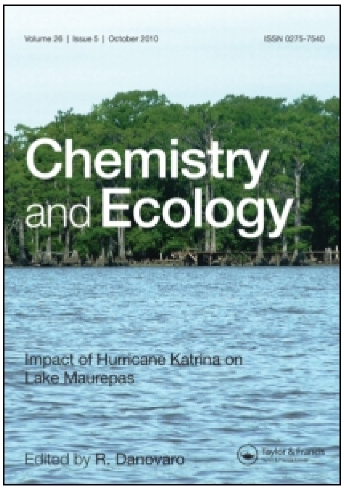

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SCOTTISH REGIONAL AND DISTRICT ESTIMATES OF NON-POINT SOURCE NITRATE NITROGEN (NO_3-N) LOADINGS USING AVHRR SATELLITE DATA

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Part of the nitrate load in UK surface waters is derived from non-point sources, principally agricultural land. Estimates of agricultural nitrate loss can be derived using an empirical model. This model is developed using catchments where nitrate losses, agricultural and non-agricultural areas are all known, the latter being derived from high resolution LANDSAT TM imagery. Such a model has been developed for Grampian Region in NE Scotland. In extending its use to deriving national estimates of agricultural nitrate loss, problems were encountered in obtaining appropriate cloud-free LANDSAT TM imagery.

Low resolution AVHRR was investigated as an alternative source of data on agricultural and non-agricultural areas. By comparing available land cover information with an AVHRR land cover classification using visible and infrared radiance data together with a banded altitude image, a model was developed that accounted for the agricultural/non-agricultural land mixture within each AVHRR pixel. Using this model, it was then possible to provide preliminary national estimates for nitrate loss on a district by district basis. The preliminary national nitrate loss estimates correlate well with published River Board information. AVHRR National estimates indicate that long term NO_3-N losses through Scottish surface waters are of the order of 54 000 tonnes per annum, equivalent to a fertilizer NO_3-N loss of approx. £17 million). A geographic breakdown of nitrate loss in Scotland indicates that the North Sea receives the bulk of this.

KEY WORDS: non-point source nitrate losses, agriculture, satellite imagery, LANDSAT TM, AVHRR, nitrate sensitive areas, Scotland

INTRODUCTION

Excessive NO_3-N concentrations can either cause or aggravate problems connected with the eutrophication of fresh waters (Stewart *et al.*, 1982). A European Economic Community (EEC) directive already specifies a 'maximum admissible concentration of 11.3 mg nitrate-nitrogen (NO_3-N) per litre in drinking waters.' In addition, eutrophication of the marine environment is now considered a major issue for those countries bordering the North Sea (UK DoE, 1987). Further European Communities (EC) guidelines are likely to be introduced regarding reduction of NO_3-N loadings to the North Sea from surface waters. Emphasis is being placed on identifying the water bodies that already exceed or are at risk of exceeding current EEC limits on fresh water nitrate pollution, particularly from non-point sources (EC, 1991). By defining these polluted water bodies, vulnerable zones or 'Nitrate Sensitive Areas' (NSAs) (UK DoE, 1988), where the risk of water pollution caused by or induced by nitrates from agricultural sources, may be identified. Few regional examinations and almost no national assessments of the agricultural contribution to nitrate loadings to surface waters have been undertaken to establish a baseline for these NSAs.

Agricultural census information, reported in the United Kingdom (UK) by parish, provides an acceptable basis of establishing the agricultural intensity within parish, district, region or national boundaries. There are several reasons why such data may not provide a clear or complete picture of the nitrate sensitive areas. Published census information is based on sampled data and may not fully represent all land cover types in all parishes since it underestimates the non-agricultural areas. The percentage of the parish represented by the census returns also varies considerably between parishes. There is an obvious need therefore to examine other independent ways of establishing the boundaries of these NSA's and investigating their spatial variation.

An examination of the problem in Grampian Region, Scotland, integrating detailed land cover information from maps and LANDSAT TM (Thematic Mapper) satellite imagery and conventional river analysis data and spatial analysis techniques, provided regression estimators for NO_3-N loss for agricultural and non-agricultural areas (Wright *et al.*, 1991). This technique could be applied at a national level, but requires complete, cloud free, high resolution imagery. Legg (1988), with a detailed analysis of 10 years of LANDSAT imagery, stated that applications requiring such imagery within a specific time interval are impractical in the UK.

This study shows how the NO_3-N regression estimators derived for Grampian Region catchments could be more widely applied through the use of coarse ground resolution (1 km) Advanced Very High Resolution Radiometer (AVHRR) satellite imagery. Using suitable, relatively cloud free, AVHRR imagery, a simple agricultural land cover classification (agriculture and non-agriculture) based on spectral separation is produced. This classification is then compared with a more detailed land cover classification for North East Scotland to establish the percentage agricultural dominance of each AVHRR cover class. Using a long term (1981–1986) NO_3-N loss regression equation based on catchment data, the AVHRR land cover classification is then converted, pixel by pixel, to an estimated NO_3-N loss (kg/ha-year) classification for Scotland. An analysis of regional, district and river authority NO_3-N losses to the marine environment from these non-point sources is then made using spatial analysis techniques.

