Intensive potato production effects on nitrate-N concentrations of rural New Brunswick well water

J.E. RICHARDS, P.H. MILBURN, A.A. MACLEAN and G.P. DEMERCHANT

Agriculture Canada Research Station, Box 20280, Fredericton, NB, Canada E3B 4Z7. *Received 10 October 1989; accepted 26 April 1990.*

Richards, J.E., Milburn, P.H., MacLean, A.A. and DeMerchant, G.P. 1990. **Intensive potato production effects on nitrate-N concentrations of rural New Brunswick well water.** Can. Agric. Eng. **32:** 189-196. This study was conducted to determine if the intensity of agricultural land use, in particular potato production, was related to NO_3-N concentrations in private rural groundwater wells in New Brunswick. A secondary objective was to determine if the concentrations of NO_3-N changed over 15 yr in these wells. Samples of 47 wells were taken from 1973 to 1976 and in 1988 from farms in three agricultural regions in northwestern New Brunswick. Wells in a rural non-agricultural region near Fredericton were sampled in 1988. The most intensely cropped region (St. André) had 20 - 25 % of its land area cropped to potatoes; the other two agricultural regions had substantially less area cropped to potatoes (7 - 9 %). Mean NO_3-N concentrations were least in the Fredericton region (1.1 mg L^{-1}) and greatest in the St. André region (9.5 mg L^{-1}). Elevated NO_3-N concentrations were due to non-point effects; average NO_3-N concentrations of the three agricultural study regions were unaltered when waters containing more than 10 coliform bacteria per 100 mL were removed from analysis, suggesting that NO_3-N in well waters was derived from soil-N or fertilizer-N. The mean concentration of NO_3-N in wells of the study agricultural regions was associated with the proportion of the land base cropped to potatoes. In one of the agricultural study regions, the mean concentration of NO_3-N decreased over the course of the study while there was no significant change in NO_3-N concentrations in the other two agricultural study regions.

Key words: potato, leaching, nitrate, NO_3-N, groundwater

INTRODUCTION

There is considerable current world-wide concern about the effects of intensive agricultural production on groundwater quality. Pesticides and/or elevated concentrations of NO_3-N have been found in groundwaters of the U.S.S.R, the E.E.C. and North America (Bashkin and Kudeyarov 1983; Owen and Jurgens-Gschwind 1986; Hallberg 1987; Hubbard and Sheridan 1989). Results of numerous studies conducted throughout the world have shown that groundwater NO_3-N concentrations have increased in regions where intensive agricultural production is concentrated (Bashkin and Kudeyarov 1983; Foster et al. 1982; Miller 1979; Owen and Jurgens-Gschwind 1986; Hallberg 1987; Hubbard and Sheridan 1989).

Leaching of NO_3-N from the root-zone occurs when precipitation exceeds evapo-transpiration (Kowalenko 1987; Scharf and Alley 1988). Hence leaching usually increases with increasing precipitation (Scharf and Alley 1988) and frequency of irrigation (Timmons and Dylla 1981; Hergert 1986) and is generally greatest during the non-cropping portion of the year (Scharf and Alley 1988; Cameron and Wild 1984; Kowalenko 1987; Milburn et al. 1990). Nitrate leaching from the root zone tends to be greater from coarse-textured soils than from fine-textured soils (Gustafson 1983) and is generally greater from soils cropped to row crops than from soils cropped to cereals or other non-row crops due to the generally higher rates of fertilizer-N applied to row crops (Meisinger 1976; Rourke 1985; Simon et al. 1988; Milburn et al. 1990). In Ontario, Hill (1982) found that NO_3-N concentrations in groundwater were associated with the proportion of the land base growing heavily fertilized crops and with fertilizer-N application rates in the vicinity of the wells.

Although it is generally acknowledged that groundwater NO_3-N concentrations will increase with increasing intensive crop production, there is no general agreement as to the source of NO_3 since there are different N-related mechanisms operative under differing soil-climatic-hydrogeological conditions. In some studies, high groundwater NO_3-N concentrations were attributed to fertilizer-N (Bashkin and Kudeyarov 1983; Hallberg 1987). Significant nitrate leaching generally occurs only when fertilizer-N is applied in quantities greater than those recommended for maximum plant growth (Gast et al. 1978; Miller 1979; Barraclough et al. 1983; Gustafson 1983). Other studies, however, have implicated mineralization of soil organic matter as the source of NO_3-N contamination of groundwaters (Dowell et al. 1984; Dowell and Webster 1984; Gustafson 1983). This mechanism appears most prevalent in climatic regions which encourage mineralization of organic matter during the dormant, non-crop portion of the year. For example, in the U.K. tracer N-15 studies of a barley-winter fallow rotation showed that fertilizers contributed only 2-3 % of the total amount of N leached below the rooting zone (Dowell et al. 1984). In addition, plowing of grassland or pasture may result in release of substantial quantities of NO_3-N (100 kg N ha^{-1}) through fall mineralization of organic matter (Bergstrom 1987; Cameron and Wild 1984). Under these climatic conditions, more NO_3-N would be expected to leach from soils on which the crop was harvested early than from soil on which the crop was harvested late in the season.

