Countermeasures:

ENVIRONMENTAL AND SOCIO-ECONOMIC RESPONSES - A LONG-TERM EVALUATION

SPATIAL ASSSESSMENT OF COUNTERMEASURES

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Spatial Assessment of Countermeasures: Land Suitability and Side-Effects

A technical deliverable of the

CESER

-**C**ountermeasures**: E**nvironmental and **S**ocio**-E**conomic **R**esponses-

Project

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1. INTRODUCTION

Accidental releases of radioactivity into the environment have the potential to cause widespread and long-term contamination of agricultural land. Although in the most severe case, food production and collection of wild foods may need to cease, more often it is possible through appropriate mitigation to allow farming to continue (Tveten *et al.,* 1998). The difficulty lies in designing countermeasure strategies that will deliver the required reduction in radiation dose in the most efficient, acceptable, cost-effective and technically feasible way. In the past this process of optimisation has typically neglected potential impacts on the environment and agricultural productivity. Equally the acceptability of different remediation options to consumers has received only limited attention.

Decision-makers faced with the task of planning countermeasures in agricultural production systems may need to operate at different geographical scales. While farm managers or agricultural advisors could be developing very specific countermeasure strategies for a single farm, it will be essential that an overall strategy for a parish, region or even country is put in place. The size of the area will depend on the extent of contamination as well as the spatial variability of those factors that determine the success of a countermeasure, e.g. the effectiveness of soil-plant-based countermeasures is often highly dependent on soil properties (Nisbet *et al.,* 1994). In livestock systems the existing infrastructure and agricultural management practices may be limiting. Topography and other environmental conditions may restrict technical feasibility. Knowledge of the spatial variability of these limiting factors allows suitable and non-suitable areas to be distinguished with respect to a particular countermeasure. A geographical information system (GIS) is capable of storing and manipulating the large spatial data sets required and offers opportunities to evaluate different spatial scenarios. In the CESER project a GIS is used to exclude unsuitable areas from the countermeasure evaluation process.

For many geographical areas a range of remediation options may be basically suitable and decision-makers have to select one or more countermeasures, appropriate for the level of contamination and mix of radionuclides. Providing that the countermeasures under consideration are sufficiently effective in terms of dose reduction and suited to the local environment, the selection process can be optimised by applying additional criteria. In the CESER project the following criteria have been applied: a) on-farm costs and benefits, b) environmental and agricultural side-effects and their costs and c) social acceptability. This requires methods by which impacts on these criteria can be measured and thus used to compare countermeasures on an equal basis. The CESER project has tested a range of approaches to quantifying environmental/agricultural (Salt *et al.,* 1999a) and socio-economic (Grande *et al.,* 1999; Wilson *et al.,* 1999) side-effects of countermeasures.

The process of evaluating and selecting suitable remediation options for large areas can be facilitated through a computer-based Spatial Decision Support System. The potential role for decision support systems in post-emergency management of radioactively contaminated land has been stressed previously (Morrey *et al.,* 1996; Borzenko & French 1996). The incorporation of multicriteria decision-aiding techniques into the spatial evaluation process gives the user the opportunity to influence the assessment criteria and generate compromise alternatives (Jankowski, 1995).

This report focuses on the spatial assessment of a) land suitability for countermeasures against radiocaesium and radiostrontium and b) environmental and agricultural impacts arising from their implementation. Results are presented at the river catchment and regional scale for case study areas in Finland and Scotland. A methodological framework as well as key components for a Spatial Decision Support System are presented.

2. OBJECTIVES

The specific objectives of the report with regard to the spatial assessment of countermeasures are:

1. Explain the methodology and data requirements
2. Describe the study catchments, countermeasures and scenarios
3. Provide examples of the environmental impacts quantified
4. Define the environmental and agricultural limitations
5. Display and interpret selected impact maps
6. Summarise changes at the catchment scale through inventories
7. Display and interpret selected suitability maps
8. Present the design of a Spatial Decision Support System

3. MATERIALS AND METHODS

3.1. General Approach

The central theme of the CESER project is the assessment of environmental and socio-economic impacts (or side-effects) of countermeasures. Hence, other aspects of the countermeasure selection process such as the prediction of contamination levels in different foods, the identification of vulnerable areas and the radiological effectiveness had to be treated in a pragmatic way. They are addressed more fully in projects such as SAVE, RESTORE and TEMAS.

This chapter summarises the methodological steps that precede the spatial assessment of countermeasures and explains the creation of impact and suitability maps. The design of a Spatial Decision Support System (SDSS) is discussed separately in Chapter 8. The methodology for assessing environmental and agricultural impacts is described in greater detail in Salt *et al.* (1999a). Wilson *et al.* (1999) explain suitable economic methods and Grande *et al.* (1999) illustrate how consumer responses to countermeasures can be taken into consideration. Figure 1 shows how the spatial assessment of countermeasures fits into the overall framework of the CESER project.

In the early stages the scope of the project was defined by selecting case study areas, radionuclide deposition scenarios and a set of broadly suitable countermeasures. The initial choice of countermeasures was made following a thorough review of the literature, taking into consideration radiological effectiveness, monetary costs, practicability and likely acceptability (Nisbet, 1995). The radionuclides targeted are radiocaesium and radiostrontium.

