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Spatial Analysis of Land Use Impact on Ground Water Nitrate Concentrations

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ABSTRACT

In spatial analyses of causes or health effects of environmental pollutants, small units of analyses are usually preferred for internal environmental homogeneity reasons but can only be done when fine resolution data are available for most units. Objectives of this study were to determine which land use practices were spatially associated with ground water nitrate concentrations across Prince Edward Island (PEI), Canada, and which spatial aggregation is the preferred unit of analyses. Nitrate concentrations were determined for 4855 samples from private wells. Validated field-by-field land use data were available. Average nitrate concentration and percentage of area for the 14 major land use categories in PEI were determined for each of three spatial aggregations: watersheds based on topography and hydrology; freeform polygon boundaries based on similar neighboring nitrate concentrations; and 500-m buffer zones around each well. Results showed that the percentages of potato, grain, and hay coverage were positive predictors of ground water nitrate concentrations. Percentage of blueberry was a marginally significant negative predictor in the watershed and freeform polygon models, and percentage of residential coverage was a positive predictor in the freeform polygon and buffer zone models. Spatial autocorrelation was present in the freeform polygon and buffer zone models even after land use was taken into account. In conclusion, analyses based on watersheds produced the best predictive model with the percentages of land cover of potato, hay, and grain being significantly associated with ground water nitrate concentrations, and the percentages of blueberry, clear-cut woodland, and other agriculture being marginally significant.

Nitrate contamination is possibly the most widespread contaminant of water (Gulis et al., 2002). Elevated nitrate levels in surface water or ground water can lead to numerous concerns, including nutrient enrichment of surface waters as a result of the discharge of nitrate-rich ground water; and a health concern to both animals (wild and domesticated) and humans (McLay et al., 2001). An understanding of the relative importance of various sources of nitrate is important to the development of appropriate remedial strategies, with the linkage between land use and ground water quality being a key element of this process.

Major sources of nitrate in the environment, and subsequent contamination of natural waters, include the use of nitrogen-based fertilizers, animal and human wastes, and to a lesser extent, industrial wastes, waste waters, and landfills (Vidal et al., 2000). Although nitrate does occur naturally in the environment as a breakdown product of the decomposition of organic matter, this source contributes only very small amounts of nitrate to ground water (Arms, 1994). Background concentrations of nitrate in North American ground water and surface waters have been estimated to be less than 3 mg L^{-1} nitrate nitrogen (NO_3-N) (Spalding and Exner, 1993). "In the industrialized Western European and North American countries, intensive agriculture is considered to be the main source of water pollution by nitrate" (World Health Organization, 2004).

The maximum acceptable concentration (MAC) for nitrate in drinking water in Canada and the United States is currently set at 10 mg L^{-1} NO_3-N (Health Canada, 1992), and the MAC recommended by the World Health Organization (WHO) and the European Union is 11.11 mg L^{-1} NO_3-N. The recommended nitrate concentration in Europe was 5.56 mg L^{-1} NO_3-N (Van Maanen et al., 2000). In general, Canadian municipal water supplies have concentrations no higher than 4.9 mg L^{-1} NO_3-N (Health Canada, 1992) where contamination is under reasonable control.

In 2001, the concept of "human affected value" was introduced [based on previous work conducted in the early 1990s (Burkart and Kolpin, 1993; Eckhardt and Stackelberg, 1995)], whereby anything greater than the background concentration of 3 mg L^{-1} NO_3-N is believed to be primarily a result of human activities (McLay et al., 2001). In Prince Edward Island (PEI), nitrate levels in the range of 0.1 to 2 mg L^{-1} NO_3-N are considered to represent background levels for relatively un-impacted, "pristine" watersheds (Young et al., 2002). A limited study in PEI found a mean nitrate level of 1.15 mg L^{-1} NO_3-N for ground water from wells in noncropped areas (Somers, 1998).

Many studies have investigated land use factors for nitrate contamination of water resources (McLay et al., 2001; Thorburn et al., 2002; Honisch et al., 2002). However, the soil, climate, and farming systems can vary substantially from one region to another, and may exert a varying influence on the nature and extent of nitrate contamination. In a study performed in sandy soils of Quebec, Canada, an association was found between intensive potato farming and nitrate concentrations. In this area, the ground water nitrate concentration was frequently above the MAC for human consumption (10 mg L^{-1} NO_3-N) (Levallois et al., 1998). As PEI is a major potato growing area with similar climate and farming systems, potentially elevated concentrations (>3 mg L^{-1}) in PEI ground water are a concern.

In PEI, all potable water is derived from ground water sources. Over half of the population resides in a rural setting, and relies on an estimated 20 000 to 25 000 private wells as their sole source of water. The remain-

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Abbreviations: MAC, maximum acceptable concentration; PEI, Prince Edward Island.

ing population is serviced by central water supply systems, deriving their supply from the same ground water source. Private domestic water supplies in PEI rely on drilled wells with an average depth of 30 m with 12 m of casing. Water quality is generally excellent; however, with high recharge rates and thin, permeable overburden, the ground water is vulnerable to contamination (Young et al., 2002). Agricultural activity is believed to be the most significant anthropogenic influence on ground water quality in PEI, and the occurrence of elevated nitrate concentrations (>3 mg L^{-1}) is considered to be one of the greatest challenges to the protection of drinking water quality (Young et al., 2002).

Previous analyses in PEI have shown that nitrate concentrations in well water were associated with local land use (Young et al., 2002). In an early study aimed at characterizing well water nitrate levels under six broad land use categories, wells located in areas of row crops showed the highest mean nitrate concentrations (Somers, 1998). The study did not include field-by-field verification of land use, and therefore was subject to possible information bias. Furthermore, only a limited number of sites (54 wells) were examined, giving it questionable representativeness with respect to the entire province. In another qualitative survey, using a more representative data set (5859 wells) than the study in 1998, it was observed that elevated ground water nitrate concentrations were more closely related to potato production intensity than to livestock density (MacLeod et al., 2002; Young et al., 2002). The same work suggested that average nitrate levels for 80% of the province exceeded background levels expected for relatively unimpacted watersheds (i.e., >3 mg L^{-1}), and 4.5% of wells had nitrate concentrations above 10 mg L^{-1} NO_3-N.

The primary objectives of this research were to (i) determine what land uses have a significant impact on nitrate concentrations in private well water samples across PEI, adjusting for spatial autocorrelation (neighboring nitrate concentrations are more similar [positive autocorrelation] or dissimilar [negative autocorrelation] than expected); and (ii) determine the best spatial aggregation for assessing these nitrate factors, balancing data scarcity problems with within unit homogeneity.

MATERIALS AND METHODS

Study Site

Situated on the eastern coast of Canada, PEI is approximately 5700 km^2 in land area with 1600 km of coastline (Somers, 1992) and a current population of almost 140 000 (Statistics Canada, 2001) (Fig. 1). The island is divided into three counties with the most densely populated being Queen's County in central PEI (53%), then Prince County in western PEI (33%), and finally King's County in eastern PEI (14%) (Statistics Canada, 2001).

