0.0286*N + 2.25$	N/A	No soil N; no sulfur; brown soil; improved cultivar yield	124
Habtegebrial and Singh 2009	$Y = -0.000192*N^2 + 0.0448*N + 2.77$	N/A	No soil N; 20 kg/ha sulfur; brown soil; improved cultivar yield	117
Habtegebrial and Singh 2009	$Y = -0.0000700*N^2 + 0.0176*N + 2.8$	N/A	No soil N; 20 kg/ha sulfur; brown soil; local cultivar yield	126
Habtegebrial and Singh 2009	$Y = -0.0000719*N^2 + 0.0179*N + 2.31$	N/A	No soil N; 20 kg/ha sulfur; black soil; local cultivar yield	125
Habtegebrial and Singh 2009	$Y = -0.000106*N^2 + 0.0340*N + 2.42$	N/A	No soil N; 40 kg/ha sulfur; black soil; improved cultivar yield	160
Habtegebrial and Singh 2009	$Y = -0.0000139*N^2 + 0.00339*N + 3.53$	N/A	No soil N; 40 kg/ha sulfur; brown soil; local cultivar yield	140
Habtegebrial and Singh 2009	$Y = -0.000168*N^2 + 0.0492*N + 1.86$	N/A	No soil N; 20 kg/ha sulfur; black soil; improved cultivar yield	146

6. Nitrogen sufficiency – corn

A large number of studies have been done on yield response of corn to N. Response of corn peaks between 150 and 500 kg N ha^{-1}, with most peaks from the literature review occurring in the 250 to 350 kg N ha^{-1} range. **Table 11** shows the regression equations obtained from the literature. According to Oberle and Keeney (1990), variation in yield

Table 8 Nitrogen sufficiency response equations for oat.

Reference	**Normalized response** N is available N in kg ha^{-1}	**Comments**	**Optimum N** kg ha^{-1}
Mohr and Heard 2002[a]	Y = -0.000042*N^2 + 0.008704*N + 0.552200	Site 1; Soil N included to 60 cm	103
Mohr and Heard 2002[a]	Y = -0.00006*N^2 + 0.01264*N + 0.34130	Site 2; Soil N included to 60 cm	105
Mohr and Heard 2002[a]	Y = -0.00006*N^2 + 0.01214*N + 0.38530	Both sites; Soil N included to 60 cm	101
Mohr *et al*. 2007[a]	Y = -0.000028*N^2 + 0.007817*N + 0.389520	Soil N included to 60 cm	139

[a]Normalized response equations.

Table 9 Nitrogen sufficiency response equations for canola.

