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Landscape, regional and global estimates of nitrogen flux from land to sea: Errors and uncertainties

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Abstract. Regional to global scale modelling of N flux from land to ocean has progressed to date through the development of simple empirical models representing bulk N flux rates from large watersheds, regions, or continents on the basis of a limited selection of model parameters. Watershed scale N flux modelling has developed a range of physically-based approaches ranging from models where N flux rates are predicted through a physical representation of the processes involved, through to catchment scale models which provide a simplified representation of true systems behaviour. Generally, these watershed scale models describe within their structure the dominant process controls on N flux at the catchment or watershed scale, and take into account variations in the extent to which these processes control N flux rates as a function of landscape sensitivity to N cycling and export. This paper addresses the nature of the errors and uncertainties inherent in existing regional to global scale models, and the nature of error propagation associated with upscaling from small catchment to regional scale through a suite of spatial aggregation and conceptual lumping experiments conducted on a validated watershed scale model, the export coefficient model. Results from the analysis support the findings of other researchers developing macroscale models in allied research fields. Conclusions from the study confirm that reliable and accurate regional scale N flux modelling needs to take account of the heterogeneity of landscapes and the impact that this has on N cycling processes within homogenous landscape units.

Introduction

In developing any model to simulate environmental behaviour the primary step is to determine the questions it needs to answer and the scale, both spatial and temporal, at which the answers are required. In the case of global N cycling the impetus to construct models is both to aid our understanding of global N cycling rates and processes, and to provide a means of assessing the origins of terrestrial, freshwater and oceanic N enrichment resulting from anthropogenic disruption of the global N balance. Oceanic N enrichment has both direct ecological consequences in the oceans and wider implications for global climatic function through the coupling of ocean-climate systems and the disruption of the global N balance (see for example, Larsson et al. 1985; Jaworski et al. 1989; Turner & Rabelais 1991; Law et al. 1992; Nixon 1995; Vitousek et al. 1997). There is, therefore, a need to develop models with the ability to distinguish accurately both the total rates of N flux from land to ocean, and the specific spatial origins and delivery zones of the N load. Associated with this requirement for spatial discrimination of N flux sources is a requirement for some estimate of the relative accuracy of the gross N flux estimates and the attribution of this flux to specific terrestrial or atmospheric sources.

A range of regional to global scale N flux models have been developed to date (see for example Meybeck 1982 as adapted in Seitzinger & Kroeze 1998; Peirls et al. 1991; Howarth et al. 1996; Seitzinger & Kroeze 1998; Caraco & Cole 1999). Each has been designed to generate an estimate of annual N flux from land to ocean from the major contributing areas on a country by country or continent by continent basis, and each provides different estimates of N flux to oceans from these contributing areas. In each of these models a subtly different selection of parameters is employed to describe the rate of N flux from land to ocean as it varies over 3–4 orders of magnitude across the globe (see discussion in Alexander et al. 2002, for details). The goodness-of-fit of each model is then reported as a function of the r^2 value of a regression relationship between observed and predicted N flux rates for a selection of major world rivers. Given the magnitude of variation in N flux rates globally it is not, perhaps, surprising that a good fit with a high r^2 value is reported for most of the models. Thus it could be argued that these models provide a reasonably good indication of the general rates of N flux from land to ocean on a global scale. What is not clear, however, is which of these models is providing the most robust and reliable estimates of N flux rates from land to ocean, and whether the regional or watershed scale estimates generated by these models are providing a reliable indication of the rates of N enrichment experienced locally by the biota in adjacent coastal waters.

In plot to catchment scale modelling the accuracy and precision of model predictions is normally ascertained through calibration and validation of model estimates against a known measure of environmental behaviour, typically field monitoring data. In physically based models ranges of values represented by the probability density function (PDF) can be generated for each model parameter based on assumptions about the likely statistical distribution of values for that parameter, under local and current environmental conditions (see, for example, Entekhabi & Eagleson 1989; Bergström & Graham 1998). Approaches such as Monte Carlo simulation within the range of uncertainty for the model parameters or the sectioning method of Addiscott and Wagenet (1985) can then be used to generate an estimate of the mathematical uncertainty associated with model predictions and the sensitivity of the model to its parameters. However, even with the statistical checks and balances possible in plot to catchment scale model development there remains the problem that the relationships between processes and controlling environmental conditions are usually observed in few spatial locations and over short periods of time. As Blöschl and Sivapalan (1995) argue these relationships are often used to form the basis of model equations describing system behaviour over a wider spatial scale and/or longer periods of time. In both cases the original observations may be insufficiently representative of the true range of variation in environmental behaviour of those parameters. Thus there is an element of uncertainty associated with the application of these parameter values to other watersheds or regions if the conditions in those systems do not directly mimic those in the original modelled catchments. As a result, upscaling of parameter ranges from plot or watershed scale to regional or global scale cannot be justified without some estimate of the relative accuracy of model output owing to the unknown and variable nature of the uncertainty associated with the model parameter ranges. Addiscott and Tuck (1996) also argue that the validity of model parameters depends on the range of values for each parameter remaining constant in time. In the case of process equations developed for physically-based models this may be a valid assumption to make given the temporal and spatial scales over which the model is expected to operate. However, for models used to generate hindcast or forecast estimates of environmental behaviour and for regional to global scale models where N flux rates are described by simple indices of human population density and extent of economic development, such assumptions would be unlikely to hold true over the spatial and temporal scales of operation for these models.

So what is the solution? How can we develop an index of robustness or a measure of the uncertainty associated with N flux estimates generated by the various regional to global scale models? The very nature of the spatial scale at which existing global N cycling models operate means that there is no robust means of validating model output against field monitoring data. Even where measurements of total N concentrations have been collected for major world rivers or estuaries, the physical scale of such water bodies means that fully representative water sample collection both in space and time is prohibited within the confines of present technology. There remains, therefore, a high level of uncertainty associated with the N flux estimates generated by these regional to global scale N cycling models.

One means of assessing model performance is to run a cross comparison of the N flux estimates generated by the regional to global scale models against predictions of N flux produced by validated watershed-scale models for data-rich areas of the world. On the basis of relative model performance, guidance can then be given on the likely errors associated with the regional and global scale models, and the limits to their robust application although as Addiscott (1998) argues, validation at one spatial or temporal scale does not confirm model validity at other scales. Alexander et al. (2002) attempt to address this question by conducting a multi-way inter-model comparison for a range of the regional to global scale N flux models compared with model estimates generated by a validated watershed scale model (SPARROW: see Smith et al. 1997) and observed N flux rates for 16 of watersheds draining the NE United States (see also Boyer et al. and Van Breemen et al. both 2002). Most of the models compared in this exercise are less than reliable in predicting watershed scale variations in N flux rates, but in terms of its representation of within-region variations in N flux rates the model developed by Howarth and colleagues (1996) for prediction of N flux to the North Atlantic Basin from its major watersheds is undoubtedly the most robust and reliable (see Alexander et al. 2002, for details). It is not perhaps surprising that this is also the most complex of the regional to global scale models, with the greatest range of model parameters. In a multi-way inter-model comparison of N flux models applied to the watersheds of nine shallow estuaries on Cape Cod, MA, Valiela and colleagues concluded that the more complex models performed better than the simpler models (Valiela et al. submitted).

For the simpler empirical models of N flux developed for global scale application and often based on an upscaling of concepts developed to explain watershed scale response, a poorer performance is also evident when model estimates are compared with observed N loading data for individual watersheds. Thus, for example, Seitzinger and Kroeze (1998) took the watershed scale model developed by Caraco and Cole (1999) and scaled this up for application on a 1° × 1° grid, using global databases. This upscaled model predicts an average DIN flux rate from England to coastal waters of 0.1 kg N ha^{-1} (reported as 10 kg N km^{-2} watershed yr^{-1}), whereas the rate calculated from a watershed scale model for the U.K. (this paper) validated against historical N flux observations for 38 U.K. watersheds, estimates an average total N flux rate of 26.4 kg N ha^{-1} from England to its coastal waters in 1991. Seitzinger and Kroeze (1998) then applied their modelled estimate of 0.1 kg N ha^{-1} as DIN flux for England to the watershed area of the U.K. Tamar Estuary (a watershed too small to be explicitly defined the 1° × 1° grid of their model adaptation) to allow subsequent calculation of N_2O emission rates from the estuary. Whilst Seitzinger and Kroeze (1998) report the resultant N_2O flux rate of 5×10^3 kg N yr^{-1} as being within a factor of 5 of emission rates measured for the Tamar Estuary by Law et al. (1992), the

N loading rate is a factor of 280 lower than the observed nitrate loading rate of 28 kg N ha^{-1} for the Tamar at its upper tidal limit (Uncles et al. in press). The total N flux rate to the upper tidal limit of the Tamar calculated by the validated watershed scale model is 39 kg N ha^{-1} (Uncles et al. submitted). Conversely, in the application of their model at watershed scale to 35 major world rivers, Caraco and Cole (1999) report a predicted 11.2 kg N ha^{-1} of nitrate export from the U.K. Thames watershed per year. Given detailed observations of the proportion of nitrate contributing to the total N load in the River Thames and its tributaries (nitrate = 60% total N; Johnes 1996; Johnes & Burt 1991), the Caraco and Cole model estimate converts to a total N export rate of 18.7 kg N ha^{-1} yr^{-1}. This compares reasonably well with the total N loading predicted by the validated watershed model (Johnes 1996; this paper) for the Thames watershed, which estimates total N flux from the Thames watershed as 22.1 kg N ha^{-1} in 1991. Thus there are marked differences in the level of agreement between the Caraco and Cole (1999) model compared to the watershed-scale model application to the Thames watershed, and the global scale Seitzinger and Kroeze (1998) model adaptation predictions for the Tamar watershed compared to both the watershed-scale model application to the Tamar Watershed and observed N flux data for the River Tamar.

The cause of these differences lies, probably, in the fact that the 1° × 1° resolution adopted by Seitzinger and Kroeze (1998) to allow global scale application led to a loss of valuable spatial resolution and precision in both the input data and model parameter values, whereas the original Caraco and Cole (1999) model was designed to be applied at major watershed scale, taking account of sub-grid scale spatial variations in the model parameter values. The difference in estimates of N flux to the Tamar estuary generated by the two models derive from the spatial scale of the modelling unit. In the Seitzinger and Kroeze (1998) model, input data and model parameter values are averaged for each 1° × 1° grid cell and the model is not physically based and cannot take account of sub-grid scale variations in the dominant process controls on N cycling and flux. In their application of this model to the Tamar estuary, the average estimate of N flux for the 1° × 1° grid cell within which England lay was assumed to provide a reliable estimate of N flux rates for the 924 km^2 Tamar catchment. In the validated watershed scale model, the basic modelling unit is the parish, an administrative unit averaging 14 km^2 in area and the model is physically based. Model estimates of N flux from each parish unit within any watershed are then lumped together to generate a watershed scale N flux estimate, allowing local variations in the dominant process controls on N flux rates to be taken into account. However, the precise nature of the poor fit between the N flux estimates generated for the Tamar estuary cannot be conclusively assigned from this simple comparison.

As Troutman (1983) argues there are two basic forms of modelling error. First there are errors where, although the input data are correct and provide a robust representation of the true environmental behaviour and variability of each model parameter, the model itself as a simplified representation of true systems behaviour is insufficiently detailed or fails to describe within its structure the dominant process controls at a particular spatial scale. These might be termed *process errors*. Second there are errors generated where the model is appropriately parameterised for the questions it has been constructed to answer at the selected spatial and temporal scale of application. In this case the errors then arise from incorrect input data describing the environmental behaviour of model parameters at the selected spatial or temporal scale, either through inaccurate field measurement or observation, or incomplete representation of the statistical properties of the distribution for each parameter over the range of environments to which it has been applied. These might be termed *input errors*. In the case of the simple empirical models developed to date to describe regional to global scale patterns of N flux from land to ocean both forms of error are likely to be present to some extent. This does not mean that these models are necessarily inappropriate if they are used solely to answer some of the macroscale questions relating to the global N cycling imbalance, particularly where they are used to assess the general origins of oceanic N enrichment and the spatial patterns in N flux as they vary from continent to continent. Indeed, as Arnell (1999) argues, the increasing interest in answering macroscale questions relating to environmental function and response over wide geographic domains requires the development of models capable of being applied at the macroscale without watershed scale calibration. However, Arnell also argues that if we wish these models to have a reliable predictive capability, then they need to be based on a physical representation of the processes involved. In this case, some of the simpler descriptive models of N flux produced to date, lacking any physically based description of the environmental controls on N cycling and flux processes within landscapes, would be unsuitable for use as tools to evaluate the specific spatial origins of oceanic N enrichment or the likely impact of management strategies to ameliorate the rate of N flux to the oceans.

Thus the primary source of error and uncertainty associated with the existing regional to global scale N flux models appears to be generated by the spatial scale or grid at which the models are applied, and the fact that none of these models is physically based. Because they are not physically based, they cannot take account of subgrid scale or landscape scale variations in local environmental controls on the dominant processes controlling N cycling and flux within particular terrestrial or freshwater environments.

They cannot, therefore, deliver spatially sensitive or robust estimates of N flux at the subgrid or landscape scale.