Prince Edward Island's topography is characterized by rolling hills reaching a maximum height of 120 m above sea level. Nearly half of the land base in the province is devoted to agriculture (InfoPEI, 2005a), with row crop production ac-

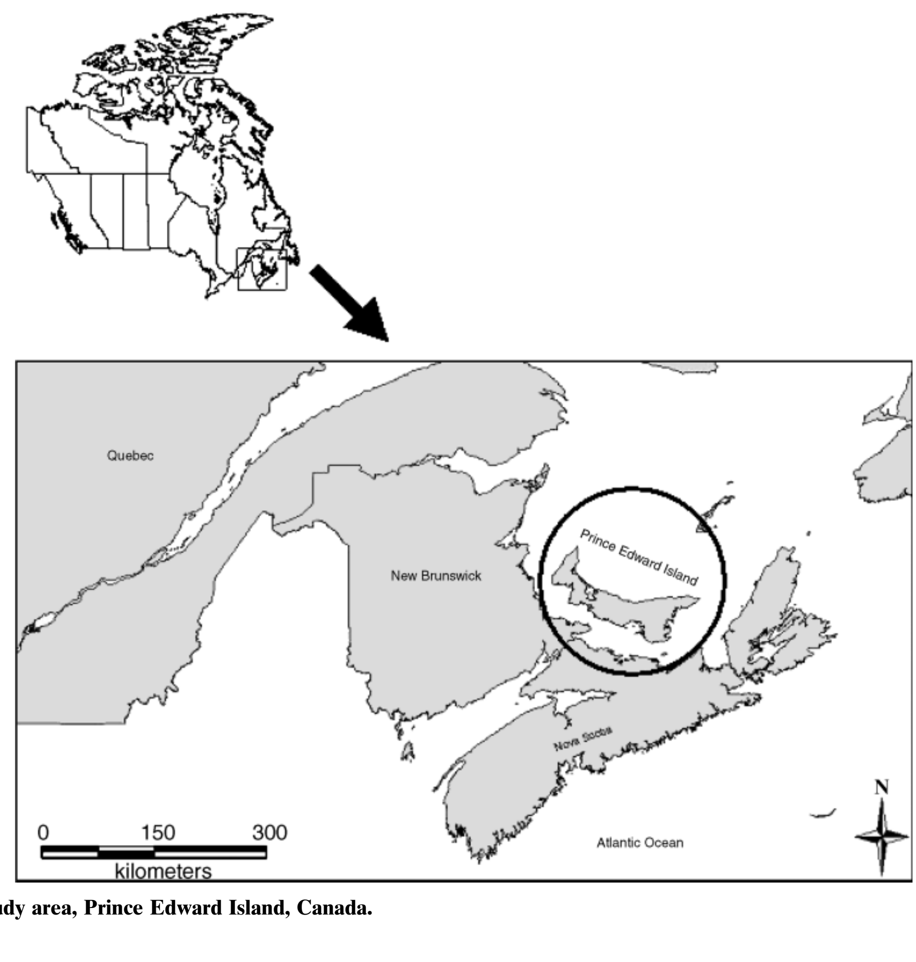

Fig. 1. Location of study area, Prince Edward Island, Canada.

counting for the largest portion of this activity. The geology in the area is comprised mainly of a Permo-Carboniferous redbed sequence (fractured sandstone bedrock) overlain by a thin generally sandy glacial till (Somers, 1992). Ground water is tapped from a highly productive sandstone aquifer, with the extent of individual ground water flow systems determined primarily by surface topography. Consequently, surface watershed boundaries provide a good approximation of individual ground water flow system boundaries (InfoPEI, 2005b). The landmass of PEI is divided into approximately 260 watersheds and subwatersheds.

Land Use Data

Validated field-by-field land use data were available for PEI from aerial photographs taken in 2000. The data were classified into 14 categories according to requirements of the Provincial Department of Agriculture. These categories were apple, bare soil, blueberry, clear-cut woodland, cranberry, forest (coniferous and deciduous), grain (the majority of which was barley, but also included winter and spring wheat, oats, winter rye, and occasionally corn), hay (for example, red clover, timothy grass, and alfalfa), meadow/dune, other agriculture (for example, lettuce, cabbage, and sunflowers), pasture (grazing livestock, predominantly beef and dairy cattle), potato, residential (grass, hedge/shrubs, and buildings/roads), and water/wetland (main areas were lakes, marshes, rivers, and beaches). Percentages of land use data within the three types of areas of analysis (watersheds, freeform polygon areas, and buffer zones) were calculated using the following steps. First, all polygons of land use that straddled an area boundary were split by that area boundary. Area boundaries in this instance were the boundaries of the watershed, freeform polygon areas, or buffer zones. Second, the percentage of each category of land use within each area was determined, based on the number of square kilometers of specific land use divided by the total number of square kilometers in the area. This procedure was performed in Mapinfo Professional 7.0 (MapInfo Corporation, 2002). Even though crop rotation occurs in PEI, it was assumed that land use percentage within an area of analysis remained similar from one year to the next.

Nitrate Data

A total of 4855 water samples from private wells sampled during 1997–2001 (part of a routine pre-mortgage sampling program in PEI) were used for the analyses. Nitrate nitrogen (hereafter, referred to as nitrate) concentrations were determined for these samples by flow injection analysis colorimetry (using the QuikChem Series 8000 FIA+ instrument; Lachat Instruments, Milwaukee, WI) with a detection limit of 0.1 mg N L^{-1}.

If well water from a property was sampled twice or more during this time frame, then an average of the concentrations was calculated. This occurred in 7.4% of the samples. This average was only accepted if a duration of at least 6 mo existed between the two samples. A 6-mo time frame was chosen to avoid repeat samples taken for reasons other than for a mortgage assessment (e.g., high chemistry or bacterial concentrations). If the period between two samples was less than 6 mo, then only the first measurement was used to utilize the sample most likely to represent pretreatment concentrations, assuming that any subsequent sample within 6 mo was to determine if the treatment was effective.

Data Aggregation

Associations between percentages of land use and nitrate concentrations were assessed using areal and point-level data. For areal data, two methods of spatial aggregation, watershed boundaries, and freeform polygon aggregations were explored. Because watersheds are defined according to hydrological properties, they were deemed to be an appropriate unit of analysis. However, within watersheds there were likely to be areas of heterogeneity of topography, soil, land use, and nitrate concentrations. Therefore, an alternative unit of analysis was investigated, freeform polygons, with improved within unit homogeneity of nitrate concentrations compared to watersheds, as described below.

The process for determining the boundaries of the freeform polygons was performed using BoundarySeer 1.1.9 (Jacquez et al., 2002). First, taking the spatial variation across all nitrate concentrations into account, a goodness-of-fit index (Jacquez et al., 2001) was used to calculate the appropriate number of spatially constrained contiguous polygons, to produce high within unit homogeneity of nitrate. Once an appropriate number of homogenous areas were estimated, polygons were created using fully constrained agglomerative clustering (Jacquez et al., 2001), meaning that clusters of similar nitrate concentration were grouped together, constrained so that they had to be adjacent in geographic space. The 0.9 linkage connectedness (comparing locations within one cluster to those of the neighboring clusters) was used to obtain the most appropriate number of polygons, as determined by the goodness-of-fit index. While aggregating small polygons may combine two areas that have different land uses, leading to a potential bias in results, the alternative was to allow a small number of wells in that polygon to produce a potentially unrepresentative nitrate value for the polygon.