Reference	**Response to Nitrogen** N is available N in kg ha^{-1} Y is yield in t ha^{-1}	R^2	**Comments**	**Optimum N** kg ha^{-1}
Racz *et al*. 1965	Y = 1.5829*N - 0.0463	1.00	Soil N included	N/A
Anderson and Kusch 1968	Y = -0.000199*N^2 + 0.078167*N - 5.414647	0.51	Soil N included	196
Soper 1971	Y = -0.000015*N^2 + 0.009277*N + 0.489611	0.96	Response to fertilizer N; soil N not reported	309
Henry and MacDonald 1978	Y = -0.000031*N^2 + 0.013851*N + 0.511902	0.99	Soil N included	223
Sheppard and Bates 1980	Y = -0.000080*N^2 + 0.023266*N + 0.636718	0.99	Soil N not included; 1972 data; early seeding	145
Sheppard and Bates 1980	Y = -0.000066*N^2 + 0.016023*N + 1.649231	0.98	Soil N not included; 1973 data; early seeding	121
Sheppard and Bates 1980	Y = -0.000054*N^2 + 0.015804*N + 1.380513	0.99	Soil N not included; 1974 data; early seeding	146
Sheppard and Bates 1980	Y = -0.000046*N^2 + 0.017853*N + 0.808205	0.97	Soil N not included; 1972 data; late seeding	194
Sheppard and Bates 1980	Y = -0.000030*N^2 + 0.009966*N + 1.581538	0.99	Soil N not included; 1973 data; late seeding	166
Sheppard and Bates 1980	Y = -0.000016*N^2 + 0.004749*N + 1.523692	0.74	Soil N not included; 1974 data; late seeding	148
Lewis and Knight 1987	Y = 0.00000052*N^3 - 0.00041372*N^2 + 0.10850464*N - 7.19761726	N/A	Soil N included; 1978 data	237
Lewis and Knight 1987	Y = -0.00006240*N^2 + 0.02841735*N - 1.11172953	N/A	Soil N included; 1979 data; 7 kg/ha seeding rate	227
Lewis and Knight 1987	Y = -0.00006240*N^2 + 0.02941735*N - 1.49049034	N/A	Soil N included; 1979 data;12 kg/ha seeding rate	235
Jackson 1999	Y = -0.000042*N^2 + 0.022000*N + 0.260036	N/A	Soil N included	262
Sykes and Mailer 1991	Y = -0.000184*N^2 + 0.034699*N + 0.604170	1.00	Soil N included; 1987 data	94.
Sykes and Mailer 1991	Y = -0.000056*N^2 + 0.016101*N + 1.237677	0.91	Soil N included; 1988 data	143
Sykes and Mailer 1991	Y = 0.006448*N + 1.774723	0.98	Soil N included; Eureka variety	N/A
Sykes and Mailer 1991	Y = 0.007424*N + 1.324247	0.97	Soil N included; Malulea variety	N/A
Jackson 2000	Y = -0.000039*N^2 + 0.020000*N + 0.365000	N/A	Soil N included; rainfed fields	256
Jackson 2000	Y = -0.000043*N^2 + 0.023000*N + 0.279000	N/A	Soil N included; rainfed fields	267
Jackson 2000	Y = -0.000022*N^2 + 0.011318*N + 0.481573	0.84	Soil N included; flood irrigated; 45 kg S/ha	257
Jackson 2000	Y = -0.000038*N^2 + 0.017494*N + 0.041962	0.99	Soil N included; flood irrigated; 22kg S/ha	230
Jackson 2000	Y = -0.000022*N^2 + 0.011739*N + 0.332351	0.88	Soil N included; flood irrigated; 0 kg S/ha	267
Jackson 2000	Y = -0.00002*N^2 + 0.01661*N + 0.27945	0.99	Soil N included; sprinkle irrigated; 45 kg S/ha	415
Jackson 2000	Y = -0.00002*N2 + 0.01406*N + 0.47002	0.99	Soil N included; sprinkle irrigated; 22kg S/ha	351
Jackson 2000	Y = -0.00003*N^2 + 0.01904*N + 0.34839	0.99	Soil N included; sprinkle irrigated; 0 kg S/ha	317
Canola Council of Canada 2001b	Y = -0.0000371*N^2 + 0.0133113*N + 0.8801347	0.99	Soil N not included	179
Canola Council of Canada 2001c	Y = -0.00001*N^2 + 0.01048*N + 0.54480	0.99	Soil N 0 to 30 kg/ha; not included in regression	524 to 554
Canola Council of Canada 2001c	Y = -0.00002*N^2 + 0.00848*N + 1.23933	0.94	Soil N 31 to 45 kg/ha; not included in regression	243 to 257
Canola Council of Canada 2001c	Y = -0.00002*N^2 + 0.01244*N + 1.16993	0.99	Soil N 46+ kg/ha: not included in regression	357+
Ozer 2003	Y = -0.0000100*N^2 + 0.00451*N + 0.661	0.97	Soil N levels included; 1994 data	226
Ozer 2003	Y = -0.0000110*N^2 + 0.00565*N + 0.614	0.95	Soil N levels included; 1995 data	257
Sidlauskas and Bernotas 2003	Y = 0.00000014*N^3 - 0.00009924*N^2 + 0.02309328*N + 0.66918928	N/A	Soil N included	207
Karamanos *et al*. 2005[a]	Y = -0.0000066*N^2 + 0.0028930*N + 0.6821038	N/A	Soil N included	219
Malhi *et al.* 2006	Y = -0.0000336*N^2 + 0.00610*N + 0.726	0.978	Initial soil N not indicated	90
Malhi and Lemke 2007	Y = -0.0000755*N^2 + 0.0256N + 0.885	0.986	Initial soil N not indicated	169
Smith *et al.* 2010	Y = -0.0000274*N^2 + 0.0121N + 0.772	N/A	Soil N included	220

[a]Normalized response equation

response to N can be due to a number of factors including timing and frequency of precipitation, soil depth, N leaching and the amount of N made available from mineralization of soil organic matter. McDonald (2004) shows corn response to N with optimal yield at about 160 kg N ha^{-1}.

Table 10 Nitrogen sufficiency response equations for alfalfa.

Reference	Response to Nitrogen N is available N in kg ha^{-1} Y is yield in t ha^{-1}	R^2	Comments	Optimum N kg ha^{-1}
Eardly *et al*. 1985	Y = -0.00001* N^2 + 0.00360*N + 2.15200	0.33	Soil N included; 1980 data	180
Eardly *et al*. 1985	Y = -0.00003* N^2 + 0.01120*N + 1.34800	0.36	Soil N included; 1982 data	186
Nuttall 1985	Y = -0.000071* N^2 + 0.017053*N + 2.040601	1.00	Soil N included; 22 kg sulfur/ha	121
Nuttall 1985	Y = -0.000475* N^2 + 0.080973*N - 0.236278	1.00	Soil N included; 45 kg sulfur/ha	85
Nuttall 1985	Y = -0.000140* N^2 + 0.037428*N + 0.947568	1.00	Soil N included; 45 kg sulfur/ha	133
Nuttall 1985	Y = -0.003561* N^2 + 0.584874*N - 14.433507	1.00	Soil N included; 45 kg sulfur/ha; established stand	82
Nuttall 1985	Y = -0.00012* N^2 + 0.01304*N + 1.92784	0.87	Soil N included; assumed 67 kg S/ha, 45 kg P/ha	54
Nuttall 1985	Y = -0.00009* N^2 + 0.01737*N + 5.48661	0.88	Soil N included; assumed 67 kg S/ha, 45 kg P/ha	96
Nuttall 1985	Y = -0.00135* N^2 + 0.22578*N - 4.46890	0.75	Soil N included; assumed 67 kg S/ha, 45 kg P/ha	83
Nuttall 1985	Y = -0.00084* N^2 + 0.15855*N - 2.37537	0.67	Soil N included; assumed 67 kg S/ha, 45 kg P/ha	94
Nuttall 1985	Y = -0.00017* N^2 + 0.03208*N + 0.05027	0.50	Soil N included; assumed 67 kg S/ha, 45 kg P/ha	94
Nuttall 1985	Y = -0.00039* N^2 + 0.11487*N + 0.07802	0.63	Soil N included; assumed 67 kg S/ha, 45 kg P/ha	147
Nuttall 1985	Y = -0.00053* N^2 + 0.15254*N + 0.39616	0.75	Soil N included; assumed 67 kg S/ha, 45 kg P/ha	144
Nuttall 1985	Y = -0.00025* N^2 + 0.07120*N + 6.39206	0.63	Soil N included; assumed 67 kg S/ha, 45 kg P/ha	142
Raun *et al*. 1999	Y = -0.0015*N^2 + 0.1615*N + 4.9785	1.00	Soil N included; 1993 data	54
Raun *et al*. 1999	Y = -0.0022* N^2 + 0.2419*N + 6.9188	0.79	Soil N included; 1994 data	55
Raun *et al*. 1999	Y = -0.0014* N^2 + 0.149*N + 7.9684	0.27	Soil N included; 1995 data	53
Raun *et al*. 1999	Y = -0.0008* N^2 + 0.0568*N + 8.5431	0.93	Soil N included; 1996 data	35