This problem is not restricted to N cycling models, but has been exercising scientists developing global climate and water balance models and, in particular, the hydrological components of these models for some time (see, for example, Entekhabi & Eagleson 1989; Federer et al. 1996; Bergström & Graham 1998; Vörösmarty et al. 1998; Boulet et al. 1999). As Boulet and colleagues (1999) argue regional land surfaces are not necessarily homogenous in terms of the processes controlling regional water balance components, and in their analysis the simple 1-dimensional SISPAT model described by Braud et al. (1995) showed a non-linear response to the spatial variability of particular parameters when upscaled to regional scale. They suggest that this heterogeneity and the problems it generates when upscaling for macroscale application can be resolved by adopting a mosaic approach in which the land surface is divided into homogenous patches, with fluxes calculated for individual patches and then lumped together to give an aggregate flux rate for the region. Becker and Braun (1999) present a similar argument, based on case studies on scaling, disaggregation and aggregation in predicting hydrological response characteristics in watersheds in Northern Germany and Bavaria. They suggest, from their analysis, that the subdivision or disaggregation of the land surface into smaller units displaying homogenous or quasi-homogenous hydrological behaviour is critical to the development of appropriate models for macroscale hydrological modelling. This argument is equally pertinent when applied to the development of solute flux models. They also argue that the behaviour of these units, which they term hydrotopes, needs to be modelled separately using unit-specific parameter values, with the calculated unit fluxes then aggregated to regional scale. They demonstrate the veracity of their contention by comparison of the errors generated where models or their parameters are extrapolated to run across large heterogenous landscape units. Similar arguments have also been presented at much finer modelling scales, as exemplified by the work of Famigletti and Wood (1995) who explored the effect of explicit patterns of environmental characteristics on areally averaged evapotranspiration at scales ranging from local to watershed scale. They concluded from their analysis that a threshold spatial scale could be defined for evapotranspiration modelling, termed the Representative Elementary Area (REA), below which fine scale spatial variations in the environmental factors controlling evapotranspiration rates would be important in describing watershed scale evapotranspiration fluxes, but above which the natural variability of environmental factors could be represented by PDFs describing the statistical distribution for each parameter. If this argument is applied to modelling in general, then the size of the REA, hydrotope, or landscape unit which can be defined as homogenous for the purposes of model application will be dependent on the dominant process controls operating on the modelled variable and their variance at the particular spatial or temporal scale at which the model is being developed.

Increased N loading results in deleterious impacts on coastal systems (such as the increased incidence and duration of anoxic/hypoxic events, and the decline of eel grass coverage). In order to effectively manage N enrichment of coastal waters, a tool is needed which can predict reliably the spatial variation in N delivery to the oceans, probably from individual watersheds as they drain to major estuaries, constricted coastal waters such as the Baltic Sea, the North Sea or the Gulf of Mexico, or directly to the oceans. For this, simple descriptive models based on regression of measured TN loading against a limited range of parameters in a limited range of environments will be insufficient for the purpose. Thus a model which provides an estimate of N flux to coastal waters as a function of the range of economic activity and agricultural intensity across a selection of major world rivers is unlikely to be able to distinguish between the rates of N flux to coastal waters generated directly as a result of high intensity agricultural production, as opposed to similar N flux rates generated where there is lower intensity of agricultural production but a lower intrinsic N retention capacity within the landscape (as a function, for example, of wetter winters, steeper slopes, impeded drainage). Instead, models which include a wider range of parameters reflecting environmental sensitivity to N flux are required. If a landscape unit can be defined as a spatial unit representing similar functional behaviour then representation of N flux at regional to global scale may be improved by defining a series of landscape units, modelling these separately with unit-specific parameter values and then lumping the model estimates together to provide regional to continental scale predictions of N flux. If this approach were to be adopted for regional to global scale N flux modelling the critical principal is that the landscape units need to be defined as homogenous in terms of the key controls on N cycling if they are to represent a valid unit for modelling. The units should never be defined by traditional political, cultural or socio-economic divisions (nations, for example), as these will rarely represent homogenous landscape units as they respond to N cycling and flux.

Another issue which arises is how the REA can be determined for regional to global scale N flux modelling, or at what level of spatial resolution the landscape units should be defined. Many of the data sets used by the existing regional to global scale N flux models have constrained these models to run at national or major watershed scale by virtue of the fact that the databases on which these models are reliant are widely available only for individual and well-researched major watersheds, usually within the developed world, or for individual nations within FAO and other statistical compilations. To avoid this constraint a landscape unitary approach would need to construct databases from the primary data sources from which these national statistics were derived. However, the original scale at which the data were collected may well, in many instances, be too fine for sensible application at regional to global scale. In the U.K. , for example, detailed statistics relating to agricultural land use and livestock production have been collected annually from 1866 to date and are available for the entire agricultural area of the U.K. in units termed parishes, each parish representing an area of land averaging 14 km^2 in area. Clearly this is too fine a scale for application across the entire global land surface. As a result, some upscaling is required if these data are to be utilised at regional to global scale. This in itself introduces a further range of issues relating to the order in which model parameters are averaged, interpolated or aggregated and the error and uncertainties that this scaling introduces to model estimates of N flux. As Addiscott and Tuck (1996) argue averaging or interpolating a parameter before running a non-linear model does not give the same result as running the model and then averaging or interpolating the results. This discrepancy between interpolating the output and interpolating the parameter is important because it raises an uncertainty in simulations. Stein et al. (1992) investigate this further. Sivapalan and Kalma (1995) raise a similar issue, arguing that the difference between lumping (aggregating) the entire mosaic of units across a landscape as opposed to representing the land surface as a combination of units acting in parallel may generate different modelling outcomes and further uncertainty in model estimates. Thus as we scale up from parish scale to major watershed or landscape unit scale, in U.K. terms, the sequence of modelling steps will be critical in determining the level of error and uncertainty associated with our ultimate regional scale N flux estimates.

In this paper we investigate the nature of the errors and uncertainties generated by upscaling in N flux models, utilising a watershed-scale model which utilises the major geoclimatic regions of the U.K. as the basis for assigning region-specific values to the model parameters to generate estimates of N (and P) flux from land to water at parish to watershed scale. The model used was the National Export Coefficient Model developed by Johnes and colleagues at the Aquatic Environments Research Centre, U.K. (for details see Johnes 1996; Johnes et al. 1996; Heathwaite & Johnes 1996; Johnes & Heathwaite 1997; Johnes & Hodgkinson 1998; Johnes et al. 1998a, 1998b; Johnes 1999; Johnes et al. 2000; Johnes 2000; Uncles et al. in press). This has the benefits that it has been (a) rigorously calibrated and validated in numerous applications at the watershed scale including multi-way intermodel comparisons and (b) developed and then applied to entire landscape units in data-rich areas of the world, including a recent multi-way inter-model comparison conducted for the Cape Cod watersheds, U.S.A. (Valiela et al. submitted).

The export coefficient model

Export coefficient modelling is a watershed or catchment scale, semi-distributed approach which calculates mean annual total N (and total P) loading delivered to a water body (freshwater or marine) as the sum of the nutrient loads exported from each nutrient source in the catchment. The model equations and modelling procedures are detailed in full in Johnes (1996) and can be summarised thus:

$$L = \sum_{i=1}^{n} E_i \, (A_i \, (I_i)) + p$$

Where L = Loss of nutrients
E = Export coefficient for nutrient source i
A = Area of catchment occupied by land use type i, or Number of livestock type i, or of people
I = Input of nutrients to source i
p = Input of nutrients from precipitation

The export coefficient (E_i) expresses the rate at which nitrogen or phosphorus is exported from each land use type in the catchment. For animals, the export coefficient expresses the proportion of the wastes voided by the animal which will subsequently be exported from stock houses and grazing land in the catchment to the drainage network, taking into account the amount of time each livestock type will spend in stock housing, the proportion of the wastes voided which are subsequently collected and applied to the land in the catchment, and the loss of nitrogen through ammonia volatilisation during storage of manures. For human wastes, the export coefficient reflects the use of phosphate rich detergents and dietary factors in the local population, and is adjusted to take account of any treatment of the wastes prior to discharge to a water body using the following equation:

$$E_h = D_{ca} * H * 365 * M * B * R_s * C$$

Where E_h = Annual export or N or P from human population (kg a^{-1})
D_{ca} = Daily output of nutrients per person (kg d^{-1})
H = Number of people in the catchment

365 = Days per year
M = Coefficient for mechanical removal of nutrients during treatment (range 0.85–0.9, reflecting removal of 10–15% of the nutrient load)
B = Coefficient for biological removal of nutrients during treatment (range 0.8–0.9, reflecting removal of 10–20% of the nutrient load)
R_s = Retention coefficient of the filter bed (range 0.1–0.8, reflecting retention of 20–90% of the nutrient load)
C = Coefficient for removal of P if phosphorus stripping takes place (range 0.1–0.2, reflecting removal of 80–90% of the P load)

Initially based on models developed in eutrophication research in the 1980s, this approach has been developed, refined and tested on 38 U.K. catchments over the past 10 years in research programmes funded by the U.K. Natural Environment Research Council, the National Rivers Authority (NRA), the Environment Agency (EA) and the Ministry of Agriculture, Fisheries and Food (MAFF; now DEFRA, the Department for Environment, Food and Rural Affairs). The nutrient source categories taken into account are:

(a) the area of land cultivated for cereal crops, other arable crops, bare fallow land, permanent grassland, temporary (ley or rotational) grassland, and fertiliser N applications to this land, the area of rough grazing land (unfertilised), and the area of woodland, and the rates of N fixation to all crops, grass and non-agricultural land;
(b) the total number of cattle, pigs, sheep and poultry, including young animals, the average amount of N produced per animal annually, and the nature of animal waste handling;
(c) the total number of people, the average amount of N produced per person annually and the nature and extent of sewage and wastewater treatment facilities;
(d) N input to the catchment from atmospheric deposition.

In the U.K. detailed information is available for each of these nutrient source categories from the Annual Agricultural Census Returns (1866 to date), the Decadal Population Census (1851 to date), the Surveys of Fertiliser Practice commissioned by MAFF, roughly on a quinquennial basis (1969 to date), and detailed models of atmospheric N deposition developed as part of national research programmes on Surface Waters Acidification (SWAP) and Global Atmospheric N Enrichment (GANE) (see Whitehead et al. 1998; Johnes 1999 for further details). In addition to these data sources detailing the nature and extent of N sources within the U.K. landscape there are also routine monthly observations of nitrate and DIN flux in all 1400 major surface water catchments in England and Wales from 1973 to date, and sometimes for earlier periods, available from the Environment Agency Monitoring Programme archive, and continuous records of flow in these catchments from the Surface Water Archive extending over the same time period and earlier. In this sense, the U.K. can be described as a data-rich region for which it could not be argued that regional N flux models were limited in their reliability through inadequate description of nutrient sources. Development of the export coefficient modelling approach has benefited from this rich data archive on which the model has been constructed and tested.

This technique has been developed at a number of spatial scales to suit different management objectives. At its finest scale it has been applied to individual watersheds from 5 to 1200 km^2 in area. At its coarsest scale (this paper) it has been applied to the 3 major drainage basins of England and Wales, representing the watersheds draining to the North Sea (62318 km^2), the North Atlantic (77937 km^2) and the English Channel (10892 km^2). At its finest scale it uses the field as the spatial modelling unit, providing output on an annual basis, and has predicted within ± 5% of observed N (and P) loadings for all sites modelled at this scale. Recently, a simpler version has been developed for the U.K. Environment Agency for application at a national scale. In this, the model was adapted to allow estimates of N and P flux to be calculated for all watersheds within England and Wales without the need for basin-specific calibration in all 1400 watersheds. The model structure was simplified to run for a limited number of landscape units types sharing similar functional behaviour in terms of process controls on N cycling and flux. These were defined based on the major classes of geoclimatic region identified in the 1st Land Utilisation Survey of Britain (1931–1940). The landscape units or geoclimatic regions defined for England and Wales are shown in Figure 1. These represent areas with broadly similar climate, geology, soil types, topography and natural vegetation cover which have, therefore, similar ranges of nutrient export potential (and nutrient retention capacity) as a function of flow volume, timing and routing from land to stream. Generic sets of export coefficients (unit-specific parameter values) were derived for each of these geoclimatic regions, which could then be applied to parish scale census data for any parish lying within each region type. The coefficients were selected to reflect the intrinsic nutrient retention capacity of each region. The coefficients selected for each nutrient source in each region were validated in a rigorous multiple validation procedure (see Johnes et al. 1998b). The validated model is very robust, producing a close fit with observed data from water quality archives for a wide variety of landscape types and production systems (r^2 = 0.98 for both N and P for 38 catchments and >90 pairs of data). The 38

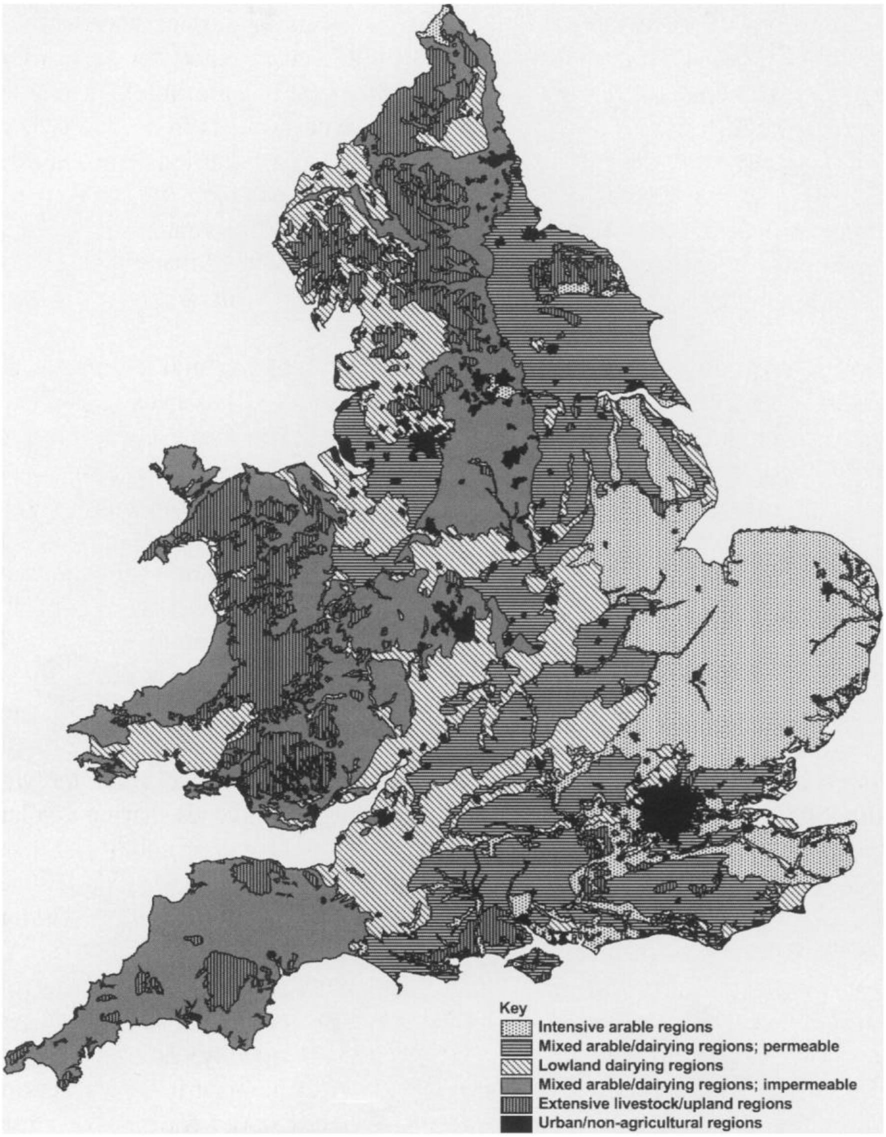

Figure 1. Characteristic Geoclimatic Region Types in England and Wales (after Johnes et al. 1998a).

catchments in which the model was validated against observed N flux data are shown in Figure 2, coded to indicate the dominant geoclimatic region type for each catchment.