Potatoes are a major cash crop in New Brunswick (NB). In the interval 1986-1988 there was an average of 20.3 kha of potatoes planted in NB (Province of NB 1988). NB potato production is concentrated in the upper St. John River Valley, a region of rolling topography. Soils of this area are generally shallow to bedrock (usually less than 2m deep with frequent bedrock outcrops), coarse textured and low in organic matter content (Fahmy et al. 1986). A large portion of these soils formed on compact basal till (Milburn et al. 1989). The average annual precipitation is approximately 1000 mm, potential evapo-transpiration 600 mm (Fisheries and Environment Canada 1977), and average frost-free period 110 days (Dzikowski et al. 1984). Runoff and subsequent soil erosion by water is a common problem associated with potato production in this area (Chow et al. 1990).

Until 1970, most fertilizer-N used in NB was for potato production. Since the early 1950's approximately 150 kg N ha^{-1} has been recommended for potato production (Personal communication: Peter Jones, Regional Director and Senior Potato Production Specialist, NB Dept. Agric., Wicklow, NB) and currently 120 - 150 kg N ha^{-1} is recommended for application (Asiedu et al. 1987). Generally, potatoes are planted in rotation with other crops, such as barley, although there are still soils cropped continuously to potatoes (Milburn et al. 1990). Soil is subjected to mixing and aeration during harvest and hence there is potential for stimulated mineralization of organic matter with a concomitant release of NO_3.

In light of the soil and climatic characteristics of the region, and the long history of potato production with associated high levels of fertilizer-N application, it was hypothesized that there were elevated concentrations of NO_3-N in private wells located in the potato producing region of New Brunswick. This study was conducted to determine the effects of intensive potato production on NO_3-N concentrations of private well water supplies. Nitrate concentrations in well waters from three regions of varying intensity of potato production were determined in 1973 to 1976 and again in 1988. For comparison purposes, the chemical composition of groundwater from private wells in a non-agricultural region was determined in 1988.

MATERIALS AND METHODS

Study regions

Four regions were selected for study. One of the regions is a non-agricultural region near Fredericton. The other three regions are parishes or portions thereof located in the potato growing area of north-western New Brunswick and will be referred to as the agricultural study regions (Fig. 1). Details of the agricultural land use in the agricultural study regions are summarized in Table I.

To quantify the extent of agricultural land use within agricultural study regions, farmland area was expressed as a percentage of each study region (Table II). Study areas were assumed to be equal to parish areas minus any large, contiguous blocks of woodland. Examination of provincial ortho-photo maps (scale 1:10 000; Land Registry Information Services, Fredericton, NB) showed that, for Wicklow and Wilmot parishes, agricultural land was uniformly distributed with no presence of contiguous blocks of woodlands. Therefore, the area of the Wicklow/Wilmot study region, hereafter referred to as Wicklow, was taken to be the sum of the two parishes areas (19 kha + 19 kha). The parish of St. André is mostly agricultural, except for a contiguous block of woodland (2 kha) on the northern boundary. Agricultural land in Kent parish is limited to a single 21 kha block adjacent to the Saint John River; the remaining area (58 kha) is almost exclusively contiguous woodland.

St. André is the most intensely cropped agricultural study region with 38 % of its land area designated as crop land and approximately 20 - 25 % cropped to potatoes. The area of land designated as crop land and area cropped to potatoes was approximately 22 % and 8 %, respectively, in the other two agricultural regions. The ratio of "potato land" to "total fertilized land" (Table I, column 8), an additional indicator of the

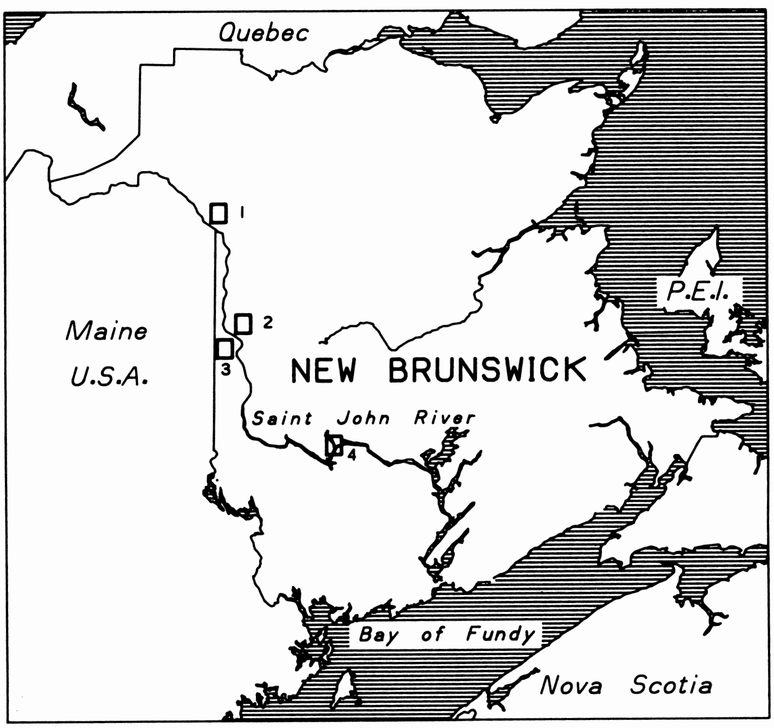

Fig. 1. The approximate locations of the four study areas in New Brunswick. 1: St. André parish; 2: Kent parish; 3: Wicklow and Wilmot parishes (referred to as Wicklow in the text); 4: Fredericton (non-agricultural).

Table I: Land use and intensity of fertilization in the agricultural study region †.