Table 11 Nitrogen sufficiency response equations for corn.

Reference	Response to Nitrogen N is available N in kg ha^{-1}; Y is yield in t ha^{-1}	R^2	Comments	Optimum N kg ha^{-1}
Oberle and Keeney 1990	Y = -0.000050*N^2 + 0.027423*N + 3.947187	N/A	Fayette (sil); Soil N included	274
Oberle and Keeney 1990	Y = -0.000059*N^2 + 0.037140*N + 3.888616	N/A	Plano (sil); Soil N included	315
Oberle and Keeney 1990	Y = -0.000100*N^2 + 0.056506*N + 0.811983	N/A	Plainfield (loam sand); Soil N included	282
Oberle and Keeney 1990	Y = -0.000041*N^2 + 0.024952*N + 7.105207	N/A	Manawa (sicl); Soil N included	304
Oberle and Keeney 1990	Y = -0.000058*N^2 + 0.033957*N + 1.229855	N/A	Withee (sil); Soil N included	293
Griffin and Hestermann 1991	Y = -0.00001*N^2 + 0.00873*N + 4.00500	0.81	Soil N not included; Site 1	436
Griffin and Hestermann 1991	Y = -0.00004*N^2 + 0.01580*N + 3.58500	0.99	Soil N not included; Site 2	197
Dhuyvetter and Schlegel 1994	Y = -0.00017*N^2 + 0.06340*N + 4.73768	0.99	P fertilizer of 44.8 kg/ha; Soil N included	186
Dhuyvetter and Schlegel 1994	Y = -0.00012*N^2 + 0.04330*N + 4.52917	0.95	P fertilizer of 0 kg/ha; Soil N included	180
Vanotti and Bundy 1994	Y = -0.000041*N^2 + 0.026560*N + 5.419634	N/A	Soil N included; Site 1	324
Vanotti and Bundy 1994	Y = -0.000056*N^2 + 0.034410*N + 2.860938	N/A	Soil N included; Site 2	318
Vanotti and Bundy 1994	Y = -0.000035*N^2 + 0.021874*N + 6.363625	N/A	Soil N included; Site 3	312
Vanotti and Bundy 1994	Y = -0.0000068*N^2 + 0.0227352*N + 3.8070576	N/A	Soil N included; Site 4	1672
Vanotti and Bundy 1994	Y = -0.000053*N^2 + 0.031457*N + 2.847704	N/A	Soil N included; Site 5	297
Vanotti and Bundy 1994	Y = -0.000108*N^2 + 0.059662*N + 1.734901	N/A	Soil N included; Site 6	276
Schmidt *et al*. 2002	Y = -0.000052*N^2 + 0.004704*N + 9.412848	N/A	Soil N included; Harvey County; 1998 data; Site 1	45
Schmidt *et al*. 2002	Y = -0.000058*N^2 + 0.026784*N + 7.490592	N/A	Soil N included; Harvey County; 1998 data; Site 2	231
Schmidt *et al*. 2002	Y = -0.00002*N^2 + 0.00784*N + 9.20405	N/A	Soil N included; Harvey County; 1998 data; Site 3	196
Schmidt *et al*. 2002	Y = -0.000083*N^2 + 0.047988*N + 4.163108	N/A	Soil N included; Harvey County; 1998 data; Site 4	289
Schmidt *et al*. 2002	Y = -0.000054*N^2 + 0.022659*N + 8.560929	N/A	Soil N included; Harvey County; 1999 data; Site 1	210
Schmidt *et al*. 2002	Y = -0.000105*N^2 + 0.058280*N + 3.522480	N/A	Soil N included; Harvey County; 1999 data; Site 2	277
Schmidt *et al*. 2002	Y = -0.000132*N^2 + 0.046038*N + 6.975124	N/A	Soil N included; Harvey County; 1999 data; Site 3	174
Schmidt *et al*. 2002	Y = -0.000131*N^2 + 0.065004*N + 2.400916	N/A	Soil N included; Harvey County; 1999 data; Site 4	248
Schmidt *et al*. 2002	Y = -0.000091*N^2 + 0.048878*N + 8.255440	N/A	Soil N included; Buffalo County; 1999 data; Site 1	268
Schmidt *et al*. 2002	Y = -0.000049*N^2 + 0.026822*N + 10.368157	N/A	Soil N included; Buffalo County; 1999 data; Site 2	273
Schmidt *et al*. 2002	Y = -0.00002*N^2 + 0.01427*N + 11.52010	N/A	Soil N included; Buffalo County; 1999 data; Site 3	357
Schmidt *et al*. 2002	Y = -0.000061*N^2 + 0.029050*N + 10.402763	N/A	Soil N included; Buffalo County; 1999 data; Site 4	238
Schmidt *et al*. 2002	Y = -0.000007*N^2 + 0.006890*N + 12.390085	N/A	Soil N included; Buffalo County; 1999 data; Site 5	492
Heard 2003	Y = -0.0000014*N^2 + 0.0011072*N + 9.9297067	0.11	Manitoba Data; Soil N included; Graysville 2002	395
Heard 2003	Y = -0.000031*N^2 + 0.022170*N + 4.273731	0.97	Manitoba Data; Soil N included; Edwin 2002	357
Heard 2003	Y = -0.000067*N^2 + 0.028138*N + 7.157345	0.76	Manitoba Data; Soil N included; Reinland 2001	210
Heard 2003	Y = -0.0000043*N^2 + 0.0012224*N + 9.3304675	0.23	Manitoba Data; Soil N included; Carman 2001	142
Kelling and Bundy 2004	Y = -0.000071*N^2 + 0.031146*N + 4.909322	1.00	Soil N not included. Response to fertilizer	219
McDonald 2004	Y = -0.00011*N^2 + 0.03840*N + 6.25776	0.99	Fine soil texture; soil N included	174
McDonald 2004	Y = -0.000107*N^2 + 0.032844*N + 4.686560	0.99	Medium soil texture; soil N included	153
McDonald 2004	Y = -0.000132*N^2 + 0.040925*N + 6.171458	0.99	Coarse soil texture; soil N included	155
McDonald 2004	Y = -0.000114*N^2 + 0.036019*N + 5.405942	0.99	All soil textures; soil N included	158