In the Environment Agency project the model was run based on 1931 parish scale Agricultural Census data to provide a baseline estimate of N

Figure 2. Export coefficient modelling applications to surface water catchments in England and Wales.

(and P) flux to U.K. lakes against which to gauge the present extent of N (and P) enrichment of these waters (see Johnes et al. 1994, 1998a, 1998b for details). In work funded by MAFF the model was updated (see Johnes et al. 2000, for details). Parish scale Agricultural Census data for 1991 were run through the model to provide a direct comparison with the earlier 1931 model predictions, allowing estimation of the rates and sources of changes in N and P loss from agriculture to water over the past 60 years. Model output was separated into its contributing layers to indicate the relative contribution of different nutrient sources to the total N and P load exported from land to water. Overall, the export coefficient model predicted a 136% increase in N flux from England and Wales to coastal waters, from an average rate of 11.2 kg N ha^{-1} in 1931 to an average of 26.4 kg N ha^{-1} in 1991.

The parish scale output from the 1991 model run is presented in Figure 3, showing the spatial variations and patterning in N flux estimates generated by the model at parish scale and the total N flux rate for adjacent coastal waters. Clear patterns are apparent, with the lowest rates of N flux predicted for the upland areas of England and Wales which support low density sheep grazing on moorland and cattle grazing on the shallower slopes at the foot of the moors. This reflects the fact that despite the abundance of runoff (averaging 1200–2000 mm annually) and the relatively high proportion of overland flow and near-surface lateral quickflow generated across this region as a function of thin soils overlying impermeable bedrock with moderate to steep slopes, the landscape is used relatively un-intensively (in the U.K. context). Thus the high N export potential of these landscapes is not translated into high N flux rates. Low to moderate rates of N flux are predicted from the flat dry counties of East Anglia, despite the use of this region for intensive arable production with associated high rates of fertiliser N applications to crops and grass. This reflects the fact that despite a high rate of N input to this landscape, the flatness of the landscape and the low rates of runoff (averaging <200 mm per year) generate a low N export potential. The highest rates of N flux are estimated for the wetter hill country of the west of England and Wales with typical annual runoff rates of 500–1000 mm per year, where higher fertiliser application rates (averaging 200 kg N ha^{-1} applied annually to grassland), and high stocking densities for dairy and beef cattle production lead to a combination of high N input rates and high N export potential. The potential distinctions made by this form of modelling, based on the landscape unitary approach, are even greater than they appear in Figure 3 because this also takes account of the spatial distribution of people in England and Wales. As a coarse generalisation, human population density is highest in the flatter, drier lands of the south and east of the U.K. and lowest in the north and west. Thus very low N flux rates from non-point agricultural sources to the

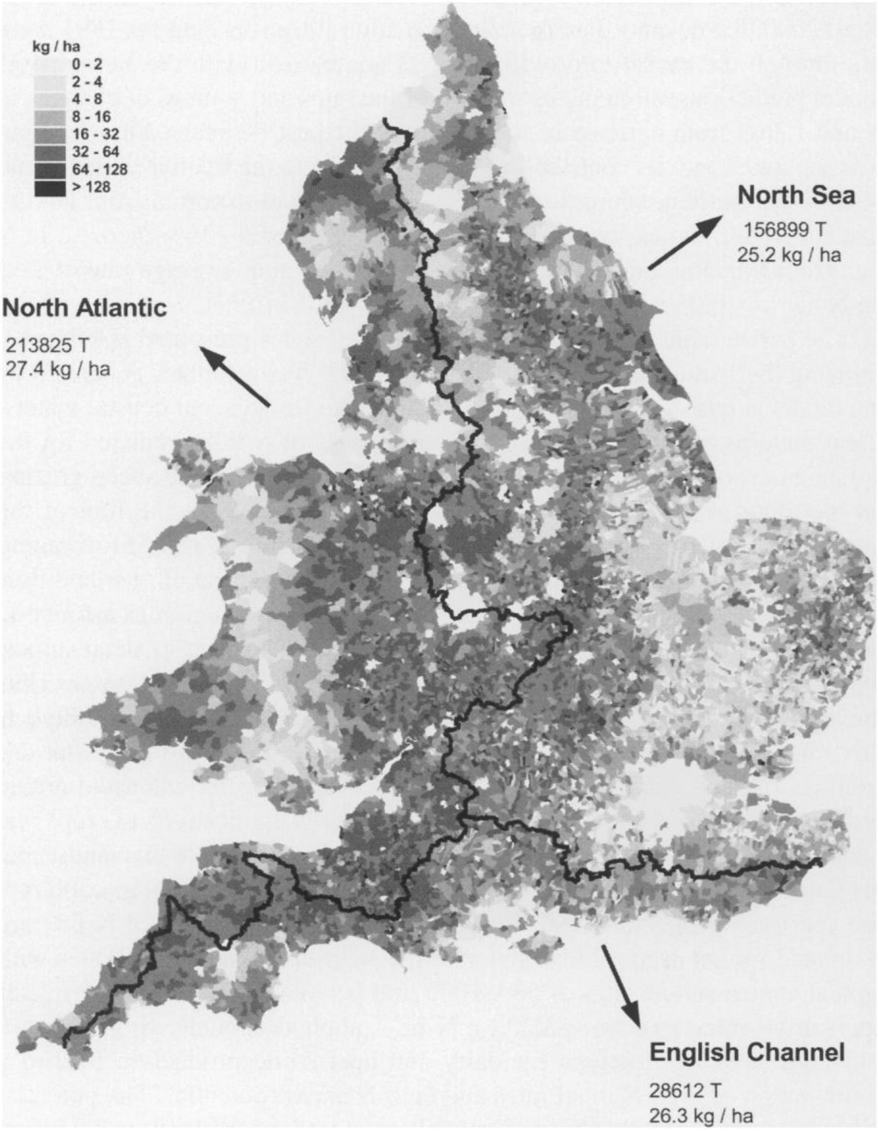

Figure 3. Export coefficient model prediction of TN export (1991) using 6 spatially distributed sets of export coefficients and parish scale input data. TN export to coastal waters calculated from aggregated parish scale TN export estimates.

North Sea and, to a lesser extent, the English Channel are compensated for in the average N flux rates to coastal waters shown in Figure 3 by higher N flux rates from the human population in each of these major drainage units. Lower population densities (generally) in the north and west mean that the total N flux estimate for the North Atlantic drainage unit is largely attributed to N flux from non-point agricultural and atmospheric sources.

The model makes a non-linear discrimination between the rates of N input to the system and the rates of N flux from land to stream by taking account of the intrinsic N retention or N export potential of the landscape of England and Wales. Within each of the regional sub-models the model is linear, but the overall national model is non-linear. The spatial distinctions that the model makes are important and real in terms of the observed rates of N flux from land to water within England and Wales, and provide valuable guidance for informing environmental management and government policy in relation to N (and P) flux from non-point and point sources to U.K. waters. The question then arises of how much of this spatial resolution would be lost, and what scale of error would be associated with N flux estimates generated by the model at watershed to regional scale if this landscape unitary approach, the spatial scale of the modelling units (currently parish scale) or the parameterisation of the model itself were to be simplified in line with the forms of model structure associated with existing regional to global scale models. In the existing model structure there are 7 classes of land use, for which fertiliser N input and N fixation rates are separately applied, atmospheric N deposition, and 4 classes of livestock, with people separately accounted for on a per capita basis. In addition there are further modifiers incorporated on a geoclimatic region basis, relating to the natural environmental characteristics of each region, particular land management practices, manure handling and management, and sewage treatment facilities. This degree of detail in accounting for N inputs to land and the intrinsic N retention capacity of landscape units is unparalleled in the existing regional to global scale models. How much of this detail would need to be retained in order to generate accurate, robust and spatially discrete estimates of N flux from land to ocean at regional to global scale is the subject of the scaling analysis conducted in this paper.

Quantifying the errors associated with upscaling from parish to regional scale

The export coefficient model was used, therefore, to estimate the errors and uncertainties inherent in the regional and global scale models as a function of scale. This provided an insight into the inherent errors built into the regional and global scale N models generated by scaling up from catchment scale studies to global applications. Two forms of scaling error have been investigated relative to their impacts on the accuracy of predictions of N flux to U.K. coastal waters (North Sea, North Atlantic, English Channel): (1) Spatial aggregation (lumping) of input data and model output and (2) Conceptual lumping of model parameters.

To achieve this the parish scale National Export Coefficient Model predictions of N export in England and Wales were systematically scaled up, coarsening either the scale of the input data, or the range of the export coefficients built into the model, or both. Parish scale units were aggregated to catchment scale, based on the 1400 watershed units routinely monitored by the Environment Agency (see Figure 2 for catchment boundaries). The spatial scale at which modelling took place was therefore scaled up from parish units averaging 1355 ha in area to catchments of an average 155 km^2 in area. These were then further aggregated, running the model using input/output units representing the major drainage basins of the England and Wales (e.g. the Thames basin, the Severn, the Trent, the Great Ouse and so on, averaging 18893 km^2 in area). The complexity of the model framework itself was also reduced, sequentially aggregating the source type categories and the degree of landscape sensitivity reflected in the number of different export coefficient groups, until the final model run used two categories of nutrient source (agricultural and non-agricultural land), one set of export coefficients for the entire land mass, irrespective of landscape sensitivity to N export and three spatial units: the major drainages to the North Sea, the North Atlantic and the English Channel. At each stage model output was then lumped together, based on the major drainage unit boundaries, to predict overall N flux from the land mass of England and Wales to the North Sea (62318 km^2), the North Atlantic (77937 km^2) and the English Channel (10892 km^2). In total, a matrix of 8 scales of spatial aggregation from the original parish scale model estimates with 5 sequentially aggregated sets of model parameters gave 40 different estimates of N flux from land to coastal waters for each of the 3 major drainage units. The forms of aggregation were as follows:

Spatial aggregation categories

1. *Lumped output (parish scale input data)*:
   TN export to coastal waters calculated from aggregated parish scale TN export estimates.
2. *Lumped output (catchments from parish output)*:
   Catchment scale export rates calculated from aggregated parish scale TN export estimates, TN export to coastal waters calculated from aggregated catchment scale TN export estimates.

3. *Lumped output (major catchments from parish output)*:
   Major catchment scale export rates calculated from aggregated parish scale TN export estimates, TN export to coastal waters calculated from aggregated major catchment scale TN export estimates.
4. *Lumped output (major catchments from catchments output)*:
   Major catchment scale export rates aggregated from catchment scale TN export estimates calculated from catchment scale input data (aggregated from parish scale input data), TN export to coastal waters calculated from aggregated major catchment scale TN export estimates.
5. *Lumped output (major catchments from catchment output from parish output)*:
   Major catchment scale export rates aggregated from catchment scale TN export estimates aggregated from parish scale TN export estimates, TN export to coastal waters calculated from aggregated major catchment scale TN export estimates.
6. *Lumped parish input to catchments, catchment output lumped to major drainages*:
   Catchment scale export rates calculated from catchment scale input data aggregated from parish scale input data, TN export to coastal waters calculated from aggregated catchment scale TN export estimates.
7. *Lumped parish input to major catchments, major catchment output lumped to major drainages*:
   Major catchment scale export rates calculated from major catchment scale input data aggregated from parish scale input data, TN export to coastal waters calculated from aggregated major catchment scale TN export estimates.
8. *Lumped parish input to major drainages*:
   TN export to coastal waters calculated from major drainage scale TN export estimates, based on aggregated parish scale input data.

