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A regression model for nitrate leaching in Northern Ireland

R.V. Smith[1] & D.A. Stewart[2]

Abstract. A model has been developed based on multiple regression which explains 95% of the variation in nitrate loading of the major rivers in the 4453 km^2 Lough Neagh catchment for the years 1971–1987. The model relates loading of nitrate in the hydrological year to fertilizer usage, previous summer rainfall, summer temperature of the current year and December–May flow. It indicates that there is an increase in nitrate loading associated with fertilizer usage, and that the equivalent of 13% of nitrogen fertilizer that is lost as leachate comprises 50% of the river loadings.

INTRODUCTION

AN INCREASE in nitrate concentrations has been evident in both surface and ground waters in the United Kingdom during the last 20 years (Royal Society, 1983). Public awareness of nitrate in water supplies has increased markedly since the introduction of the EC directive on the quality of water for human consumption which has set a maximum admissible concentration of 11.3 mg l^{-1} of nitrate N in potable water (European Community, 1980). As a result the Department of the Environment in the UK has received 52 applications from Water Authorities for derogations for nitrate and is considering new strategies to reduce nitrate concentration such as the designation of protection zones (Department of the Environment, 1986).

Despite this increase in nitrate there is considerable variation in both seasonal and year-to-year concentration in river waters. To assist planning by the water industry two types of empirical model have been developed to forecast future trends. The first type has simply aimed at determining the underlying trends after removing variation due to flow and seasonality. Examples of the application of this approach were the studies of Warn & Page (1984) on the River Welland and that of Warn (1984) on the River Stour. The second type sought to derive causal relationships between nitrogen inputs and changes in nitrate concentration in rivers. A notable example of this approach was the study of Onstad & Blake (1980) on the Thames catchment which showed that 78% of the historical variation in nitrate concentration could be explained by changes in agricultural inputs. This relationship was then used to predict future nitrate concentrations in the Thames based on predicted increases in agricultural production.

The present study describes a model of the second type derived from multiple regression analysis which explains 95% of the variation in nitrate loading for the Lough Neagh rivers in Northern Ireland for the years 1971–1987. The model was developed using a database of annual nitrate loadings and environmental variables. The model employs losses expressed as loads for rivers, instead of concentration, in order to avoid the anomaly that increased flows can result in a reduction in concentration (Webb & Walling, 1985) thus obscuring other underlying trends. The hydrological year from October to September is used instead of the calendar year January to December because the latter splits the hydrological cycle. An important assumption of the model is that the fertilizer usage for the Lough Neagh

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[1] Freshwater Biological Investigation Unit, Department of Agriculture for Northern Ireland, Greenmount Road, Antrim BT41 4PX, Northern Ireland.

[2] Biometrics Division, Department of Agriculture for Northern Ireland, Newforge Lane, Belfast BT9 5PX, Northern Ireland.

system reflects that for Northern Ireland as a whole. This assumption is based on an intensive comparison of the two areas which showed that their land use and management were almost identical (Government of Northern Ireland, 1971).

THE STUDY AREA

The Lough Neagh catchment covers 4453 km^2 which is about 1/3rd of the land area of Northern Ireland (see Fig. 1). It has an average rainfall of 1028 mm (1941–1970 average). Six inflow rivers: Main, Sixmile Water, Upper Bann, Blackwater, Ballinderry and Moyola drain 88% of the total catchment. Outflow is via the Lower Bann. The geology of the catchment has been described by Wilson (1972). The soil material is mostly basaltic glacial till and the principal soil associations are acid brown earths and gleys on the lowland and climatic peat over 200 m. During the study the major land use was pasture and rough grazing, which together covered 85–87% of the area with only an additional 7–9% under cultivation. Moisture stress limits grass growth for only two to three weeks in the average growing season (Keatinge *et al.*, 1979), and although the soil contains more organic matter than that in many other parts of the UK the soil is probably typical of much of the northern UK. Farming consists mainly of small mixed livestock farms with milk, beef and pig production being the most important. In 1971 the total human population was estimated at 335 100 of which 199 400 were connected to sewage disposal works. By 1986 the total population had increased by 11.4% to 373 210. Of this increase the greater proportion was in urban settlements connected to sewage disposal works whose population increased by 14.4% compared to a 6.8% increase in the rural population.

