Landscape-Scale Variability of N_2 Fixation by Pea

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ABSTRACT

The landscape-scale variability of N_2 fixation by pulse crops is an important part in the intensity of N cycling in a hummocky terrain. A 100-gridpoint landscape-scale research design was established at a site in the Thick Black Soil Zone in the spring of 1993. At the time of seeding, gridpoints classified as footslope landform complexes had 6.4% more water and 21.7 kg ha^{-1} more available N than those classified as shoulder. Pea seed yield ranged from 400 to 3750 kg ha^{-1} and straw yield ranged from 1900 to 12500 kg ha^{-1}. Median seed yield on footslopes was 35% lower than that on shoulders, while median straw yield was 18% greater on footslopes in comparison to shoulders. Total N_2 fixed in pea straw and seed ranged from 0 to 239 kg N ha^{-1}. Median N_2 fixed on shoulders was 116 kg N ha^{-1} and 91 kg N ha^{-1} on footslopes, despite the fact that total N did not show a spatial pattern. Spatial variability of available N, controlled by the redistribution of water, was considered to be the major process controlling the landscape-scale variability of N_2 fixation.

INTRODUCTION

Nitrogen-cycle research has typically considered variability only at the plot and regional scales (Parkin, 1993). However, processes within the N-cycle have been shown to vary at the landscape scale, a scale moderate to that of a plot or region (Pennock et al., 1992; Sutherland et al., 1993; van Kessel et al., 1993). An understanding of the processes controlling the landscape-scale variability of N cycling is crucial if producers are to be expected to maintain soil fertility and minimize negative effects of N-fertilizer applications.

On the prairies, the amount of N_2 fixed by pea varied from 4–185 kg-N ha^{-1} or 5–79% of the total N in pea (Rennie and Dubetz, 1986; Cowell et al., 1989; Kucey, 1989). Mahler et al. (1979) found that the total N fixed by pea was 22% in upper-slope positions and 33% in lower-slope positions in Oregon. In the Thin Black soil zone of Saskatchewan, Androsoff (1993) showed that the percentage of seed N fixed by pea was 28.1% on convergent shoulders and 68.6% on divergent footslopes. The same study found that % Ndfa in pea seed ranged from 0-92.8 with an index of variation of 79% (Androsoff, 1993).

It is apparent that knowledge on the landscape-scale variability of N_2 fixation by pea is incomplete. To address this concern, a field study was conducted to assess the landscape-scale variability of N_2 fixation by pea in the Thick Black soil zone of Saskatchewan.

MATERIALS AND METHODS

Research Design

A field experiment was established in a field near Birch Hills, Saskatchewan, a site in the Thick Black soil zone (105° 1' 49" W, 53° 2' 30" N). A pulse crop had never been previously grown on this field.

In May of 1993, a 100x100-m grid was surveyed using a 10-m square-grid design. Survey information and a digital elevation model were used to characterize each of the 100 gridpoints as either shoulder or footslope landform complexes (Pennock et al., 1987). In general, the SW and NE corners of the Birch Hills grid were classified as shoulders (Figure 1). Gridpoints in the central portion running diagonally from NW to SE corners were predominately classified as footslopes.

Site Preparation

In the spring of 1993, lower-slope positions were burned to alleviate tillage problems associated with the excessive residue. Tillage operations prior to sowing were similar to those used by most producers in the Thick Black soil zone. One of the field operations included the broadcasting and incorporation of granular ethalfluralin (Edge). On May 27th, 'Trapper' pea was inoculated with a commercial inoculant (C-1; MicroBio RhizoGen Corp., Saskatoon, SK) and sown at a rate of 120 kg ha^{-1}. Six kg-N ha^{-1} and 28 kg-P_2O_5 ha^{-1} was applied with seed in the form of mono-ammonium phosphate. A post-emergent grassy-weed herbicide quizolofop ethyl (Assure) was applied in the 1st week of July to control late-emerging grassy weeds.