Conceptual lumping categories

1. *Original method (6 spatially distributed sets of export coefficients) applied to*:
   land use units (cereals, other arable crops, bare fallow, permanent grass, temporary grass, rough grazing, orchards and woodland);
   livestock units (cattle, pigs, sheep, poultry); people; atmospheric N deposition
2. *Original coefficients (6 spatially distributed sets) with amalgamated input data units*:
   land use units (crops, grass, moorland, woodland);

livestock units (cattle, pigs, sheep, poultry); people; atmospheric N deposition

3. *Aggregated coefficients (1 set) with amalgamated input data units*:
   land use units (crops, grass, moorland, woodland);
   livestock units (cattle, pigs, sheep, poultry); people; atmospheric N deposition
4. *Original coefficients (6 spatially distributed sets) with coarsely amalgamated input data units*:
   land use units (agricultural land, semi-natural vegetation);
   livestock units (cattle, pigs, sheep, poultry); people; atmospheric N deposition
5. *Aggregated coefficients (1 set) with coarsely amalgamated input data units*:
   land use units (agricultural land, semi-natural vegetation);
   livestock units (cattle, pigs, sheep, poultry); people; atmospheric N deposition

Results of spatial aggregation:

The model estimates of TN flux from each of the 3 drainage units to the North Sea, the North Atlantic and the English Channel, generated by this matrix of model forcing are presented in Table 1 (units are kg ha^{-1} and tonnes per annum for 1991). By comparing the estimates of landscape scale N flux to each of these coastal waters with the initial estimates produced by the parish scale National Export Coefficient Model, it was then possible to derive an estimate of the relative loss of model accuracy (compared to estimates generated with the original model parameterisation and input scale) in each step of scaling in the prediction of N flux from land based sources to the adjacent oceans for England and Wales. The results of this analysis are presented in Table 2. A final comparison was made to assess the impact of scaling and coarsening of model parameters on the spatial discrimination of the model estimates for the 3 major drainage units draining to coastal waters. One of the strengths of the original model is that it allows accurate representation of the spatial variations in N flux estimates as a function of both the rates of N input to the system, and the intrinsic nutrient retention capacity or nutrient export potential of landscape units as defined by those environmental variables controlling N cycling and hydrological transport efficiency within each landscape unit. By comparing the range of variation in model estimates generated at each stage of spatial aggregation or conceptual lumping it was possible to determine the relative loss of spatial discrimination associated with the scaling process. The results of this analysis are presented in Tables

Table 1. Model estimates of TN from land to coastal waters generated through scaling from parish to major drainage scale and from coarsening model structure

Drainage to…	Area (km^2)	Original Method (tonnes)	Original coefficients, amalgamated input data (tonnes)	Aggregated coefficients, amalgamated input data (tonnes)	Original coefficients, coarsely amalgamated input data (tonnes)	Aggregated coefficients, coarsely amalgamated input data (tonnes)	Original Method (kg ha^{-1})	Original coefficients, amalgamated input data (kg ha^{-1})	Aggregated coefficients, amalgamated input data (kg ha^{-1})	Original coefficients, coarsely amalgamated input data (kg ha^{-1})	Aggregated coefficients, coarsely amalgamated input data (kg ha^{-1})
Lumped output (Parishes):											
North Sea	62318	156899	149774	171746	141503	145317	25.2	24.0	27.6	22.7	23.3
North Atlantic	77937	213825	204463	194170	219854	187535	27.4	26.2	24.9	28.2	24.1
English Channel	10892	28612	27776	29753	26487	26834	26.3	25.5	27.3	24.3	24.6
Lumped output (Catchments from Parish output):											
North Sea	62318	153662	146866	168054	138834	142485	24.7	23.6	27.0	22.3	22.9
North Atlantic	77937	206776	197966	187335	212731	180845	26.5	25.4	24.0	27.3	23.2
English Channel	10892	27465	26732	28542	25540	25824	26.2	25.5	27.2	24.3	24.6
Lumped output (Major Catchments from Parish output):											
North Sea	62318	156866	149741	171723	141473	145300	25.2	24.0	27.6	22.7	23.3
North Atlantic	77937	213802	204417	194118	219800	187483	27.4	26.2	24.9	28.2	24.1
English Channel	10892	28612	27775	29753	26487	26834	26.3	25.5	27.3	24.3	24.6
Lumped output (Major Catchments from Catchment output):											
North Sea	62318	150098	144345	166409	136168	141241	24.1	23.2	26.7	21.9	22.7
North Atlantic	77937	196661	190467	183696	203996	177273	25.2	24.4	23.6	26.2	22.7
English Channel	10892	26913	26189	28283	24989	25619	25.6	25.0	27.0	23.8	24.4

Table 1. Continued

Drainage to…	Area (km^2)	Original Method (tonnes)	Original coefficients, amalgamated input data (tonnes)	Aggregated coefficients, amalgamated input data (tonnes)	Original coefficients, coarsely amalgamated input data (tonnes)	Aggregated coefficients, coarsely amalgamated input data (tonnes)	Original Method (kg ha^{-1})	Original coefficients, amalgamated input data (kg ha^{-1})	Aggregated coefficients, amalgamated input data (kg ha^{-1})	Original coefficients, coarsely amalgamated input data (kg ha^{-1})	Aggregated coefficients, coarsely amalgamated input data (kg ha^{-1})
Lumped output (Major Catchments from Catchment output from Parish output):											
North Sea	62318	153123	146358	167581	138382	142085	24.6	23.5	26.9	22.2	22.8
North Atlantic	77937	205307	196645	186284	211237	179819	26.3	25.2	23.9	27.1	23.1
English Channel	10892	27465	26731	28542	25540	25824	26.2	25.5	27.2	24.3	24.6
Lumped Parish input to Catchments, Catchment output lumped to Major Drainages:											
North Sea	62318	150643	144860	166881	136629	141641	24.2	23.2	26.8	21.9	22.7
North Atlantic	77937	197901	191663	184658	205348	178210	25.4	24.6	23.7	26.3	22.9
English Channel	10892	26913	26189	28283	24989	25619	25.6	25.0	27.0	23.8	24.4
Lumped Parish input to Major Catchments, Major Catchment output lumped to Major Drainages:											
North Sea	62318	153356	145562	170348	136583	144264	24.6	23.4	27.3	21.9	23.1
North Atlantic	77937	203551	192131	191027	205119	184437	26.1	24.7	24.5	26.3	23.7
English Channel	10892	28433	27134	29356	25652	26505	26.1	24.9	27.0	23.6	24.3
Lumped Parish input to Major Drainages:											
North Sea	62318	153818	147543	170445	137524	144310	24.7	23.7	27.4	22.1	23.2
North Atlantic	77937	198218	191727	190996	204567	184484	25.4	24.6	24.5	26.2	23.7
English Channel	10892	28086	27135	29356	25652	26505	25.8	24.9	27.0	23.6	24.3

Table 2. Error propagation resulting from scaling from parish to major drainage scale, and from coarsening model structure. Percentage change is calculated relative to the sum of parish scale estimates of TN export to coastal waters generated by the original model

Drainage to...	Original Method (% change)	Original coefficients, amalgamated input data (% change)	Aggregated coefficients, amalgamated input data (% change)	Original coefficients, coarsely amalgamated input data (% change)	Aggregated coefficients, coarsely amalgamated input data (% change)
Lumped output (Parishes):					
North Sea	0.00	–4.54	9.46	–9.81	–7.38
North Atlantic	0.00	–4.38	–9.19	2.82	–12.30
English Channel	0.00	–2.92	3.99	–7.43	–6.22
Lumped output (Catchments from Parish output):					
North Sea	–2.06	–6.40	7.11	–11.50	–9.19
North Atlantic	–3.28	–7.40	–12.40	–0.50	–15.40
English Channel	–0.37	–3.03	3.53	–7.35	–6.33
Lumped output (Major Catchments from Parish output):					
North Sea	–0.02	–4.56	9.45	–9.83	–7.39
North Atlantic	0.01	–4.38	–9.20	2.81	–12.30
English Channel	0.00	–2.93	3.99	–7.43	–6.22
Lumped output (Major Catchments from Catchment output):					
North Sea	–4.34	–8.00	6.06	–13.2	–9.98
North Atlantic	–8.01	–10.90	–14.10	–4.58	–17.10
English Channel	–2.38	–5.00	2.60	–9.35	–7.07
Lumped output (Major Catchments from Catchment output from Parish output):					
North Sea	–2.41	–6.72	6.81	–11.80	–9.44
North Atlantic	–3.97	–8.02	–12.90	–1.19	–15.90
English Channel	–0.37	–3.03	3.53	–7.35	–6.33
Lumped Parish input to Catchments, Catchment output lumped to Major Drainages:					
North Sea	–3.99	–7.67	6.36	–12.90	–9.73
North Atlantic	–7.45	–10.40	–13.60	–3.96	–16.70
English Channel	–2.38	–5.00	2.60	–9.35	–7.07
Lumped Parish input to Major Catchments, Major Catchment output lumped to Major Drainages:					
North Sea	–2.26	–7.23	8.57	–12.90	–8.05
North Atlantic	–4.79	–10.10	–10.60	–4.06	–13.70
English Channel	–0.63	–5.17	2.60	–10.30	–7.37
Lumped Parish input to Major Drainages:					
North Sea	–1.96	–5.96	8.63	–12.30	–8.02
North Atlantic	–7.30	–10.30	–10.70	–4.33	–13.70
English Channel	–1.84	–5.17	2.60	–10.30	–7.37

Table 3. Statistical properties of TN export estimates generated through scaling from parish to major drainage scale, and from coarsening model structure: interquartile range

Drainage to...	Number of modelling units (n)	Lower Quartile (Q1)					Upper Quartile (Q3)				
		Original Method (kg ha^{-1})	Original coefficients, amalgamated input data (kg ha^{-1})	Aggregated coefficients, amalgamated input data (kg ha^{-1})	Original coefficients, coarsely amalgamated input data (kg ha^{-1})	Aggregated coefficients, coarsely amalgamated input data (kg ha^{-1})	Original Method (kg ha^{-1})	Original coefficients, amalgamated input data (kg ha^{-1})	Aggregated coefficients, amalgamated input data (kg ha^{-1})	Original coefficients, coarsely amalgamated input data (kg ha^{-1})	Aggregated coefficients, coarsely amalgamated input data (kg ha^{-1})
Lumped output (Parishes):											
North Sea	6500	10.50	10.30	11.50	10.20	10.90	60.10	57.80	55.30	56.30	47.00
North Atlantic	3615	8.14	8.00	9.01	8.43	8.66	64.0	61.80	50.20	68.80	49.90
English Channel	1390	13.90	13.70	15.60	13.70	14.50	59.50	56.90	53.70	60.70	50.80
Lumped output (Catchments from Parish output):											
North Sea	465	11.50	11.40	12.70	11.50	11.90	42.50	41.00	36.90	41.40	33.90
North Atlantic	313	8.24	8.08	8.58	8.25	8.45	41.60	39.90	33.20	45.60	33.70
English Channel	147	15.80	15.50	16.90	15.60	16.70	44.00	43.20	41.90	47.50	42.20
Lumped output (Major Catchments from Parish output):											
North Sea	5	13.50	12.30	13.10	11.90	11.40	33.20	32.10	30.00	33.60	28.40
North Atlantic	5	19.70	15.80	14.40	16.80	13.80	30.40	29.00	26.90	30.80	26.30
English Channel	3	13.90	14.10	14.20	14.00	13.80	37.10	35.70	4.30	37.70	33.20
Lumped output (Major Catchments from Catchment output):											
North Sea	5	22.30	21.40	22.90	20.00	20.20	32.30	31.30	29.50	32.30	27.60
North Atlantic	5	20.30	19.80	20.50	20.10	20.20	28.50	27.50	25.50	28.80	24.20
English Channel	3	25.40	24.70	26.50	23.70	24.00	35.10	34.20	32.90	36.10	31.90

Table 3. Continued

Drainage to...	Number of modelling units (n)	Lower Quartile (Q1)					Upper Quartile (Q3)				
		Original Method (kg ha^{-1})	Original coefficients, amalgamated input data (kg ha^{-1})	Aggregated coefficients, amalgamated input data (kg ha^{-1})	Original coefficients, coarsely amalgamated input data (kg ha^{-1})	Aggregated coefficients, coarsely amalgamated input data (kg ha^{-1})	Original Method (kg ha^{-1})	Original coefficients, amalgamated input data (kg ha^{-1})	Aggregated coefficients, amalgamated input data (kg ha^{-1})	Original coefficients, coarsely amalgamated input data (kg ha^{-1})	Aggregated coefficients, coarsely amalgamated input data (kg ha^{-1})
Lumped output (Major Catchments from Catchment output from Parish output):											
North Sea	5	22.60	21.60	23.00	20.30	20.20	33.10	32.00	29.60	33.10	27.70
North Atlantic	5	21.60	20.60	21.40	20.90	20.50	29.20	28.00	25.80	29.60	24.50
English Channel	3	25.90	25.20	26.70	24.20	24.20	36.20	34.80	33.30	36.90	32.30
Lumped Parish input to Catchments, Catchment output lumped to Major Drainages:											
North Sea	465	12.20	12.10	13.20	11.90	12.30	42.00	40.90	36.90	41.40	33.70
North Atlantic	313	7.69	7.62	8.70	7.63	8.58	41.00	40.20	33.20	45.30	33.50
English Channel	147	15.90	15.70	16.80	15.20	16.50	44.10	43.30	41.90	47.50	42.20
Lumped Parish input to Major Catchments, Major Catchment output lumped to Major Drainages:											
North Sea	5	15.60	15.50	15.00	14.90	12.80	32.50	30.90	29.90	32.10	28.10
North Atlantic	5	9.78	9.46	10.00	9.58	9.63	29.60	27.70	26.50	29.40	25.20
English Channel	3	13.70	13.60	13.90	13.40	13.60	36.20	34.40	33.80	36.20	32.70
Lumped Parish input to Major Drainages:											
North Sea	1	24.70	23.70	27.40	22.10	23.20	24.70	23.70	27.40	22.10	23.20
North Atlantic	1	25.40	24.60	24.50	26.20	23.70	25.40	24.60	24.50	26.20	23.70
English Channel	1	25.80	24.90	27.00	23.60	24.30	25.80	24.90	27.00	23.60	24.30

Table 4. Statistical properties of TN export estimates generated through scaling from parish to major drainage scale, and from coarsening model structure. % deviation of quartiles from quartiles of data distribution generated by original method, operating at parish scale