Each polygon area (watershed or freeform) was to meet the following criteria. First, areas required a minimum of five nitrate points to create a valid estimate for that area. Areas of aggregation with less than five observations were combined with neighboring polygons, provided the mean difference between the two areas did not differ by more than 2.5 mg L^{-1} NO_3-N. This concentration difference was determined from the freeform polygon creation process using a goodness-of-fit index (Jacquez et al., 2001). Second, aggregated areas must not stretch over two coastlines, without the inclusion of a peninsula. This was not an issue for the watersheds because they were created with this factor in mind. A few freeform polygons spanned across the coastlines, but manually splitting the polygon into two equal parts rectified this.

After application of the two criteria mentioned above, 174 watersheds with an average size of 32.6 km^2 (range of 0.89 to 196.8 km^2) and 664 freeform polygons with an average polygon size of 8.55 km^2 (range of 0.005 to 175.63 km^2) were used for the analyses. The smaller freeform polygon areas were typically areas with one high or low nitrate concentration compared to their neighbors (differed by $>$2.5 mg L^{-1} NO_3-N), and therefore could not be aggregated with neighbors to form larger areas, according to the criteria.

The point-level analyses were conducted using 500-m radius circular buffer zones of land around individual wells sampled during 2001. Only one year was used to minimize overlapping buffers and repeated well samples, which would violate the regression assumption of independent observations. The year 2001 was chosen because the land use data were from 2000. Information on ground water flow was not available and therefore an equal distance in every direction (circular) around each well was utilized. A smaller buffer zone ($<$500 m) would not allow for many other land uses except for house and lawn. The buffer zone method of analysis assessed the association between nitrate concentrations and land use at a more local level compared to the regional level used in the watershed and freeform polygon methodologies.

Statistical Analyses

Comparisons of nitrate concentrations among years were assessed using a linear mixed effects model in SAS Version 8 (SAS Institute, 2001) with an autoregressive (AR1) correlation structure. No significant difference in nitrate concentrations among years was revealed ($p > 0.05$), therefore, all five years of nitrate data were combined and used for the areal analyses to maximize the number of data points available for aggregation in each area. Also, no significant difference in nitrate concentrations among seasons was observed ($p > 0.05$).

Multiple linear regression was performed on the data and spatial autocorrelation was controlled, if significant. Forest was chosen for the reference value as it was common land use in the dataset, and because ground water nitrate concentrations in forests are typically stable and unaffected by human influence. Two-way interactions of all significant main effects were assessed and removed using backward-stepwise elimination until only those which were significant ($p < 0.05$) remained in the model.

Model diagnostics were performed to detect violations of assumptions for multiple linear regression. These assumptions were homoskedasticity (equal variance) among the full model residuals, a normal distribution of residuals, a linear relationship between the response variable and each predictor, and independence of the response variable values (accounting for spatial autocorrelation when necessary). Potential outliers and influential values were assessed as well as several transformations to improve the model fit. As the nitrate data were not normally distributed, a Box-Cox analysis (Box and Cox, 1964) was performed in Stata 8.2 (Stata, 2004) to investigate various transformations. The natural logarithm (+1) was found to be the most appropriate transformation to achieve a normally distributed nitrate outcome variable.

Spatial Statistics

Initially, Moran's I was used to assess global autocorrelation of the nitrate concentrations for all three methods of analysis when no predictors were in the model. Values of Moran's I less than 0 indicated negative spatial autocorrelation, that is, clustering of dissimilar values, while those greater than 0 indicated positive spatial clustering, that is, clustering of similar values in similar areas (Wakefield et al., 2000).

For the watershed and freeform polygon analyses, a binary weights matrix was created, using Queen contiguity, identifying which areas were considered neighbors. This method takes into account those areas that share the edge to the immediate left, right, up, and down as well as taking diagonal edges into account (reflecting how a queen moves in a game of chess). In this matrix, a "one" was assigned if location i was neighboring location j, otherwise a zero was assigned. For the buffer zone analyses, a distance weights matrix was utilized based on the inverse distance between points. The threshold distance obtained (using Euclidean Distance) was 7.57 km, representing the minimum distance required so that each observation had at least one neighbor (Anselin, 2003a).

A spatial lag model (Florax and de Graff, 2004) was run for each of the three final ordinary least squares regression models using the contiguous (polygon models) or distance (buffer zone model) weights matrix. The spatial lag model is a linear regression model with a spatial variable incorporated to reflect spatial autocorrelation. The spatial lag variable represents the average nitrate concentration of all neighbors of each watershed, as defined by the contiguity weights matrix. Spatial autocorrelation among the areas was assessed using the Lagrange Multiplier test (Florax and de Graff, 2004; Anselin, 1995). If the p value was significant and the rho (the spatial autocorrelation coefficient) was either positive or negative in value, then spatial autocorrelation was evident and needed to be controlled. All spatial analyses were conducted using GeoDa 0.9.5-i (Anselin, 2003b).

RESULTS

All nitrate results are reported as NO_3-N. The mean and median nitrate concentrations of the 4855 individual nitrate measurements were 3.42 and 2.87 mg L^{-1}, respectively, with a range of 0.1 to 27.5 mg L^{-1}. A total of 113 (2%) of the nitrate values exceeded the Canadian MAC (10 mg L^{-1}) and 882 (18%) exceeded the recommended concentration (5.56 mg L^{-1}).

Watershed Results

The average number of individual nitrate points per watershed was 29 with a range of 5 to 294 (median = 15). The mean and median nitrate concentrations at the watershed level were 3.4 and 3.24 mg L^{-1}, respectively, with a range of 0.3 to 9.56 mg L^{-1}. No watersheds exceeded the Canadian MAC limit of 10 mg L^{-1}, whereas 20 (11%) of the 174 watersheds exceeded the recommended concentration (5.56 mg L^{-1}).

Table 1 shows the significant land use variables present in the final watershed regression model on nitrate concentrations, controlling for the effects of other variables in the model. Within watersheds, percentages of potato, grain, and hay cover had very similar interquartile ranges of approximately 10% land use cover, with the percentage of hay having the highest median. Clear-cut woodland, blueberry, and other agricultural land uses were present in watersheds in very small percentages of cover and were frequently not present in watersheds.

Before land uses were incorporated into the model, spatial autocorrelation between two neighboring water-

Table 1. Final model of significant land use variables associated with average nitrate concentrations in 174 watersheds in Prince Edward Island.

Land use	Coefficient (ln + 1)	Confidence intervals	Land use interquartile range (median)	Watersheds containing land use	p
			%	number (% of total)	
Potato	0.026	0.018 to 0.034	3.7 to 13.6 (6.9)	168 (96.5)	0.001
Grain	0.010	0.002 to 0.020	6.5 to 17.3 (10.5)	174 (100)	0.021
Hay	0.010	0.003 to 0.017	9.9 to 22.2 (14.4)	173 (99.4)	0.007
Clear-cut woodland	0.030	−0.0002 to 0.061	0.8 to 4.0 (2.0)	162 (93)	0.051
Other agriculture†	0.050	−0.002 to 0.102	0 to 1.1 (0.3)	127 (73)	0.058
Blueberry	−0.024	−0.050 to 0.001	0 to 0.05 (0)	46 (26)	0.059

† For example: carrots, cabbage, sunflowers.

sheds was present (Moran's I of 0.4164, $p = 0.001$), suggesting a reasonably strong positive autocorrelation among average nitrate values at the watershed level. Spatial autocorrelation was assessed using the Lagrange Multiplier test when all land use variables were taken into account, and was subsequently found to be non-significant ($p = 0.28$). Therefore, most spatial autocorrelation among nitrate measurements was removed once land use was incorporated into the model.