Phosphorus sufficiency

Developing statistical relationships to describe the yield response of crops to P application poses a challenge. While the frequency and magnitude of yield responses to P fertilizer is not as great for soils testing high in P as for soils with low P levels (Bottcher *et al.* 1992; Penas and Sander 1993; Potash and Phosphate Institute 1999b; Howard 2003), a number of studies have demonstrated a relatively poor relationship between soil test P levels and yield responses to P fertilizer application, making the determination of an optimal P level challenging (Fixen and Carson 1978; McKenzie and Bremer 2003; Flaten *et al.* 2002). In fact, Howard (2003) found that soil test P levels have a greater influence on yield than added fertilizer. Adapted from a study by Penas and Sander (1993), **Table 12** shows the probability of

Table 12 Probability of crop response to applied P fertilizer.

Soil Test P		Corn	Grain	Seeded Alfalfa
Acidic / Neutral	**Calcareous**			
0 to 11.2	0 to 6.7	HP	HP	HP
13.5 to 33.6	9.0 to 22.4	P-Po	P	P
359 to 53.89	24.7 to 35.9	D	Po	Po
56.0 to 67.3	38.1 to 44.8	D	D	D
> 67.3	> 44.8	D	D	D

HP->highly probable, P->probable, Po->possible, D->doubtful
Source: Penas and Sander 1993

crop response to applied fertilizer P for corn, grains and alfalfa, taking into account soil pH. It is noteworthy that, while excessive levels of P in potato can be toxic and thereby reduce yields, P toxicity is not observed in all crops (Hopkins and Ellsworth 2003).

In reviewing the literature, differences in the method of soil P analysis used, and in the results obtained, make comparisons among studies and the identification of a single statistical model to describe yield responses to P, more challenging.

For the purposes of this paper, methods of soil P analysis were not differentiated from one another, and yield responses were related to "available P" which was defined as soil P levels plus the available fraction of the applied P fertilizer.

1. Phosphorus sufficiency – potato

Potato is often considered to have a high P requirement, and therefore may receive high rates of P fertilizer. The application of large amounts of fertilizer P can lead to accumulation in the soil, and potentially to contamination of surface and subsurface water if P is lost from the soil (Khiari *et al.* 2001). Other studies suggest that potato does not have an especially high P requirement, however. While some reports claim that potatoes do not response to P fertilizer (Woods *et al.* 2002), most studies found that response was found as long as soil P levels were below 45 kg P ha^{-1} (Gaia Consulting 1995; Allison *et al.* 2001; Crozier *et al.* 2004; Mohr and Tomasiewicz 2004), a level which is often classed as a medium soil P test. Some studies (e.g. Kelling 1999; Potash and Phosphate Institute 1999a) have reported, however, that responses to fertilizer phosphorus could be observed even on soils with high soil test P levels.