Four days after sowing peas, 'Cyclone' canola (*Brassica napus* L.) was hand broadcast at a rate of 8 kg ha^{-1} in a 1-m^2 area within 1 m of each gridpoint. Pea seedlings in each canola microplot were removed a few days after emergence.

A meteorological station was set up to monitor daily air temperature and precipitation.

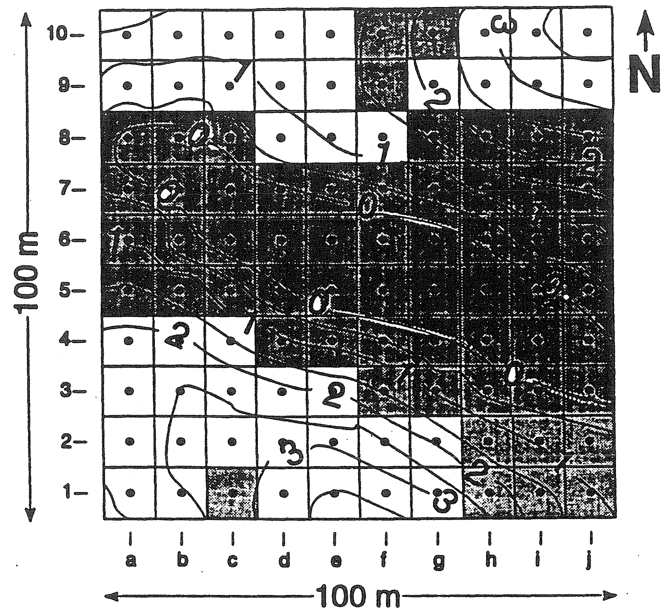

Figure 1. A contour map showing the proximity of landform complexes at each gridpoint in relation to the topography at the Birch Hills grid. Unshaded areas indicate shoulders and shaded areas indicate footslopes.

Nitrogen-15 Microplot Preparation

At the five-trifoliate leaf stage of pea, double labelled $^{15}NH_4^{+15}NO_3^-$ 10 atom % ^{15}N, was applied to a 1-m^2 area of pea, within 1 m of the gridpoint, at each gridpoint, at a rate of 15.6 kg-N ha^{-1}. Canola microplots received single labelled $^{15}NH_4^{+14}NO_3^-$ 5 atom % ^{15}N at a rate of 20.0 kg-N ha^{-1}.

Response Design

On May 31st, soil was sampled to the 0–30-cm and 30–60-cm depths at each gridpoint. From each sample, a 2M KCL extract was taken and steam distilled to determine available N (NO_3^- and NH_4^+) (Keeney and Nelson 1982). A subsample of each original soil sample was oven dried at 105°C to determine % soil-water content. Available N and % soil-water content for the 0–60-cm depth were calculated by totalling the respective variables over both depths.

Physiological maturity of pea was reached in the third week of September. Three to four plant samples were removed at ground level from the center of each microplot, dried at 40°C, separated into straw and seed, and ground in a Cyclone mill. Straw samples were ground further in a ball mill. Percent N and atom % ^{15}N were determined on an ANCA-MS (Europa Scientific, Crewe, UK) equipped with a single inlet and triple collectors. A subsample which gave the equivalent of 10 µg of N was used for mass-spectrometry determinations. Working standards were ^{15}N pea straw (atom % ^{15}N excess = 0.2322; SD = 0.0019) and ^{15}N pea seed (atom % ^{15}N excess = 0.1455; SD = 0.0029). The *A*-value method was used to calculate N_2 fixation in straw and seed. Percent N derived from fertilizer (% Ndff) was calculated as follows:

$$\% \text{ Ndff} = \left(\frac{\text{atom } \%^{15}\text{N excess}_{plant}}{\text{atom } \%^{15}\text{N excess}_{fertilizer}}\right) \times 100 \qquad [1].$$

A value (kg ha^{-1}) was equal to:

$$A \text{ value} = \left(\frac{100 - \% \text{ Ndff}}{\% \text{ Ndff}}\right) \times \text{rate of fertilizer N applied} \qquad [2].$$