There were three significant land use predictors at the $p < 0.05$ level: potato, grain, and hay cover; and three marginally significant predictors ($p > 0.05$ but $p < 0.06$): clear-cut woodland, other agriculture, and blueberry cover (Table 1). All coefficients were positive except for blueberry, which had a negative association with ground water nitrate concentration. No interactions between these land uses were significant. The final regression model obtained an R^2 of 0.53. Therefore, this final regression model explained 53% of the variation found in private drinking water nitrate concentrations in PEI.

Choropleth maps of nitrate concentration in PEI and each significant land use were created to visually demonstrate the associations between nitrate and the land uses among watersheds. Figures 2 and 3 show average nitrate concentration and the percentage of potato production at the watershed level. Fig. 2 also shows the 2001 buffer zone distribution in PEI, discussed later in this section. When assessing the distribution of potato production using the same unit of analyses, watersheds, there was clear evidence that elevated nitrate concentrations were found in areas of high potato production. A similar trend was seen with hay and grain production, while watersheds with low nitrate concentrations (<3 mg L^{-1}) were often located where blueberry production was present (Fig. 4).

Freeform Polygon Results

The average number of individual nitrate points per freeform polygon was 7 with a range of 1 to 154 (median = 7). The mean and median nitrate concentrations were 5.3 and 5.0 mg L^{-1}, respectively, with a range of 0.1 to 27.5 mg L^{-1} (see Fig. 5 for nitrate concentration in PEI averaged at the freeform polygon level). This average is close to the European recommended concentration of 5.56 mg L^{-1} and exceeds the human affected value of 3 mg L^{-1}. The freeform polygon mean was particularly high because many of the higher nitrate concentrations were in polygons with only one or a few nitrate samples. A total of 76 (1%) of the freeform polygons exceeded the Canadian MAC, and 290 (44%) exceeded the recommended 5.56 mg L^{-1}.

Table 2 shows the significant land use variables present in the final freeform polygon regression model. Again, the percentages of potato, hay, and grain coverage had very similar interquartile ranges (approximately 15%) with hay having the highest median, again (Table 2). The percentage of blueberry coverage had a zero interquartile range, but that was because it was grown in only 8.7% of the freeform polygons.

The freeform regression model with no land use predictors obtained a slightly negative but not significant Moran value of −0.047 ($p = 0.07$), which increased once the land use variables were incorporated in the model; therefore, a spatial lag model was assessed. Spatial auto correlation in the full model was highly significant and

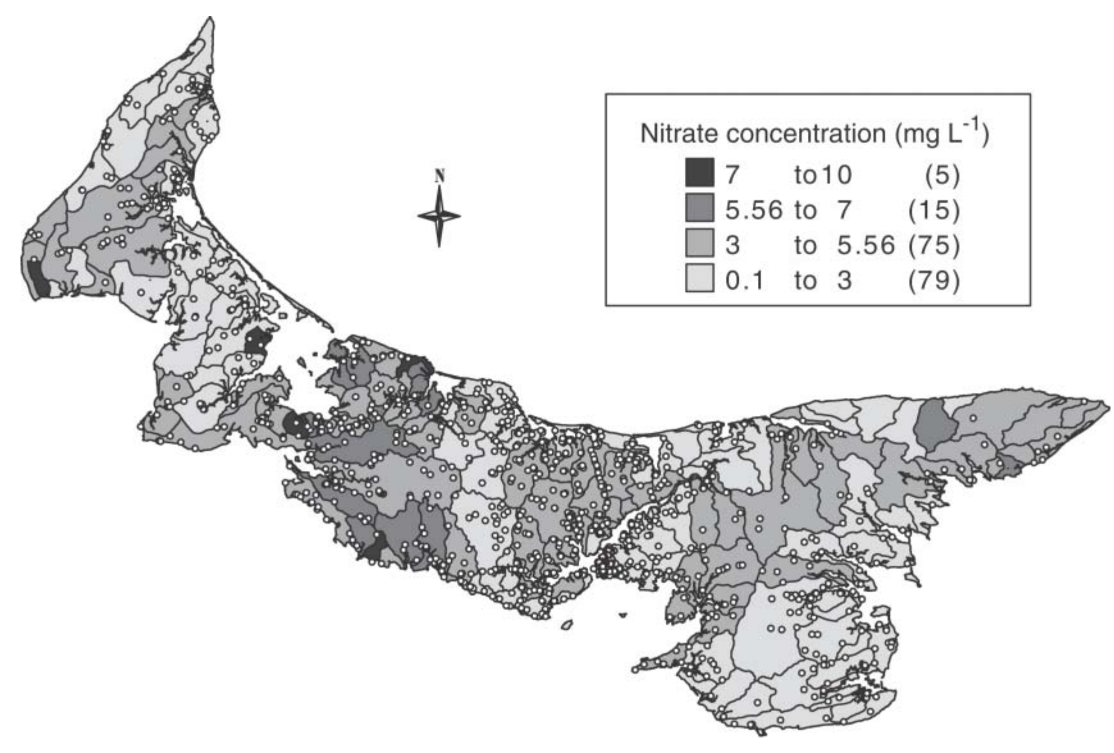

Fig. 2. Average ground water nitrate concentrations in 174 watersheds in Prince Edward Island (number of watersheds in each nitrate category in parentheses), 1997–2001. Buffer zone locations (○) are also included for the year 2001.