All image processing procedures used in this study and the earlier individual catchment and regional investigations were performed using ERDAS Image Processing Software. A detailed explanation of procedures and algorithms used in these studies may be found in ERDAS 7.5 Field Guide (1991) and in Wright *et al.* (1991).

BACKGROUND

International Context

There has been in operation for some time, a European Economic Council directive (EEC, 1975 and EEC, 1980) which specifies a 'maximum admissible concentration' of 11.3 mg NO_3-N per litre in drinking water with a defined target concentration of 5.65 mg NO_3-N per litre. Waters affected by these levels of pollution are used to identify vulnerable zones or 'Nitrate Sensitive Areas' according to the criteria laid down in the European Communities (EC) Council Directive 91/676 (1991). In some regions of Scotland with moderate to high rainfall and mixed farming, actual NO_3-N loadings (flow x concentration) into the marine environment are of more concern (UK DoE, 1987).

Rivers provide a significant input of nutrients to the sea. Most of these remain within the shelf areas, with little reaching the open ocean. Over the past few decades increased discharges of nutrients to the vulnerable coastal zone have occurred worldwide. In some locations, the increases in concentrations of dissolved nitrate and phosphate, and of organic carbon, together with organic accumulations in the sediments, have brought about changes in the structure of planktonic and benthic communities, often with substantial ecologic and economic consequences (GESAMP, 1990). Within the EC there are plans to reduce the NO_3-N pollution to the marine environment by 50 percent (NUTAG, 1993).

Non-point sources of nitrate from modern agricultural land use have been strongly linked with increased nitrate concentrations in run-off and surface waters (Haith, 1976; Haith and Dougherty, 1976; Klepper, 1978; Edwards *et al.*, 1990; UK DoE, 1979; UK DoE, 1986; UK DoE, 1988; ECETOC, 1988, SSLRC/ITE, 1989). There is a need, therefore, to identify the vulnerable zones, or Nitrate Sensitive Areas, not only in the UK but in North Sea riparian countries whose surface waters influence marine water quality.

Importance of Agricultural Nitrate

In general terms, the amount of nitrate leached from soil is seasonal and dependent on three main factors (UK DoE, 1979): water balance (rainfall and evapotranspiration), the quantity of available nitrogen present in the soil (dependent on soil type, atmospheric and fertilizer input), and vegetation cover present at the site (Ryden *et al.*, 1984; Gasser, 1982; Kolenbrander, 1983, Foster *et al.*, 1986).

Inputs of nitrogen compounds from the atmosphere originate from both wet and dry deposition. Estimating inputs from the latter is difficult and suitable techniques are not well established (Soderlund, 1980). Wet deposition may be of the order of 10 kg N/ha-year (Edwards *et al.*, 1985) and dry deposition of a similar amount (Royal Society, 1983). In some upland catchments with little or no other inputs, output may be less than 2 kg/ha-year (Edwards *et al.*, 1990).

Nitrate leaching has been shown to increase as land use changes from moorland through forest and grassland to arable agriculture (Burt *et al.*, 1992) and varies with time of year, disturbance and site characteristics. In semi-natural grassland or moorland communities, there is very little NO_3-N loss, of the order of 1 or 2 kg NO_3-N per ha/year (Edwards *et al.*, 1985). The NO_3-N loss can increase dramatically when nitrogen fertilizer is added, depending on the management practices, but there is no simple relation between nitrogen application and leaching loss. Nitrate losses may remain small where application rates are appropriate for crop requirements but can increase dramatically where the amount of nitrogen fertilizer is large or applied at rates in excess of crop needs, producing little or no additional crop yield (Burt and Haycock, 1992). Isotopic studies on the efficiency of fertilizer N, have shown that 20 to 60 percent of that applied to various crop types may be unaccounted for by the crop (Carey, 1985).

NO_3-N LOSS MODELS

Grampian NO_3-N Loss Model 1

Early investigations into the fate of agricultural nitrate used individual catchment information from the rivers Dee and Don in North East Scotland (Edwards *et al.*, 1990). These catchments show a wide range of agricultural intensity, as well as varied soil and other physical and climatic conditions. However, a larger number of river catchments needed to be investigated to provide a greater range of agricultural intensity on which to test how robust was a relationship between agricultural intensity and nitrate loss in the Dee and Don river systems.

River Catchment Information

The western and central catchments used in the regional studies are dominated by the North East Grampian Highlands with its extensive plateaux of the Cairngorm Mountains. To the north, north-east and south-east, the lowlands form the main arable belt in Scotland with major rivers flowing in a north-easterly or easterly direction. Traversing this highland and lowland separation, the river catchments of the Grampian Region provide a wide range of agriculture (AGRIC) to non-agricultural (NON-AGRIC) variation.