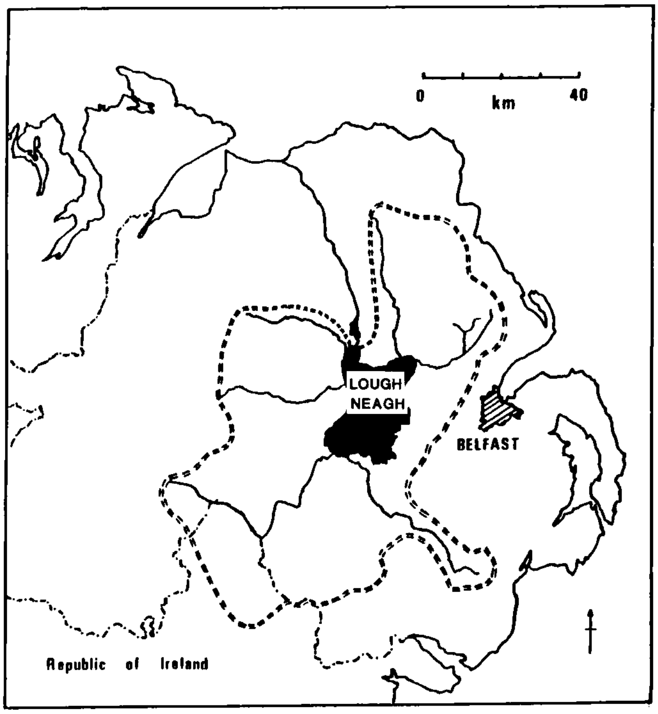

Fig. 1. Map of Northern Ireland showing dilineation of the Lough Neagh catchment area (= =).

METHODS

During the study samples were taken weekly between 10.00 and 14.00 hr from the six major rivers entering Lough Neagh. The sampling stations were as conveniently close to Lough Neagh as possible but avoiding any backwash from the Lough. Flow data were collected from gauging stations and mean daily flows computed from observations at 8-hr intervals. Conversion factors to predict flows entering Lough Neagh (Smith, 1977) were applied to the data because gauging stations were located upstream from the Lough.

The nitrate content of samples was determined by a Technicon Auto Analyser 1 method where nitrate was reduced to nitrite by copper sulphate and hydrazine followed by diazotization of the nitrite with N-l-naphthylethylenediamine (Chapman *et al.*, 1967).

Two methods were used to estimate the nitrate N loadings. The first used the regression (equation 1) considered by Smith & Stewart (1977) to be reliable for predicting N and P loadings:

$$\log L = a + b \log F, \tag{1}$$

where L is the load, and F is the mean daily flow.

Regression equations were derived annually for individual rivers from days on which flow and chemical concentration data were available, and, by using daily flow observations, daily loads were predicted. This method was initially employed in the present study but because of the strong seasonal trend in nitrate concentrations in the rivers (Smith *et al.*, 1982) we decided to calculate monthly loads by multiplying monthly total flows for each of the major input rivers by mean monthly nitrate concentrations calculated from weekly observations (equation 2):

$$ML = MF \times \text{nitrate N conc.}, \tag{2}$$

where ML is the monthly nitrate N load, and MF is the total monthly flow for all rivers.

The results from the two methods showed good agreement. A comparison of the nitrate N loading predictions using equations (1) and (2) gave a correlation ($r = 0.95$, $P < 0.001$) with similar total values. The relationship between the hydrological year (October–September) loadings of nitrate N expressed on an area basis and independent environmental variables was investigated using multiple regression analysis with the choice of variables based on a forward selection procedure (Chatterjee & Price, 1977).