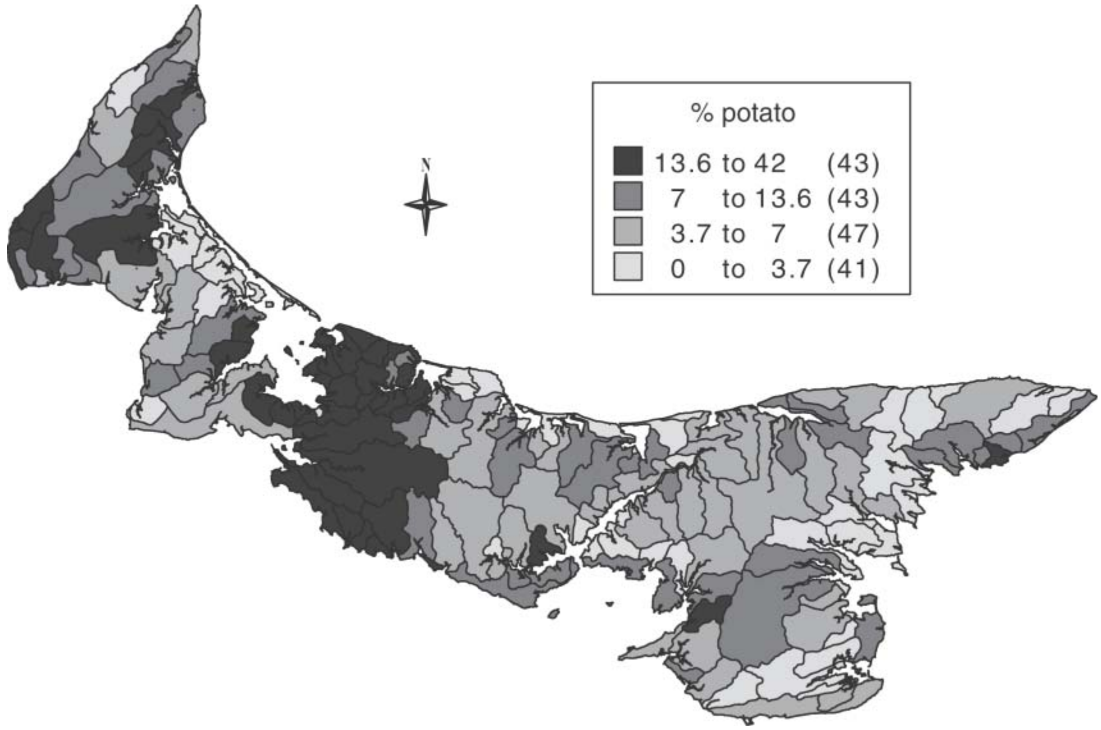

Fig. 3. Percentage of potato cover in 174 watersheds in Prince Edward Island (number of watersheds in each nitrate category in parentheses), 2000.

negative (rho = −0.41), as the Lagrange Multiplier test reported a p value of <0.001, suggesting that many of the neighboring freeform polygons nitrate values differed by greater than 2.5 mg L^{-1}.

The final spatial lag model consisted of five significant land use variables: potato, hay, grain, residential, and blueberry. Again, blueberry was the only predictor with a negative coefficient. Blueberry coverage was also the strongest coefficient in the model. There were no significant interactions between any of these land use variables. Similar to watersheds, the freeform polygon maps demonstrated that high potato production was

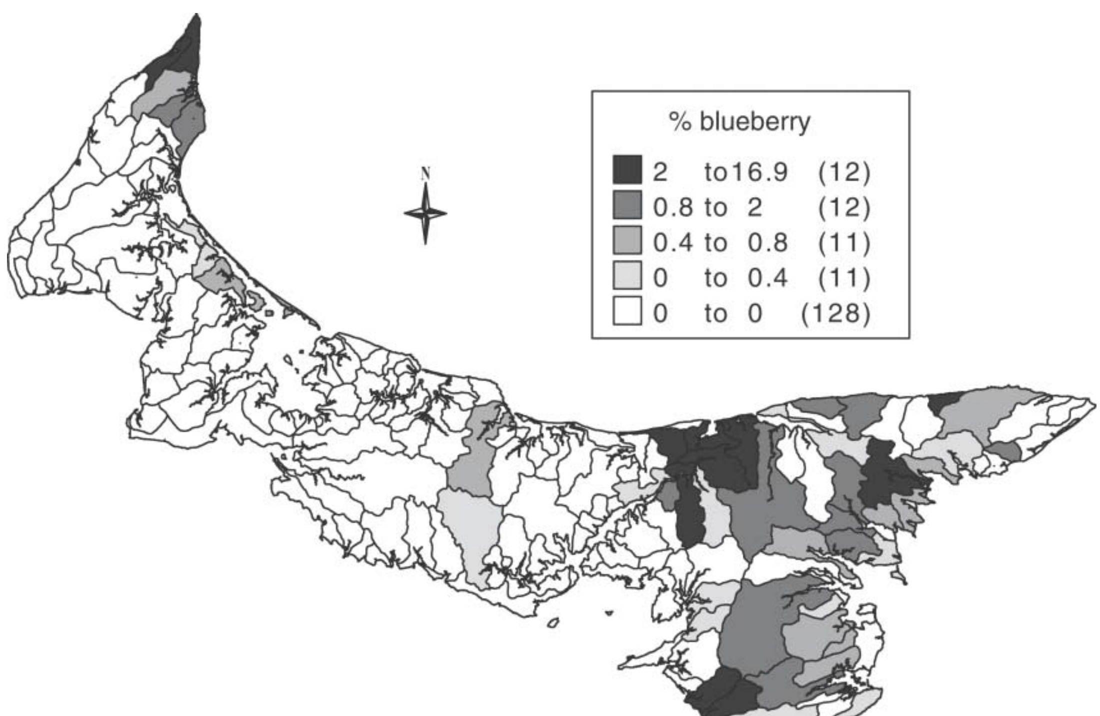

Fig. 4. Percentage of blueberry cover in 174 watersheds in Prince Edward Island (number of watersheds in each nitrate category in parentheses), 2000.

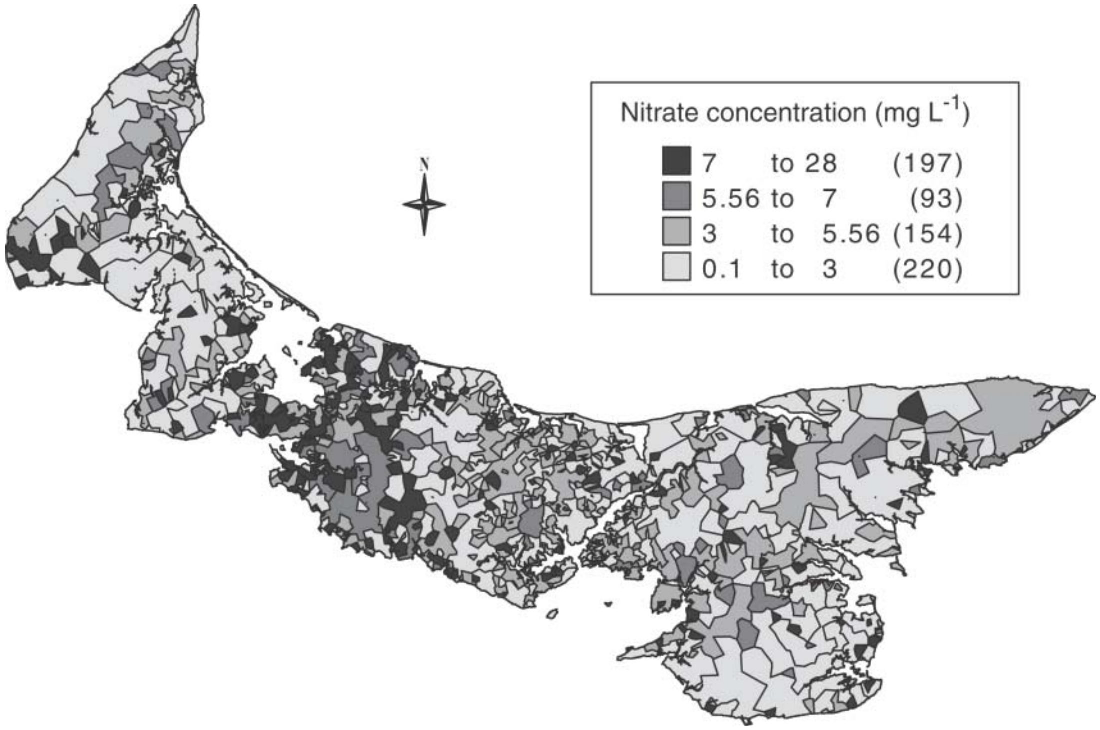

Fig. 5. Average ground water nitrate concentrations in 664 freeform polygons in Prince Edward Island (number of freeform polygons in each nitrate category in parentheses), 1997–2001.

closely correlated with high nitrate concentrations and blueberry production with low concentrations. Fig. 5 shows average nitrate concentrations at the freeform polygon level, which can be compared to Figs. 3 and 4 to visualize average potato and blueberry coverage.