Drainage to…	Number of modelling units (n)	Lower Quartile (Q1)					Upper Quartile (Q3)				
		Original Method (%)	Original coefficients, amalgamated input data (%)	Aggregated coefficients, amalgamated input data (%)	Original coefficients, coarsely amalgamated input data (%)	Aggregated coefficients, coarsely amalgamated input data (%)	Original Method (%)	Original coefficients, amalgamated input data (%)	Aggregated coefficients, amalgamated input data (%)	Original coefficients, coarsely amalgamated input data (%)	Aggregated coefficients, coarsely amalgamated input data (%)
Lumped output (Parishes):											
North Sea	6500	0.00	-1.90	9.52	-2.86	3.81	0.00	-3.83	-7.99	-6.32	-21.80
North Atlantic	3615	0.00	-1.72	10.70	3.56	6.39	0.00	-3.44	-21.60	7.50	-22.00
English Channel	1390	0.00	-1.44	12.20	-1.44	4.32	0.00	-4.37	-9.75	2.02	-14.60
Lumped output (Catchments from Parish output):											
North Sea	465	9.52	8.57	21.00	9.52	13.30	-29.30	-31.80	-38.60	-31.10	-43.60
North Atlantic	313	1.23	-0.74	5.41	1.35	3.81	-35.00	-37.70	-48.10	-28.80	-47.30
English Channel	147	13.70	11.50	21.60	12.20	20.10	-26.10	-27.40	-29.60	-20.20	-29.10
Lumped output (Major Catchments from Parish output):											
North Sea	5	65.80	51.10	60.90	46.20	40.00	-48.10	-49.80	-53.10	-47.50	-55.60
North Atlantic	5	41.70	13.70	3.60	20.90	-0.72	-48.90	-51.30	-54.80	-48.20	-55.80
English Channel	3	32.40	34.30	35.20	33.30	31.40	-38.30	-40.60	-92.80	-37.30	-44.80
Lumped output (Major Catchments from Catchment output):											
North Sea	5	60.40	54.00	64.70	43.90	45.30	-45.70	-47.40	-50.40	-45.70	-53.60
North Atlantic	5	93.30	88.60	95.20	91.40	92.40	-52.60	-54.20	-57.60	-52.10	-59.70
English Channel	3	212.00	203.00	226.00	191.00	195.00	-45.20	-46.60	-48.60	-43.60	-50.20

Table 4. Continued

Drainage to…	Number of modelling units (n)	Lower Quartile (Q1)					Upper Quartile (Q3)				
		Original Method (%)	Original coefficients, amalgamated input data (%)	Aggregated coefficients, amalgamated input data (%)	Original coefficients, coarsely amalgamated input data (%)	Aggregated coefficients, coarsely amalgamated input data (%)	Original Method (%)	Original coefficients, amalgamated input data (%)	Aggregated coefficients, amalgamated input data (%)	Original coefficients, coarsely amalgamated input data (%)	Aggregated coefficients, coarsely amalgamated input data (%)
Lumped output (Major Catchments from Catchment output from Parish output):											
North Sea	5	115.00	106.00	119.00	93.30	92.40	–44.90	–46.80	–50.70	–44.90	–53.90
North Atlantic	5	165.00	153.00	163.00	157.00	152.00	–54.40	–56.30	–59.70	–53.80	–61.70
English Channel	3	86.30	81.30	92.10	74.10	74.10	–39.20	–41.50	–44.00	–38.00	–45.70
Lumped Parish input to Catchments, Catchment output lumped to Major Drainages:											
North Sea	465	49.90	48.60	62.20	46.20	51.10	–34.40	–36.10	–42.30	–35.30	–47.30
North Atlantic	313	–44.70	–45.20	–37.40	–45.10	–38.30	–31.10	–32.40	–44.20	–23.90	–43.70
English Channel	147	51.40	49.50	60.00	44.80	57.10	–26.60	–28.00	–30.30	–21.00	–29.80
Lumped Parish input to Major Catchments, Major Catchment output lumped to Major Drainages:											
North Sea	5	12.20	11.50	7.91	7.19	–7.91	–45.40	–48.10	–49.70	–46.10	–52.80
North Atlantic	5	–6.86	–9.90	–4.76	–8.76	–8.29	–50.70	–53.90	–55.90	–51.10	–58.10
English Channel	3	68.30	67.10	70.80	64.60	67.10	–43.40	–46.30	–47.20	–43.40	–48.90
Lumped Parish input to Major Drainages:											
North Sea	1	135.00	126.00	161.00	110.00	121.00	–58.90	–60.60	–54.40	–63.20	–61.40
North Atlantic	1	212.00	202.00	201.00	222.00	191.00	–60.30	–61.60	–61.70	–59.10	–63.00
English Channel	1	85.60	79.10	94.20	69.80	74.80	–56.60	–58.20	–54.60	–60.30	–59.20

3 and 4 in the form of the interquartile range (Q1 and Q3) for the range of estimates of N flux to coastal waters mapped at each stage. In interpreting these results it is important to bear in mind that land draining to the North Atlantic Ocean generally has a lower intrinsic nutrient retention capacity than land draining to the English Channel and the North Sea. This reflects the fact that land in the North and West of the U.K. tends to be wet, cold and steep (in the U.K. context), with drier, warmer and flatter landscapes towards the South and East. These characteristics are, of course, represented in the geoclimatic region units defined for England and Wales (see Figure 1), but will nevertheless have a bearing on how the model performs through the sequence of spatial aggregation and conceptual lumping steps, particularly where the regional sub-model structure is modified.

Figures 4 to 10 illustrate column one of each of Tables 1 to 4 (Original Method), showing the effects of spatial aggregation on modelled estimates of N flux from the 3 major drainage units to coastal waters. These estimates are based on the original model parameterisation with 7 categories of land use unit, 4 categories of livestock unit, people, atmospheric N deposition, and the 6 sets of spatially distributed export coefficients reflecting the intrinsic N export potential of the 6 landscape unit categories for England and Wales. What is apparent from these figures is that by lumping either the parish scale input data, or the parish, catchment or major catchment scale N flux estimates, the estimate of total N flux to coastal waters from each of the three major drainage units decreases, even where the original model parameterisation is maintained (see column 1, Tables 1 and 2). This probably reflects the fact that by upscaling the model input data the coincidences where areas with a low intrinsic nutrient retention capacity (perhaps as a function of high rainfall and/or steep slopes) are combined with high intensity agriculture are lost in the accounting process. The greatest errors associated with spatial aggregation occur in the estimates of TN export from the North Atlantic drainage unit, with a maximum error of 8% (Table 2, column 1, row 11) associated with running the original model where the parish scale input data were lumped into the catchment units, and the resultant catchment scale TN estimates aggregated into the major catchments and then into the major drainage units. This is probably a function of the greater range of variation in both the parish scale N flux estimates and the comparatively low intrinsic nutrient export potential of the landscape units in the North Atlantic Drainage unit, compared to the drainages for the English Channel and North Sea. Even so this form of spatial aggregation also produced the maximum errors for the estimates of TN export from the English Channel (2.38%; Table 2, column 1, row 12) and North Sea (4.34%; Table 2, column 1, row 10) drainage units. The analysis, conducted solely on the original model parameterisation, suggests that the minimum

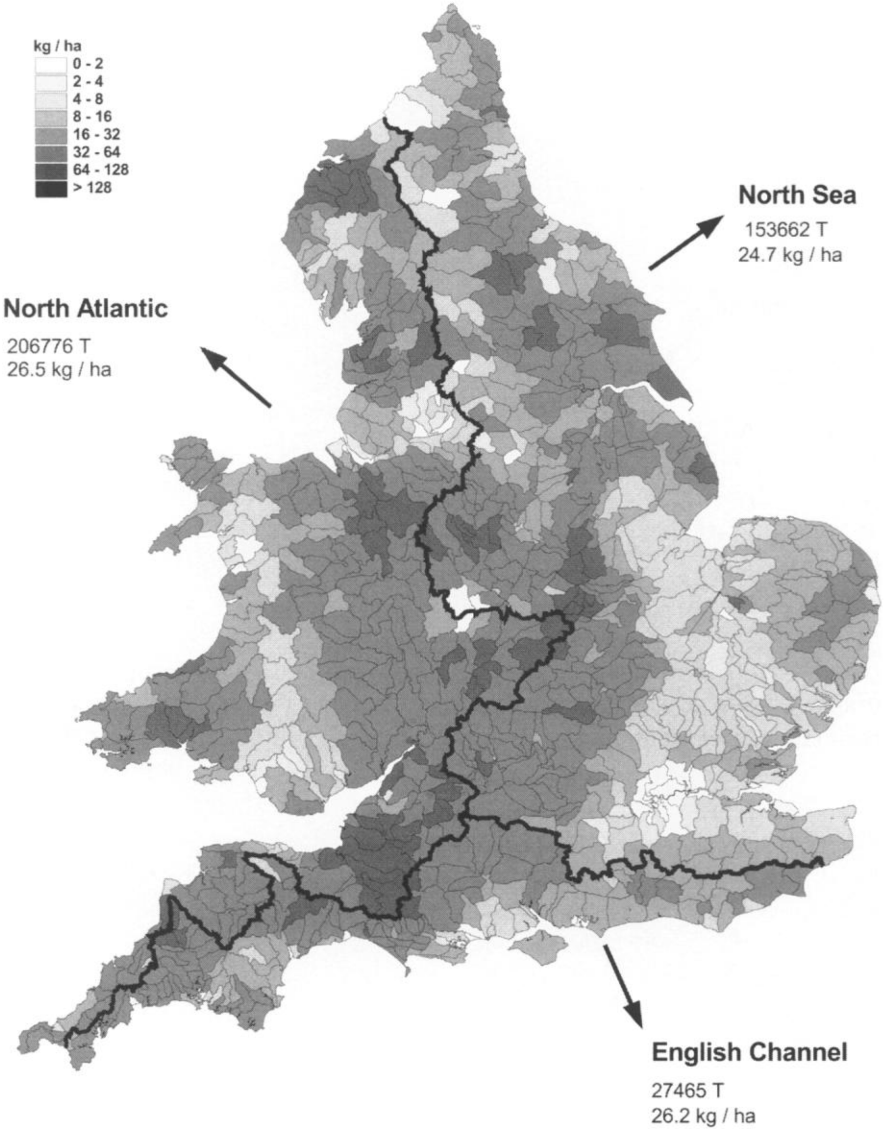

Figure 4. Export coefficient model prediction of TN export (1991) using 6 spatially distributed sets of export coefficients. Catchment scale export rates aggregated from distributed parish scale TN export estimates. TN export to coastal waters calculated from aggregated catchment scale TN export estimates.

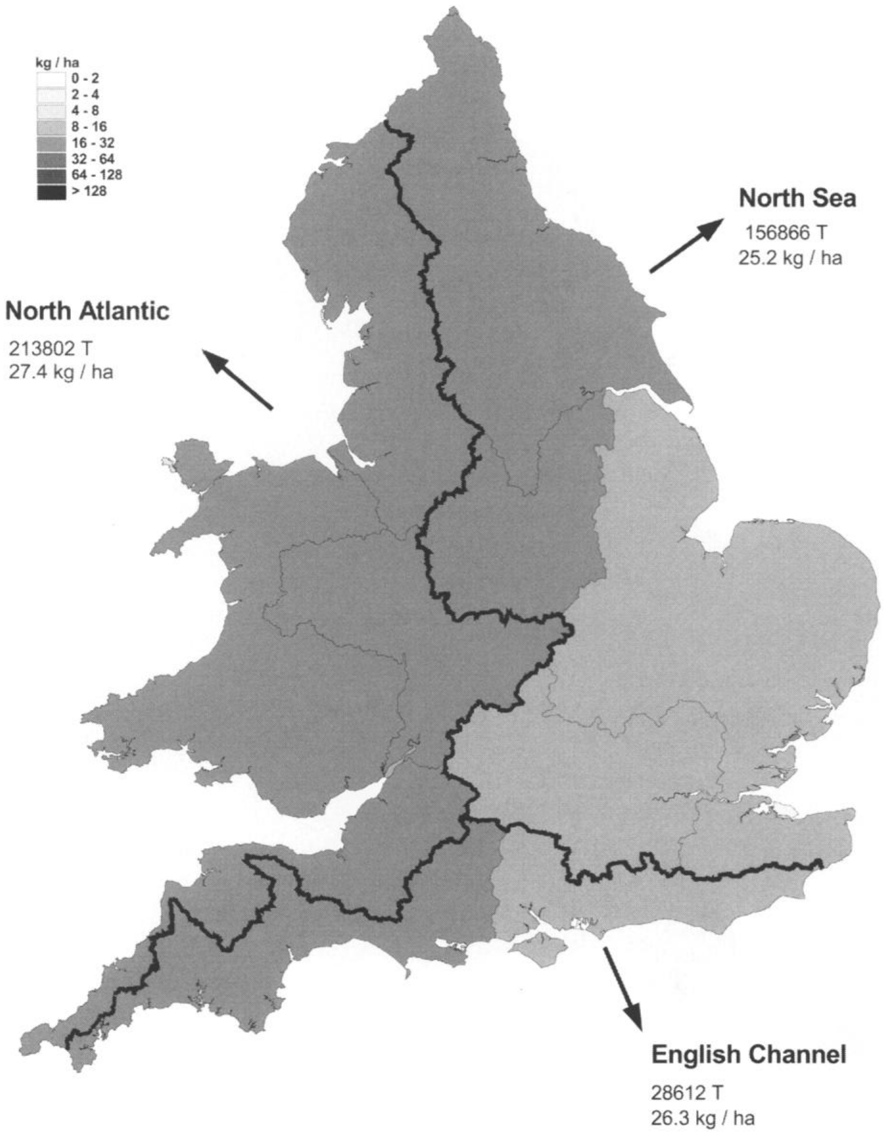

Figure 5. Export coefficient model prediction of TN export (1991) using 6 spatially distributed sets of export coefficients. Major catchment scale export rates aggregated from distributed parish scale TN export estimates. TN export to coastal waters calculated from aggregated major catchment scale TN export estimates.