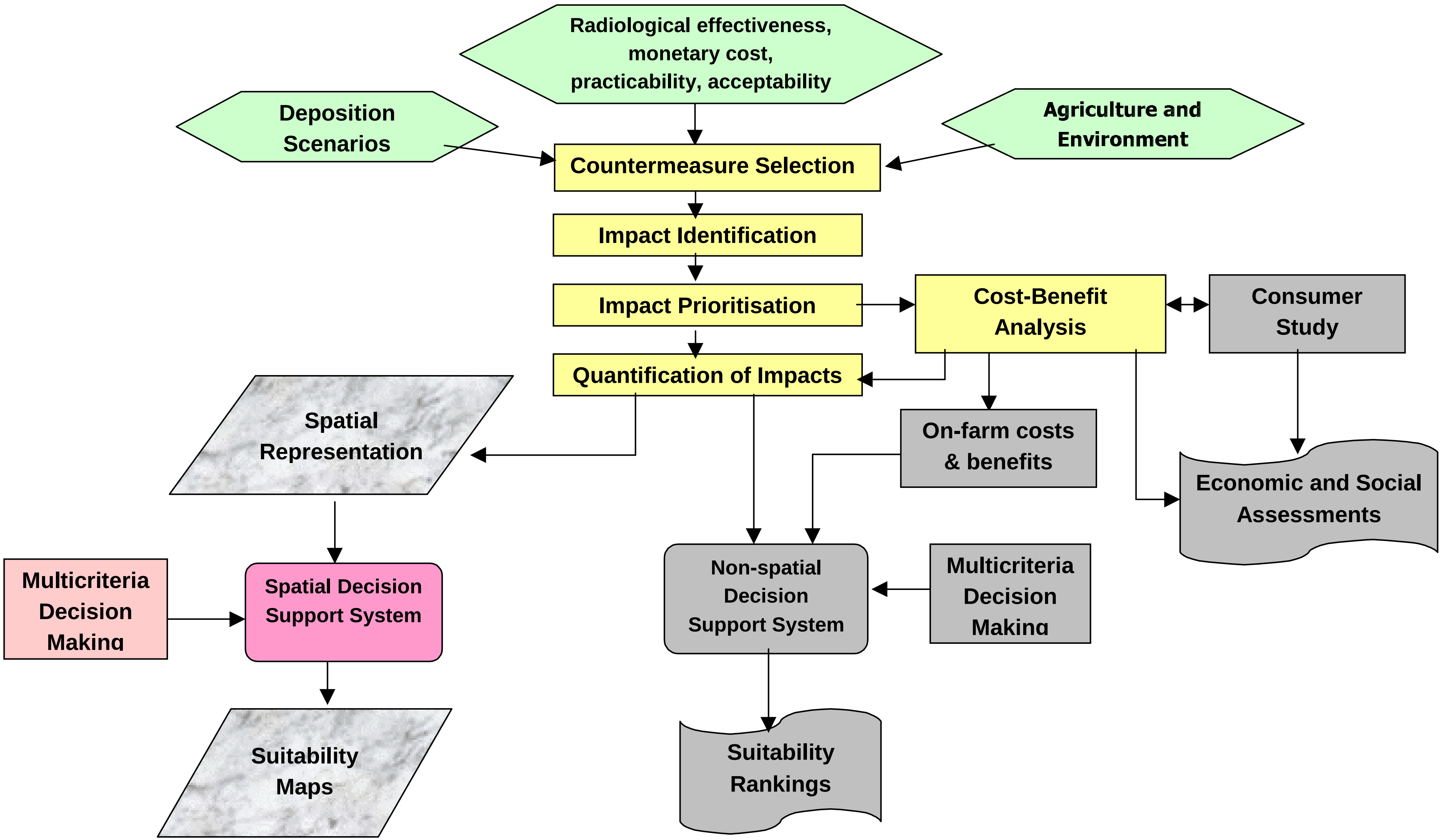

Figure 1. Overview of CESER methodology for environmental and socio-economic assessment of countermeasures. Aspects not directly relevant to this report are shaded in grey.

The next step was to allocate specific countermeasures to each agricultural production system for each of four deposition scenarios (see Table 1). This required prediction of contamination levels in food products, research into farming practises in the study areas and calculation of the potential dose to farmers or other persons executing the countermeasures. Assumptions had to be made about likely decontamination factors based on existing literature (e.g. IAEA, 1994; Roed, *et al.,* 1995; Wilkins *et al.,* 1996). Detailed definitions of each countermeasure were compiled and the potential side-effects were identified through literature review and expert judgement.

Table 1. Radionuclide deposition scenarios.

	^{137}Cs	^{90}Sr	alpha-Pu	Situation
	kBq m^{-2}	kBq m^{-2}	kBq m^{-2}	
Scenario 1	100	2	0.02	Far-field of Chernobyl-like source term
Scenario 2	100	100	0.02	Far-field of source term with higher Sr fraction
Scenario 3	1000	200	0.2	Close to site of accident
Scenario 4	5000	500	1	Very close to site of accident

Given the wide range of side-effects initially identified, it was necessary to develop a set of criteria that would allow a formal assessment of all countermeasures. The criteria were selected to represent the most significant side-effects likely to occur, taking care to minimise overlap between criteria. Some potential impacts of uncertain significance were omitted from the assessment, e.g. changes in greenhouse gas and road vehicle emissions. A key task within the project was to select suitable methods that would allow the impacts of countermeasures to be quantified. A mixture of simulation modelling, calculation, experimental measurement, contingent valuation and expert judgement was applied. Table 2 lists the environmental and agricultural criteria selected together with the main methods applied to quantify them (for further details see Salt *et. al.,* 1999a). A varying degree of expert judgement had to be applied to all criteria.

Table 2. Impact criteria and methods of quantification applied

Criteria	Methods
Soil Erosion and Sedimentation	Modelling
Soil Organic Matter	Expert judgement
Soil Nutrient Transport to Water	Modelling, experimentation
Soil Pollutant Transport to Water	Modelling, experimentation
Animal Welfare	Expert judgement
Agricultural Product Quality	Expert judgement
Agricultural Product Quantity	Calculations, expert judgement
Ammonia Emissions	Spreadsheet calculations
Biodiversity	Landscape structure analysis, expert judgement
Landscape Quality	Contingent valuation, expert judgement

The most detailed results were produced through mathematical modelling where impact estimates were generated for all combinations of slope, vegetation/crop type, soil type and management within a river catchment. Mapping of impacts was focused on these since they are spatially the most diverse.
A series of four countermeasure scenarios was created and applied to Finnish and Scottish test areas to demonstrate potential impacts at the catchment scale (see Section 3.4.). Inventories of changes in

soil loss, losses of particulate and dissolved phosphorus, and ammonia emissions were created to compare impacts across different catchments.

The environmental impacts arising from countermeasures can only be spatially represented in the form of maps once the areas suitable for remediation have been identified. Therefore the limits of application for each countermeasure were defined in terms of environmental and agricultural conditions. In the GIS these limits are used to 'mask out' cells within each catchment that are unsuitable for a particular remediation technique. For the suitable areas, the impact estimates are then combined with the topography, soil and land use data to create spatial data coverages depicting the magnitude of 'impact risk' posed by each countermeasure or countermeasure scenario. For each combination of countermeasure and assessment criterion an individual impact map exists. These maps form the basis of the countermeasure land suitability scores calculated during the MCDM (Multicriteria Decision Making) process in the Spatial Decision Support system (explained in Chapter 8).

3.2. Data Requirements

The quantification and mapping of environmental impacts resulting from countermeasures requires a considerable amount of spatial and non-spatial data for the catchment of interest. In addition the assessment of land suitability for countermeasures requires data on environmental and agricultural limitations that might restrict the use of certain techniques.

3.2.1. Finland

The data sets acquired to allow modelling and upscaling of impacts for Finnish study sites are listed in Table 3. The agricultural land was identified using the ‘Land Cover and Forest Classification of Finland’ provided by the National Land Survey of Finland (NLSF), is based on satellite images. The accuracy was improved by using an agricultural area mask, digitised from 1:50,000 topographic maps based on 1:20,000 maps. The grid used for the classification of land use has a cell size of 25*25 m. The generalised grid (200*200 m) used for the analysis of the whole country was derived from the FEI classification.

The digital soil map covering the whole country has been scanned from the 1:1 M map of Quaternary deposits. Grids of 200*200 m were used for the whole country. For the southern areas (Yläneenjoki and Lepsämänjoki) a more detailed map was used, with a cell size of 25*25 m, originating from a scanned 1:100,000 soil map. The suitability of the large scale data (1:1M and 1:100,000) is poor. They are based on maps of quaternary deposits in Finland, and the classification is not suitable for agricultural purposes.

Field slopes were calculated from a digital elevation model (DEM), prepared by NLSF, based on the contour and shore lines of the Finnish base map (1:20,000). The contour interval on the base map is 5 m for the main part of the country and 2.5 m in some flatter areas. The DEM in raster format has been generated from vector data of contour lines and shore lines by using a triangulation net interpolation (TIN) method. The DEM grid’s cell size is 25m*25m and the elevation values of cells are expressed in decimetres.

Table 3. Spatial and non-spatial data sets acquired for Finnish sites (FEI = Finnish Environment Institute).

Data Set	Owner of Data	Scale	Age	Description
Soil Maps	Geological Survey of Finland/FEI	1:10,0000	Varies	Quaternary deposits of Finland
Landcover	National Board of Survey/FEI	1:100,000	1995	Interpretation of satellite images
Land Contour Data	National Board of Survey/FEI	1:20,000 1:50,000	Varies	
Municipality Boundaries	National Board of Survey/FEI	1:1000,000	1995	
Soil Properties	FEI database		varies	Soil physical & chemical properties; initial soluble phosphorus amounts; for topsoil and subsoil separately
Meteorological Data	Finnish Meteorological Institute/FEI		10 years of daily data (1981-90)	Taken from meteorological station close to the study areas
Agricultural Census Data	Ministry of Agriculture and Forestry/FEI; Agricultural Research Centre		1997	Acreage of crops and animal densities
Land Management Data	FEI database; Extension Services; Agricultural Research Centre; open literature		1997	Crop management practices: tillage and fertilisation; animal feeding regimes

In the slope calculations the elevation difference of each 25*25 m 'field cell' (= a cell representing agricultural land) to all its neighbouring 'field cells' (0-8 nearest neighbours) was determined. A slope value (expressed in %, i.e. m*100/m) was then calculated by dividing the elevation difference by the distance between the centre of the processing cell and the neighbouring cell (25 m or 1.414*25 m for those cells that have only a common corner with the processing cell) and multiplying this quotient by 100. A mean of the calculated slopes was used as a final slope value for every field cell. Only those neighbouring cells that are in agricultural use according to the land use map were used in the calculations. For the countrywide analyses a 200 m generalisation from 25 m grid data was prepared.