ENVIRONMENTAL VARIABLES

The independent environmental variables chosen were those that had potential to explain the variation in nitrate

Table 1. Nitrate loadings and the four environmental variables used in the model. Variables X_1, X_3, and X_4 are for the current year

Year*	Y Nitrate loading (kg N $ha^{-1} yr^{-1}$)	X_1 Fertilizer usage (kg N $ha^{-1} yr^{-1}$)	X_2 Previous Apr–Sept rain (mm day^{-1})	X_3 June–Sept. air temp (°C)	X_4 Dec–May flow ($10^6 m^3 month^{-1}$)
1971	6.59	29.20	2.23	13.65	190.6
1972	13.96	40.12	2.30	12.45	277.3
1973	8.62	29.93	1.92	13.90	248.0
1974	12.27	27.70	1.98	12.62	282.3
1975	7.75	36.63	2.13	14.41	248.6
1976	8.09	43.79	2.03	14.80	198.6
1977	15.84	49.64	1.75	13.38	323.2
1978	17.45	53.01	1.68	13.07	282.3
1979	19.14	59.71	1.82	13.32	362.0
1980	14.85	58.53	2.26	13.44	310.0
1981	12.64	50.45	2.36	13.54	335.3
1982	10.43	52.69	2.83	13.80	295.8
1983	12.59	56.88	1.92	14.67	310.3
1984	16.71	57.90	1.70	14.14	342.1
1985	17.04	65.03	1.65	13.23	233.1
1986	14.33	73.82	2.88	12.55	310.9
1987	13.75	70.30	2.20	13.07	260.8

*Refers to hydrological year, i.e., 1971 is the period October 1st 1970 to September 30th 1971.

loading. These included climatic variables for sunshine hours, rainfall and soil and air temperatures for Aldergrove, Co Antrim, which is located centrally in the Lough Neagh catchment. Human population data of the electoral districts which form the Lough Neagh catchment area were obtained from DoE (NI) for each year from 1971 to 1986. These have been calculated from the 1971 and 1981 censuses and changes in electoral roles which are revised annually. For the proportion of the catchment that lies in the Republic of Ireland annual estimates of populations were obtained by interpolating and extrapolating the results of 1971 and 1979 Republic of Ireland censuses. Land use and fertilizer usage data for Northern Ireland as a whole were obtained from the Department of Agriculture (NI). Flow data were obtained from the Water Data Unit, DoE (NI) and meteorological data from the Meteorological Office, Belfast.

RESULTS

A significant correlation was obtained between the dependent variable nitrate loading (Table 1) and the current year fertilizer usage for Northern Ireland as a whole. Figure 2 compares observed nitrate loadings with predicted loadings based on equation (3).

$$Y = 4.38+0.17X_1, \quad r^2 = 0.42 (p < 0.01), \quad (3)$$

where Y is the nitrate loading (in kg N $ha^{-1} yr^{-1}$) and X_1 is the fertilizer usage (in kg N $ha^{-1} yr^{-1}$).

Other independent environmental variables were examined as possible explanatory factors of the residual variation in nitrate loading. With the limited number of data available and reduction in degrees of freedom as each variable is included it is desirable to attempt to explain the variation with the fewest independent variables. Although there was a scientific rationale for the choice of variables in the database, the most appropriate representations of these were not known. For example, although there is strong evidence that larger losses of nitrate in drainage waters occur following a dry period it is not clear whether to use rainfall or flow to represent this effect or indeed what is the appropriate time period to employ.

The selection procedure involved calculating residual values from equation (3) for each year and regressing these against the data in the database. The largest correlation in absolute terms ($r = -0.59$) was obtained with previous summer rain for the period April–September. Other rainfall variables for the previous May–September ($r = -0.56$) and June–September ($r = -0.45$) were correlated, as were previous summer flows ($r = -0.46$) for April–September. Combining the previous summer rain data for April–September in a multiple regression (equation 4) gave an improved correlation:

$$Y = 13.38+0.19X_1-4.67X_2, \quad R^2 = 0.63, \quad (4)$$

where X_1 is the fertilizer usage (in kg N $ha^{-1} yr^{-1}$) ($t = 4.34$, $p < 0.001$) and X_2 is the previous April–September rain (in mm day^{-1}) ($t = -2.80$, $0.05 < p < 0.01$).

The forward selection procedure was continued to identify the variable which showed the largest correlation with nitrate loading after adjustment for the effect of the first two variables (X_1, X_2). The strongest correlation was obtained with the current year air temperature for the months of

June–September ($r = -0.72$). Other temperature variables for different periods of the year gave slightly weaker correlations as did soil temperatures for June–September ($r = -0.55$). Combining the June–September air temperature variable with the X_1 and X_2 variables gave equation (5):

$$Y = 30.18+0.17X_1-5.60X_2-2.51X_3, \quad R^2 = 0.83, \quad (5)$$

where X_1 is the fertilizer usage (in kg N ha^{-1} yr^{-1}) ($t = 5.66$, $p < 0.001$), X_2 is the previous April–September rain (in mm day^{-1}) ($t = -4.79$, $p < 0.001$) and X_3 is the June–September air temperature (in°C) ($t = -4.08$, $p < 0.001$).