A study by Payton *et al.* (1989) suggests that the P response curve for potato is a fit to the Mitscherlich-Bray equation:

$$y = A\{1 - \exp[-c(bT + X)]\} \qquad (8)$$

where Y is predicted yield; A is maximum yield; c is related to efficiency of soil and fertilizer P; T is the amount of plant available P from the soil; X is the amount of P applied to the soil; and b is a constant, with bT+X being a linear combination of soil and fertilizer P. The equation for a soil with

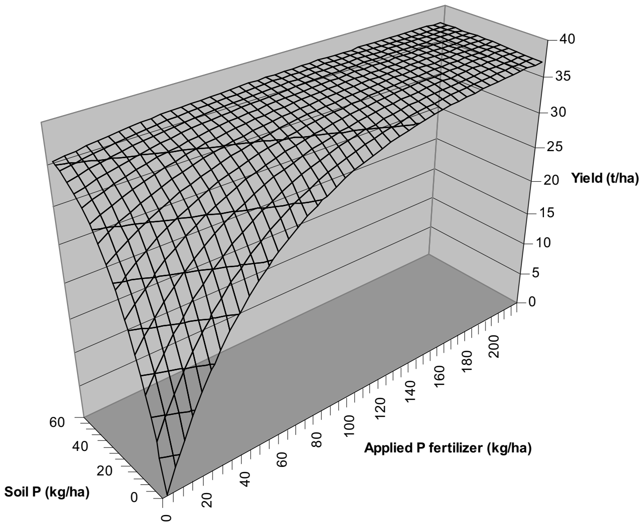

Fig. 3 Plot of Mitscherlich-Bray equation for pH of 5.4.

a pH of 5.4 is:

$$y = 37.843 \times \{1 - \exp[-0.019 \times (2.152 \times T + X)]\} \qquad (9)$$

This equation, shown in **Fig. 3**, is an exponential rise to a maximum; however, excess P can decrease yield and quality (Hopkins and Ellsworth 2003). Taking the toxicity of excess P to potatoes into account, the use of a quadratic has been used, giving optimal available P levels in the range of 45 and 73 kg P ha^{-1}, as shown in **Table 13**. It should be noted that the data is for available P, which consists of soil P levels plus the available fraction of the applied P fertilizer. Westermann (1993) reported that the daily average P use for 'Russet Burbank' potato is 0.42 to 0.61 kg ha^{-1} day^{-1}.

A Manitoba data set provided by Gaia Consulting (1995) for the Carberry region of Manitoba was used to develop a potato response curve. The relation developed, however, was not quadratic as shown in the above table, but an exponential relation of:

$$Y = \frac{55.2221}{1 + e^{\frac{(P_{avail} - 7.6494)}{2.7288}}} \qquad (10)$$

where Y is normalized relative yield and P_{avail} is the amount of available P in kg P ha^{-1}. Peak yield occurs when P_{avail} is greater than about 50 kg P ha^{-1}.

2. Phosphorus sufficiency – wheat

Responses of wheat to P have been reported as linear, quadratic and exponential. Optimal levels of total available P, as shown in **Table 14**, are between 15 and 50 kg available P ha^{-1}. This excludes the data set from Potash and Phosphate Institute (1999a), which indicated that optimal total available P would be greater than 60 kg ha^{-1}, as soil levels

Table 13 Phosphorus sufficiency response equations for potato.

Reference	Response to Phosphorus P is available P in kg ha^{-1} Y is yield in t ha^{-1}	R^2	Comments	Optimum P kg ha^{-1}
Herawati 1994	Y = -0.0034*P^2 + 0.3115*P + 14.426	0.75	Soil P levels not published; chicken manure added to improve P availability (reduces P fixation)	46
Herawati 1994	Y = -0.0042*P^2 + 0.3768*P + 10.875	0.89	Soil P levels not published; green manure added to improve P availability (reduces P fixation)	45
Tomasiewicz 1994	Y = 0.008*P + 36.272	0.01	Russet Burbank; soil levels included	N/A
Gaia Consulting 1995	Y = -0.00136*P^2 + 0.13621*P + 50.11516	0.86	Russet Burbank; soil levels included	50
Allison *et al.* 2001	Y = -0.01817*P^2 + 2.65625*P - 64.86256	1.00	Soil levels included	73
Hopkins and Ellsworth 2003	Y = 0.0982*P + 10.922	0.95	Soil levels included	N/A
Hopkins and Ellsworth 2003	Y = -0.00222*P^2 + 0.32082*P + 11.50537	0.37	Soil levels included	72
Hopkins and Stark 2003	Y = -0.01287*P^2 + 1.35280*P - 9.21699	1.00	Russet Burbank; soil levels included; 2001 data	52
Hopkins and Stark 2003	Y = -0.0365*P^2 + 3.5849*P - 58.45	1.00	Russet Burbank; soil levels included; 2002 data	49

Table 14 Phosphorus sufficiency response equations for wheat.