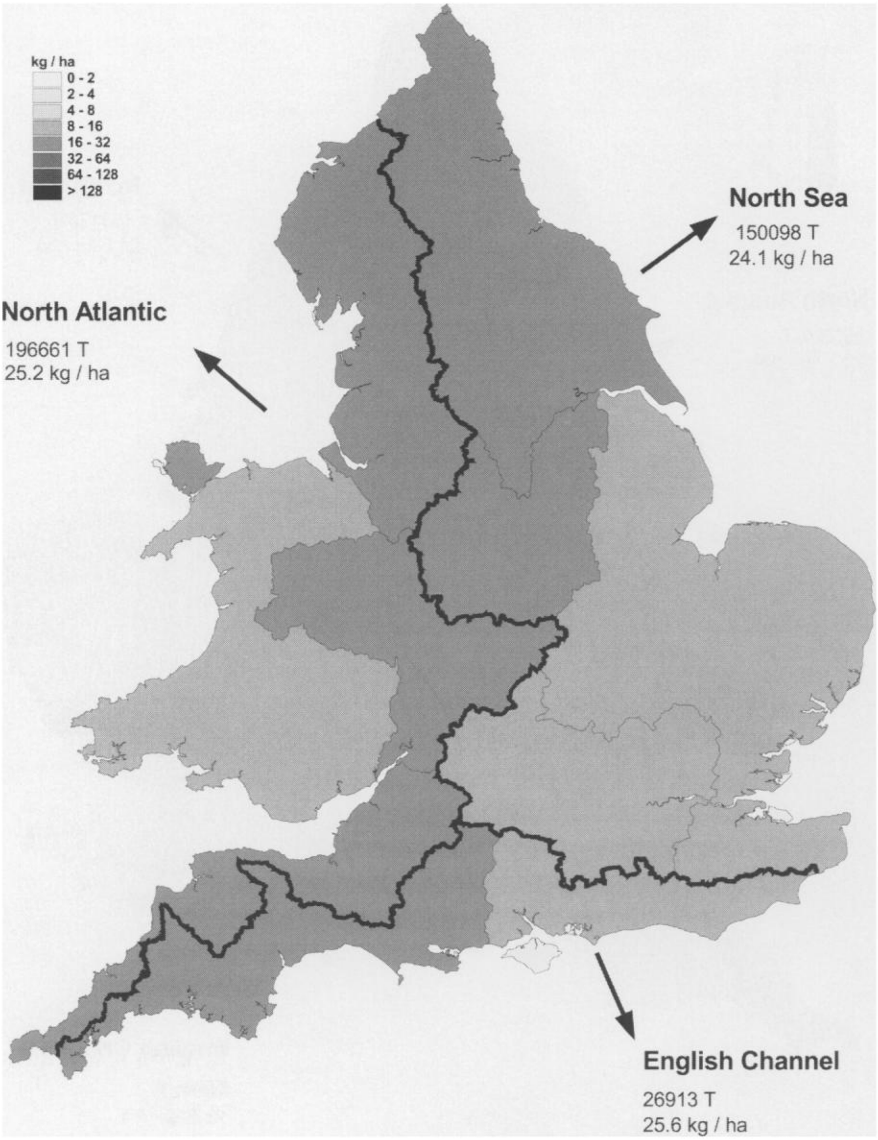

Figure 6. Export coefficient model prediction of TN export (1991) using 6 spatially distributed sets of export coefficients. Major catchment scale export rates aggregated from catchment scale TN export estimates calculated from catchment scale input data. TN export to coastal waters calculated from aggregated major catchment scale TN export estimates.

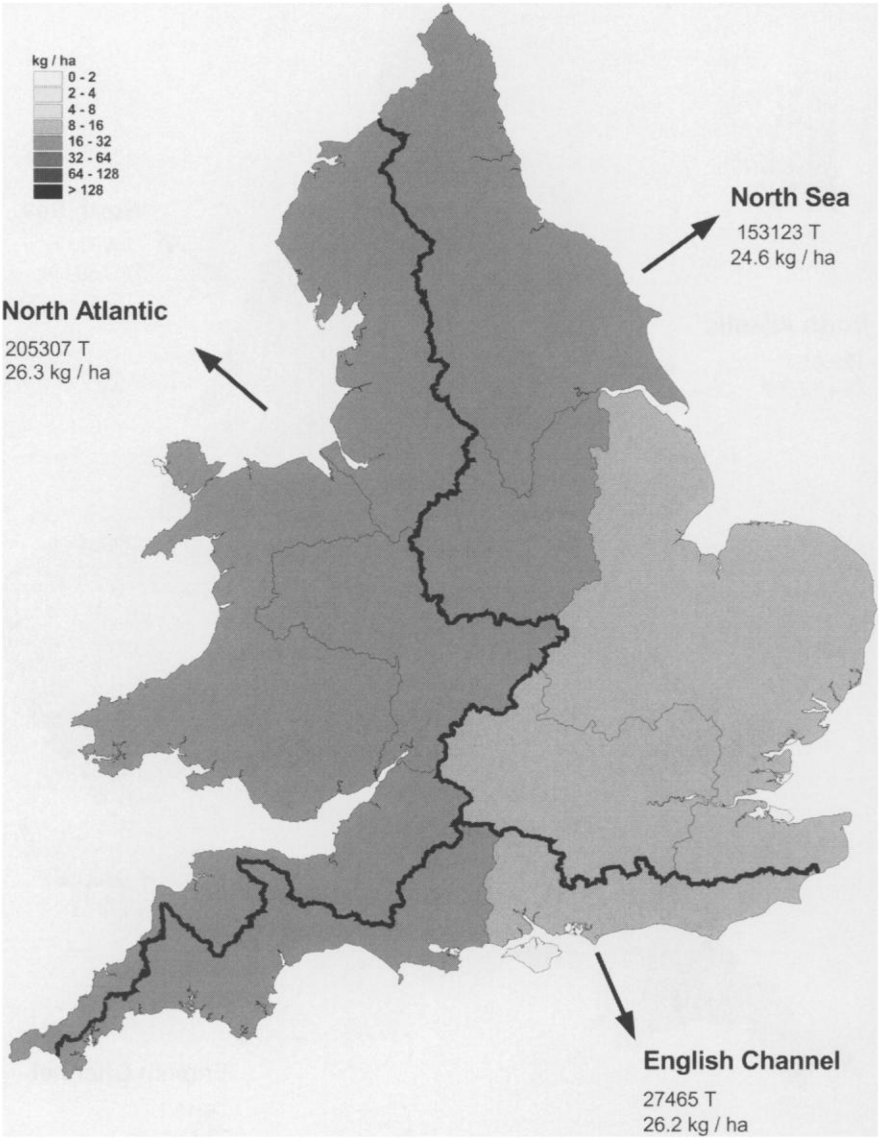

Figure 7. Export coefficient model prediction of TN export (1991) using 6 spatially distributed sets of export coefficients. Major catchment scale export rates aggregated from catchment scale TN export estimates, aggregated from distributed parish scale TN export estimates. TN export to coastal waters calculated from aggregated major catchment scale TN export estimates.

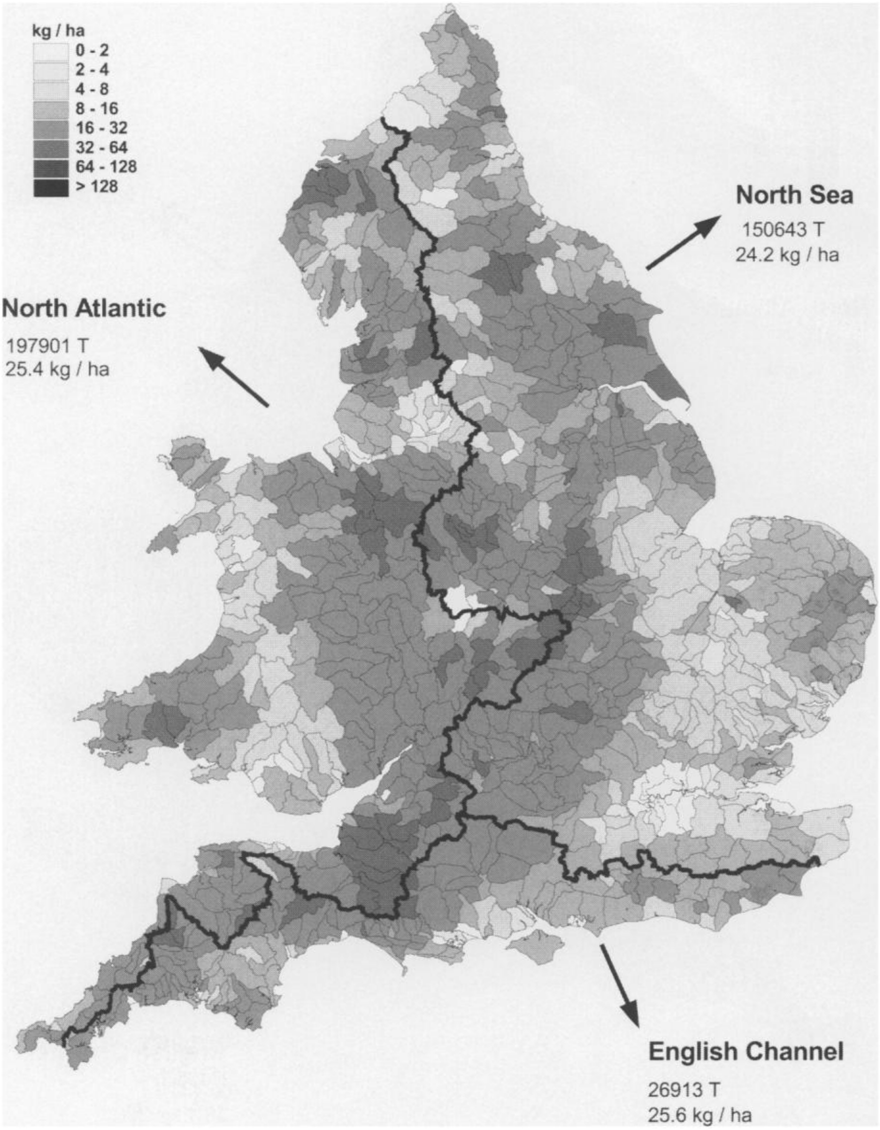

Figure 8. Export coefficient model prediction of TN export (1991) using 6 spatially distributed sets of export coefficients. Catchment scale export rates calculated from catchment scale input data aggregated from parish scale input data. TN export to coastal waters calculated from aggregated catchment scale TN export estimates.

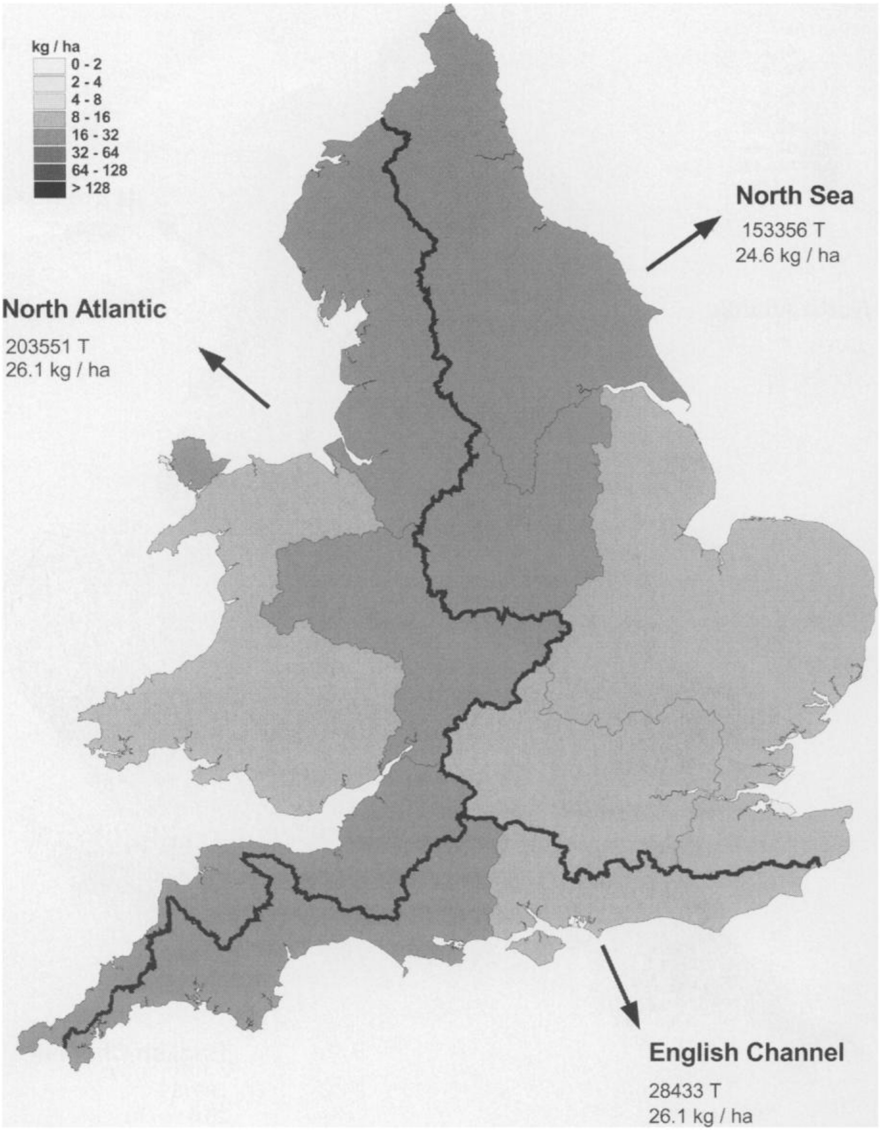

Figure 9. Export coefficient model prediction of TN export (1991) using 6 spatially distributed sets of export coefficients. Major catchment scale export rates calculated from major catchment scale input data aggregated from parish scale input data. TN export to coastal waters calculated from aggregated major catchment scale TN export estimates.