Percent N derived from N_2 fixation (% Ndfa) was calculated as follows:

$$\% \text{ Ndfa} = (A_{pea} - A_{canola}) \times \frac{\text{FUE}_{pea}}{100} \qquad [3]$$

where FUE_{pea} = fertilizer use efficiency of pea:

$$\text{FUE} = \frac{\% \text{ Ndff} \times \text{total N}}{\text{rate of fertilizer N applied}} \qquad [4]$$

Total N derived from N_2 fixation (Ndfa; kg ha^{-1}) was calculated as follows:

$$\text{TotalNdfa} = \left(\frac{\% \text{ Ndfa}_{straw} \times \text{total N}_{straw}}{100}\right) + \left(\frac{\% \text{ Ndfa}_{seed} \times \text{total N}_{seed}}{100}\right) \qquad [5].$$

A 1-m^2 area independent of the pea microplot was removed at ground level from each gridpoint to determine straw and seed yield. Samples were dried, threshed, and weighed to determine pea straw and seed yields.

Statistical Analysis

Quartile maps were drawn to show the spatial pattern and the range of responses for each variable across the grid. A Kolmogorov-Smirnov statistic was calculated to determine if the response variables were normally distributed. Significant ($P \leq 0.05$) non-normal distributions were found for a number of the response variables. As a result, the non-parametric Mann-Whitney U test was used to confirm if the spatial pattern for each response variable was similar to the spatial pattern of shoulders and footslopes (Figure 1). Other studies using a similar research design have considered responses significant at $P < 0.20$, since error variability at the landscape scale can be greater than with experiment designs like a RCBD (Androsoff, 1993). Spearman correlation coefficients were used to relate ($\alpha = 0.10$) total Ndfa to the other response variables.

Gridpoints in transect 10 were found to have unusually high levels of available N at seeding in relation to other gridpoints (Figures 1 and 2). It was suspect that these gridpoints accidently received a ≈100 kg-N ha^{-1} fertilizer application prior to soil sampling. Data from transect 10 was ignored when drawing the quartile map for available N. Other statistical analyses were not adversely affected when data from transect 10 were included.

RESULTS

Mean daily temperatures from June 1st–August 31st were 3°C less than the 30-year average (1951-1980) of 14.8°C. As a result, growing degree days during this same period were 860°C less than the 30-year average of 1470°C. June precipitation was 31 mm greater than the 30-year average and July precipitation exceeded the 30-year average by 53 mm. August precipitation was near normal. Lower than average daily temperatures were thought to be responsible for a ≈3 week delay in pea-nodule initiation. Also, a mid-September frost affected pea-seed development, especially in the footslope position.

A distinct footslope-centered spatial pattern was observed for both available N (Figure 2). The spatial pattern of % soil-water content at seeding was similar to that for available N. Median available N was 121% greater ($P < 0.001$) and % soil-water content was 31% greater ($P < 0.001$) on footslopes in comparison to shoulders (Table 1).