(1) Study region	(2) Year	(3) Total farmland	(4) Improved farmland	(5) Crop‡ land	(6) Area fertilized§	(7) Potatoes	(8) Ratio, (7) / (6)	(9) Avg. fertilizer§ application tonnes ha^{-1}
		kha						
St-André	1971	8.2	5.2	4.2	—	2.8	—	—
	1981	9.7	6.9	5.0	3.3	2.6	0.8	1.4
	1986	7.6	5.3	4.3	3.8	2.2	0.6	0.8
Kent	1971	12.3	6.0	4.4	—	1.9	—	—
	1981	10.4	5.8	4.5	2.7	1.7	0.6	1.0
	1986	10.8	5.8	4.7	3.3	1.7	0.5	0.9
Wicklow	1971	17.6	9.2	7.6	—	3.1	—	—
	1981	15.1	8.7	7.1	5.4	2.3	0.4	0.8
	1986	18.4	10.1	9.0	7.5	2.6	0.3	0.6

† Source: Statistics Canada, Census of Agriculture, New Brunswick. 1971, 1981, 1986. Names of study regions and the parishes (national census subdivisions) in which they are located are the same.
‡ All field crops, fruits and vegetables, including forage and potatoes.
§ Areas and tonnes fertilizer applied reported for the previous crop year, i.e. 1980, 1985.

Table II: Percent farmland in the agricultural study regions †‡.

Study region	1971 Improved farmland	1971 Crop land§	1971 Potatoes	1986 Improved farmland	1986 Crop land	1986 Potatoes
	%					
St-André	47	38	25	48	39	20
Kent	24	20	8	27	24	7
Wicklow/ Wilmot	29	21	9	28	22	8

† Source: Statistics Canada, Census of Agriculture. New Brunswick, 1971, 1986. Area of parishes taken from Statistics Canada, Catalogue 98-701 (SG-1), Geography - land areas and densities of statistical units. June 1973.
‡ Study areas assumed equal to sum of parish areas for Wicklow; large contiguous tracts of woodland were subtracted from parish areas in Kent and St. André. Calculated areas were 11, 21, and 38 kha for St. André, Kent, and Wicklow, respectively.
§ All field crops, fruits, and vegetables, including forages and potatoes.

intensity of land use, is also greatest for St. André. Since the potato is the most intensely fertilized crop in New Brunswick, the average fertilizer application rate is highest in the St. André study region (Table I; column 9).

Sampling and analytical procedures

Water samples of private wells in the three agricultural regions were taken six times during the period 1973-1976 and twice in 1988 (Table III). Wells in the non-agricultural region were sampled in 1988 only. Details on well depth are noted in Table III; the depth below the water table from which samples were drawn is unknown. Samples from each well were taken after running the water supply for a minimum of 5 min, placed into plastic bottles and stored at 6.5 °C prior to analyses. The same wells were sampled at each sampling interval. The millipore filtration method (APHA 1980) was used to determine the number of coliform bacteria in well water; microbiological analyses were conducted within 24 hr of sample collection.

Concentrations of K, Ca, Mg, SO_4-S, PO_4-P, Cl, NH_4, NO_2, and NO_3 were determined as well as pH and conductivity. Since only NO_3 data are presented here, methods used for analyses of the other parameters are not given. Concentrations of NO_3-N were determined by two methods. During the interval between 1973-1976 NO_3-N was determined by steam distillation as described by Bremner (1965). In 1988, NO_3-N concentrations were determined colorimetrically on an au-

Table III: Number of wells, well depth, and sampling schedule by study regions.

Region	No. of wells sampled	Mean well depth and range§ (m)	No. wells <15 m depth	Sampling schedule 1973-76†	1988‡
St-André	18	37 (7-102)	2(11%)	x	x
Wicklow/Wilmot	15	28 (7-62)	2(13%)	x	x
Kent	14	19 (7-26)	6(43%)	x	x
Fredericton (non agricultural)	6	42 (30-121)	0(0%)		x

† Once each in October and November 1973, June and August 1974, May 1975, June 1976.
‡ Once each in August and November 1988.
§ Average depth to bottom of well.

toanalyzer by a Cd-reduction technique (Richards 1987; soil chemist, Agr. Can. Res. Station, Fredericton, N.B, unpublished method). Prior to changing techniques for all samples in 1988, selected samples were done by both methods. Steam distillation and colorimetric methods gave the same values for NO_3-N. Note that concentrations are expressed on an elemental basis i.e. mg NO_3-N L^{-1}.

Statistical analysis

To facilitate interpretation of the chemical composition of well waters, all possible linear correlations were examined. Principal Component Analysis (PCA) was conducted to identify groups of similar wells and to reduce the dimensionality of the data so that relationships among wells may be elucidated. PCA was conducted on all chemical parameters measured in 1988. The PRINCOMP procedure of SAS was used to calculate principal components (Statistical Analysis System, Inc. 1985).

For the agricultural regions, there was no apparent cyclical trend in NO_3 concentrations during the interval 1973-1976, nor were there significant changes in NO_3 concentrations within years (data not shown). Therefore, values for each well from the six sample periods in the 1973-1976 interval were averaged as were the values from the two sample periods in 1988. For each of the three agricultural regions, a paired t-test was used to determine if the overall mean of the 1973-1976 period and the 1988 period differed.