Buffer Zone Results

A total of 1090 water samples were available during the year 2001, with mean and median nitrate concentrations of 3.5 and 2.9 mg L^{-1}, respectively (range of 0.1–17.0 mg L^{-1}). A total of 36 (3%) of the buffer zones exceeded the MAC and 218 (20%) exceeded 5.56 mg L^{-1} nitrate.

Table 3 shows the significant land use variables present in the buffer zone regression model. The percentage of residential areas had an interquartile range of 27%, and also a very large median. A small median of 3.3% existed for potato cover because almost 40% of the buffers did not contain any potato growth.

Spatial exploration of the buffer zones produced a positive Moran statistic of 0.17 ($p = 0.001$), which was still evident once the full model was introduced. Spatial autocorrelation among neighboring buffer zones was highly significant and positive in the spatial lag model (rho = 0.31, $p < 0.001$). Spatial autocorrelation of the full model was highly significant as the Lagrange Multiplier test reported a p value of <0.001, suggesting that buffers close together have nitrate values more similar than those farther apart. Buffer zone distribution is shown in Fig. 2.

Three main effects, percentage cover of potato, pasture, and other agriculture, and two interaction variables, one between hay and grain and the other between hay and residential, were significant in the final buffer zone model (Table 3). Therefore, the coefficients for hay, grain, and residential areas cannot be interpreted independently. Figures 6 and 7 demonstrate the effects of these interactions. For both figures, the quartiles of the percentage of hay were graphed with either the percentage of grain or the percentage of residential areas on the x axis, and predicted nitrate values on the y axis. Figures 6 shows the negative interaction on nitrate con-

Table 2. Final model of significant land use variables associated with average nitrate concentrations in 664 freeform polygons in Prince Edward Island.

Land use	Coefficient (ln + 1)	Confidence intervals	Land use interquartile range (median)	Polygons containing land use	p
			%	number (% of total)	
Rho†	−0.410	−0.319 to −0.501	–	–	<0.001
Potato	0.017	0.013 to 0.0212	2.1 to 16.6 (7.1)	556 (83.7)	<0.001
Grain	0.011	0.007 to 0.016	5.5 to 19.6 (11.9)	606 (91.3)	<0.001
Hay	0.011	0.007 to 0.014	9.1 to 25.4 (16.6)	627 (94.4)	<0.001
Residential‡	0.0033	0.0001 to 0.006	7.5 to 18.9 (11.6)	664 (100)	0.045
Blueberry	−0.040	−0.072 to −0.006	0 to 0 (0)	58 (8.7)	0.0204

† Spatial autocorrelation among neighboring freeform polygons, as defined by the spatial weights matrix.
‡ Including buildings, lawns, parks, and golf courses.

Table 3. Final model of significant land use variables associated with average nitrate concentrations in 500-m buffer zones around 1090 private wells in Prince Edward Island.

Land use	Coefficient (ln + 1)	Confidence intervals	Land use interquartile range (median)	Buffers containing land use	P
			%	number (% of total)	
Rho†	0.308	0.1908 to 0.4247	–	–	<0.0001
Potato	0.017	0.0143 to 0.0205	0 to 13.3 (3.3)	668 (61.3)	<0.001
Pasture	0.007	0.0020 to 0.0118	0 to 4.0 (0)	454 (41.7)	0.006
Other agriculture‡	0.014	0.0046 to 0.0241	0 to 0 (0)	193 (17.7)	<0.001
Residential§	0.0003	0.0002 to 0.003	13.4 to 40.1 (22.8)	1088 (99.8)	<0.0001
Hay	0.013	0.0090 to 0.0172	5.6 to 25.8 (15.2)	977 (89.6)	<0.0001
Grain	0.021	0.0166 to 0.026	1.1 to 19.1 (9.5)	871 (79.9)	<0.0001
Hay × grain	−0.0004	−0.0006 to −0.0002	–	–	<0.001
Hay × residential	1.57×10^{-5}	0.000002 to 0.00003	–	–	0.023

† Spatial autocorrelation among neighboring buffer zones, as defined by the spatial weights matrix.
‡ For example: carrots, cabbage, sunflowers.
§ Including buildings, lawns, parks, and golf courses.

centrations when grain and hay are both present in the same buffer zone. The slopes of the percentage of hay quartiles decrease with increasing hay cover. The percentage of hay cover has a positive but lower coefficient than the percentage of grain cover and therefore, higher hay quartile lines have a higher nitrate concentration on the y axis at grain cover = 0%. However, as grain cover increases within a buffer zone, nitrate concentrations increase, but the amount of this increase is reduced when there is a larger percentage of hay cover in the buffer zone. The opposite trend is seen with the synergistic hay-residential interaction, with the percentage of hay quartile lines widening with increasing percentage of residential cover (expressed on the x axis).

DISCUSSION

This is the first detailed regression analysis of relationships between land use practices and ground water nitrate concentrations comparing these three different spatial analytical units. The mean nitrate concentration of 3.42 mg L^{-1} indicates that there is some human influence on nitrate concentrations in ground water. Therefore, the results of this study should assist in the determination of significant sources of nitrate, aiding in the development of systems to keep the levels within acceptable limits.

Land Use

Regardless of unit of analysis, the percentages of potato, grain, and hay production were all significantly and positively associated with nitrate concentrations in PEI private well water. This was not surprising as these land uses frequently have nitrogen-based fertilizers applied to improve crop yield. Potatoes are generally heavily fertilized at the start of the growing season (400 kg ha^{-1} of 18-46-0 [nitrogen, phosphorus, potassium]), and then another quantity of 500 kg ha^{-1} of 15-0-20 is added later into the growing season (Prince Edward Island Gov-