Using annual flow data, 1980–1986, long-term average values were calculated (millions cubic metres per year). From corresponding monthly water quality sample data, an annual average, and then a long term (1980–1986) average concentration (mg/litre) for NO_3-N was obtained. Boundaries were obtained from the North East River Purification Board (NERPB) for all catchments and sub-catchments with primary and secondary gauging stations. From these data, digital map images were produced for inclusion into a geographic information system, which provided the means to obtain area information related to the catchments. Using both long term flow, concentration and area results, NO_3-N loading (tonnes/year) and NO_3-N losses (kg/ha-year) could then be calculated (Wright *et al.*, 1991).

Preliminary Regional Model

A preliminary assessment for the Grampian Region was made by combining Land Capability for Agriculture (LCA) maps, agricultural census returns and a satellite forestry classification, providing primary and secondary land cover information (Wright *et al.*, 1991). A simple regression model was produced using the aggregated LCA classes as agricultural cover types to represent agriculture as a primary or level 1 land cover class, compatible with a remotely sensed classification (Ryerson, 1975). In this model (Equation 1), the aggregated agriculture cover types were regressed against the spatially averaged (by catchment and sub-catchment) NO_3-N losses (kg/ha-year) or loadings (flow x concentration) accumulated temporally into annual and long term values for the NERPB river catchments.

NO_3-N loss Model I assumed a non-agricultural loss of 1.66 kg/ha-year (Edwards *et al.*, 1990) (NO_3-N loss in kg/ha-year; agricultural land cover, AGRIC, as percentage of catchment area):

Agricultural NO_3-N Loss

$$= 0.225(\%AGRIC) \quad (1)$$

$$(r^2 = 0.84, df = 26, p = 0.001, CV = \pm 32.6\%)$$

Further investigation found that the accuracy of NO_3-N loss predictions for catchments dominated by agriculture could be improved considerably by not fixing the non-agricultural component (Equation 2) and removing some sub-catchments which appeared as outliers in the regression. However, this was at the possible expense of prediction of the less important (in terms of NO_3-N losses) non-agriculture component:

Total NO_3-N Loss

$$= 0.320\sqrt{NON - AGRIC} + 0.00250(AGRIC)^2 \quad (2)$$

$$(r^2 = 0.96, df = 21, p = 0.001, CV = \pm 14.2\%).$$

(CV is coefficient of variation)

GRAMPIAN NO_3-N LOSS MODEL II

LANDSAT Thematic Mapper (TM) Land Cover Classification

The Land Capability for Agriculture (LCA) maps produced by the Soil Survey of Scotland (MISR, 1983a) have been used to segment all land into 2 categories, land suitable to arable cropping (Agriculture, AG) and land suitable only for upland grassland and rough grazing (Non-agriculture, NAG). It was felt that the LCA map scale at 1: 250 000 did not provide a sufficiently accurate spatial pattern for agriculture and non-agriculture. A LANDSAT TM forestry classification had been used in the preliminary regional model (Wright *et al.*, 1991) and it was decided to replace the LCA and agricultural census non-spatial data with a complete land cover classification form LANDSAT TM.

The high resolution satellite imagery was a LANDSAT TM scene 205/21, from 17 April 1987. The image was geometrically registered to the British National Grid (BNG) through the selection of ground control points. A third-order polynomial transformation was used to model the relationship between image and BNG map co-ordinates. Control points with large residuals were iteratively deleted until final residuals ranged from 0 to ± 1.2 pixels. The final iteration gave an east-west and north-south fit within 1 pixel, approx. 20 to 30 metres. A simple nearest-neighbour interpolation was used to resample the original LANDSAT TM data to the desired output pixel location (BNG) and size (50 metre pixels).

The land cover classes were obtained from an unsupervised minimum distance classification, which produced some 56 spectral land cover classes. This classification was aggregated into non-agriculture and agriculture spectral classes, using the LCA urban, AG and NAG masks as guides in a visual assessment, as well as a soil map

Table I Comparison of accuracy estimates of major satellite land cover classes from LANDSAT TM and LCS88 land cover data.

LCS88 ground data	LANDSAT SATELLITE LAND COVER CLASS AS PERCENTAGE OF GROUND DATA							
	Non-agric. grassland	Moor/grass mosaic	Agric. grassland*	Agric. arable*	Forest or woodland	Undiff. moorland	Urban areas	Other** classes
Undiff. grassland	19.95	8.44	7.03	4.41	1.17	2.38	1.64	2.20
*Agric. imp. pasture	22.27	6.85	32.92	14.78	2.04	1.21	4.23	8.08
*Agric. arable land	8.84	17.34	54.97	72.50	2.28	1.24	8.12	70.04
Coniferous woodland	7.39	4.01	0.67	1.06	76.62	5.26	0.75	1.55
Mixed or broadleaf woodland	5.21	4.76	0.99	2.03	4.88	2.37	1.65	1.18
Wood management	7.79	5.96	0.80	1.16	9.09	3.16	0.04	0.83
Heather moorland	17.95	36.07	0.74	0.61	3.17	54.51	0.12	0.83
Undiff. blanket bog	4.87	11.72	0.26	0.61	0.39	17.84	0.00	0.56
Undiff. montane vegetation	0.48	2.91	0.00	0.00	0.03	9.23	0.00	0.01
Built up area	4.47	0.70	1.19	1.51	0.10	0.15	81.87	4.06
Misc. bare ground	0.09	0.07	0.13	0.31	0.04	0.41	0.16	0.67
Undiff. cover types	0.55	1.02	0.24	0.84	0.12	1.88	1.23	5.98
Area (ha)	18976	101381	180450	249970	100437	192281	11521	20073