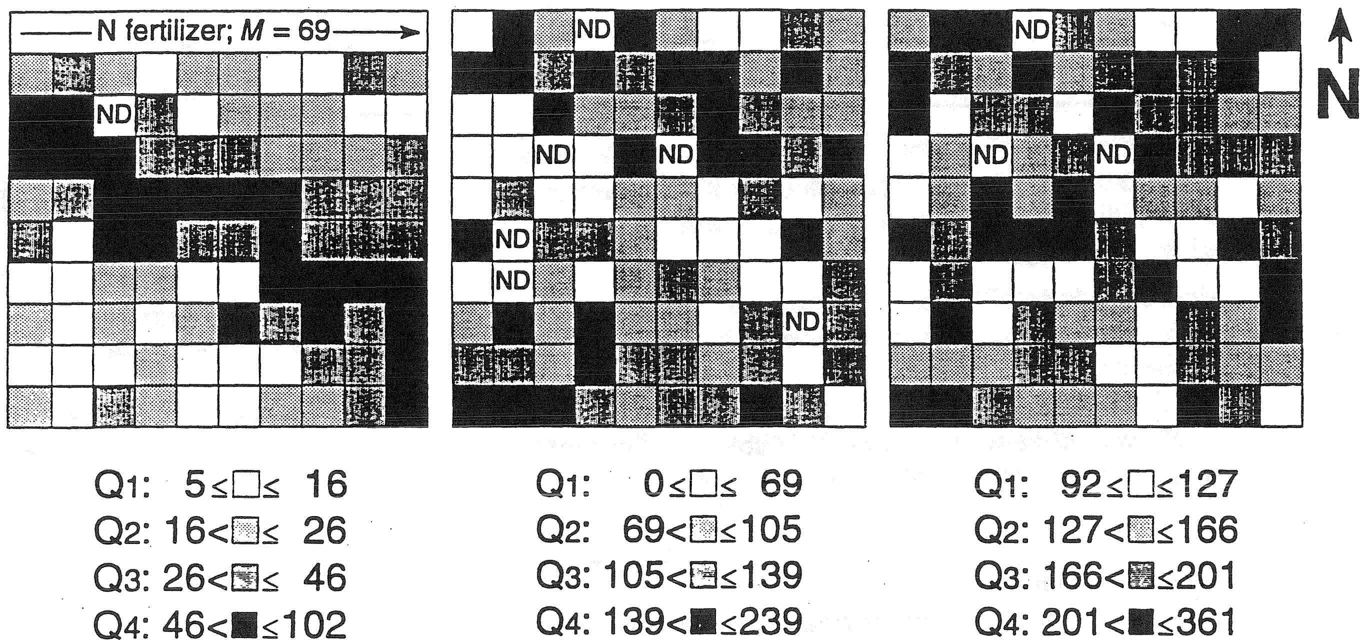

Figure 2. Quartile maps showing footslope-centered pattern for available N at seeding (far left; *M* = median for transect 10), shoulder-centered pattern for total Ndfa and random pattern for total N (far right) at Birch Hills.

Yield of pea straw ranged from 1900–12500 kg ha^{-1} and seed yield ranged from 400–3750 kg ha^{-1} (Figure 2). A footslope-centered spatial pattern was shown for straw yield, while seed yield emulated a shoulder-centered spatial pattern (see Figure 2). Median straw yield was 18% greater ($P = 0.003$) and median seed yield was 35% lower ($P < 0.001$) on footslopes, with a median harvest index of 52% on shoulders and 27% on footslopes (Table 1).

Total N ranged from 92–361 kg ha^{-1} and total Ndfa ranged from 0–239 kg ha^{-1} (Figure 2). A random spatial variation was observed for total N (Figure 2). Median total N over the entire grid was 166 kg ha^{-1} (Table 1). A shoulder-centered spatial pattern was found for total Ndfa (Figure 2). Median total Ndfa was 22% lower ($P = 0.024$) on footslopes (Table 1). The

Table 1. Medians and interquartiles (IQR) for each response variables in shoulder and footslopes positions at the Birch Hills grid. Spearman correlation coefficient (r_s) related total Ndfa to the other response variables.

	Shoulders			Footslopes		
Response variables	Median	IQR	r_s†	Median	IQR	r_s
Soil-water content (%)	29.0	14.4	0.090	42.06	15.4	-0.236
Available N (kg ha^{-1})	14.3	16.1	-0.021	30.7	28.8	-0.399**
Straw yield (kg ha^{-1})	3860	1240	0.432**	4550	2060	0.335**
Grain yield (kg ha^{-1})	2060	1220	0.295	1330	980	0.486**
Total N (kg ha^{-1})	166	83.0	0.693*	166	70.0	0.608**
Ndfa straw (%)	66.6	29.9	0.345*	51.3	35.7	0.873**
Ndfa seed (%)	74.9	25.4	0.496**	69.4	29.4	0.826**
Total Ndfa (kg ha^{-1})	116	77.0	-	91	74.9	-

†Significance levels for r_s is based on N = 39 on shoulders. Significance levels for r_s is based N = 55 on footslopes, with the exception of available N where N = 54. * indicates those correlation coefficients significant at the 5% level and ** indicates those coefficients significant at the 1% level.

decrease in total Ndfa on footslopes corresponded with a median % Ndfa in straw that was 22% (P = 0.004) lower and median % Ndfa in seed that was 7% lower (P = 0.048) on footslopes (Table 1).