For calculations of impacts at the catchment, regional and national level, municipality and catchment grids were used, after converting from the digital vector coverages. The municipality coverages (digitising scale 1:100,000 and 1:1M) were made by NLSF. Finland has been divided into 5840 catchments. The digitising scale of this coverage is 1:50,000 and it is made by FEI.

3.2.2. Scotland

The data sets acquired to allow modelling and upscaling of impacts for Scottish study sites are listed in Table 4.

Table 4. Spatial and non-spatial data sets acquired for Scottish sites.

Data Set	Owner of Data	Scale	Age	Description
Soil Maps	Macaulay Land Use Research Institute	1:50,000* 1:25,000	Varies	Polygon coverage of the different soil types found in Scotland
Landcover	The Scottish Office	1:25,000	1988	Land use of Scotland, surveyed from aerial photographs taken for the whole of Scotland in March 1988
Land Contour Data- Landform Profile	The Ordnance Survey	1:10,000	Survey dates vary	Elevation contours and spot heights; used to create a Digital Terrain Model of the study areas
Parish Boundaries	Copyright Expired on Maps over 50 Years in the United Kingdom	1: 250,000	All Maps > 50 years old; digitised 1997	Digitised from old maps; administrative boundaries used to create a spatial coverage from the Agricultural Census Data
Soil Properties Properties	Macaulay Land Use Research Institute (MLURI)		Sample ages vary	Soil profile descriptions with physical and chemical properties for each horizon; one profile for each soil type.
Meteorological Data	The MET Office		10 Years of daily data (1986 – 1995)	Taken from met stations within or very close to the study areas.
Agricultural Census Data	The Scottish Office		1996	Areas (ha) of all crop types and numbers of livestock aggregated at Parish level.
Land Management Data	Agricultural advisors, farmers and landowners in study areas; open literature		1997	Local practices of crop and animal management e.g. tillage, fertilisation, feeding regimes.

* For three remote areas only data at this smaller scale is available.

Land use information from two different sources had to be combined to produce the land use coverages most appropriate for countermeasure assessments. A digital data set based on air photo interpretation, the Land Cover of Scotland or LCS88 (MLURI, 1988), was modified on the basis of agricultural statistics for parishes. Since field parcel boundaries are confidential and hence not available, the following approach was taken to allocating crops and types of grassland onto LCS88 categories of arable land and improved grassland. The actual area of arable land and improved grassland was determined for the catchment on the basis of the LCS88. Within this area it was assumed that the different arable crops and grazing and mowing grass occurred in the same proportion as in the relevant parish or parishes. For impact mapping weighted averages of the crop types occurring were used.

For soils in Scotland spatial coverage of soil types is available in digitised form. Attribute data for soil properties are held in a separate database in the form of soil profile descriptions with chemical properties for each soil horizon. For common soil types and those surveyed in lowland areas, many entries per soil type may exist, while for others none or only incomplete entries may exist. From this database typical soil profile data was extracted for each of the soil types occurring in the test catchments. In many instances data collected outside the catchments had to be used. Between 5 and 22 soil types could occur in a single catchment. Soils contributing 1% or less to the catchment were amalgamated with similar soils. Alluvium and mixed bottom land could not be modelled or mapped since no typical profile data exists. Where possible, similar soils were grouped together to limit the number of simulations required during impact quantification.

Slope coverage was calculated using the slope algorithm in ARC/INFO-GRID which interpolates in between the contour lines of the digitised topographical maps. The contour interval is 5 m, except in mountain areas where it is 10 m.

3.3. Description of the Case Study Areas

The river catchment was selected as the smallest unit of study since hydrological processes are connected with the environmental impacts of many countermeasures, e.g. soil and nutrient losses. It is also a convenient unit for spatial studies of land use change and agricultural pollution (Hamlett *et al.,* 1992; O'Callaghan 1995). For Finland an assessment of ammonia emissions at the regional and national scale was also conducted.

3.3.1. Finland

Four river catchments representing a wide range of natural conditions in terms of climate and soils, as well as different agricultural production structures were selected. Two catchments are located in southern Finland (Lepsämänjoki and Yläneenjoki) and two in the north (Lestijoki and Taipaleenjoki) (see Fig. 2 & Table 5). The agricultural land use varies from 10 to 50% with the remaining area taken up by forests. Farm and field parcel data were collected by interviewing 400 farmers in 1997 (Grönroos *et al.,* 1998a).

With regard to field slope the catchments can be divided into very flat northern catchments and less flat southern catchments. The slopes in the north do not exceed 4 % with emphasis on the class 0-0.55 %. Around 40 % of the southern catchment also belongs to this class with only few fields having the maximum slope of 10 %.

The most frequent soil types are: clay loam and silt loam in Yläneenjoki, silty clay and clay loam in Lepsämänjoki, silt loam and sandy loam in Lestijoki and silt loam and silt in Taipaleenjoki. The variation in plant available phosphorus in the soil is very similar between the catchments: 40-50 % of the fields in the southern catchments and Lestijoki belong to the class 7.5-15 mg/l (analyzed by a method described by Vuorinen & Mäkitie, 1955). The majority of the Taipaleenjoki fields and 40 % of the Lepsämänjoki fields show values in the class 3-7.5 mg/l whereas 20 % of the Lestijoki fields belong to the class 15-25 mg/l.