RESULTS

Nitrate concentrations among regions

There was a large range in NO_3-N concentrations within and among the study regions (Figs. 2 and 3). Over the entire period of the study, mean NO_3-N concentrations and ranges within regions were: Fredericton, 1.1 (0.2 to 3.4) mg L^{-1}; Wicklow, 5.7 (0.9 - 13.7) mg L^{-1}; Kent, 5.0 (1.7 - 9.9) mg L^{-1}; and St. André, 9.5 (4.0 - 31) mg L^{-1}. Lowest NO_3-N concentrations occurred in the non-agricultural region of Fredericton while the highest values occurred in the St. André region, the agricultural study region with the highest proportion of total improved farmland and area cropped to potatoes (Tables I and II). There was no significant ($P = 0.05$) correlation between NO_3-N concentrations and well depths over all three agricultural study regions and within each study region.

The mean NO_3-N concentration in the St. André study region is only 0.5 mg L^{-1} less than the Canadian Water Quality Guidelines for potable water of 10 mg L^{-1} (CCREM 1987); 39% of the wells had NO_3-N concentrations which exceeded the 10 mg L^{-1} limit (Fig. 2). Note that only 6.3 % of the wells sampled had NO_3-N concentrations less than 5.0 mg L^{-1}.

In the Wicklow study region, approximately 26 % of the wells had concentrations which exceeded 10 mg L^{-1} in samples taken during 1973-1976. Only one well exceeded the limit in 1988. No wells in the other two regions had NO_3-N concentrations which exceeded the 10 mg L^{-1} guideline (Figs. 2 and 3).

Change in nitrate concentrations with time

The mean NO_3-N concentration in well water decreased significantly ($P < 0.05$) in the Wicklow region over the course of the study. This is illustrated in Fig. 2. During 1973 to 1976, the mean concentration was 6.3 mg L^{-1}, but in 1988, declined to 3.7 mg L^{-1}. As mentioned previously, the number of wells exceeding the 10 mg L^{-1} limit also declined. This decline was accompanied by an increase in the proportion of wells in the 0 - 2.5, and 5.0 - 7.5 mg L^{-1} increments. There was no significant change in mean NO_3-N concentrations over the course of the study in the Kent and St. André regions. Fredericton wells were not sampled during 1973 to 1976.

Principal component analysis

A scatter plot of the first principal component versus the second principal component shows that there were three distinct populations of well waters, based on chemical properties. The populations corresponded to a large extent with sample regions (Fig. 4). Hence, the most dissimilar sample regions were Fredericton and St. André with Kent and Wicklow regions falling between the two extreme regions. It should be noted that agricultural intensity in Kent and Wicklow are very similar (Table II). As would be expected, the mean NO_3-N concentrations within regions followed a similar trend (ie lowest at Fredericton and highest at St. André).