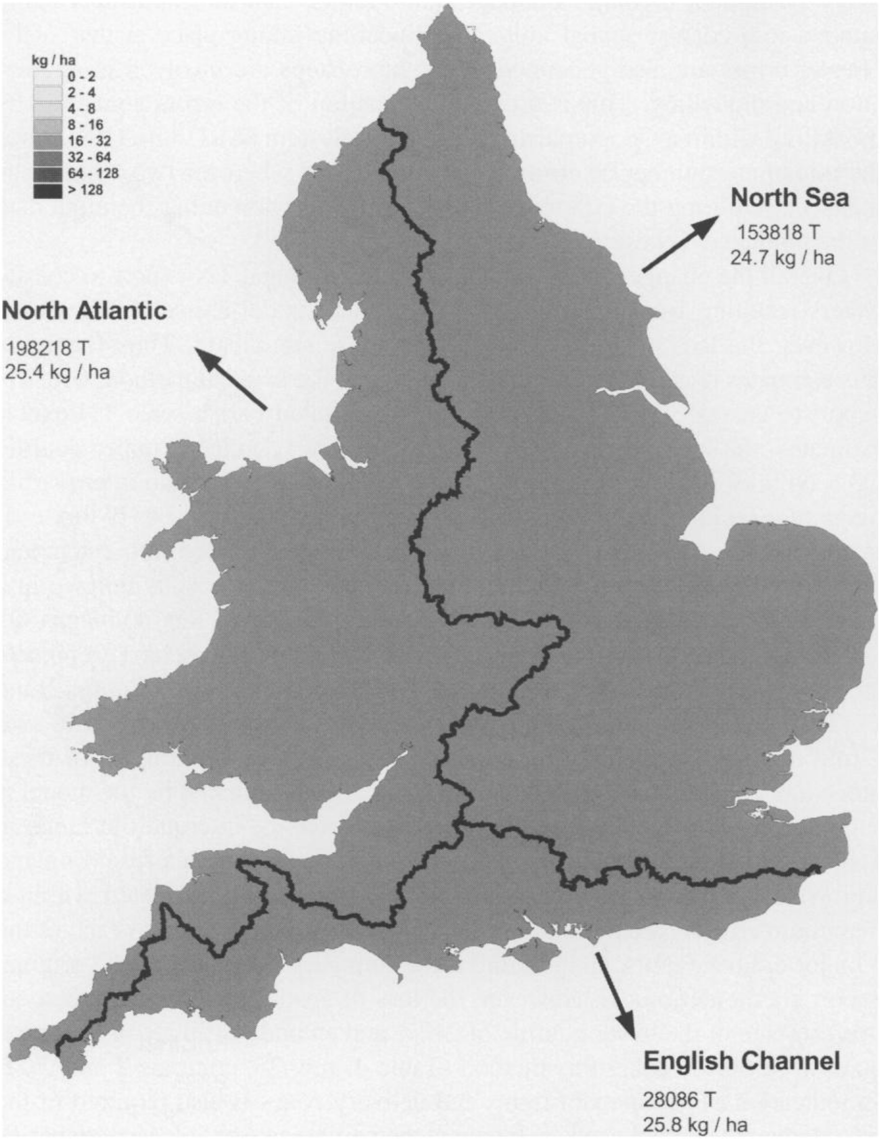

Figure 10. Export coefficient model prediction of TN export (1991) using 6 spatially distributed sets of export coefficients. TN export to coastal waters calculated from major drainage scale TN export estimates, based on aggregated parish scale input data.

error is generated in upscaling where modelling takes place at parish scale and parish scale TN export estimates are lumped directly into the catchment, major catchment or major drainage units, rather than the input data being lumped into coarser spatial units and modelling taking place at that scale. Greater errors are also generated where more steps are involved in aggregation and modelling. This is probably a function of the errors generated by modelling within a Geographical Information System (ARC-info GIS), since the maximum number of errors will be generated wherever two boundaries intersect, requiring the GIS to mathematically apportion either the input data or the modelled TN estimates between polygons.

Overall the changes in the estimates of mean annual TN export to coastal waters resulting from upscaling of the original model are relatively small. However, the loss of spatial resolution is more significant. Thus for the N flux estimates to coastal waters calculated using the original method, with TN export to coastal waters calculated from aggregated parish scale TN export estimates, the lower quartile Q1 = 8.14 kg N ha^{-1}, with the upper quartile Q3 = 64.0 kg N ha^{-1}, both for the North Atlantic, represent an interquartile range of 49.6 kg N ha^{-1} (Table 3, row 2, columns 2 and 7). For N flux estimates where parish scale TN export estimates were lumped into catchment units, those were lumped into major catchments and the results lumped into the 3 major drainage units, the lower quartile for North Sea drainages Q1 = 21.6 kg N ha^{-1}, with the upper quartile Q3 = 29.2 kg N ha-1, represent an interquartile range of 7.6 kg N ha^{-1} (Table 3, row 14, columns 2 and 7). Thus by spatial aggregation in the export coefficient model there was 7-fold decrease in spatial discrimination in the model. The impact of these procedures on the range of variation in N flux rates estimated by the model is summarised as a % change in N flux estimates for the interquartile range in Table 4. This suggests that where an estimate of the bulk N flux from England and Wales to its coastal waters is required, this can be estimated within a maximum error of 8% by lumping the parish scale input data into each of the 3 major drainage units, and running these summary data through the original export coefficient model. However, the loss of spatial resolution leads to an overestimate of the lower quartile of 212% and an underestimate of the upper quartile of 60.3% using this method (Table 4, row 23, columns 2 and 7). If an indication of the spatial origins and delivery zones is also required of the model, then the model needs to be run at the parish scale or at least with parish data lumped within individual watersheds and then run through the original model to retain credible spatial resolution. The impact of spatial aggregation on the range of variation in N flux estimates follows the same pattern as on the mean estimate of N flux estimate at each stage. Greater errors are generated where more steps are involved in modelling and aggregation, owing to the issue of boundary intersection and the problems associated with apportioning modelled data to output polygons. Errors are also higher where parish scale data were lumped into larger spatial units and then modelled than where the model was run at parish scale and the parish scale N flux estimates aggregated into larger spatial units. This probably reflects the problem associated with missing the coincidences between low nutrient retention capacity and high intensity agricultural production which would otherwise be captured by more accurate apportioning of input data to geoclimatic regions classes at the parish scale.

Two conclusions may be drawn from this analysis. First, it is intuitive that there will be a loss of spatial resolution when lumping export data from the parish scale to the major drainage scale, and the model cannot be expected to generated reliable estimates of N flux rates in small watersheds based on input data averaged at a larger scale. Second, and more importantly, is the fact that provided the landscape unitary approach is retained, then predicted regional flux rates do not change dramatically as inputs are lumped at progressively larger scales. This suggests that scaling up of such simple empirical watershed scale models to continental scale might be possible and provide a robust tool for generating regional to global scale N flux estimates in the future.

Results of conceptual lumping

Figures 11 to 14 illustrate row one of each of the tables (Lumped output (Parishes)) and show the effects of conceptual lumping on modelled estimates of N flux to coastal waters modelled at the parish scale, with parish scale TN export estimates then lumped to the 3 major drainage units draining to coastal waters. The original model parameterisation was modified by first reducing the number of land use units from 7 to 4 (amalgamated input data), and then to 2 (coarsely amalgamated input data), and then by removing the landscape unitary approach underpinning the model by running the model using only 1 set of export coefficients (originally those representing the mixed arable and dairying regions underlain by permeable bedrock as those reflecting the most typical agricultural practices across England and Wales). In this analysis the full range of livestock units (cattle, pigs, sheep, poultry) were maintained in each step, essentially because the only way to normalise the livestock populations would be on the basis of the per capita N production rate of each livestock type, and this would then preclude inclusion of issues relating to manure handling and stock management. Also, in U.K. conditions it would be conceptually impossible to exclude the livestock population from any valid representation of the sources of aquatic and atmospheric N flux. Conservatively estimated, livestock contribute approximately half of the total N flux

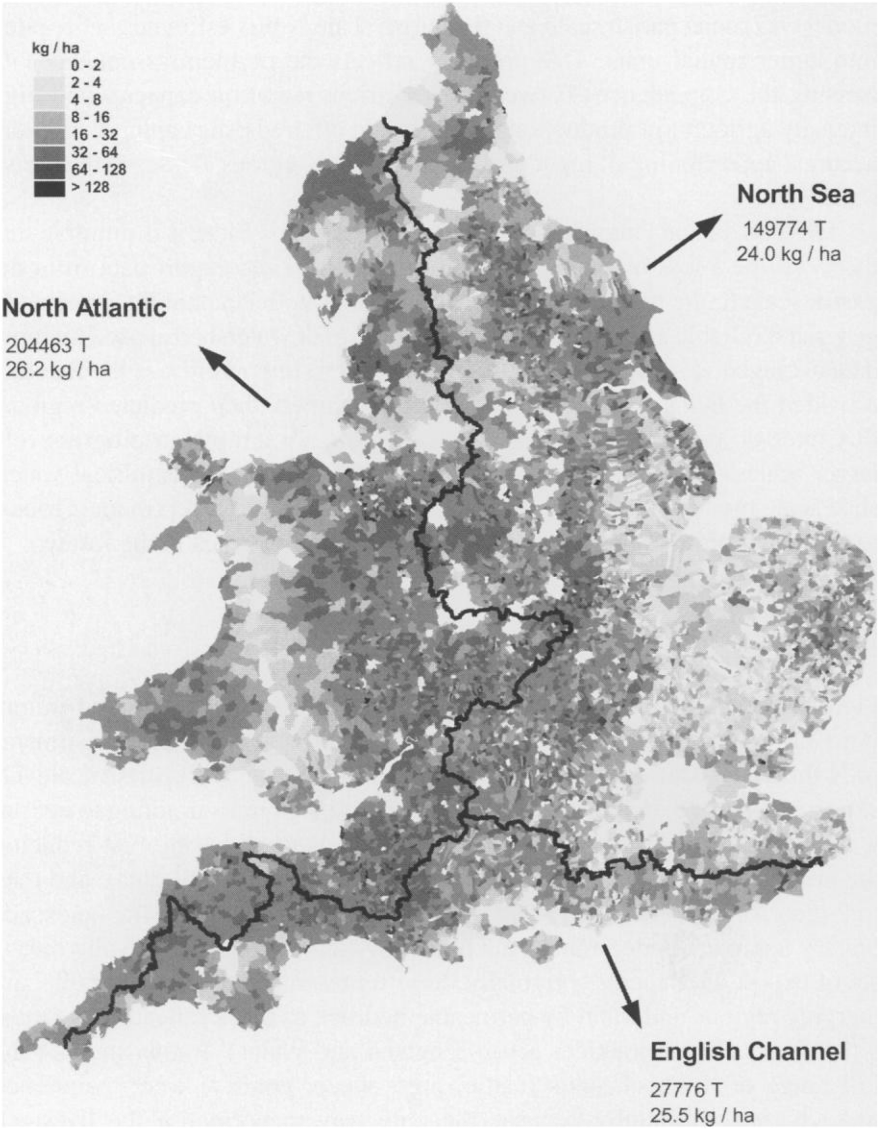

Figure 11. Export coefficient model prediction of TN export (1991) using 6 spatially distributed sets of export coefficients and amalgamated parish scale input data. TN export to coastal waters calculated from aggregated parish scale TN export estimates.

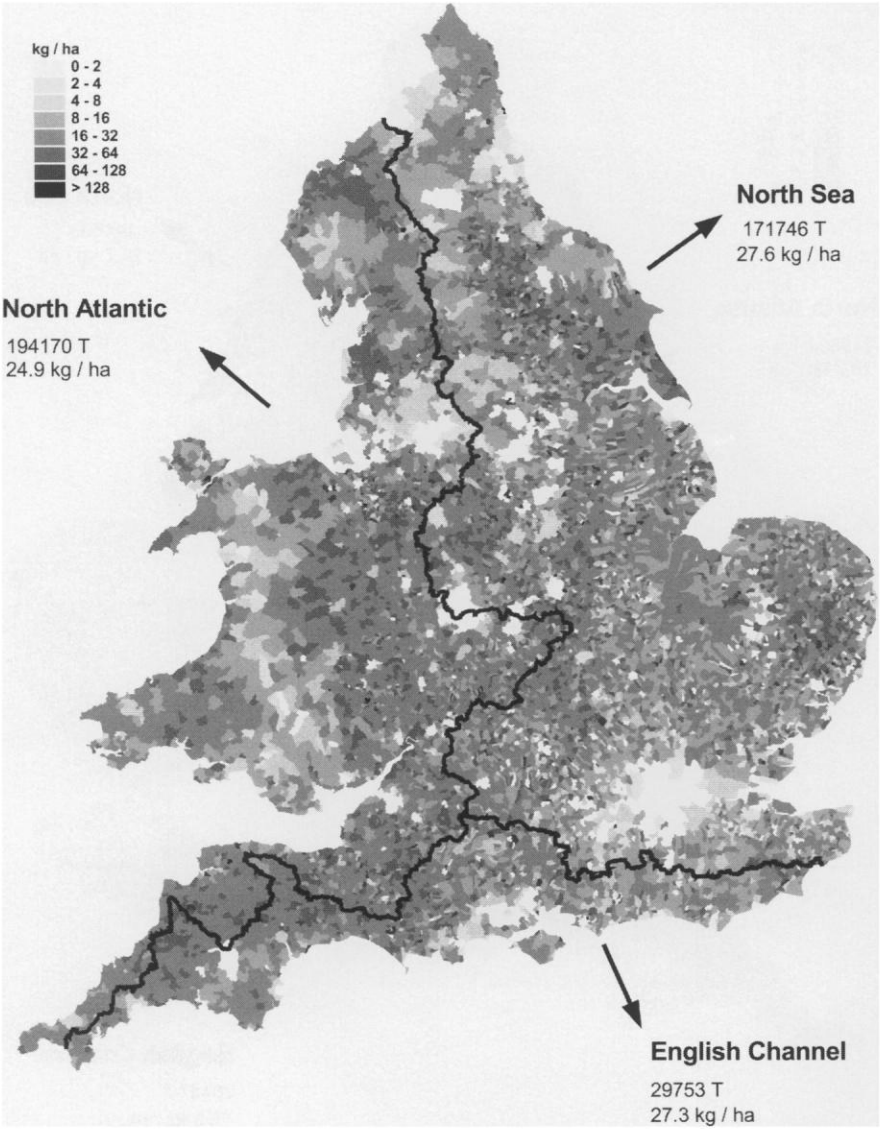

Figure 12. Export coefficient model prediction of TN export (1991) using 1 set of spatially aggregated export coefficients and amalgamated parish scale input data. TN export to coastal waters calculated from aggregated parish scale TN export estimates.