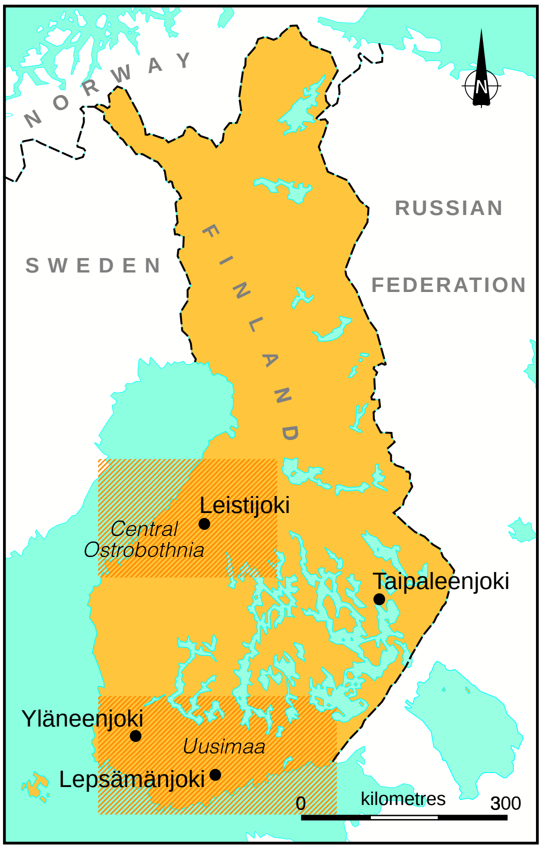

Figure 2. Finnish study areas

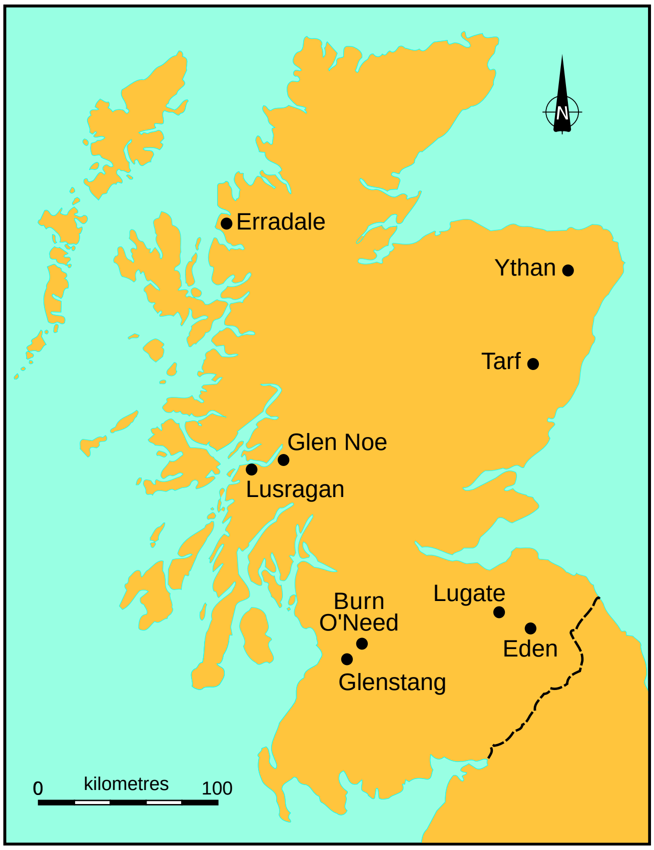

Figure 3. Scottish study areas

The two southern catchments represent typical arable farming areas concentrating on cereal production with some pork and poultry, whilst the more northern areas represent dairy production areas (Table 6 & 7). The grass production is almost entirely for silage, usually kept under grass for 4-5 years, then ploughed for cereals. The animal densities within the interviewed farms were below 1.5 animal units/ha with very few exceptions.

In Yläneenjoki the number of farms under organic production was relatively high (13%), in other areas it varied from 4 to 5%. The farming intensity indicated by nitrogen (N) surplus (N input - N output in yields) showed relatively low input farming. The median N surplus in all studied field parcels was ca. 20 kg/ha in all areas except Taipaleenjoki, where it was somewhat lower, ca. 15 kg/ha.

3.3.2. Scotland

Nine small Scottish catchments were selected in areas dominated by intensive as well as extensive farming (Fig. 3). They represent a wide range of production systems and natural conditions in terms of climate, soils and topography (Table 5 - 7). In contrast to the Finnish study areas, many Scottish areas have moderate to steep slopes and are dominated by semi-natural vegetation. Forest cover is very low. Stocking densities vary from 1.5 livestock units in areas with significant dairy farming to 0.04 LU/ha in areas of extensive sheep grazing.

Table 5. Physical characteristics and land use in the case study areas (F = Finland, S = Scotland).

Catchment		Annual rainfall mm (1)	Area km^2	Median Slope degrees	% arable (3)	% improved grassland	% rough grazing
Yläneenjoki	F	712	227	1	27	0	0
Lepsämänjoki	F	718	214	1	23	0	0
Lestijoki	F	632	1373	0	10	0	0
Taipaleenjoki	F	758	35	0	50	0	0
Glenstang Burn	S	1256	9	2	3.5	90	0
Burn O'Need	S	1256	23	3	0	51	41
Eden Water(2)	S	690	22	2	88	7.5	0
Lugate Water	S	858	33	9	1	31	66
Water of Tarf	S	1286	49	9	0	3	97
River Ythan (2)	S	797	14	3	91	8	0
Lusragan Burn	S	1978	7	4	0	10	85
River Noe	S	1978	18	20	0	0	100
River Erradale	S	1839	14	3	0	2	97

1) 10 year average Finland 1981-1990, Scotland 1986-1995
2) Only a sub-section of these catchments was assessed
3) This includes rotational grass using for cutting or grazing.

Table 6. Percentage distribution of crops in the catchments dominated by arable land use.

	Spring cereals	Winter cereals	Spring OSR	Winter OSR	Sugar beet	Potato	Swedes	Mowing grass	Grazing grass
Yläneenjoki	67	6	4	0	1.0	1.0	0	9	0
Lepsämänjoki	65	3	5	0	0.2	0	0	13	0
Lestijoki	31	0	0	0	0	5	0	63	0
Taipaleenjoki	39	0	0	0	0	0.1	0	51	0
Eden Water	29.8	42.3	0	6.1	0	1.4	1.5	10.7	8.1
River Ythan	44.7	9.3	1.7	6.8	0	3.8	3.9	14.9	14.9

Table 7. Number and type of animals in the case study areas

Catchment	Number Dairy cattle	Number Beef cattle	Number Poultry	Number Pigs	Number Sheep	Number Red Deer (1)
Yläneenjoki(4)	831 (3)		150159	4595	0	0
Lepsämänjoki	512	357	0	690	42	0
Lestijoki	2072	800	0	377	151	0
Taipaleenjoki(4)	1120 (3)		89	0	0	0
Glenstang Burn	866	946	0	0	1356	0
Burn O'Need	969	1023	0	0	5588	0
Eden Water(2)	0	1185	0	0	4400	0
Lugate Water	0	1314	0	0	12510	0
Water of Tarf	0	14	0	0	900	200
River Ythan (2)	0	787	0	8521	1810	0
Lusragan Burn	0	40	0	0	800	20
River Noe	0	0	0	0	1872	200
River Erradale	0	0	0	0	850	100

1) Estimates of red deer numbers only available where game management is practised
2) Only a sub-section of these catchments was assessed
3) Predominantly dairy farms
4) 1995 data

The existing range of farming systems had to be simplified focussing on the most common crops and the most common forms of livestock husbandry. Pork and egg production were omitted, partly because they are not common in the catchments selected but also because they only require countermeasures under deposition scenario 4. This situation has been assessed for the Finnish catchments. Specific sets of countermeasures were developed for the following Scottish agricultural production systems:

- Dairy = Farms producing milk from dairy cows.
- Lowland sheep = Farms that breed and fatten lambs, and do not receive payments for being in a 'less-favoured area'.
- Upland/hill sheep = Farms that breed lambs, and either fatten them or sell as store lambs, and receive payments for being in a 'less-favoured area'.
- Lowland beef = Farms that breed and fatten beef calves, and do not receive payments for being in a 'less-favoured area'.
- Upland/hill beef = Farms that breed beef calves and either fatten them or sell as store cattle, and receive payments for being in a 'less-favoured area'.
- Arable = Farms growing wheat, barley, oilseed rape, potatoes, swedes or similar crops.
- Management for deer = Land managed for the hunting of wild red deer. The number of red deer in Scotland is estimated at 300,000. Generally deer hunting takes place on large privately owned sporting estates in upland areas. Income is derived from the sale of venison and hunting (mainly stags).

3.4. The Countermeasures and Scenarios

Through a careful process of screening and pre-selection, a list of basically suitable countermeasures was compiled for the main agricultural systems in the Finnish and Scottish test areas (Table 8). The selection process is explained in detail in Salt *et al.* (1999a) while extended definitions of the countermeasures and their potential side-effects are provided for Scotland in Salt *et al.* (1999b).

A comprehensive assessment of countermeasure suitability and side-effects for a catchment or region should ideally consider in detail all the countermeasures listed in Table 8 for each agricultural production type occurring within that area. However, it is not possible to employ simulation modelling or other time consuming quantification methods to determine all environmental and agricultural impacts arising from the implementation of countermeasures. The CESER project has focussed on detailed quantification of impacts for which a) suitable models or calculation routines were available and b) significant spatial variation in impacts was expected to occur. As explained in Salt *et al.* (1999a), the application of models widely used to simulate soil loss and nutrient transport processes is restricted to mineral soils. This had no effect on the Finnish impact quantification since all soil types within the 4 catchments are mineral. However, in Scotland, 5 of the 9 catchments have a large proportion of organic soils for which currently suitable models are not available. Therefore soil loss and nutrient modelling for Scotland had to be restricted to the catchments Ythan, Eden, Glenstang and Burn O'Need.