* Satellite classified agricultural land (accumulated) = 87 per cent of LCS88 agricultural classes
** includes 18914 ha of cloud

'image' (MISR, 1983b) to eliminate confused bare soil and rough-grazing cover types on agriculturally suitable and unsuitable soil types.

The accuracy of the final classified (segmented) image was established using ground truth data from test farms and preliminary data from the Scottish Land Cover Project 1988 (LCS88) (MLURI, 1988; Dry *et al.*, 1992). Accuracy estimates of the major satellite classes are presented in Table I. The overall accuracy for satellite agricultural cover types was 87%. The remaining variation could be assigned to other satellite spectral classes, such as non-agricultural grassland and moorland/grassland mosaics. These are classes which would be associated with LCA class 5, a category included in the 'unsuitable for agriculture' mask, but possibly interpreted (for LCS88 project) as agricultural improved grassland and as a result may include areas of rough grazing. Because a preliminary LCS88 dataset has been used, there is no measure of its accuracy, but there are indications that there may be significant regional interpretation variation in such grassland categories (MLURI, 1993).

Land Use and NO_3-N Loss Estimation

Previous results (Wright *et al.*, 1991) suggested that regression analysis should be performed against NO_3-N total catchment loads (tonnes/year) with losses (kg/ha-year) and cover type catchment percentages rather than concentrations or areas, thus further reducing bias due to irregularities in catchment area, rainfall or flow characteristics. It was also necessary to modify the number of catchments and sub-catchments used in the second model. Some of the sub-catchments for the two main rivers, the Dee and the Don, were removed from the regression and other individual river catchments added. This was to reduce any bias from nested sub-catchments.

A stepwise regression on all primary land cover data (no separation of agricultural type) indicated that the area under agriculture was indeed the most significant land cover characteristic responsible for total NO_3-N load within mixed land cover catchments. Several regression models were tested, and for the catchments under examination, no significant role was found for urban or inland water bodies. A measure of the accuracy of the equation is given as a coefficient of variation (CV), or the standard deviation of the predicted value as a percentage of the mean value of all samples used in the dataset.

The regression model for agriculture and non-agriculture was as follows (NO_3-N Loss in kg/ha-year; land cover types, as percentages of catchment areas):

NO3-N Loss

$$= 23.7 - 2.21\sqrt{\%NON - AGRIC} + 0.000527(AGRIC)^2 \quad (3)$$

$$\left(r^2 = 0.9680,\ df = 19,\ p = 0.001,\ CV = \pm 12.5\%\right).$$

This model, accounting for nearly 97 percent of all NO_3-N variation, gave non-agricultural losses as 1.6 kg/ha-year, a figure within the range given by Nilsson and Grennfelt (1988), and similar to the fixed value used in Edwards *et al.* (1990) and Wright *et al.* (1991). A more accurate prediction of average agricultural loss, approx. 29 kg/ha-year, was also obtained. This increase in the agricultural loss compared to the preliminary model may be due to a LANDSAT TM classification reduction in 'agricultural' area with the exclusion of some upland and rough grazings (LCA class 5). As a result of this a greater proportion of the nitrate load in a catchment would be assigned to a smaller area of agriculture, with the upland and rough grazings not receiving an appreciable amount of added nitrate, providing a more realistic average figure for all agriculture (crops and grass).

AVHRR: SCOTTISH NITRATE LOSSES

AVHRR

In recent years, research has been performed to explore the possible land resource applications of TIROS-N series of meteorological satellites and in particular the Advanced High Resolution Radiometer (AVHRR). These satellites have a nominal spatial resolution of 1.1 km at nadir, while LANDSAT TM has a nominal spatial resolution of 30 m. The AVHRR satellites have only 2 spectral channels measuring radiance within the visible (Band 1) and infra-red (Band 2), whereas LANDSAT TM has five within the range. However, the AVHRR platforms provide daily coverage of the whole of the earth's surface, as compared to LANDSAT coverage of the same place every 16 days. For land surface studies the occurrence of cloud severely limits the amount of usable imagery received, especially as a satellite overpass coincident with a cloud-free sky is rare for some areas (Legg, 1988). The daily availability of AVHRR imagery improves significantly on this situation. In addition, there is significant overlap of the ground area imaged each orbit, providing data of the same area for up to three successive passes.