Reference	Normalized response P is available P in kg ha^{-1}	R^2	Comments	Optimal P kg ha^{-1}
Racz *et al*. 1965	Y = 2.2808*P - 9.9553	1.00	Soil P included	N/A
Potash and Phosphate Institute 1999a	Y (t/ha) = -0.001906*P^2 + 0.221187*P + 3.160762	1.00	P is available P in kg/ha; soil P levels not included	58
Nuttall and Button 1990	Y = -0.0212*P^2 + 1.1174*P - 11.5852	0.98	Seedplaced P; broadcast N; soil P levels included	26
Nuttall and Button 1990	Y = -0.0040*P^2 + 0.2493*P - 0.8748	0.73	Seedplaced P; deepbanded N; soil P levels included	31
Nuttall and Button 1990	Y = -0.0048*P^2 + 0.3080*P - 1.8088	0.88	Deepbanded P; broadcast N; soil P levels included	32
Nuttall and Button 1990	Y = 0.0788*P + 0.9089	0.99	Deepbanded P; Deepbanded N; soil P levels included	N/A
Belcher *et al*. 2003	See equation 2.64		P is available P in kg/ha	> 50
Kastens *et al*. 2003	Y = -0.07982*P^2 + 2.38319*P - 15.35866	0.99	Soil test 5 ppm	15
Kastens *et al*. 2003	Y = -0.04125*P^2 + 2.13681*P - 25.15270	0.99	Soil test 10 ppm	26
Kastens *et al*. 2003	Y = -0.01875*P^2 + 1.39247*P - 23.27704	0.99	Soil test 15 ppm	37
Kastens *et al*. 2003	Y = -0.00964*P^2 + 0.92787*P - 19.72732	0.95	Soil test 20 ppm	48

Table 15 Phosphorus sufficiency response equations for oat.

Reference	Response to Phosphorus P is available P in kg ha^{-1} Y is yield in t ha^{-1}	R^2	Comments	Optimum P kg ha^{-1}
Eberhardt and Clark 1998	Y = -0.005333*P^2 + 0.265570*P + 1.762285	0.58	Soil P included	25
Mohr *et al*. 2007	Y = 0.01289*P + 3.43738	0.85	Site 1; soil P levels included	N/A
Mohr *et al*. 2007	Y = -0.00417*P^2 + 0.23850*P + 0.21876	N/A	Site 2; soil P levels included	28

Table 16 Phosphorus sufficiency response equations for canola.

Reference	Response to Phosphorus P is available P in kg ha^{-1} Y is yield in t ha^{-1}	R2	Comments	Optimum P kg ha^{-1}
Racz *et al*. 1965	Y = 1.6014*P - 0.5129	1.00	Soil P included	N/A
Sheppard and Bates 1980	Y = -0.002694*P^2 + 0.148117*P + 0.161255	0.83	Soil P included	27
Alberta Agriculture, Field Branch, 1985	Y = 0.041813*P + 0.145580	0.99	Low soil P; soil levels not indicated; yield increase, NOT yield response	N/A
Alberta Agriculture, Field Branch, 1985	Y = 0.024526*P + 0.106915	0.96	Medium soil P; soil levels not indicated; yield increase, NOT yield response	N/A
Alberta Agriculture, Field Branch, 1985	Y = 0.012419*P + 0.025672	0.91	High soil P; soil levels not indicated; yield increase, NOT yield response	N/A
Nuttall and Button 1990	Y = 0.03000*P + 0.60755	0.87	Seedplaced P; broadcast N; soil P levels included	N/A
Nuttall and Button 1990	Y = -0.01880*P^2 + 0.99500*P - 11.60019	0.82	Seedplaced P; deepbanded N; soil P levels included	26
Nuttall and Button 1990	Y = -0.00360*P^2 + 0.18679*P - 1.03640	0.26	Deepbanded P; broadcast N; soil P levels included	26
Nuttall and Button 1990	Y = -0.00520*P^2 + 0.32252*P - 3.52325	0.99	Deepbanded P; Deepbanded N; soil P levels included	31
Canola Council of Canada 2001d	Y = -0.021262*P^2 + 0.180625*P + 0.009143	0.99	Yield increase in Manitoba; soil levels not mentioned	N/A
Canola Council of Canada 2001d	Y = -0.0084*P^2 + 0.111*P + 0.0239	0.97	Low soil P; soil levels not indicated; yield increase, NOT yield response	N/A
Canola Council of Canada 2001d	Y = -0.007*P^2 + 0.0795*P + 0.021	0.96	Medium soil P; soil levels not indicated; yield increase, NOT yield response	N/A
Canola Council of Canada 2001d	Y = -0.0025*P2 + 0.0314*P - 0.001	0.99	High soil P; soil levels not indicated; yield increase, NOT yield response	N/A
Roswell *et al*. 2004	Y = -0.002006*P^2 + 0.212550*P - 1.256708	0.99	Site NL92; soil P included	53
Roswell *et al*. 2004	Y = -0.001310*P^2 + 0.090808*P + 0.926707	0.99	Site NL94; soil P included	34
Roswell *et al*. 2004	Y = -0.001387*P^2 + 0.100621*P + 0.143923	0.64	Site EMO92; soil P included	36
Roswell *et al*. 2004	Y = -0.003695*P^2 + 0.227985*P - 1.366207	0.58	Site EMO93; soil P included	31

were not reported.