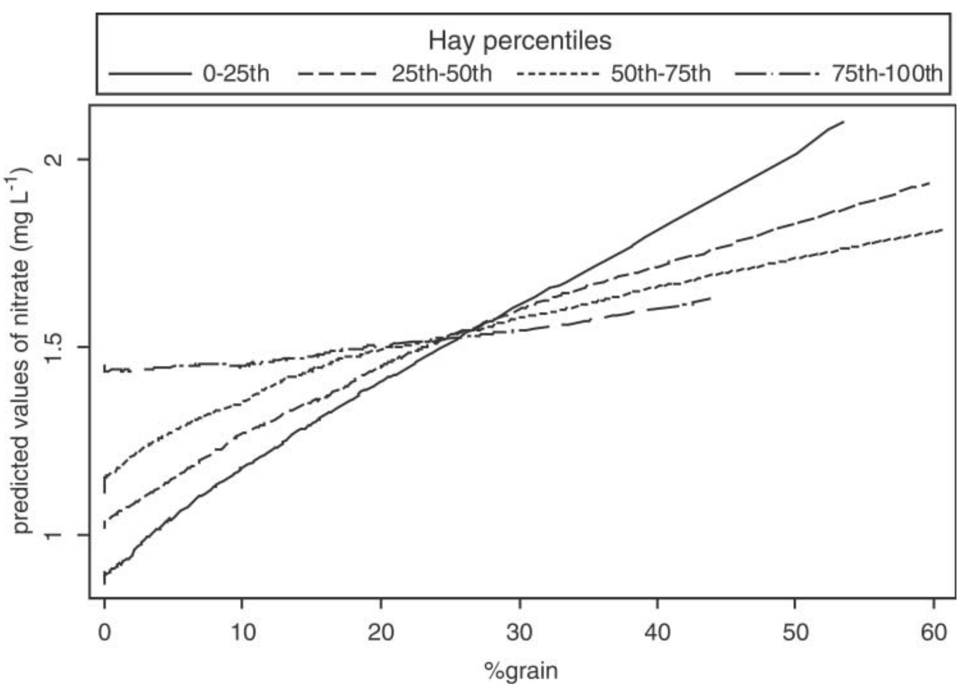

Fig. 6. Predicted values of ground water nitrate concentrations versus percentage of grain coverage for interquartile ranges of percentage of hay, as found in buffer zone analyses in Prince Edward Island, 2001.

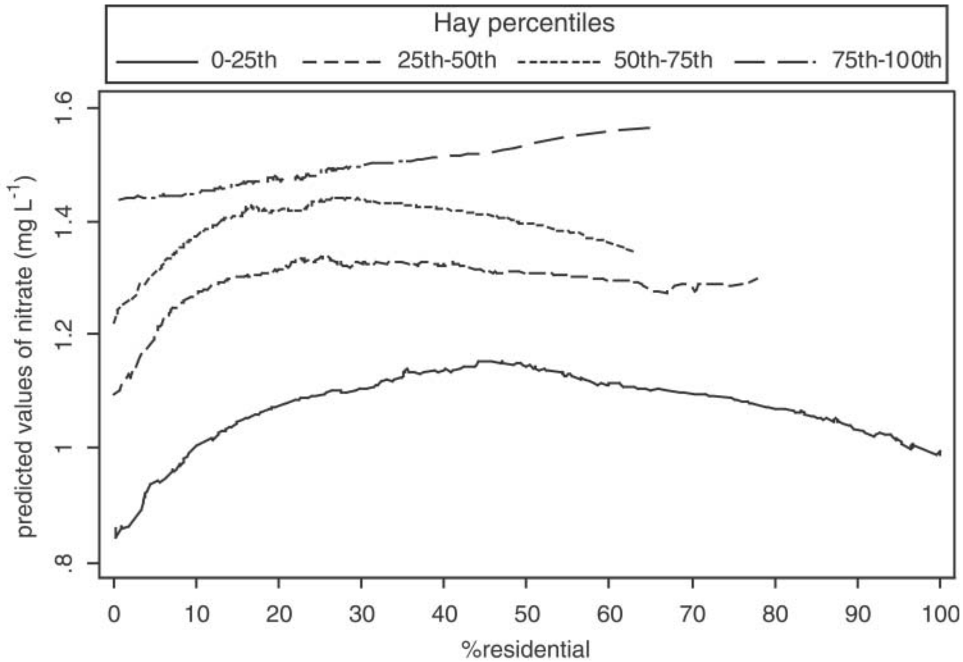

Fig. 7. Predicted values of ground water nitrate concentrations versus percentage of residential coverage for interquartile ranges of percentage of hay, as found in buffer zone analyses in Prince Edward Island, 2001.

ernment, 2000). A study in Quebec, Canada, concluded that intensive potato production on sandy soils was a significant predictor of high nitrate concentrations. The results also showed that potato fields within a 2-km distance of the sampled wells were a contributing factor to this significant finding (Levallois et al., 1998).

Grain fertilization application varies depending on the type of grain, but typically spring crops are fertilized at a rate of 300 kg ha^{-1} of 18–36–18 at the start of the growing season (Prince Edward Island Government, 2001), whereas hay is fertilized at a rate of 400 kg ha^{-1} of 5–10–30, with an additional amount added after each cut (300 kg ha^{-1} of 0–10–30) (Prince Edward Island Government, 1998). Therefore, little nitrogen is added to hay fields, especially if the majority of the hay field contains legumes. However, a study in PEI showed that plowing hay fields, especially in late October, enhances nitrate leaching, leading to high nitrate concentrations being associated with hay fields (Sanderson et al., 1998). It should be noted that all of these fertilizer application rates are general recommendations, as specific quantities will depend on results from a soil analysis.

Other agriculture and residential areas were significant positive predictors in two of the three models, while pasture and clear-cut woodland areas were positive predictors in only one model each (buffer zones and watersheds, respectively). Fertilization on pastured land would typically be in the form of manure directly from the livestock (primarily cattle in PEI) grazing on the land, but amounts would depend on stocking density. Pastures sometimes have inorganic fertilizer applied to the land, but not consistently, depending on the farm (Hovingh, 1998). Other agriculture was located in many of the spatial units, but was only represented by a very small area of the polygons. This land use would include such crops as lettuce, carrots, cabbage, and sunflowers, but due to the variety of crops included within this category, no general statements on fertilizer use would be appropriate.

Residential areas included not only buildings and gardens, but also roads, shrubs/individual trees, and recreational grassy areas such as playing fields and golf courses. Therefore, it is possible that the association between nitrate concentrations and these land uses, designated residential, are from fertilized lawns and golf courses, as well as on-site septic system discharges. An assessment of stream water chemistry upstream and downstream from operating golf courses and those under construction concluded that nitrate concentrations were higher downstream from golf courses compared to upstream or local un-impacted areas (Winter and Dillon, 2005). Another study noted that contamination from urban environments is a source of elevated nitrate levels (>3 mg L^{-1}), but not to the same degree as from vegetable fields (Babiker et al., 2003). Clear-cut woodland, on the other hand, has no fertilizer added, but the additional nitrate in these areas is primarily due to the breakdown of organic matter left behind from tree felling. An association between organic matter and nitrate in both well water in rural areas, and spring water in urban areas was observed in Spain (Vidal et al., 2000).

Blueberry production was the only negative predictor, and was significant in two of the three aggregation methods (watersheds and freeform polygons). One possible explanation for blueberry fields having a slightly negative effect on nitrate concentration is that wild blueberries in PEI are usually grown in acidic soils and do not require many additional nutrients. Blueberry bushes in PEI are typically only fertilized every second year and with low amounts of nitrogen (application rate of 300 kg ha^{-1} at 10–10–10) (K. Sanderson, personal communication, 2005). Because of this low-level fertilizing, very little leaches into the water table below, as the majority is utilized by the bushes. If the blueberries are a new crop, then all of the available nitrogen will be used for growth and maturation. There may also be a possibility of denitrification as the plants are typically grown in areas where the water table is high and dissolved oxygen is low (Hayden, 2001). It may be beneficial to grow potatoes and blueberries in close proximity; however, due to differing agricultural needs, this is not possible.

Significant interactions among land uses were present in the buffer zone analyses. These analyses were not at the field level, but at a larger area level, with effects on the ground water from multiple farms that were likely to be the result of years of land use. With this spatial and temporal context, where crop rotations in space and time can occur, interactions between land use categories within areas are biologically possible. For example, rotations can lead to different nitrate concentrations than if the same crop were grown on the same land area year after year (Power et al., 2001). One of the strengths of regression models is the ability to investigate these interactions. However, historically, few investigators have looked for interactions among historical land use data using regression models.