Studies have shown that it is possible to produce primary land cover intensity and vegetation index classifications from the AVHRR satellite (Gervin *et al.*, 1985; Saull, 1985; Hayes and Cracknell, 1985). Gervin (1985) found that the overall accuracy of LANDSAT Multispectral Scanner (MSS) classification for Level 1 was 76.8 percent. The corresponding AVHRR accuracy was 71.9%, again reflecting excellent mapping of the most prevalent category, but generally undependable identification of the remaining categories. There is not, therefore, a significant loss of accuracy between LANDSAT and AVHRR Level 1 land cover categories.

AVHRR Imagery and Processing

There was no suitable cloud-free AVHRR imagery from near the mid-point (mean year 1983) of the long term river analysis. However, agricultural census returns (HMSO, 1984; 1990) indicated that the total area of Scottish agricultural and non-agricultural land had only very minor fluctuations from 1983 to 1990 ($\pm < 0.5\%$). Therefore, a near perfect cloud-free UK scene from May 1990 was used to produce the agriculture 'Land Cover' classification required for national nitrate loss prediction.

The AVHRR image was also geometrically registered to the British National Grid (BNG), through the selection of ground control points; a third-order polynomial transformation was used to model the relationship between image and BNG map co-ordinates. Large residuals were iteratively deleted until final residuals ranged from 0 to ± 1.2 pixels giving an east-west and north-south fit within 1 pixel, approx. 800 to 1100 metres. A simple nearest-neighbour interpolation was used to resample the original AVHRR waveband-set to the desired output pixel location (BNG) and size (500 metre pixels, chosen to match other datasets).

Land Cover Classification

The AVHRR wavebands used were Bands 1 (visible) and 2 (infra-red), together with a simple vegetation ratio (Band1/Band2) and a more complex normalised vegetation index, (Band2 − Band1)/(Band2 + Band1). Included in the image band-set for this classification was a banded altitude 'map' image, principally to differentiate high and low altitude grassland classes.

An unsupervised approach to image classification, using ERDAS software, was employed to generate training statistics for classification. The unsupervised classification operates on the assumption that homogeneous land cover types will produce specific spectral signatures. However, instead of using the spectral signatures of

Table II Spatial comparison over Grampian Region of LANDSAT TM and LCS88 Land Cover agricultural classes and AVHRR classes.

AVHRR class	LANDSAT agric. percent.*	SOEnD agric. percent.*	Nitrate loss. Grampian regression**
1	84.04	84.19	19
2	8.00	8.75	3
3	0.53	0.00	2
4	94.94	89.89	23
5	8.00	6.57	3
6	0.53	0.00	2
7	80.28	75.49	17
8	88.36	68.91	20
9	56.67	30.66	11
10	68.80	46.08	14
11	33.33	37.15	6
12	26.09	42.08	5
13	59.76	54.20	12
14	82.38	77.59	18
15	90.11	88.03	21
16	86.02	85.44	19
17	92.46	83.15	22
18	52.68	45.95	10
19	24.24	28.75	5
20	2.41	2.17	2
21	11.11	12.03	3
22	45.79	58.67	9
23	0.00	0.00	2
24	76.25	64.18	16
25	85.87	87.62	19
26	0.00	0.00	2
27	0.53	0.00	2
28	79.26	63.93	17
29	80.00	92.71	17
30	1.26	0.38	2
31***	0.00	0.00	0
32	32.75	27.75	6
33	0.53	0.09	2
34	8.00	2.94	3
35	36.79	58.03	7

* Correlation between LANDSAT TM and LCS88 agricultural cover classes is 0.964

** Loss in kg/ha-yr

*** Urban areas - nitrate not estimated

known areas on the image, or a supervised approach, this technique seeks to identify clusters within the spectral characteristics of the whole dataset.

The unsupervised clustering produced a total of 30 spectral classes. The statistics derived by the clustering algorithm were then used in a minimum distance algorithm to classify the original image data bands into one spatial classification of 30 spectral classes. With the 1 km resampled (500 m) AVHRR image used, these classes may be defined as areas with similar mixes or dominance of cover types, as it is rarely possible to attribute these large pixels to pure areas of one cover type.

Water bodies and urban areas were masked out using a preliminary 500 m resolution dataset from the LCS88 project. As with the LANDSAT TM imagery used in the regional study, there was a need to eliminate classification confusion between agricultural bare soil and semi-natural species, especially rough grazing areas with dead and decaying vegetation on the surface. Therefore a further 'map' image masking was undertaken using the agriculturally suitable and unsuitable soil 'map' image derived from the 1:250 000 soil map (MISR, 1983b). This resulted in a final classification of 35 land cover or area 'types'.