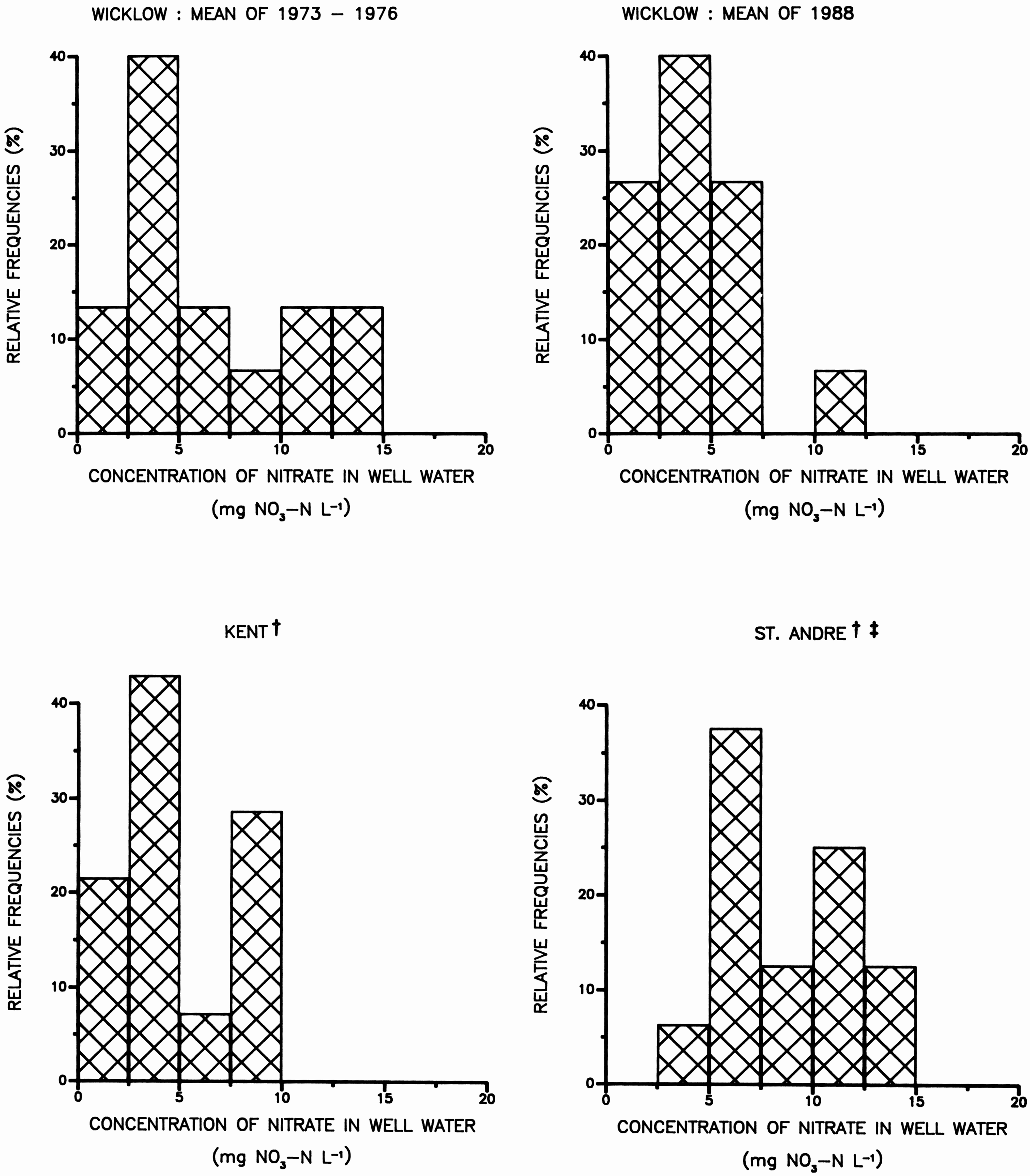

Fig. 2. Histograms of nitrate concentrations of well water in the three agricultural study regions. Mean NO3-N concentrations were 5.0 and 9.5 mg L^{-1} for Kent and St. André, respectively, and 6.3 and 3.7 mg L^{-1} for Wicklow in 1973 to 1976 and in 1988, respectively.

+ Means of samples taken in 1973-1976 and in 1988.

‡ 6.1 % of wells were in the 30 -32.5 mg N L^{-1} and are not presented in the figure.

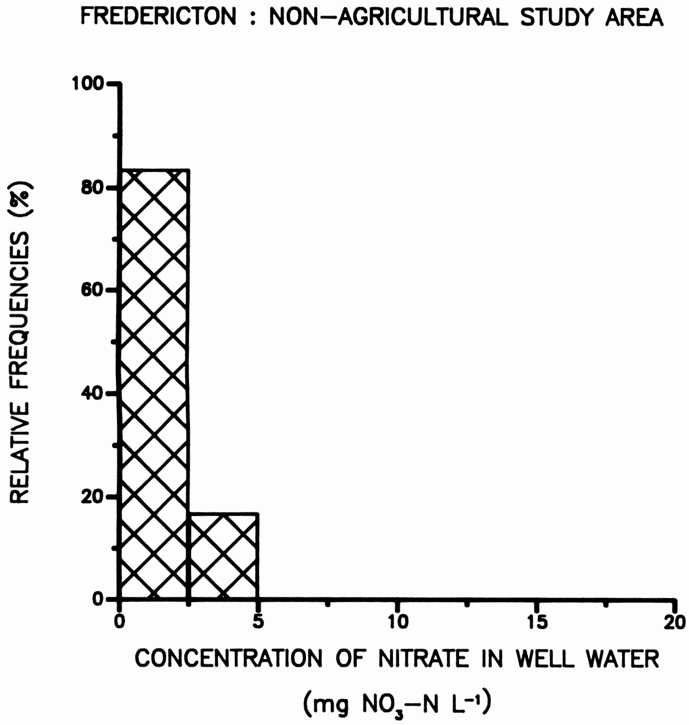

Fig. 3. Histogram of 1988 nitrate concentrations of well water in Fredericton. Mean NO_3-N concentration was 1.1 mg L^{-1}.

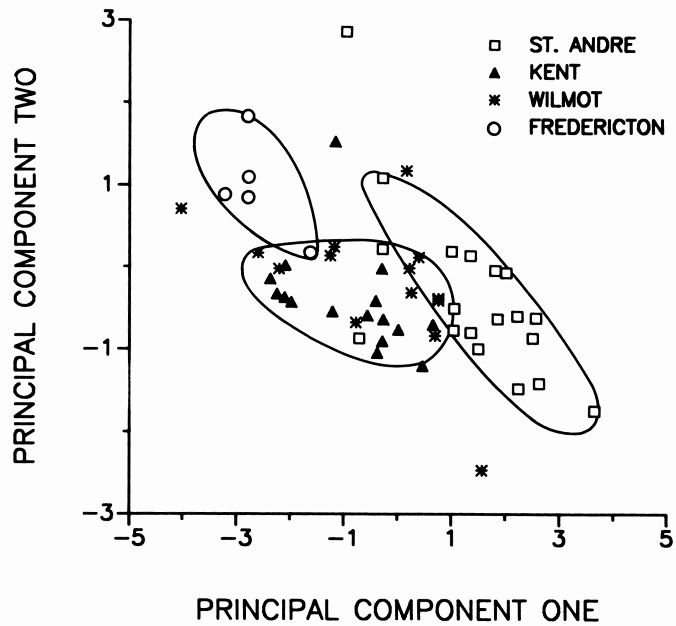

Fig. 4. Scatter diagram of principal component one versus principal component two.

Bacteriological quality of the water

The Canadian Water Quality Guidelines (CCREM 1987) for potable water of 10 coliform organisms per 100 mL were exceeded in 33 % of the wells in the Wicklow region, 36 % of the wells in the Kent region, and 22 % of those in St. André. No coliform bacteria were present in wells in the Fredericton region.