The residual search was continued to identify a potential X_4 variable. The strongest correlation was obtained with flow for the period December–May ($r = 0.74$). Other flow variables gave weaker correlations: flows January–May ($r = 0.73$), January–April ($r = 0.69$) and January–March ($r = 0.66$). Similarly, rainfall during the period December–March ($r = 0.74$) and January–March ($r = 0.73$) also gave good correlations. Equation (6) shows the results of combining flow for the period December–May with the other three variables:

$$Y = 39.20+0.13X_1-5.29X_2-2.20X_3+0.03X_4, \quad R^2 = 0.95, \quad (6)$$

where X_1 is the fertilizer usage (in kg N ha^{-1} yr^{-1}) ($t = 6.86$, $p < 0.001$), X_2 is the previous April–September rain (in mm day^{-1}) ($t = -8.19$, $p < 0.001$), X_3 is the June–September air temperature (in°C) ($t = -6.43$, $p < 0.001$) and X_4 is the December–May flow (10^6 m^3 month^{-1}) ($t = 5.56$, $p < 0.001$).

The model which is shown in Fig. 2 explains 95% of the variation in nitrate loading with the individual variables all recording t ratios at a significance level $p < 0.001$. The value of 0.13 for the coefficient of X_1 in equation (6) has 95% confidence limits of 0.09 to 0.16. While such coefficients must be used with caution the value of 0.13 suggests that the equivalent of 13% of fertilizer nitrogen is lost as leachate which amounts to 50% of the mean river nitrate N load.

The forward selection procedure may be continued further using the four-variable model to give an additional fifth variable which is solar radiation for the November–February period which has a negative relationship. However, the t ratio for this variable is only significant at the $p = 0.05$ level of probability and explains only an additional 1.6% of the variation in nitrate loading.

A basic test of any model is how well it predicts data not used to establish it. Initially the present model was established on the data for the years 1971–1985 and successfully predicted, in turn, observed loadings for both the years 1986 and 1987. To test the 1971–1987 model further, six years (1975–1980) inclusive were removed from the data because these years cover a central peak. The equation using the same variables based on 13 years' observations successfully predicted the six missing years 1975–1980 with a correlation of $r = 0.99$ ($p < 0.001$). Similarly, the removal of every second year's values yielded a new equation which predicted removed years with a correlation of $r = 0.96$ ($p < 0.001$). These procedures clearly establish the robust character of the model.