On both shoulders and footslopes, total Ndfa was related to straw and grain yield, % Ndfa in straw and seed, and total N (Table 1). On footslopes, total Ndfa was also related to % soil-water content and available N at seeding.

DISCUSSION

Spatial Variability of Yield

Overall median yield of pea seed was close to the Saskatchewan average (1971–1989) of 1600 kg ha^{-1}, despite above-average rainfall in June and July. Reduced median seed yield on footslopes does not concur with the results from past research that suggest at least similar or greater seed yield in lower slope positions (Mahler et al., 1979; Androsoff, 1993). Greater median straw yields on footslopes corresponded with prolonged vegetative growth that allowed a mid-September frost to cease proper seed development. A reduced number of growing degree days and above-average rainfall are implicated as important factors responsible for the unexpected spatial pattern for seed yield.

Spatial Variability of N_2 Fixation

A range in total Ndfa of 0–239 kg ha^{-1} is similar to that reported in other research conducted at the landscape (Androsoff, 1993) and regional scale (Rennie and Dubetz, 1986; Cowell et al., 1989; Kucey, 1989). Van Kessel et al. (1993), utilizing a similar research design, showed that denitrification varied from 0–2770 g-N ha^{-1} d^{-1} within different landform complexes. It would appear that our research design effectively captured most of the landscape-scale variability that might occur for N_2 fixation by pea.

The footslope-centered spatial pattern for total Ndfa was contrary to that shown in past research (Mahler et al., 1979; Androsoff, 1993). Neither Mahler et al. (1979) nor Androsoff (1993) provided a model to explain their results.

A Landscape-scale Model

Percent soil-water content at seeding was greater in the lower footslope portions of the Birch Hills grid. Water incident within a hummocky terrain, like that at the Birch Hills site, will move as surface runoff and throughflow to convergent areas of the landscape (Pennock et al., 1987). Pennock et al. (1987) stated that this redistribution of water is the most important process responsible for the landscape-scale variability of soil properties and plant productivity.

Water redistribution was thought to be responsible for the unusually large cereal-straw yields in footslope areas of the Birch Hills grid from 1990–1992. The excessive cereal stubble necessitated burning on footslopes prior to seeding in the spring of 1993. Stubble burning may have increased available N in these landforms. Greater median available N at seeding suggests: 1) more intense leaching of NO_3^- occurred on shoulders, and/or 2) more rapid N mineralization had already occurred on footslopes prior to seeding. Results from Goovavaerts and Chiang (1993) indicate the higher rates of N mineralization can be expected in lower areas of a landscape.

Evidence suggests that the inhibition of N_2 fixation in footslope during vegetative growth was one explanation for reduced total Ndfa on footslopes. Greater levels of available N in footslopes would directly inhibit nitrogenase activity within pea nodules (Munns, 1977; Sprent and Minchin, 1983; Jensen, 1986). The potential for greater N mineralization on footslopes would directly contribute to the effect of this factor. Also, % Ndfa in straw was more strongly related to total Ndfa than was % Ndfa in seed, and the median difference for % Ndfa in straw between footslopes and shoulders was greater than for % Ndfa in seed. This implies that processes controlling the shoulder-centered pattern of total Ndfa likely were most influential prior to pod set and seed fill. Finally, the difference in median total N between footslopes and shoulders was within 1 kg ha^{-1}. This would suggest that N_2 fixation adjusted according to soil-N availability among landforms. Jensen (1986) showed that pea was capable of utilizing soil N at any time during the growing season. The small difference in median % Ndfa in seed between landforms implies N-mineralization rates were beginning to equalize across the whole grid with the onset of reproductive growth.