Within the three agricultural study regions, the number of coliform bacteria were not significantly ($P = 0.05$) correlated with well depth ($r = 0.14$). In addition, in wells which exceeded the 10 coliform per 100 mL guideline, the number of coliform bacteria were also not significantly ($P = 0.05$) correlated with well depth ($r = 0.36$). The average depth of wells which exceeded the guidelines was 23.5 m whereas the average depth of all wells in the agricultural study regions was 24.5 m. These results clearly show that, in this study, shallow wells were not more highly contaminated than deep wells.

There was no association between the presence of coliform organisms and NO_3-N concentrations. When wells containing more than 10 coliform organisms per 100 mL were excluded from analysis, mean NO_3-N concentrations within regions were unaltered. Evidently, the presence of NO_3-N in the well waters of the three agricultural regions was not due to leakage from septic fields or to infiltration of surface waters.

DISCUSSION

Source of nitrates in well waters

The lack of correlation of NO_3-N concentrations in well waters with the presence of coliform bacteria suggests that there was a general contamination of the aquifers from non-point sources, such as fertilizers and/or soil-N. The results of Ecobichon et al. (1988) corroborate this finding; they reported that, for samples of wells in the potato growing area of north west NB , there was no correlation between the proportion of wells over 10 mg L^{-1} NO_3-N and the presence of coliform bacteria.

The lack of correlation of NO_3-N concentrations with well depth suggests that, regardless of depth, well water quality was a product of land use in the region. This would explain why the principal component analysis was able to clearly identify three distinct groups of wells. Other workers also have shown a strong relationship between intensive row-crop production and NO_3-N concentrations in groundwater (Hill 1982; Hallberg 1987; Simon et al. 1988). Indeed groundwater NO_3-N concentrations of the St. André region are similar to those reported for other areas of North America where intensive production of row crops is practiced (Hallberg 1987).

Milburn et al. (1990) found that, in NB, NO_3-N concentrations in tile effluent from soils cropped to potatoes exceeded 10 mg L^{-1} whereas tile effluent NO_3-N concentrations from soils historically cropped to cereals or forages were approximately 3 mg L^{-1}. Based on our results and the foregoing, it is hypothesized that mean NO_3-N concentrations of well waters in the agricultural study regions are related to the extent of potato production within each region.

Changes with time

Perhaps the most striking aspect of this work is that NO_3-N concentrations have not increased in rural NB well waters during the interval between 1973-1988. Indeed, in the Wicklow region mean NO_3-N concentrations decreased significantly during the course of the study. On first examination, it appears that this trend is contrary to most world literature. For example, Hallberg (1987) reported that NO_3-N concentrations in rural Iowa ground waters have increased during the past thirty years and concluded that the increase was caused by

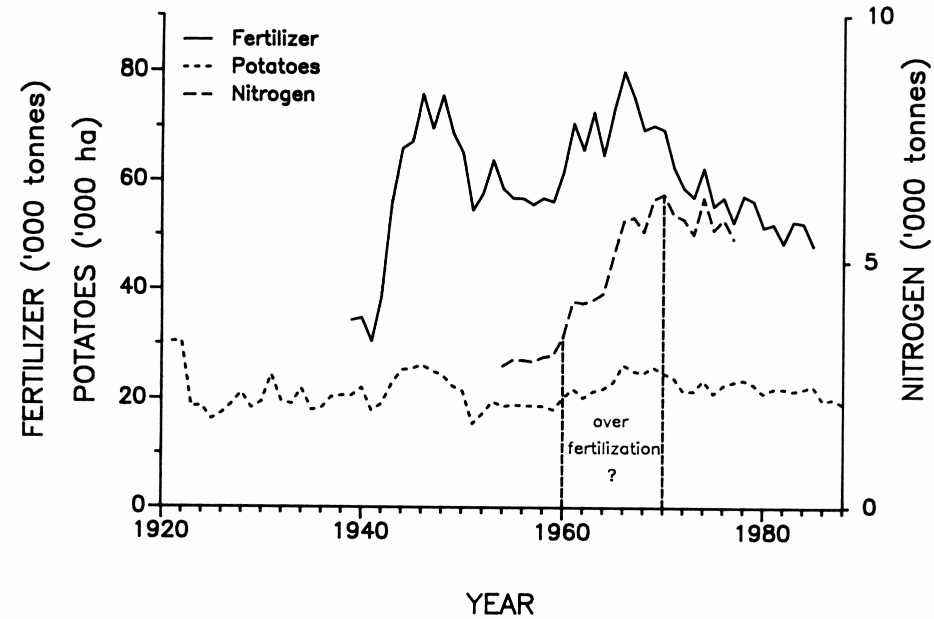

Fig. 5. Annual area seeded to potatoes in NB and total annual fertilizer sales for all NB crops. Note: the average N content of fertilizer increased from approximately 5% in 1954 to 10 % in 1971. (Source: Statistics Canada1975; Province of New Brunswick 1968, 1972, 1978, 1988).

progressively higher rates of fertilizer-N application.

The reasons for both the stabilization or decline in NO_3-N concentrations, and the elevated NO_3-N concentrations in all three agricultural regions by 1973, are not known absolutely. The following observations are presented as a reasonable explanation.