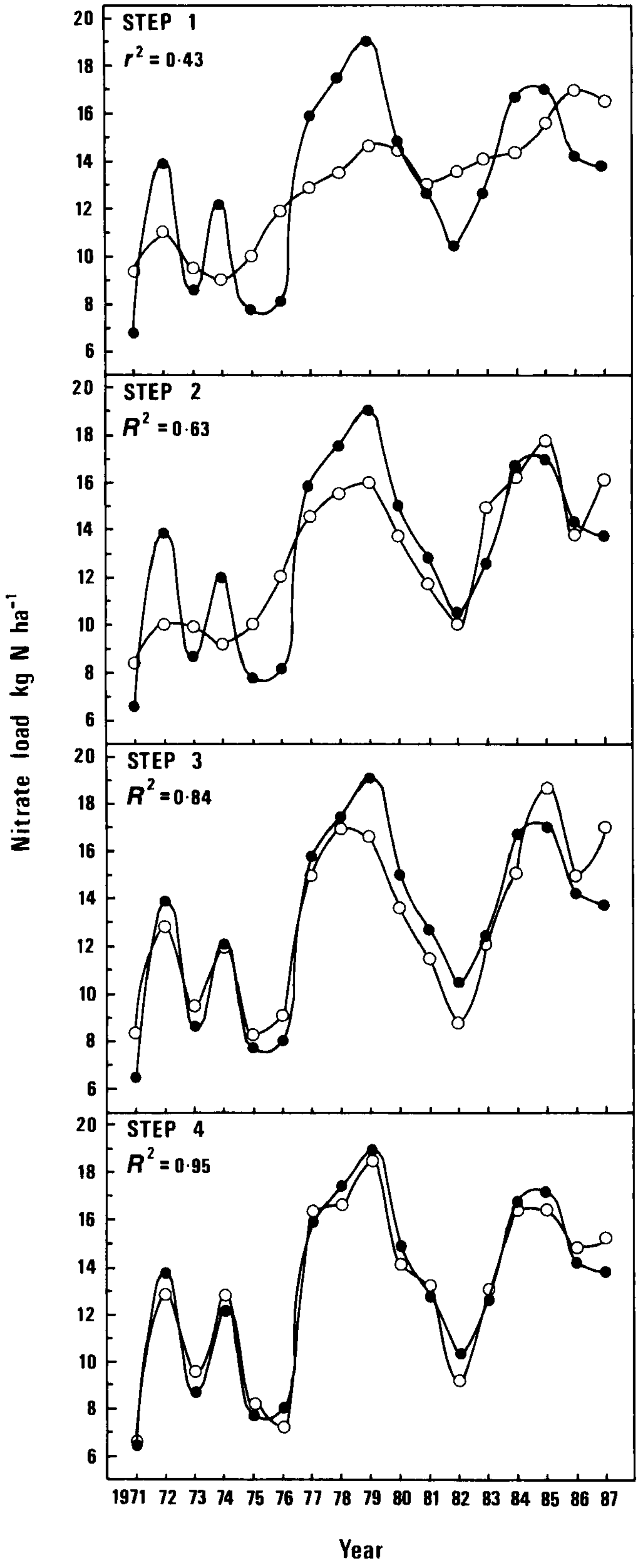

Fig. 2. The four steps in the construction of the model. The equations and statistical analysis at each step are described in the main text. The observed nitrate load is plotted as —●— and the predicted load as —○—.

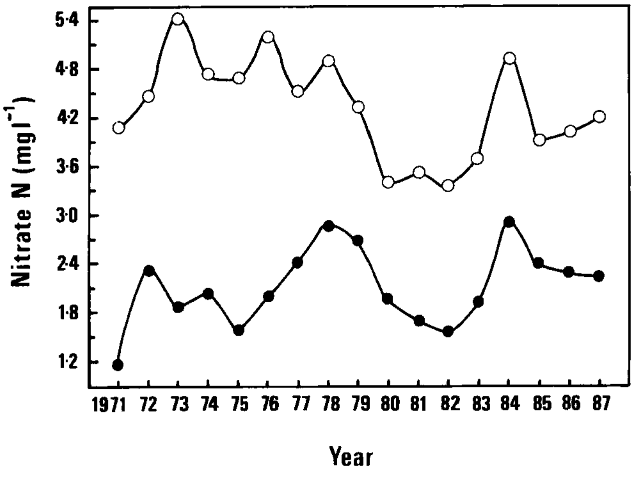

Fig. 3. Observed mean concentrations of nitrate N for the major rivers entering Lough Neagh.

Figure 3 shows the 1971–1987 variation in mean nitrate N concentration for the major rivers entering Lough Neagh. The values are less than 3 mg nitrate N l^{-1} which is much less than the EC maximum acceptable concentration of 11.3 mg nitrate N l^{-1}. The model can be used to predict the effect of combining the maximum fertilizer usage in the data with a 'worst case' climatic scenario chosen from observations for the period 1971–1987. If we insert data for the driest previous summer, the coolest current summer and the highest flows observed during the period December–May we predict that concentrations would be less than 6.0 mg nitrate N l^{-1}.

DISCUSSION

It is generally acknowledged that increased use of nitrogen fertilizers has been the major cause of larger nitrate concentrations in surface waters in the UK (Department of the Environment, 1986). Studies of nitrate concentrations in rivers for selected catchments of the Welsh Water Authority (Brooker & Johnson, 1984) for the period 1967–1981 and for Lough Neagh rivers for 1969–1979 (Smith *et al.*, 1982) showed significant correlations with fertilizer usage. There does, therefore, appear to be compelling justification for the inclusion in the model of a variable for fertilizer usage. The inclusion of the second variable, previous summer rain, is supported by strong evidence that much nitrate is lost in drainage waters following a prolonged dry period (Garwood & Tyson, 1973; Williams, 1976; Foster & Walling, 1978; Jordan & Smith, 1985; Roberts, 1987). The negative correlation between nitrate loading and the summer temperature can reflect either increased uptake of nitrogen by grass or increased loss rates due to denitrification (Ryden, 1983). The inclusion of the last variable, flow, emphasizes the importance of run-off during the period December–May in removing nitrate from the soil profile when both flows and concentration are at their greatest (Smith *et al.*, 1982).