Estimation of Ground Cover Proportions

The most satisfactory thematic classification is a result of large areas of homogeneous cover types or where each ground resolution element (pixel) is allocated exclusively to a known category. This is, however, rarely the case and often the thematic classification is a poor representation of reality. One of the most obvious examples of this is where the area on the ground viewed as a single pixel is very much greater than the natural size of ground cover units. Many recent studies have examined ways of modelling the percentage reflectance contribution from each cover type within a pixel (Settle and Drake, 1993). In this study we are fortunate in having 2 complete land cover classifications covering the Grampian Region, an area corresponding to approximately 11% of our national AVHRR classification. A direct comparison of cover classes was therefore possible without having to estimate the percentage contributions.

Using the GIS overlaying technique, a complete spatial comparison of the Grampian Region study area was made using LCS88 data, LANDSAT TM agriculture and non-agriculture cover types with the AVHRR cover classes. This comparison provided a measure of the agriculture dominance or intensity within each 500 m AVHRR pixel (Table II). The overall correlation coefficient between the LANDSAT TM agricultural cover and the LCS88 agricultural cover for AVHRR cover classes was a very satisfactory 0.964.

National Nitrate-N Loss Estimates

The main aim of this study was to test the use of AVHRR data to extend a LANDSAT TM derived regional NO_3-N loss estimator to a national level. It was decided therefore, to use the LANDSAT TM agricultural percentages to model AVHRR pixel class values. Using these percentages and Equation (3), NO_3-N losses (kg/ha-year) for each AVHRR class were calculated, converting the AVHRR classification into a NO_3-N loss thematic map image. Using GIS overlay and summary techniques on other Region, District and River Board map images, administrative comparisons were made. AVHRR average NO_3-N loss (kg/ha-year) and NO_3-N loading (tonnes/ year) statistics for each Scottish Region as well as River Boards are presented in Table III. The average NO_3-N loss (kg/ha-year) for Scottish Districts is illustrated in Figure 1.

Table III Nitrate loads and losses for Scottish Regions and River Purification Boards from AVHRR land classes and Grampian long term estimator.

Regions and River Boards	AVHRR areas (sq. km)	Urban areas (sq. km)	Total NO_3-N loadings (tonnes/y)	Nitrate loss (NO_3-N) (kg/ha-y)	NO_3-N loss in non-urban areas (kg/ha-y)
*Western Isles (W. Isles RPB)	2205	7	740	3.4	3.4
Highland	24400	50	10650	4.4	4.4
Grampian	8665	174	8750	10.1	10.3
Tayside	7440	133	6715	9.0	9.2
Fife	1280	111	1885	14.7	16.1
Lothian	1685	234	1850	11.0	12.7
*Borders (Borders RPB)	4710	41	4940	10.5	10.6
Central	2580	97	2395	9.3	9.6
*Strathclyde (Clyde RPB)	12875	715	9700	7.5	8.0
*Dumfries & Galloway (D & G RPB)	6265	65	6135	9.8	9.9
Highland RPB	22085	72	9800	4.4	4.5
North-east RPB	10980	182	9830	9.0	9.1
Tay RPB	8175	157	7880	9.6	9.8
Forth RPB	4810	416	4965	10.3	11.3

*Region also River Purification Board (RPB)

NB., AVHRR areas exclude water bodies and may differ from official area statistics

The total NO_3-N loading from surface waters for Scotland, excluding Orkney and Shetland, is 53 750 tonnes/year ±6720 tonnes/year (based on 1980–1986 long term averages). This is the equivalent to some 7.5 kg/ha-year, and at 1983 NO_3-N prices, the same year as the Royal Society figures and the 1980–1986 mid point, represents a resource loss of approx. £17.2 million. The model is for non-point source losses, and in Table III the regional and river board estimated losses are given for total land areas and areas excluding urban areas. For most administrative areas, especially where urban areas are a small percentage of the total area, the