Fertilizer sales increased near the end of World War II and generally followed the area seeded to potatoes to 1970 (Fig. 5). Prior to 1970, virtually all fertilizer sold in NB was applied to potatoes. Grain and hay, grown in rotation with potatoes, were generally not fertilized whereas high rates of fertilizer-N (150 kg N ha^{-1}) have been recommended for potato production since the early 1950's. Between 1960 to 1970, there was a change to more concentrated blends of fertilizers. This change caused considerable confusion at the farm level, and in many cases the pre-1960 bulk tonnage was applied to potato fields resulting in approximately double the rate of fertilizer-N application (Personal communication: Peter Jones, Regional Director and Senior Potato Production Specialist, NB Dept. Agric., Wicklow, NB). Note that the amount of fertilizer-N sold in NB doubled between 1960 and 1970, and has remained relatively stable thereafter while potato acreage during this time only increased by about 25 % (Fig. 5).

Since 1970, potato acreage has remained relatively stable, fertilizer sales have decreased, and the area of non-potato crop crops subject to fertilizer application has substantially increased (Fig. 5; Statistics Canada 1986). For example, 37 kha and 84 kha were fertilized in 1971 and 1985, respectively, while the potato crop for those years was only about 20 kha. Assuming that the N content of fertilizer remained constant after 1977 (data not available thereafter), similar to the trend shown in Fig. 5, it would appear that the over-fertilization of potatoes which occurred during the 1950's and 1960's was corrected in subsequent years. Therefore we postulate that: 1: The elevated mean NO_3-N concentrations which occurred in 1973 were due to over-fertilization during 1960-1970 when the potato industry was changing over to higher analysis fertilizers. 2: Mean NO_3-N concentrations have stabilized or decreased since 1973 because over-fertilization practices were corrected and potato acreage in the study regions have decreased or remained stable.

Other considerations

Our interpretation of well water quality was based on an agricultural land use overview. Determination of hydrogeological conditions specific to the wells and aquifers sampled were beyond the scope of our study. Appropriate hydrogeological studies on the movement of selected agro-chemicals to rural NB water supply aquifers would help to define more precisely the relationships between agricultural land use and groundwater quality. In addition, future studies should concentrate on ascertaining whether the NO_3-N present in rural NB ground waters is derived from fertilizer and/or soil-N so that appropriate remedial soil management practices can be developed.

SUMMARY AND CONCLUSIONS

1: A substantial portion of the wells in two of the three agricultural regions sampled had NO_3-N concentrations in excess of 10 mg L^{-1}. The source of NO_3-N was non-point; fertilizer-N and/or soil-N.

2: Mean concentrations of NO_3-N in rural well waters were positively related to the intensity of agricultural production, particularly potato production.

3: There was no increase in mean NO_3-N concentrations of well water over 15 years; in one region mean NO_3-N concentrations declined with time. The stabilization or decline in NO_3-N concentrations appeared to be related to a combination of decreased potato production and correction of over-fertilization of N which occurred in the 1960's.

4: More work is required to determine the source of the NO_3-N in the well waters so that appropriate remedial soil management practices can be developed. Future studies will concentrate on N-balance of crop production systems common to or adaptable to NB conditions.

ACKNOWLEDGMENTS

We thank Mrs. Marguerita Clark of the New Brunswick Dairy Products Laboratory, NB Dept. of Agriculture for conducting the microbial analyses. The assistance of Mr. Clare Gartley, NB Dept. of Agriculture in organizing the collection of water samples is gratefully acknowledged. Finally we would like to thank Dr. G.C. Tai for his helpful suggestions on statistical analyses and, in particular, Principal Component Analysis.

REFERENCES

APHA 1980. Standard methods for the examination of water and wastewater. Am. Public Health Assoc.; Am. Water Works Assoc.; Water Poll. Control Fed. 15th Ed.

ASIEDU, S., S.E. COLEMAN, T. HALIBURTON and M.C. HAMPSON (eds.) 1987. Atlantic Canada potato guide. Publication 1300/87. Published by authority of the Atlantic Provinces Agricultural Services Co-ordinating Committee. 47 pp.

BARRACLOUGH, D., M.J. HYDEN and G.P. DAVIES. 1983. Fate of fertilizer nitrogen applied to grassland. I. Field leaching results. J. Soil Sci. 34:483-497.

BASHKIN, V.N. and V.N. KUDEYAROV. 1983. Nitrate content of groundwaters in agricultural areas of the Oka River Basin. Soviet Soil Sci. 15:41-47. (Translated from Agrokhimiya, 1983, No. 2: 14-19).

BERGSTROM, L. 1987. Nitrate leaching and drainage from annual and perennial crops in tile-drained plots and lysimeters. J. Environ. Qual. 16:11-18.

BREMNER, J.M. 1965. Inorganic forms of nitrogen. Chapter 84. In: Methods of soil analysis, part 2. Chemical and microbiological properties. Agronomy monograph No. 9. Soil Sci. Soc. Am., Madison WI. C.A. Black, Editor-in-Chief.

CAMERON, K.C. and A. WILD. 1984. Potential aquifer pollution from nitrate leaching following the plowing of temporary grassland. J. Environ. Qual. 13:274-278.

CCREM 1987. Canadian Water Quality Guidelines. Canadian Council of Resource and Environment Ministers. Water Quality Branch, Inland Waters Directorate, Environment Canada, Ottawa, ON.

CHOW, T.L., J.-L. DIAGLE, I. GHANEM and H. CORMIER. 1990. Effects of potato cropping practices on water runoff and soil erosion. Can. J. Soil Sci. 70: 137-148.

DOWELL, R.J., C.P. WEBSTER, D. HILL and E.R. MERCIER. 1984. A lysimeter study on the fate of fertilizer nitrogen in spring barley crops grown on shallow soil overlying Chalk : crop uptake and leaching losses. J. Soil Sci. 35:169-181.