The parameters modelled for the Countermeasure Scenarios are:

a) soil loss (erosion), kg/ha
b) loss of dissolved phosphorus in surface runoff (DP_r), kg/ha
c) loss of particulate phosphorus in surface runoff (PP), kg/ha
d) loss of dissolved P in deep percolate (DP_p), kg/ha

In addition, a series of nitrogen simulations for Finnish sites was undertaken for particulate N in soil loss (PN), dissolved nitrate and ammonia in surface runoff ($D(NO+NH)_r$), nitrate in percolation ($D(NO)_p$), denitrified N (denN) and ammonia volatilisation (volNH). However, the results are not sufficiently reliable to be presented.

Four specific Countermeasure Scenarios were modelled:
Scenario 1. Deep ploughing
Scenario 2. Skim and burial ploughing
Scenario 3. Changes in the feeding of livestock
Scenario 4. Cessation of production. Moving of livestock.

Table 8. Countermeasures selected (AFCF= ammonium-iron-hexacyanoferrate = Prussian blue; F = Finland, S = Scotland)

Short title	Short description	DY	SL	SU	BL	BU	AR	DE
Administer AFCF	0.4 g per day to dairy cows; 0.1 g per day to lactating ewes / 0.06 g to fattening lambs; 0.4 g per day to winter finishing cattle; as boli or feed blocks to summer finishing cattle and upland lambs/fattening calves	F/S	S	S	F/S	S		
Supply hay and AFCF	Feed hay treated with AFCF during autumn/winter. Wait a minimum of 1 month before hunting							S
Supply calcium	Give 200 g Ca to cows daily when indoors for milking	F/S						
Feed clean concentrate	Supply cows with uncontaminated concentrate up to 80% of energy intake	F/S						
Feed concentrate grown on the farm	Convert enough grassland to barley cultivation to supply cows with home grown concentrate up to 80% of energy intake	F/S						
Fatten on clean feed	Feed beef cattle uncontaminated concentrate and roughage during the last part of the fattening period. Sell for slaughter.				F/S	S		
Fatten on clean concentrate	Wean lambs early and fatten on uncontaminated concentrate indoors. Sell for slaughter		S	S				
Fatten on clean roughage	Feed lambs uncontaminated roughage during the last part of the fattening period and sell for slaughter		S	S				
Sell early for fattening	Wean lambs early and sell for finishing outside the contaminated area			S				
Sell for fattening.	Sell lambs after one grazing season/sell beef cattle for finishing outside the contaminated area. Apply slaughter restrictions.			S		S		
Apply lime	Apply 2 t/ha of lime to the soil surface every 2 years		S	S	S	S		
Shallow plough & apply lime	Apply lime every 2 years followed by mouldboard ploughing to 25 cm.						S	
Apply potassium fertiliser	Apply 100 kg/ha of potassium to the soil surface annually		S	S	S	S		
Shallow plough & apply potassium	Apply K annually followed by mouldboard ploughing to 25 cm.						S	
Improve land	Improve rough grazing by cultivation, application of lime and N-P-K fertiliser and sowing of grass/clover mix			S		S		S
Intensify the use of improved land	Reseed existing improved grassland more frequently and increase annual fertiliser application of N-P-K			S		S		
Deep plough	Ploughing to 50 cm depth.						F/S	
Skim & bury plough	Remove the top 5 cm of soil and place at 50 cm depth						F/S	
Convert to oilseed rape	Grow spring oil seed rape instead of cereals or root crops.						F/S	
Exclude animal production/hunting	Cease animal or crop production and leave land fallow/cease hunting.	F/S	F/S	S	F/S	S	F/S	S
Afforestation	Convert to conifer forestry	F/S	F/S	S	F/S	S	F/S	S

For Scenarios 3 and 4 ammonia emissions were also calculated at the catchment and regional/national level. In Scenarios 1 and 2 the countermeasures were only applied to those areas within a catchment that fulfilled the suitability requirements, as outlined in Chapter 5. While Scenarios 1 and 2 were simulated in the same way for both countries, slightly different approaches were taken for Scenarios 3 and 4, reflecting differences in the agricultural systems and different scales of the assessment.

3.4.1. Countermeasure Scenario 1 and 2 (ploughing techniques)

To simulate the changes resulting from deep as well as skim and burial ploughing three separate soil property databases were created: an original database describing the *status quo* and two databases describing the change in soil properties due to the ploughing. In the deep ploughing scenario the top 50 cm layer of the soil was inverted such that the originally lowest layer became the surface layer. This alters the following properties of the plough layer: particle size distribution, organic matter content, pH, and the initial values of plant available, inorganic phosphorus fractions. Changes in the first two parameters made it necessary to recalculate the soil erodibility factor. The soil database describing the effect of skim and burial ploughing showed only a minor change in the order of the layers, since only the top 5 cm are removed and placed at a depth of 50 cm, causing the other layers to move upwards (Roed, *et al.,* 1996). The impact of each ploughing method was calculated as the difference between the original and modified simulation results on a catchment scale using GIS techniques.

3.4.2. Countermeasure Scenario 3 (changes in the feeding of livestock)

This scenario involves a significant change in the diet of dairy cows to achieve a reduction in the daily intake of contaminated feed. The level of imported concentrate or home-grown barley in the diet is raised to 80% of the net energy intake from a typical level of 40% in Finland and 28% in Scotland.

For Finland, the impact on soil and nutrient losses was simulated, assuming that in each catchment 50% of the grass fields are converted to barley fields “as random as possible”. Simultaneously the P-fertilization on barley fields is increased by 20% and the N-fertilization by 25%. The potential impacts on ammonia emissions were studied using a worst case scenario of radioactive deposition over the whole of Finland, necessitating a change in the feeding of all dairy cows.

For Scotland, changes in the diet of dairy cows as well as beef calves and lambs were studied for the Glenstang and Burn O’Need catchments. Scenario 3A assumes that all concentrate feed is imported. The area of mowing and grazing grass is reduced accordingly and a corresponding area of green fallow created. Scenario 3B assumes that all concentrate is provided through increased on-farm production of barley. The area of mowing and grazing grass is reduced, however, a large proportion of this is converted to barley leaving only a small area fallow. The area of barley required is calculated on the basis of separate summer and winter diets and catchment specific crop yields. The retained fields of mowing and grazing grass are managed as previously, but the amount of N and P spread onto mowing grass via manure is increased by 27% and 20%, respectively. In addition, N and P inputs from animal faeces during grazing increase as less grazing land. Green fallow was simulated as a special crop. Changes in the relative areas of crops and the introduction of fallow areas were implemented in the GIS.

Lowland beef calves are assumed to be treated via a diet of uncontaminated roughage and concentrate during the last 40 days of the fattening period. The diet composition is the same as normal, but the clean feed is imported. The resulting changes in mowing and grazing grass areas were calculated and combined with those resulting from the dairy countermeasure.

Sheep farms in the Glenstang area are lowland farms fattening lambs. In the Burn O'Need area there is a mixture of lowland and upland sheep farms, some with a considerable amount of rough grazing and not all lambs are fattened in the area. The aim of the countermeasure scenario was to prevent lambs from grazing organic soils in areas of rough grazing where radiocaesium transfer would be high. This was achieved by moving 2300 of the 3000 lambs from Burn O'Need to Glenstang where they graze lowland pasture for 2 months prior to a 6 week fattening period on clean roughage. Under Scenario 3a the lambs and ewes remaining in Burn O'Need are kept on the improved land only. Under Scenario 3b, half the ewes have to be kept on rough grazing since part of the improved grass is converted to barley production for the dairy cows. In Glenstang some of the land left fallow as a result of changes in the diet of dairy cows, is utilised to provide grazing for the extra lambs.