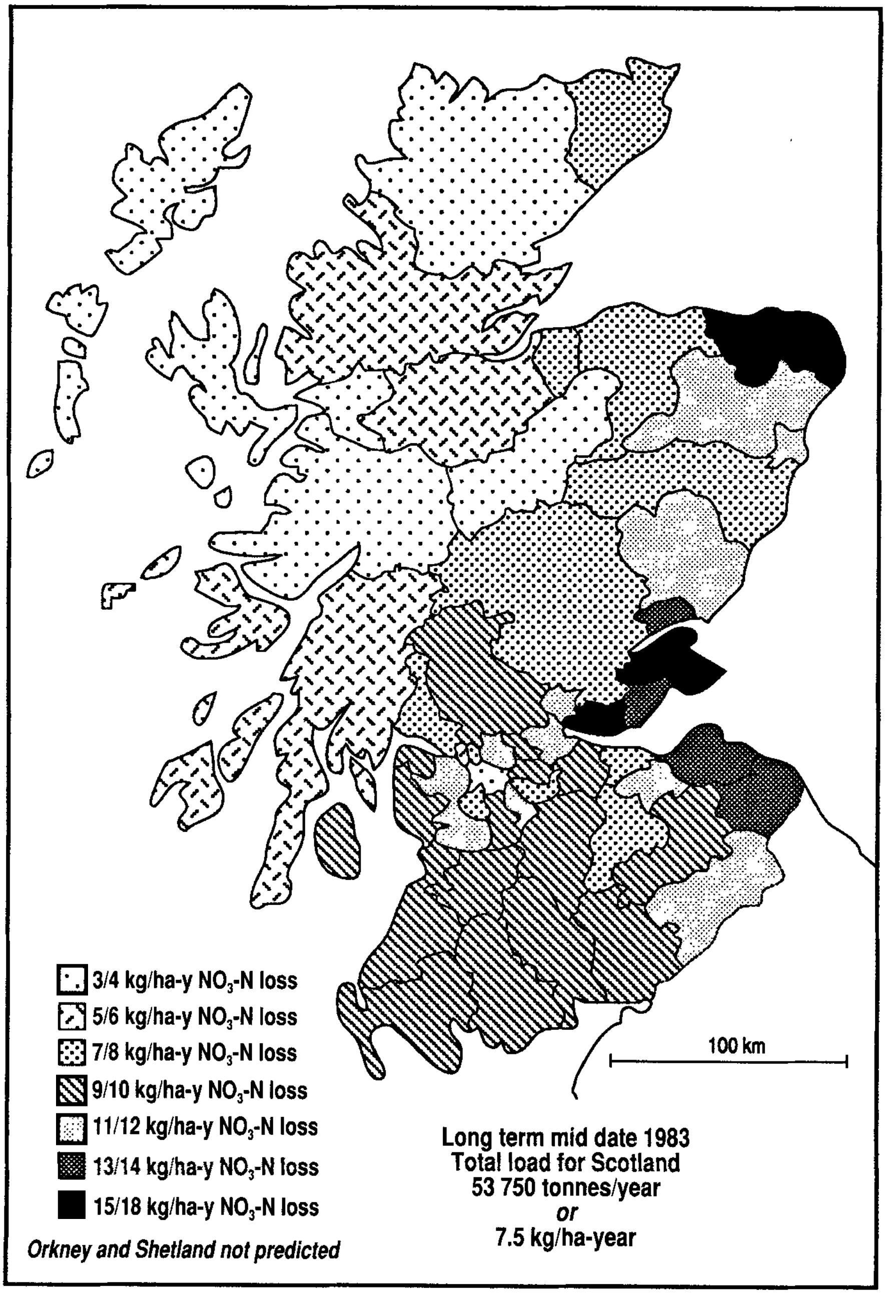

Figure 1 Estimated (long term – 1983 mid point) NO_3-N losses using AVHRR satellite imagery and Grampian Region regression estimators.

difference is minimal. However, for Fife and Lothian Region the difference is quite large and the value for non-urban land suggests the need for some concern in these regions with a NO_3-N loss twice the national average. In Figure 1, these Regional trends are separated into District patterns and it is the agriculturally important east coast districts which show the highest losses.

DISCUSSION

Model Assumptions and Limitations

At this stage it is important to note that point source loadings, such as urban and factory areas, form a small and insignificant part of the regional catchments used in these calculations. In the North East these areas are normally outwith the catchment boundary associated with the flow and chemical sampling points, but where they are within a catchment, they were assigned to non-agricultural classes. The variable NO_3-N input for livestock as manurial products is also assumed to be part of the measure of agricultural intensity as represented by the aggregated average agricultural area class.

This pilot study assumes that other variables such as soil type, regional variation in average fertilizer application rates as opposed to differences between crop type, and rainfall variations are responsible for only a small percentage of the national variation in average agricultural NO_3-N losses. As the current Grampian Model (II), Equation (3), accounted for nearly 97% of the variation using an aggregated average agricultural cover type, these assumptions appear to be acceptable.

The annual rainfall range from catchments in the model was 600 to 2000 mm. Only areas with very little or no agriculture exceed these values and might be expected to have NO_3-N losses of only 1 to 3 kg/ha-year. This situation is no different to that found across Scotland. Using loadings to estimate NO_3-N losses in both the regional and national part of the study, some of the variation which may have been due to rainfall is reduced.

The survey of fertilizer practice between 1983 and 1989 (SFPS, 1989) showed that with a national average of 124 kg/ha-year $\pm 3\%$, regional variation in the average application of fertilizer N in Scotland was $< \pm 7.5\%$. The north-west, with large areas non-agricultural rough grazings, had the greatest negative variation (100 kg/ha-year) with the largest positive variation occurring in Fife (147 kg/ha-year) and Lothian Region (134 kg/ha-year). However, considerable variation in the amount of fertilizer applied to different crops may be reflected in losses from grassland, or winter and spring crops, which are hidden in the average or aggregated agriculture NO_3-N losses.