DOWELL, R.J. and C.P. WEBSTER. 1984. A lysimeter study on the fate of fertilizer nitrogen in spring barley crops grown on shallow soil overlying Chalk : denitrification losses and the nitrogen balance. J. Soil Sci. 35:183-190.

DZIKOWSKI, P.A., G. KIRBLY, G. READ and W.G. RICHARDS. 1984. The climate for agriculture in Atlantic Canada. Agdex No. 070. Published by authority of the Atlantic Provinces Services Co-ordinating Committee. 19 pp. plus figures.

ECOBICHON, D.J., R. HICKS, M. ALLEN and R. ALBERT. 1988. Ground water contamination in rural New Brunswick. Unpublished report. New Brunswick Dept. of Health. Fredericton, NB.

FAHMY, S.H., H.W. REES and J.K. MACMILLAN. 1986. Soils of New Brunswick: A first approximation. Plant Industry Branch. New Brunswick Dept. of Agriculture.

FISHERIES and ENVIRONMENT CANADA. 1977. Handbook on Agricultural and Forest Meteorology. Supply and Services Canada. ISBN 0-660-50075-2 R.A. Treidl, Editor

FOSTER, S.S.D., A.C. CRIPPS and A. SMITH-CARRINGTON. 1982. Nitrate leaching to groundwater. Phil. Trans. R. Soc. Lond. 296:477-489.

GAST, R.G., W.W. NELSON and G.W. RANDALL. 1978. Nitrate accumulation in soils and loss in tile drainage following nitrogen applications to continuous corn. J. Environ. Qual. 7:258-261.

GUSTAFSON, A. 1983. Leaching of nitrate from arable land into groundwater in Sweden. Environ. Geol. 5:65-71.

HALLBERG, G.R. 1987. Nitrates in Iowa Groundwater. In: D'Itri, F.M. and L.G. Wolfson, Ed. Rural Groundwater Contamination. Lewis Publishers, Inc. Chelsea MI, pp.23-68.

HERGERT, G.W. 1986. Nitrate leaching through sandy soil as affected by sprinkler management. J. Environ. Qual. 5:272-278.

HILL, A.R. 1982. Nitrate distribution in the ground water of the Alliston Region of Ontario, Canada. Ground Water. 20:696-702.

HUBBARD, R.K and J.M. SHERIDAN. 1989. Nitrate movement to groundwater in the southeastern Coastal Plain. J. Soil Water Conserv. 44:20-27.

KOWALENKO, C.G. 1987. The dynamics of inorganic nitrogen in a Fraser Valley soil with and without spring or fall ammonium nitrate applications. Can. J. Soil Sci. 67:367-382.

MEISINGER, J.J. 1976. Nitrogen application rates consistent with environmental constraints for potatoes on Long Island. Search Agric., Cornell Univ. Agric. Expt. Stn. Agr. 6:1-19.

MILBURN, P., H. REES, S. FAHMY, and C. GARTLEY. 1989. Soil depth groups for agricultural land development planning in New Brunswick. Can. Agric. Eng. 31:1-5.

MILBURN, P, J.E. RICHARDS, C. GARTLEY, T. POLLOCK, H. O'NEILL and H. BAILEY. 1990. Nitrate leaching in systematic tile drainage waters from potato fields in New Brunswick, Canada. J. Environ. Qual. (in press).

MILLER, M.H. 1979. Contribution of nitrogen and phosphorus to subsurface drainage water from intensively cropped mineral and organic soils in Ontario. J. Environ. Qual. 8:42-48.

OWEN, T.R. and S. JRGENS-GSCHWIND. 1986. Nitrates in drinking water: A review. Fert. Res. 10:3-25

PROVINCE of NB. 1988. Agricultural Statistics, 1968, 1972, 1978 and 1988. Published jointly by Statistics Canada and the New Brunswick Dept. of Agriculture. Fredericton, NB.

ROURKE, R.V. 1985. Soil solution levels of nitrate nitrogen in a potato-buckwheat rotation. Am. Potato J. 69:258-264.

RYDEN, J.C., P.R. BALL and E.A. GARWOOD. 1984. Nitrate leaching from grassland. Nature 311:50-53.

SCHARF, P.C. and M.M. ALLEY. 1988. Nitrogen loss pathways and nitrogen loss inhibitors: A review. J. Fert. Issues. 5:109-125.

SIMON, W., B. HUWE, and R.R. van der PLOEG. 1988. Die Abschaetzun von nitrataustraegen aus landwirtschaftlichen nutzflachen mit hilfe von Nmindaten. (The estimation of nitrate leaching from agricultural land on the basis of inorganic nitrogen data). Z. Pflanzenernaehr. Bodenkd. 151:289-294.

STATISTICAL ANALYSIS SYSTEM, Inc. 1985. SAS user's guide : statistics, Version 5 Edition. SAS Institute, Inc. Cary, NC. 956 pp.

STATISTICS CANADA 1975. Handbook of Agricultural Statistics. Part I. Field Crops 1921-1974. Catalogue 21-516. Published by authority of the Minister of Industry, Trade and Commerce. Ottawa, ON.

TIMMONS, D.R. and A.S. DYLLA. 1981. Nitrogen leaching as influenced by nitrogen management and supplemental irrigation levels. J. Environ. Qual. 10:421-426.