No adjustments to nutrient inputs to soil via faeces/manure were necessary for the sheep and beef scenarios since clean feeding of the normal diet does not change the amounts produced. Changes in inputs due to the movement of lambs were accounted for by increasing the area of grass via data manipulation in the GIS.

3.4.3. Countermeasure Scenario 4 (cessation of production)

For Finland the effects of abandonment were studied, assuming cessation of dairy production in the Lestijoki catchment and switching of this production to the Lepsämänjoki catchment. The effects on losses of soil and nutrients in Lestijoki were simulated using green fallow as a crop for all field parcels in comparison with the original practice. In the Lepsämänjoki catchment the P- and N-fertilization was increased in accordance with the increase in animals, by +13 kg/ha/year for P and +34 kg/ha/year for N (as NH_4-N). This increased fertilization was applied to all crops and all field parcels. Additionally all barley fields were converted to grass fields.

Changes in ammonia emissions for Finland were studied at the regional level. It was assumed that due to regionally variable radioactive deposition, dairy production would cease in the province of central Ostrobothnia, which includes the Lestijoki catchment. A corresponding increase in dairy production in the southern province of Uusimaa in which the Lepsämänjoki catchment lies and which is normally dominated by cereal production, was then modelled.

For Scotland cessation of crop and animal production was assumed to occur in all 4 test catchments. All crops and improved grassland were replaced with green fallow. The plant and management parameters in the model were selected to mimic a good cover of vegetation with no tillage or inputs of fertilisers. In contrast to Finland, regional movement of animals was not included.

4. IMPACT QUANTIFICATION

4.1. Soil and Nutrient Loss Simulations

Owing to climate, topography and soils in countries like Scotland and Finland, surface runoff and soil loss are significant carriers of nutrients, particularly phosphorus, to surface waters. Thus a model containing descriptions of these processes had to be selected for this study. Most of the existing erosion/phosphorus models are related to the CREAMS model developed in the late 1970's in the U.S (Knisel, 1980). The ICECREAM model (Tattari *et al*., In prep.), is a field-scale mathematical simulation model predicting water, soil and nutrient losses at the edge of the field and out of the root zone (Fig. 4). It is an extension of the CREAMS/GLEAMS models (Knisel 1980; 1993; Leonard *et al.,* 1987) developed to assess and compare the impact of different agricultural management practices on soil and nutrient losses. The hydrology, crop growth and soil loss calculations have been modified by Rekolainen and Posch (1993).

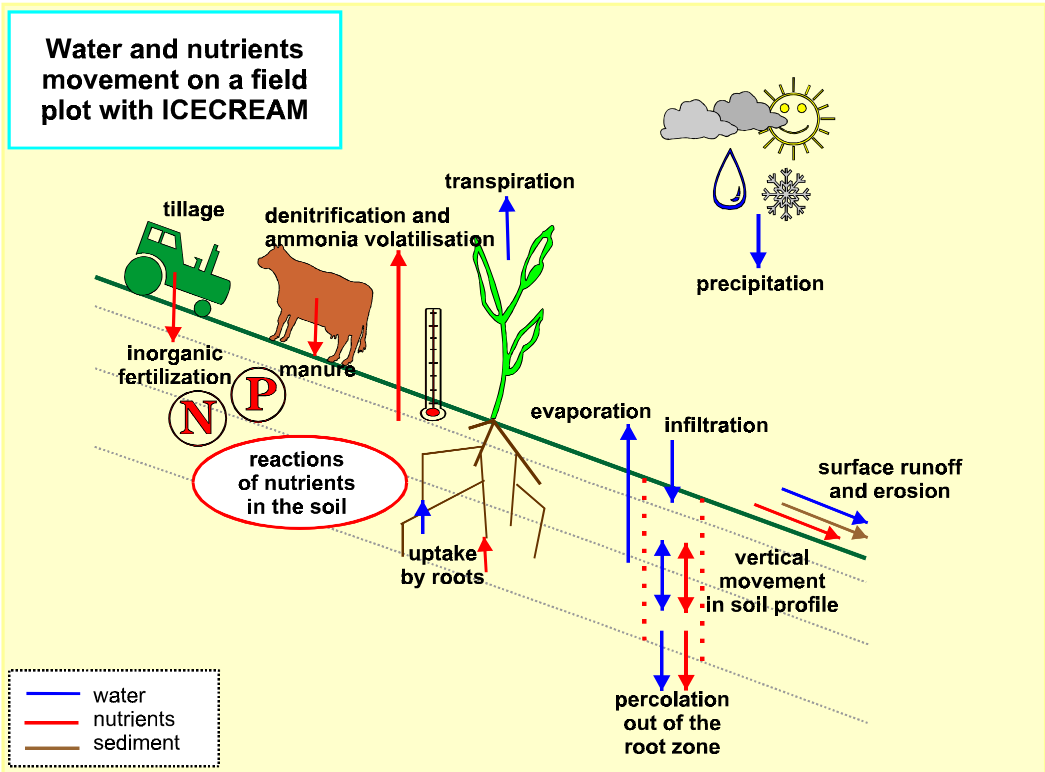

Figure 4. The main processes simulated in the ICECREAM model

The CREAMS/GLEAMS models are widely tested and validated. The ICECREAM model has been specifically tested for Finnish conditions (Rekolainen & Posch, 1993; Tattari *et al.,* In prep.) and the uncertainty analysis for the model has been carried out by Bärlund & Tattari (1998). Hence ICECREAM was selected for this study. The results for soil and phosphorus losses for individual crop and soil types are illustrated for selected catchments areas.

The output variables presented are:
- soil loss (erosion), kg/ha
- loss of dissolved phosphorus in surface runoff (DP_r), kg/ha
- loss of particulate phosphorus in surface runoff (PP), kg/ha

Results for dissolved P in deep percolate (DP_p) and all nitrogen parameters are not presented due to uncertainties about the reliability of the model predictions. For Scenarios 1 and 2 the nitrogen results are currently unsatisfactory while for Scenarios 3 and 4 they are in agreement with expert judgement. For each catchment a large matrix of model output parameters was generated for all possible combinations of slope, soil type, crop type and management regime. The overall impacts at the catchment scale are explained in Chapter 6.

4.1.1. Finnish Results

The results are illustrated for the southern Yläneenjoki catchment only, since similar results were obtained for the other 3 catchments. The abbreviations of soil types are explained in Table 9. If not mentioned separately, the simulations are presented for the typical Yläneenjoki soil types silt loam (HHt) and clay loam (HtS), for the most frequent crop, barley, for a field slope of 1 % and for an initial soil P-status of 10 mg/l. For the output variables only relative values are presented by setting the highest value in each graph to 100 % and the others in relation to this maximum.

Table 9: Soil type abbreviations based on an approximate conversion of the Finnish soil textural classes into the USDA classification.

Finnish	English	Finnish	English
Lj	organic silt (6-20 % organic matter)	KHs	silt
AS	heavy clay	He	silt loam
HsS	silty clay	HHt	silt loam
HeS	clay loam	KHt	sandy loam
HtS	clay loam	HHk	sand
HHs	silt loam	HtMr	sandy moraine

To illustrate the effect of soil type, results for all types occurring in Yläneenjoki are shown in Figures 5-7. The two most frequent types, HtS and HHt, have relatively low soil loss and consequently low PP values. Deep ploughing increases soil loss but can either decrease or increase PP loss. This is dependent on the degree of change in erosion relative to the initial P status of the subsoil brought to the surface. The marked increase in soil loss following deep ploughing for HHt is due to the high organic matter content of the original topsoil (12%) compared to the subsoil (1%), which affects soil erodibility. Deep ploughing clearly decreases DP_r output.