Validation and Improvement

National evaluation of the predicted Scottish NO_3-N losses is a problem, for very few regionally and nationally collated NO_3-N loading values exist to test the predictions. However, regional assessments made so far are of the same order of magnitude and similar to values published by some river authorities (e.g. NERPB, 1993). In respect of the assumptions made above, and the need for further validation of the national picture, the results presented here should be interpreted as showing trends in NO_3-N loss, rather than absolute values at this stage.

How might the method and results be improved? For initial examination of this method, only one classification technique and set of AVHRR data has been used to provide the national assessment of agricultural intensity. Examination of the use of multi-temporal imagery and a variety of classification techniques may help to produce a more robust land cover classification. Validation with river analysis results of a year more appropriate to the AVHRR imagery used would help to produce a classification where absolute values may be used with more confidence. If possible, the issue of different farm cropping patterns, such as grassland and arable (winter and spring crops) systems needs to be addressed. This may be achieved by comparing district or parish AVHRR land cover summaries with agricultural census information. Many of these parameters and others such as soil types continue to be addressed as part of the current research.

IMPLICATIONS

This study was not intended to produce a complete and accurate model at this stage, but comparison with documented results have indicated a true potential for AVHRR data and this approach, especially in areas with poor quality land cover information. The data presented here were taken from a variety of conventional and remotely sensed sources as well as maps of varying scales, and had not been collected specifically with the present study in mind. For this reason the data are not as comprehensive or robust as the author might have wished. The approach does, however, allow the expansion of the model and enable identification of potentially 'high risk' or vulnerable areas relative to other areas, which may be further examined with a more detailed survey, therefore meeting the aims of the study.

National NO_3-N Loadings

An estimate of the total 1980 NO_3-N loading to the seas surrounding the UK from non-point sources was of the order of 202 000 tonnes/year (Goodman, 1981 and Royal Society, 1983). From England the nitrate loading was 146 000 tonnes, representing in financial terms a loss of approximately £43.80 million (1980 prices), Wales 18 500 (£5.55 million) and Scotland 37 500 (£11.25 million). These results were obtained from the Department of the Environment water authorities' and river purification boards' sampling programme, the Harmonized Monitoring Scheme. Because only about 60% of the area in England and Wales is drained by rivers in the harmonized scheme and some 50% in Scotland, it could be argued that these figures should be increased proportionately (Rodda, J.C., 1981). AVHRR predicted values for Scotland, using the long-term nitrate loss predictor (1980–1986, with 1983 as mid-term), gave a total of 53 750 tonnes (£17.20 million 1983/1984 prices). This represents a NO_3-N loading increase of 43% and a 53% increase in financial terms (based on fertilizer N prices) compared to the 1980 figure.

Fife Region appears to give cause for concern (average nitrate loss 14.7 kg/ha-year), but its contribution to the marine loading is small. In terms of surface water

NO_3-N loadings to the marine environment, those from Highland, Grampian and Strathclyde account for over 54% of annual Scottish losses. Highland and Strathclyde Regions form 34 and 18% of the Scottish land area respectively, with average NO_3-N losses of 4.4 and 7.5 kg/ha-year respectively. Grampian, with only 12% of the Scottish land area, accounts for over 16 percent of the Scottish total NO_3-N loading or 10.1 kg/ha-year.

The model assumes fertilizer N application rates of 124 kg/ha-year (SFPS, 1989) and suggests complete agriculture cover would result in a 29 kg/ha-year NO_3-N loss, with nonagricultural losses of 1.6 kg/ha-year. Although not directly related, if this loss were reduced completely; it would allow a 23% saving in the amount of fertilizer applied. This figure is also within the range (20 to 60%) quoted by Carey (1985) of fertilizer unaccounted for by isotopic studies.

Nitrate Sensitive Areas

The investigation has shown that an AVHRR cover classification, linked to a NO_3-N loss estimator, is capable of providing a spatial pattern of NO_3-N losses and identifying NSAs. The study is capable of providing satisfactory values for average NO_3-N losses from the agricultural intensity estimate of a pixel, providing boundaries of low to high losses. At a regional level, Fife, Lothian and Grampian have been identified as high loss areas. Fife and Lothian Regional losses may be partially explained by a greater than the national average fertilizer N application, 147 kg/ha-year and 134 kg/ha-year respectively.

Examination of the district map (Figure 1) enables a finer assessment to be made. Based on national average fertilizer application rate (124 kg/ha-year) used in the model, the City of Dundee, North East Fife, East Lothian and Berwick are the most sensitive districts, with apparent NO_3-N losses estimated to be twice the Scottish national average. Losses almost as high are calculated for Banff and Buchan, Kirkcaldy and Midlothian. These estimates could easily be summarised at a parish or catchment level, thus producing a more refined pattern by which to identify potential NSAs.

Investigation of the impact of NO_3-N losses and the use of the remotely sensed data and spatial analysis techniques to model the relationship with agriculture continues. There is a need to examine further seasonal effects, soil types under different crop practices, as well as different cropping practices and other non-agricultural cover types such as forestry.

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