In a study by Jackson *et al.* (1998), optimal available P levels were found to be dependent upon soil test P. With a high soil test P level, small yield increases could be found at available P fertilizer levels of about 14 kg ha^{-1}, while at low soil P sites, large yield increases could be found at slightly higher (20 kg ha^{-1}) amounts of available fertilizer P.

The normalized response equation 11 was found in Belcher *et al.* (2003) study. While the equation is not quadratic in nature, the plateau at 54 kg P ha^{-1} reflects that P toxicity is not present in wheat.

$$\frac{Y}{Y_{Max}} = \frac{1.0112}{1 + e^{\left(-\frac{P_{plantavail} - 22.909}{7.5197}\right)}} \quad (11)$$

3. Phosphorus sufficiency – oat

As with oat response to water, very limited data is available for oat response to P. As shown in **Table 15**, reported response curves are fit either linearly or quadratically, with optimum available P levels between 25 and 29 kg ha^{-1}.

The data from Mohr *et al.* (2007) for Manitoba shows a quadratic response curve, with optimal yield at approximately 29 kg available phosphorus ha^{-1}.

4. Phosphorus sufficiency – canola

Yield response in canola to fertilizer P is strong only when soil P levels are less than 20 kg ha^{-1} (Soper and Racz 1963; Soper 1971; Sheppard and Bates 1980; Grant and Bailey 1993; Canola Council of Canada 2001d). High rates of P application at planting can reduce yield due to reduced seedling emergence (Alberta Agriculture, Field Branch 1985). As shown in **Table 16**, optimal available P levels for canola are generally between 26 and 36 kg available P ha^{-1}. Yield responses are in the range of 1 to 2.5 kg yield kg^{-1} of available P fertilizer for high soil test P soils; 2.5 to 7 for medium soil test P soils; and 4.5 to 8.5 for low soil test P fields (Alberta Agriculture, Field Branch, 1985; Canola

Table 17 Phosphorus sufficiency response equations for alfalfa.

Reference	Response to Phosphorus P is available P in kg ha^{-1} Y is yield in t ha^{-1}	R^2	Comments	Optimum P kg ha^{-1}
Smith and Powell 1979	Y = - 0.0051 *P^2 + 0.6227 *P - 10.8276	1.00	Soil P levels included	61
Wichman *et al*. 1998	Y = -0.00045*P2 + 0.04334*P + 1.19782	0.95	Soil P levels not reported	48
Wichman *et al*. 1998	Y = -0.00067*P^2 + 0.08687*P + 8.94366	0.93	Soil P levels not reported	65
Wichman *et al*. 1998	Y = -0.00024*P^2 + 0.02143*P + 2.67326	0.99	Soil P levels not reported	44
Potash and Phosphate Institute 1999a	Y = -0.00135*P^2 + 0.13004*P + 18.21802	0.91	Soil P levels not reported	48
Potash and Phosphate Institute 1999a	Y = -0.00105*P^2 + 0.16588*P + 17.34890	0.96	Soil P levels not reported	79
Potash and Phosphate Institute 1999a	Y = -0.00150*P^2 + 0.18380*P + 16.58007	0.99	Soil P levels not reported	61
Potash and Phosphate Institute 1999a	Y = -0.00105*P^2 + 0.14738*P + 15.98952	0.96	Soil P levels not reported	70
Potash and Phosphate Institute 1999a	Y = -0.00120*P^2 + 0.18264*P + 20.34624	0.99	Soil P levels not reported	76
Potash and Phosphate Institute 1999a	Y = -0.00075*P^2 + 0.16241*P + 18.39630	0.98	Soil P levels not reported	108
Ottman *et al*. 2000	Y = -0.027608*P^2 + 1.977695*P - 9.498298	0.93	1997 Water Run P application; soil P levels included	36
Ottman *et al*. 2000	Y = -0.011303*P^2 + 0.876148*P + 11.114348	0.91	1998 Water Run P application; soil P levels included	39
Ottman *et al*. 2000	Y = -0.020883*P^2 + 1.546089*P - 2.829840	0.84	1999 Water Run P application; soil P levels included	37
Ottman *et al*. 2000	Y = -0.022789*P^2 + 1.796975*P - 7.510606	0.73	1997 Broadcast P application; soil P levels included	39
Ottman *et al*. 2000	Y = -0.008620*P^2 + 0.701196*P + 13.924482	0.90	1998 Broadcast P application; soil P levels included	40
Ottman *et al*. 2000	Y = -0.013782*P^2 + 1.147915*P + 2.524296	0.95	1999 Broadcast P application; soil P levels included	41
Mullen *et al* 2000	Y = -0.0000152*P^2 + 0.0162*P+ 12	1.00	Soil P included	
Mullen *et al*. 2001	Y = 0.039*P + 10.991	0.98	Soil P levels included	110
Berrada and Westfall 2005	Y = -0.0000332*P^2 + 0.0131*P + 12	0.998	1998 data; no soil P indicated	197
Berrada and Westfall 2005	Y = -0.000126*P^2 + 0.0317*P + 8.25E+00	0.984	1999 data; no soil P indicated	126

Table 18 Phosphorus response equation for corn.