Crop type has a large effect on all output variables studied (Figs. 8-10). Mowing grass and green fallow have the lowest soil and PP losses. Grass has the highest DP_r loss due to the surface application of fertilizer. The effects of deep and of skim and burial ploughing are similar for spring barley, winter wheat and sugarbeet. Bare fallow shows the highest PP losses and ploughing has a negligible impact. DP_r increases due to deep ploughing for grass as a result of soil and crop type. The distinct difference between the PP and DP_r losses for spring barley and grass explains some of the effects seen in Scenario 3 where land use changes occur as a results of changes in animal feeding.

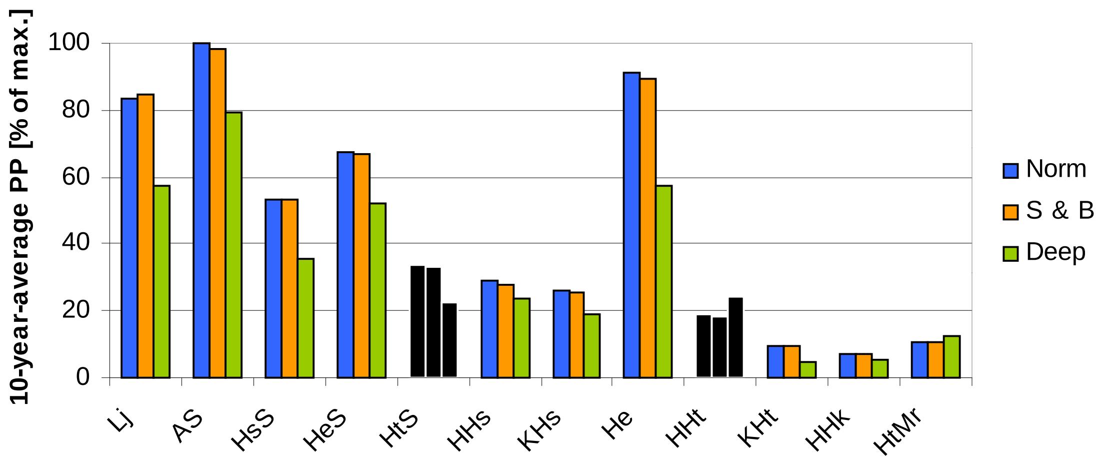

Figure 5. The effect of soil type on PP for normal practice (Norm), deep (Deep) and skim and burial ploughing (S&B). The most frequent soil types are marked in black.

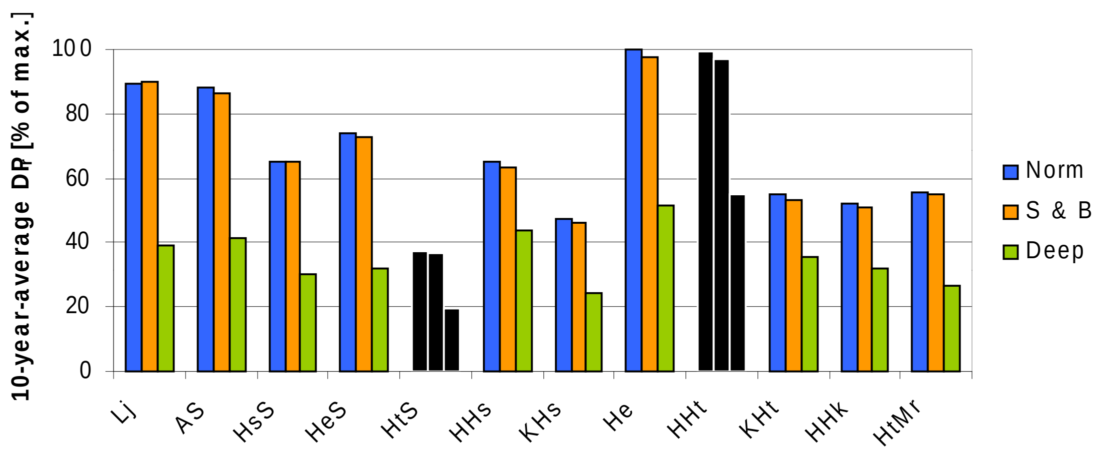

Figure 6. The effect of soil type on DP_r for normal practice (Norm), deep (Deep), and skim and burial ploughing (S&B). The most frequent soil types are marked in black.

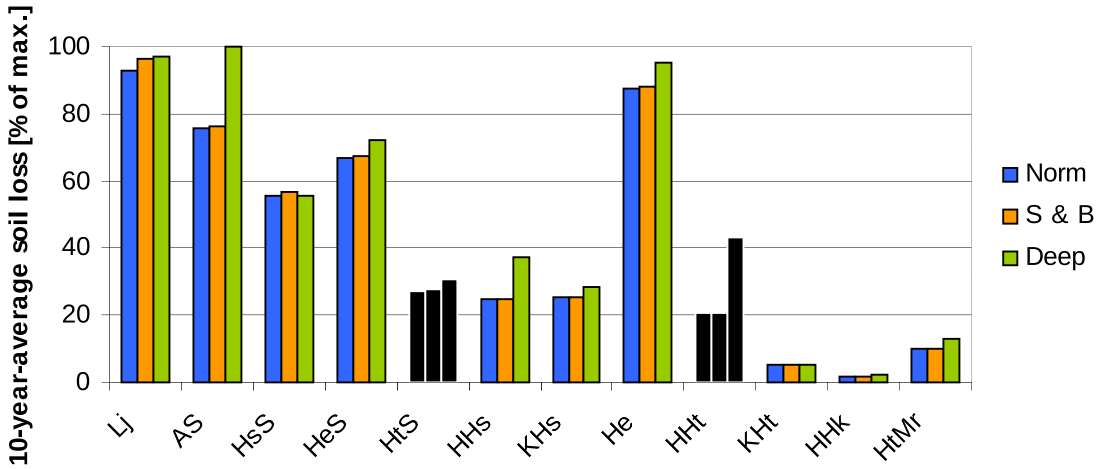

Figure 7. The effect of soil type on soil loss for normal practice (Norm), deep (Deep) and skim and burial ploughing (S&B). The most frequent soil types are marked in black.

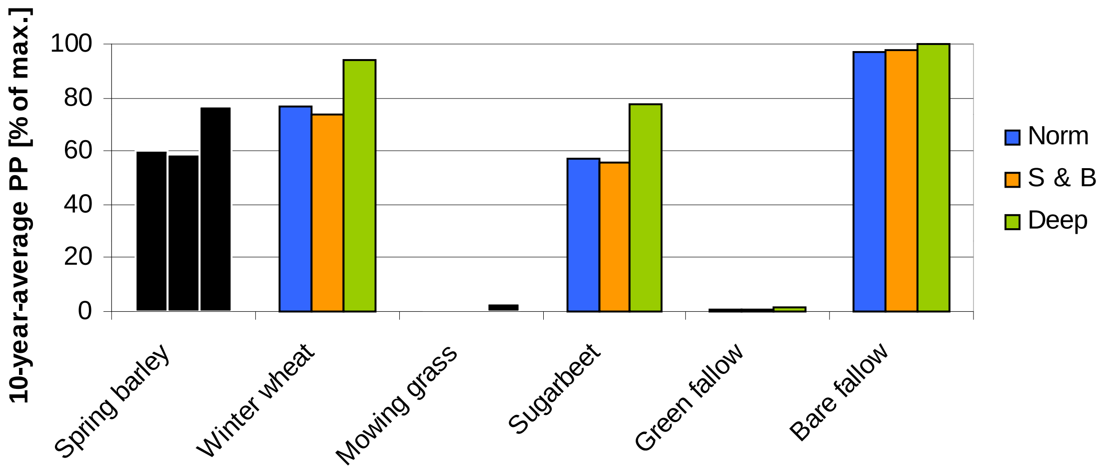

Figure 8. The effect of crop type on PP for normal practice (Norm), deep (Deep) and skim and burial ploughing(S&B). The most frequent soil types are marked in black.