The observed interactions were between hay and grain, and hay and residential land use. Interactions occur when an antagonistic (between hay and grain) or synergistic (between hay and residential) effect is present, thus implying that more of the variation in nitrate can be explained in more detail by an interaction term rather than simply by the variables being interpreted independently.

The interpretation of the negative interaction between hay and grain could provide additional support that crop rotations lead to beneficial environmental effects. When a small amount of hay and large amounts of grain were present, there was a noticeable grain effect increasing nitrate concentration (solid line in Fig. 6). When there were large amounts of hay and small amounts of grain (see increasing quartiles of percentage of hay along the y axis where grain is 0%), nitrate also increased. However, there are decreasing lines for the four lines representing hay percentiles in Fig. 6, indicating that with more hay cover in an area, increases in grain cover have a reduced impact on nitrate concentration. For the 75th to 100th percentile, there was only a small increase in nitrate concentration with increasing grain cover. With lower quartiles of hay, there is less possibility for crop rotations to be in place. Accurate land use data for other years were not available; therefore, it cannot be confirmed that crop rotation was the reason for this observed negative interaction. In 1997–2001 crop rotation was not mandatory, only recommended, however it was frequently performed. Frequent crop rotations practiced in PEI are grain–hay rotations and potato–grain–hay rotations (unpublished data). It is probable that the grain–hay interaction was significant (versus potato–grain or potato–hay) because it is a part of both three-way potato farming rotations and two-way cattle farming rotations, two systems that occupy a large part of the agricultural land cover in PEI. A reduced effect on ground water nitrate from crop rotations was also noted in a study looking at corn–soybean rotations, which were effective at decreasing nitrate leachate compared to growing corn continuously (Power et al., 2001).

The interaction between hay and residential areas represents a synergistic effect between these two land uses. No obvious reason can explain what is shown in Fig. 7. There is a possibility that this interaction is spurious and simply due to chance when examining multiple interactions. Further research is warranted to determine an explanation for this finding.

While potato, grain, and hay coverage were significant variables in all three aggregation methods, there were other significant variables that were only detected in one or two of the methods. The reasons for these differences relate to the strengths and weaknesses of each of the analyses. First, the number of analytical units was highest for the buffer zone analysis and lowest for the watershed analysis. The interactions were likely detected with the buffer zone analyses because there were more units of analysis, leading to a higher power to detect significant associations if they were present. Conversely, the watershed analyses had the fewest units of analysis, and therefore the lowest power to detect significant associations.

Model Comparisons

With regression analysis, it was assumed that the outcome variable, average nitrate concentration of all tested wells within each watershed, was representative of each watershed. However, within each watershed and freeform polygon, there was variability around each mean nitrate concentration, and the average of the standard deviations around these means gives a measurement of this variability. The average standard deviation for nitrate concentrations within watersheds was 2.22 versus 0.93 for freeform polygons. With this improved homogeneity over the watershed units, the freeform polygon model could have more power to detect significant predictors. It is important to be aware that the data and analyses were scale-dependent, and the interpretation of the results should depend on the scale of analysis used. Within-unit homogeneity was not an issue in the buffer zone analyses as each buffer zone represented a single nitrate measurement.

The watershed analyses actually detected more significant associations with nitrate concentration than the freeform analyses, and this may be due to another methodological difference between these analyses, boundary selection for each analysis. Watershed boundaries have been determined primarily to reflect inherent hydrological mixing of ground water within watersheds, whereas in the freeform analysis, the boundaries were created to maximize within-unit homogeneity of nitrate. However, the percentages of land uses that contributed to each freeform polygon may have been partially misclassified due to erroneous boundary allocation. For this reason, the watershed analysis may have been able to detect more significant associations than the freeform analysis.

Reliability of the watershed model was assessed using a split-sample analysis, whereby the full dataset was randomly split into two groups (60 and 40%). A linear regression model was then built on 60% of the data and predicted values were obtained and compared to the observed values using a correlation coefficient (R). The difference between the square of this correlation coefficient and the R^2 from the original model is called the "shrinkage" on cross-validation. If the shrinkage value is small, then reliability of the original model is acceptable (Dohoo et al., 2003). A small growth value (rather than a shrinkage value) of 0.06 was obtained (original R^2 of 0.53 versus 0.59), so the full model was considered robust and reliable for predicting nitrate concentrations in PEI using land use data.

Disadvantages of the buffer zones were that only a portion of the data could be used for computational reasons, and as the buffers were small relative to the other units (watersheds and freeform polygons), many of the land uses, both significant and not, were not present in many of the buffers. For example, the buffer zone analyses did not detect blueberry coverage as a significant predictor of ground water nitrate partly due to the very low number of buffers zones with substantial blueberry cover. Conversely, the area analyses included the potential impacts of all blueberry fields in PEI.

Spatial Autocorrelation

Spatial autocorrelation among nitrate concentrations was evident when no land use predictors were present in all three regression methods, particularly for watersheds. However, when the land uses were added to the models, only the freeform polygon and buffer zone models showed remaining significant spatial autocorrelation. Spatial autocorrelation in these two methods could be due to a greater number of units used, thus adding power and enabling detection of spatial autocorrelation if it truly did exist.

Negative spatial autocorrelation (rho = -0.41) in the freeform polygons could have occurred for a number of reasons. One common explanation for negative spatial autocorrelation is due to aggregation bias; meaning positive autocorrelation exists at a smaller spatial scale than what is being analyzed (Smith, 2001). Another possibility could be due to a localized nitrate source for the high values among lower ones, or treatment for high nitrate levels in one well among an elevated nitrate area. However, a likely reason is the method in which the polygons were created due to the current limitations of the software. A freeform polygon consisting of several similar nitrate concentrations can have an "island" of a single extreme concentration within it. A physical explanation for these islands may relate to very localized effects on that well, or characteristics of the well that lead to increased contamination of nitrate, such as shallow well depth and amount of casing protecting the well.

To further understand the associations between ground water nitrate concentration and land use, it may be effective to consider other possible influential factors such as livestock densities, ground water depth and flow, crop rotations, and water treatment practices. Well depth and construction would also be useful when assessing nitrate concentrations in ground water. This study was somewhat limited by these absent variables, but land use was both thoroughly and efficiently evaluated with the reliable resources available and techniques utilized.

CONCLUSIONS

In conclusion, there were significant associations between several land use variables and nitrate concentrations in PEI private well water, regardless of the spatial unit of analysis used. All three regression models showed strong positive associations for the percentage of potato coverage and moderate positive associations for grain and hay. Two models, watersheds and freeform polygons, showed strong negative associations for blueberries. Although watersheds did not possess high within-unit homogeneity of nitrate concentrations, they were considered the most suitable method of data aggregation for the following reasons: they were created according to hydrological factors; they were large enough to accurately determine average nitrate concentrations; and they created a model which best explained the variance, according to the R^2 values of the ordinary least square regression models. The 500-m buffer zones were suitable for assessing very localized land use effects in these data, but only a subsample of the data could be used (Year 2001). Finally, freeform polygons showed high within-unit homogeneity, but owing to the method of their creation, significant negative spatial autocorrelation was produced.

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