Reference	Response to Phosphorus P is available P in kg ha^{-1} Y is yield in t ha^{-1}	R2	Comments	Optimum P kg ha^{-1}
Moody *et al*. 1997	Y = -0.000100038*P^2 + 0.019097141*P + 0.065863880[1]	0.88	Soil P levels included; quadratic fit	95
Moody *et al*. 1997	N/A	0.86	Mitsecherlich equation	> 95
Potash and Phosphate Institute 1999a	Y = -0.01186*P^2 + 0.33629*P + 9.53716	0.97	Soil P levels not reported	14
Heard 2003	Y = 0.0521*P + 7.1769	0.10	Manitoba data; Soil P included; Graysville 2002	N/A
Heard 2003	Y = 0.0912*P + 4.8665	0.75	Manitoba data; Soil P included; Edwin 2002	N/A
Heard 2003	Y = 0.0521*P + 7.0952	0.92	Manitoba data; Soil P included; Reinland 2001	N/A
Heard 2003	Y = 0.1042*P + 2.5088	0.97	Manitoba data; Soil P included; Carman 2001	N/A
Mallarino and Atia 2005	Y = -0.00029*P^2 + 0.01918*P + 0.672[1]	N/A	Olsen soil test	33
Mallarino and Atia 2005	Y = -0.000101*P^2 + 0.011598*P + 0.651[1]	N/A	Resin soil test	57
Mallarino and Atia 2005	Y = -0.000084*P^2 + 0.010706*P + 0.65[1]	N/A	Mehlich soil test	63
Mallarino and Atia 2005[a]	Y = -0.000098*P^2 + 0.011152*P + 0.658	N/A	Bray soil test	57

[a]Normalized response P is available P in kg ha^{-1}

Council of Canada 2001d).

5. Phosphorus sufficiency – alfalfa

Response of alfalfa to P levels indicates that optimal yields can be obtained when total available P is between 36 and 60 kg ha^{-1} (Smith and Powell 1979; Ottman *et al.* 2000). Most of the data found did not include soil P levels, as shown in **Table 17**, so comparison between all collected data sets was not possible. Assuming that soil P levels, in the cases where soil P was not reported, was not equal to zero, optimal P levels could be greater than 110 kg ha^{-1} of available P (includes soil P and available fertilizer P) (Potash and Phosphate Institute 1999a; Mullen *et al.* 2001).

6. Phosphorus sufficiency – corn

As shown in **Table 18**, information with regards to corn response to P is quite limited. The dataset includes data from Manitoba (Heard 2003); however, the response is linear. The two quadratic response curves obtained also had very different optimal P levels for optimal yield. The Potash and Phosphate Institute (1999a) study found optimal yield was achieved with as little as 15 kg available P ha^{-1}, while the quadratic fit of the Moody *et al.* (1997) data set gave a peak at 95 kg available P ha^{-1}. A study by Mallarino and Atia (2005) looked at P response curves based on different soil tests of phosphorus. Peak P levels ranged from 33. to 64 kg P ha^{-1} depending on the soil test method used.

CONCLUSIONS

Crop water and nutrient sufficiency is very important for optimal economic and environmental sustainability. Crop yield on the Great Plains is often proportional to difference between precipitation and potential evapotranspiration, and water deficit is common. Crop water sufficiency for a given crop is a function of both the amount of water available to the crop and when that water is available during the growing season. This study showed that a quadratic response of crop yield to water is common, but that the optimal requirement differs among crop species and regions within the Great Plains. Crop water response may also vary within a given field in that both water deficits and excesses may occur in the same field. The statistical crop-water response models that were identified in this study can be used to select optimal crop production practices that minimize impacts of water deficit by either meeting the crop water requirement or avoiding crop water stress during critical periods.

Nutrients may also strongly impact crop yield. The N requirement of a crop is proportional to crop yield potential which, on the Great Plains, is often determined by moisture availability. Soil test N is a reasonable predictor of crop N requirements, but in-season N mineralization must also be taken into account. Accurate prediction of crop N needs is important because N deficiencies may reduce crop yield and quality, while excess N may negatively affect crop quantity and quality as well as the environment. Unlike the case with N, soil test P is not as clear a predictor of crop P requirements. Studies have demonstrated a relatively poor relationship between soil test P levels and yield responses to P fertilizer application, making the determination of an optimal P level challenging. This study reviewed statistical relationships that described crop response to fertilizer application in an effort to identify nutrient levels that optimize crop yield and profit. An improved understanding of nutrient requirements, in addition to providing economic benefits, has the potential to minimize nutrient losses into the environment by avoiding over-application, and thereby to increase the nutrient and energy use efficiency of cropping systems.

The functional relationship between crop yield and water, and between crop yield and nutrients, is integral to many modelling tools for understanding biological systems and the impact of factors such as climate change. A review of research conducted in the Great Plains demonstrated wide variations among crops in terms of the amount and type of information available, and the yield functions reported in the literature. Water and nutrient requirement varied among regions within the Great Plains and models, and was influenced by crop species and factors such as temperature, soil water and nutrient content. Selection of the appropriate yield function is critical for the development of models that effectively describe biological systems and potential changes to them.

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