Waterlogging in lower areas of the Birch Hills grid was also thought to be another process contributing to the landscape-scale variability of N_2 fixation. In June and July, above-average rainfall was received at the Birch Hills grid. Above average rainfall would have emphasized surface runoff and throughflow towards convergent areas, causing short periods of waterlogging (Pennock et al., 1987). Waterlogging would have reduced the aerobic activity of rhizobia (Munns, 1977; Sprent and Minchin, 1983). The importance of waterlogging is diminished by the fact that flooding in lower-slope positions likely only lasted for a few hours during about three days in June and July.

Water redistribution was implicated as a primary control for spatial patterns for N mineralization and waterlogging, that in turn controlled the landscape-scale variability of N_2 fixation at the Birch Hills grid. Evidence for these landscape controls of N_2-fixation inhibition was provided in the preceding text. Evidence for the outcome of these processes can be derived from the strong relationship of available N and % soil-water content with total Ndfa only on footslopes. It would appear that available N and soil-water content were not affecting N_2 fixation on shoulders to the degree that they were on footslopes. The significant correlation between straw and seed yield with total Ndfa indicates that water redistribution and N mineralization also may have been responsible for the landscape-scale variability of yield noted at Birch Hills.

A Generalized Landscape-scale Model

The landscape-scale model presented here can be generalized for a broader applicability. The model utilizes the variables: (1) water redistribution as a function of growing season precipitation and topography, and (2) spatial patterns for N mineralization as a function of water redistribution. The model assumes that plant growth, through the effect of precipitation on soil-water availability, will be the primary factor dictating rates of N_2 fixation (Munns, 1977; Sprent and Minchin, 1983). The effects of water redistribution on the mineralization of soil-organic matter N mineralization will be assumed to obscure the primary effect of plant growth (Munns, 1977; Sprent and Minchin, 1983). This model was used to predict the landscape-scale variability of N_2 fixation for extremes of precipitation and total-soil N (Table 2).

Table 2. Spatial patterns of pea N_2 fixation that were predicted for extremes of growing season precipitation and total-soil N.

Precipitation	Total-soil N	Spatial pattern
≤ normal	≤ normal	footslope-centered
≤ normal	> normal	footslope-centered/random
> normal	≤ normal	shoulder-centered/random
> normal	**> normal**	**shoulder-centered**

If precipitation is greater than normal, water will converge in lower areas, and if less than normal levels of soil N are present, rates of N_2 fixation will be greatest on footslopes (Table 2). However, if soil-N availability is normal–high, N_2 fixation on footslopes will be inhibited and the previously-mentioned footslope-centered pattern will become obscured. Water will converge on lower areas, even when precipitation is less than normal. However, plant growth will be restricted on shoulders due to lack of available soil-water. If normal–high levels of soil N are present, rates of N_2 fixation will be greatest on shoulders (Table 2). However, if soil-N availability is less than normal, N_2 fixation on footslopes will be less inhibited and the previously-mentioned shoulder-centered pattern will become obscured.

The 4^{th} scenario in Table 2 represents the growing conditions thought to be responsible for spatial patterns of total Ndfa at the Birch Hills grid. These predictions provide some rationale as to why our results did not concur with those of past research (Mahler et al., 1979; Androsoff, 1993).

CONCLUSIONS

The landscape-scale variability of pea N_2 fixation has practical implications with regards to Variable Rate N-fertilizer Application Technology (VRAT). If pea is frequently included in a crop rotation, the soil N pool may become depleted in parts of the landscape. Also, the fixed N_2 which has been mineralized from pea residue, the 'N benefit' of pea, might vary within a given landscape. To account for soil-N depletion and the mineralization fixed N_2, N-fertilizer application might be adjusted within the landscape to insure that plant-N demands of subsequent crops are met.

ACKNOWLEDGEMENTS

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