It is not altogether surprising that the residual search procedures used in constructing the model have not identified human population or land use changes as significant contributors to the annual variation in nitrate loading. Assuming that land use in the Lough Neagh catchment has changed in the same way as that of Northern Ireland as a whole, then land use in the catchment has remained fairly constant over the study period. In 1971 the total area of crops and grassland in Northern Ireland was 835 000 ha and by 1987 it had increased to only 841 000 ha, an increase of less than 1%. There has been a decrease in arable farming from 96 000 ha in 1971 to 73 400 ha and an increase in grass for silage from 238 000 to 274 000 ha. The human population in the catchment has increased from 335 100 to 373 210 over the period 1971–1986 with an urban increase of 14.4%. However, assuming a *per capita* production of 6 g N person^{-1} day^{-1} (Smith, 1976) this increase would have contributed only 80 tonnes of N to a river loading which in 1987 was 6200 tonnes of nitrate N. Indeed, the total urban population in 1986 of 228 197 would have contributed only 500 tonnes of N. Elsewhere in Britain agricultural catchments lose more nitrate N per unit area than that observed in the present study. The mean loss rate during 1971–1987 for the Lough Neagh system was 13 kg N ha^{-1} with a range of 6.5–17.4 kg N ha^{-1}. The annual loss rate for the River Dart, Devon (Webb & Walling, 1985), was 24 kg N ha^{-1} with a range from 8.3–51.4 kg N ha^{-1}. The Shenley Brook (Roberts, 1987) in Buckinghamshire showed a mean loss rate of 32 kg N ha^{-1} with a range of 17–74 kg N ha^{-1} These loss rates are typical of grassland catchments in Britain with the exception of upland catchments such as the Wye where only 2.7 kg N ha^{-1} were lost (Osborne *et al.*, 1980). In marked contrast to these observations, Ryden *et al.* (1984) reported losses of 29 and 162 kg N ha^{-1} for cut and grazed swards, respectively, from an experimental site at Hurley, Berkshire. Although much more fertilizer was applied per unit area at Hurley (420 kg N ha^{-1}) than the 70 kg N ha^{-1} applied to the total Lough Neagh catchment it represents losses of nitrate N equivalent to 6.9 and 38% of nitrogen applied. Results from the present model indicate that the equivalent of 13% of the N applied in the Lough Neagh system appears as leachate. This shows a remarkably good agreement with the results of Foy *et al.* (1982) who estimated that the equivalent of 12% of nitrogen fertilizer applied was lost in drainage water in the same system.

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Soil erosion and its control in the loess plateau of China

Bojie Fu[1]

Abstract. The loess plateau in China is the most developed region of loess in the world in terms of extent, thickness and depositional sequence. It is also the region with the most serious soil erosion in the world. This paper reviews the factors and reasons for soil erosion in this area. The loess is prone to vertical cleavage and its surface soils are soft and loose. Rainstorms are frequent with intense rain concentrated during the summer. Irrational land use and exploitive management have been carried out for thousands of years and express themselves through the loss of grassland and natural forests. Finally, some soil conservation schemes for use in the loess plateau are suggested.

INTRODUCTION

THE LOESS plateau of central China appears to have the largest rates of erosion in the world. Although some work on erosion of the plateau has been published in English, this paper reviews literature previously inaccessible to non-Chinese speakers. The reasons for accelerated erosion are outlined and some conservation measures which could be taken to reduce the incidence and rates of erosion are discussed.

The loess plateau in China lies in the middle reaches

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[1] Department of Geography, Peking University, Beijing, P. R. China. Visiting Research Fellow in the Department of Environmental Science at University of Stirling, Stirling, FK9 4LA, UK, 1987–88.