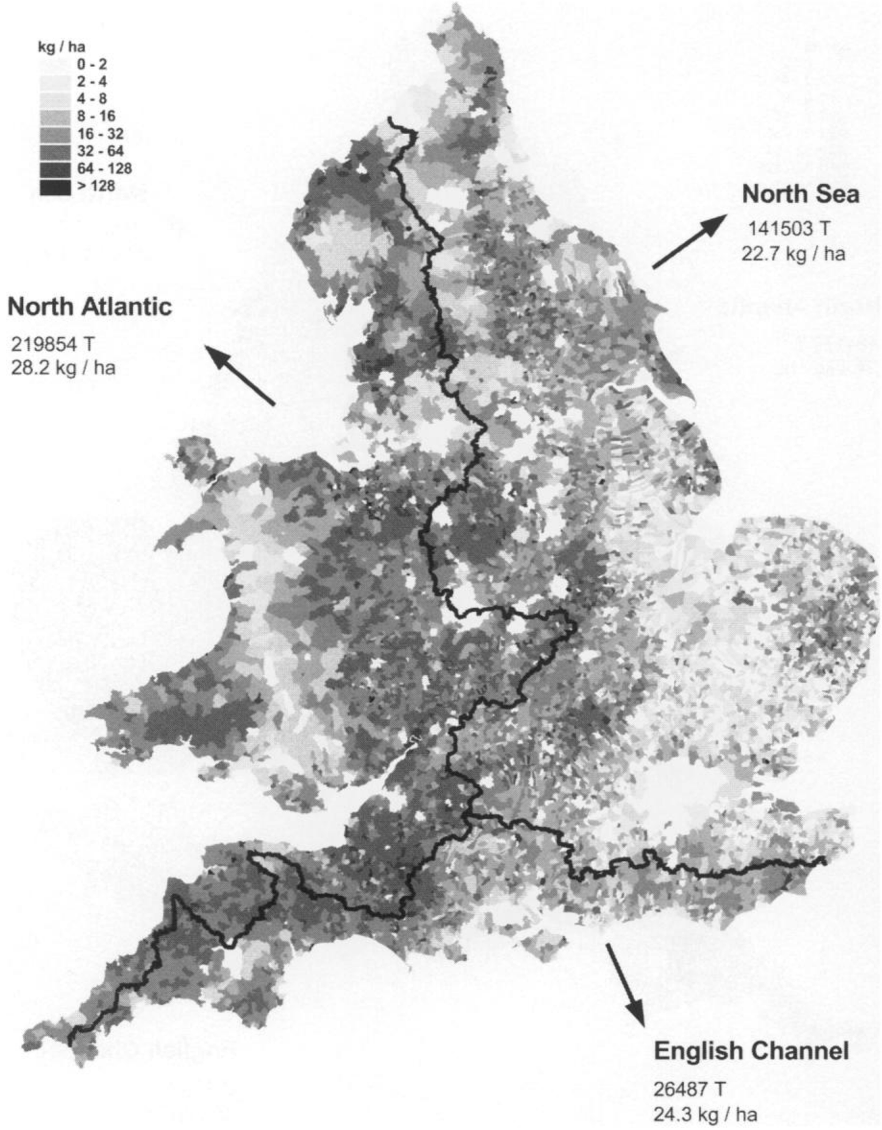

Figure 13. Export coefficient model prediction of TN export (1991) using 6 spatially distributed sets of export coefficients and coarsely amalgamated parish scale input data. TN export to coastal waters calculated from aggregated parish scale TN export estimates.

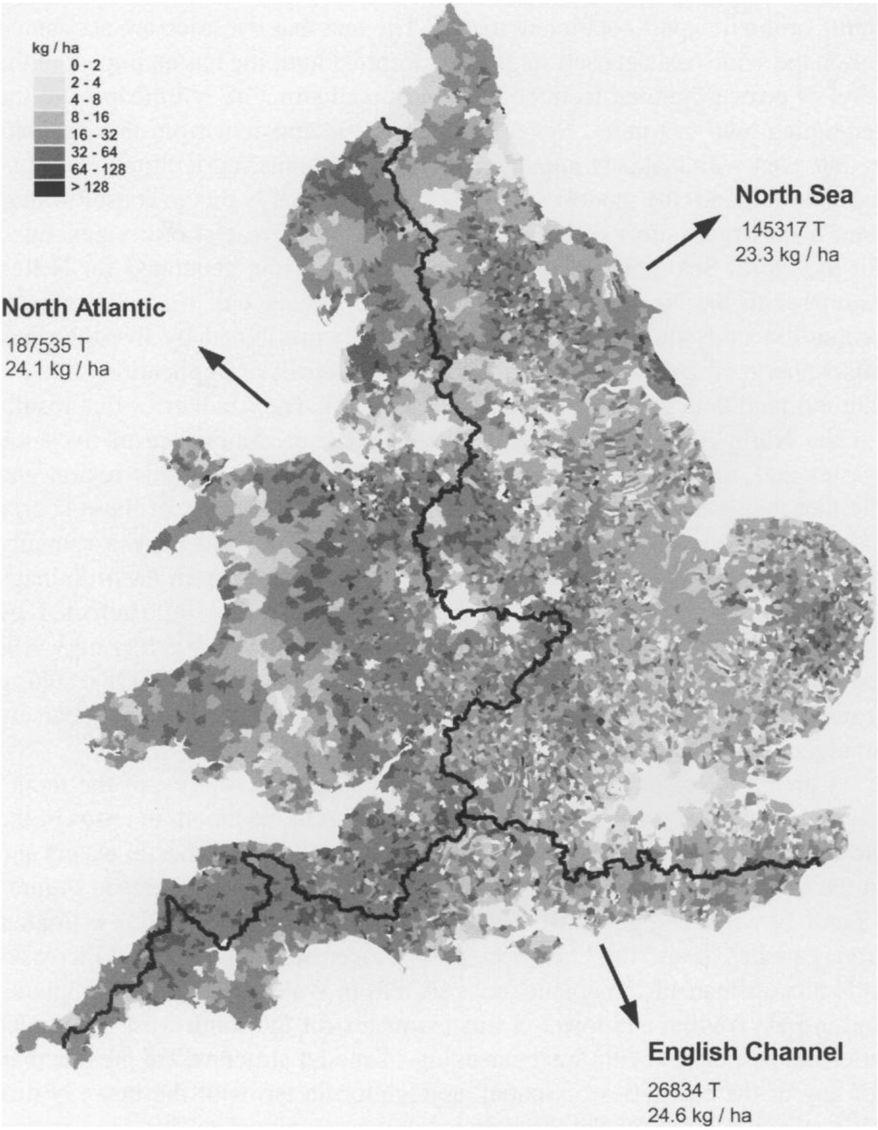

Figure 14. **Export coefficient model prediction of TN export (1991) using 1 set of spatially aggregated export coefficients and coarsely amalgamated parish scale input data. TN export to coastal waters calculated from aggregated parish scale TN export estimates.**

from England and Wales to coastal waters. Having accepted that they should not be excluded from the analysis, it was then impossible to generate any coarser units for livestock numbers beyond the species units already utilised in the original export coefficient model. The fact that livestock are accounted for on the same basis in each stage of conceptual lumping has an impact of the level of error generated from coarsening model structure with respect to the remaining land use units. Nevertheless, what is apparent from this analysis is that even with coarsely amalgamated land use units (agricultural and non-agricultural land) the model estimates of mean annual N flux to coastal waters have a maximum error of less than 10%, with the greatest errors generated for the North Sea drainage unit, and the lowest errors generated for N flux estimates to the North Atlantic. This reflects the fact that a much greater proportion of N flux to the North Atlantic is contributed by livestock and atmospheric N deposition and much less from fertiliser applications to agricultural land than in the North Sea drainage unit. The small error that results for the North Atlantic drainage unit reflects the predominance of livestock wastes and atmospheric N deposition in the N budget for this region and the fact that conceptual lumping was not possible for either of these source categories. Thus modifications to model parameterisation have a spatially variable impact, relative to the dominant nutrient sources in each drainage unit. The range of variation in N flux estimates is also little affected by coarsening the input data units for land use, with maximum errors of 3.56% in the lower quartile (Q1) and 7.50% in the upper quartile (Q3) resulting from using the original model, applied at parish scale, and run using coarsely amalgamated input data (see Table 4, row 2, columns 5 and 10).

A greater error is apparent where the landscape sensitivity of the model (the geoclimatic regions sub-model division) is removed, both in terms of the error associated with the mean annual estimate of N flux to coastal waters and in the range of variation in these estimates. This is most apparent in Figures 12 and 14 when compared with Figure 3 (original method). N flux estimates from parishes across the U.K. become homogenised, with marked increases in N flux estimates from upland areas such as in Wales and northern England, and in East Anglia, and lower N flux estimates for the south west. The order of errors associated with this coarsening of model structure are greater than for any of the categories of spatial aggregation in terms of the mean N flux estimates generated for the three major drainage units. They are also greater than the effects of amalgamation of input data units, particularly in terms of the range of variation in parish scale N flux estimates. The maximum error associated with removal of the landscape sensitivity of the model is an underestimate of 22% of the upper quartile Q3, and an overestimate of 12.2% of the lower quartile Q1. Thus the effect of removing landscape sensitivity from the export coefficient model is to reduce the range of variation in N flux estimates around the mean.

Error propagation in the export coefficient model and implications for regional to global scale N flux modelling

The overall effect of modifying the export coefficient model to make it more similar in terms of parameterisation and form to the existing regional to global scale models is illustrated where both spatial aggregation and conceptual lumping are combined. None of the existing regional to global scale models contains input data at less than major watershed scale, and only the Howarth et al. (1996) model contains any reference to livestock as a nutrient source category (implicitly accounted for in their model through estimates of food and feed imports by region). Thus, if livestock were to be excluded from the export coefficient model estimates of N flux to coastal waters then the model would underestimate by approximately 50%, before any spatial aggregation or conceptual lumping errors were introduced. The lack of adequate accounting for livestock as a N flux source in any of the existing regional to global scale N flux models generates significant uncertainty in model predictions, not least for subsistence economies where livestock and human wastes will be the dominant sources of N input to the land surface.

Our work suggests that the rates of riverine N flux estimated for England and Wales by simple, global scale regression type models may be significantly lower than is suggested by a validated catchment scale model which explicitly takes account of landscape sensitivity to N export. The reasons for this derive from two sources. First there will be errors in the input data used to drive these models. This reflects in part the fact that none of the existing regional to global scale models seem to provide an adequate accounting for the impact of livestock and livestock wastes on N cycling and flux, meaning that they will systematically underestimate N flux rates from land to ocean where livestock are a dominant part of the farm economy. Second there is the issue of the insensitivity of these simple regression models to spatial variations in the intrinsic nutrient retention capacity of smaller landscape units, as described by variations in the routing and efficiency of runoff from land to water. This may suggest that even if the global N flux from land to ocean predicted by these simple models is correct the N flux estimates at specific points of discharge to coastal waters will be incorrect for many oceans.

In terms of the effect of modelling N flux from land to water as a function of landscape sensitivity to N cycling processes, it is apparent from this analysis that the errors associated with bulk N flux estimates to coastal waters can be predicted within 10% of the original model estimates for the three major drainage units if the model is run at parish scale, with a maximum error of 21.6% associated with under-prediction of the upper quartile of the range for parish scale estimates. However, where it is run at major catchment or major drainage unit scale, the errors associated with the interquartile range are significant, with the lower quartile overestimated by over 200% and the upper quartile underestimated by over 60% when parish scale input data are lumped into the 3 major drainage units and then modelled. The message here seems to be that the incorporation of landscape sensitivity within national model structure is possible, defensible and vital to the production of sensible and robust estimates of N flux to estuaries and coastal waters. The way in which this has been incorporated in the export coefficient model, with definition of characteristic geoclimatic regions, allows account to be taken of regional scale variations in the sensitivity of the landscape to N cycling and flux. Existing regional to global scale models lacking this refinement have an additional element of uncertainty associated with their N flux predictions. Without this element within the model structure, the export coefficient model, at least, would provide an inaccurate and unreliable indication of the likely biogeochemical response to N loading on coastal waters.

Thus the conclusions of Becker and Braun (1999) regarding the necessity for subdivision of the land surface into smaller units displaying homogenous hydrological behaviour seem to hold true for the modelling of N flux to coastal waters at watershed to regional scale. It is also apparent from this analysis that the geoclimatic units defined within the export coefficient model need to be modelled separately using unit-specific export coefficient values, with the calculated unit N fluxes then aggregated to watershed or major drainage unit scale. This analysis also supports the arguments of Addiscott and Tuck (1996) and clearly demonstrates the point that averaging or lumping parish scale data into larger spatial units before running the export coefficient model does not give the same result as running the model and then averaging or lumping the resultant N flux estimates. The latter procedure generates fewer errors, both in terms of the mean and range of variation in N flux estimates generated by the model. Sivapalan and Kalma (1995) discussed the differences generated in model estimates as a result of lumping the entire mosaic of units across a landscape, as opposed to representing the land surface as a combination of units acting in parallel. This analysis has confirmed the principle that this generated different modelling outcomes and is thus a source of further error and uncertainty in model estimates. Thus as we scale up from parish scale to major watershed or landscape unit scale, in U.K. terms, the sequence of modelling steps does appear to be critical in determining the level of error and uncertainty associated with our ultimate regional scale N flux estimates. The principles that have emerged from this analysis have highlighted the areas where greatest error and uncertainty are introduced to regional scale N flux estimates. These principles can provide guidance on the steps necessary to minimise error propagation in the future development of regional to global scale N flux models.

If we accept, from this analysis, that regional to global scale modelling can be improved by adopting the principles emerging from watershed scale N flux modelling and from macroscale modelling in other related disciplines, then appropriate parameterisation of the models relative to the spatial scale at which the problem needs to be described will need to be re-visited. Further progress in regional to global scale N flux modelling will only be made if we build models not on a national or major watershed basis, but explicitly on a landscape unitary basis, taking account of the natural environmental controls of N flux rates as they vary between units. Another issue which then arises is how the landscape units can be determined for regional to global scale N flux modelling, or at what level of spatial resolution the landscape units should be defined. As discussed earlier, many of the national or major watershed data sets used by the existing regional to global scale N flux models have constrained these models to run at national or major watershed scale. However, many of the data required are available in national databases at a sub-national scale, or may be provided from remotely sensed images for certain model parameters. The current lack of readily available databases at landscape scale should not in itself limit the development of more accurate and more spatially explicit regional to global N flux models in the future.

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