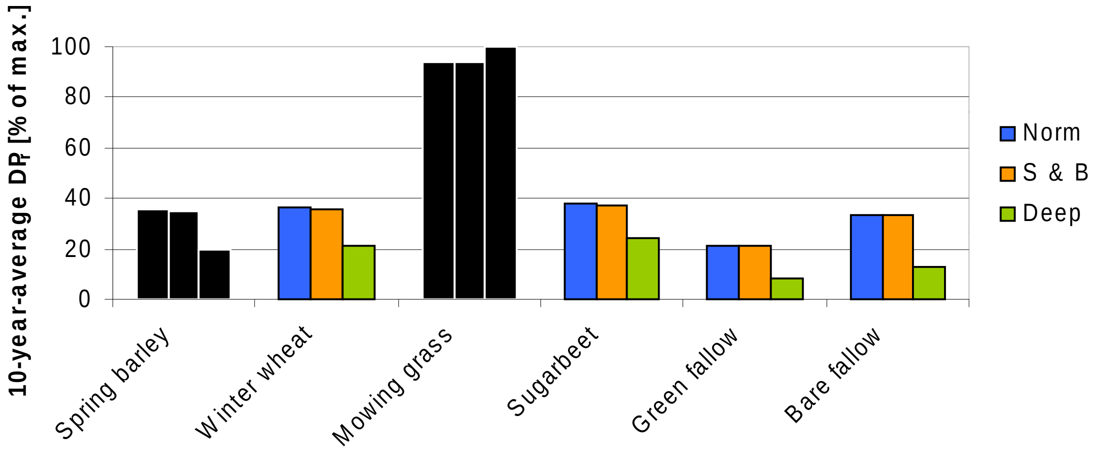

Figure 9. The effect of crop type on DP_r in surface runoff for normal practice (Norm), deep (Deep) and skim and burial ploughing (S & B). The most frequent soil types are marked in black.

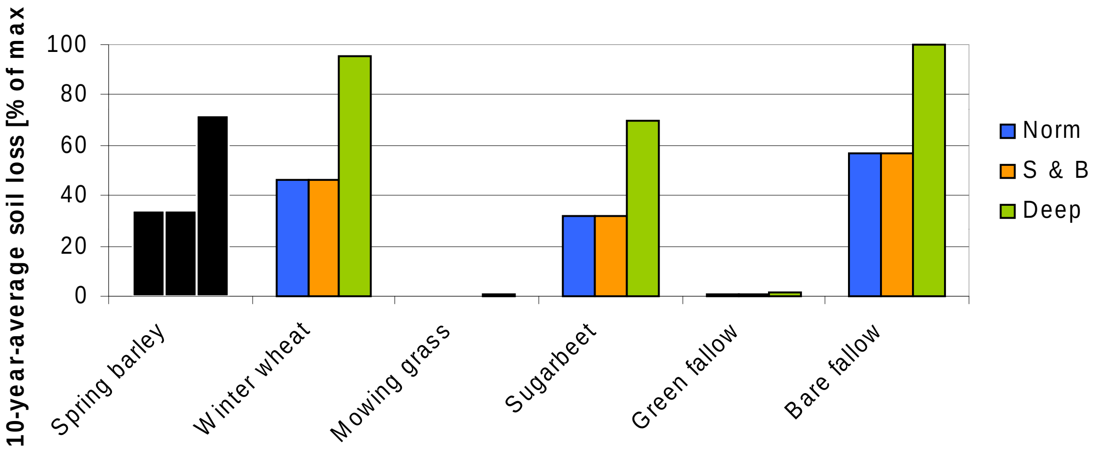

Figure 10. The effect of crop type on soil loss for normal practice (Norm), deep (Deep) and skim and burial ploughing (S&B). The most frequent soil types are marked in black.

Soil loss and consequently PP loss increase with field slope (Figs. 11-13). The effects of deep ploughing and soil type are distinct. The coarser soil (HHt) shows higher soil loss, PP and DP_r values than the clayey HtS soil. No effect of deep ploughing on soil loss can be detected for these two soil types, however, the poor subsoil coming to the soil surface causes a drop in PP and DP_r losses. The difference in the original PP output between the soil types, caused by differences in topsoil erosivity, is diminished by deep ploughing. DP_r decreases with increasing slope, most likely due to decreasing P content in the surface layer caused by the increased P loss in erosion. The most frequent slopes in the catchments of this study are below 3 %.

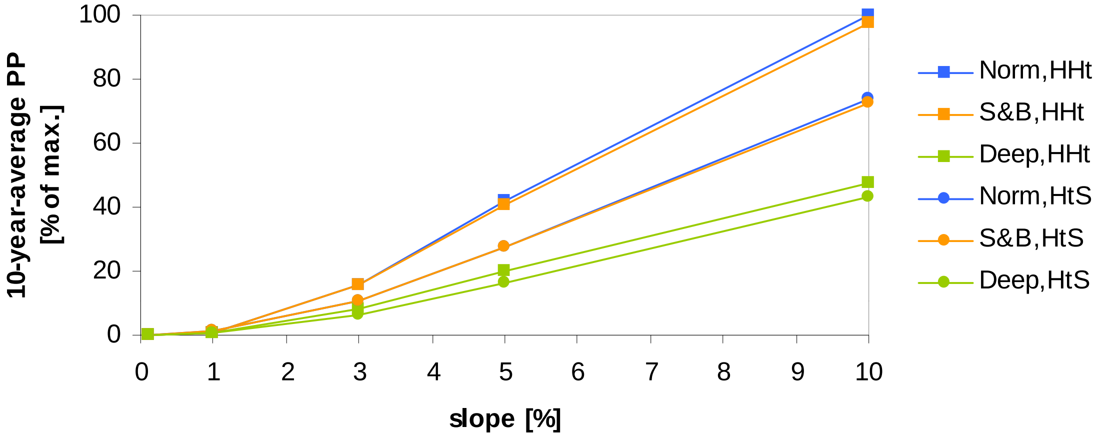

Figure 11 The effect of field slope on particulate phosphorus in surface runoff for normal practice (Norm), deep (Deep) and skim and burial ploughing (S & B).

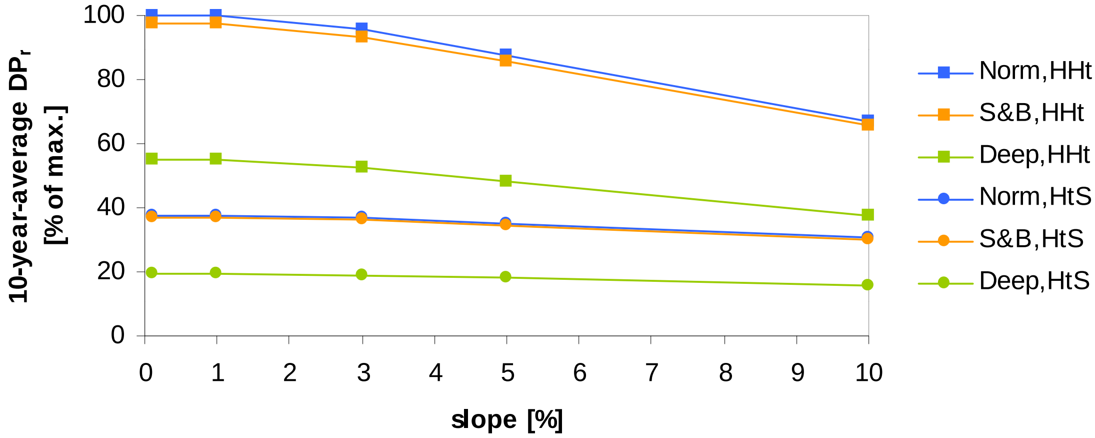

Figure 12. The effect of field slope on dissolved P in surface runoff for normal practice (Norm), deep (Deep) and skim and burial ploughing (S & B).

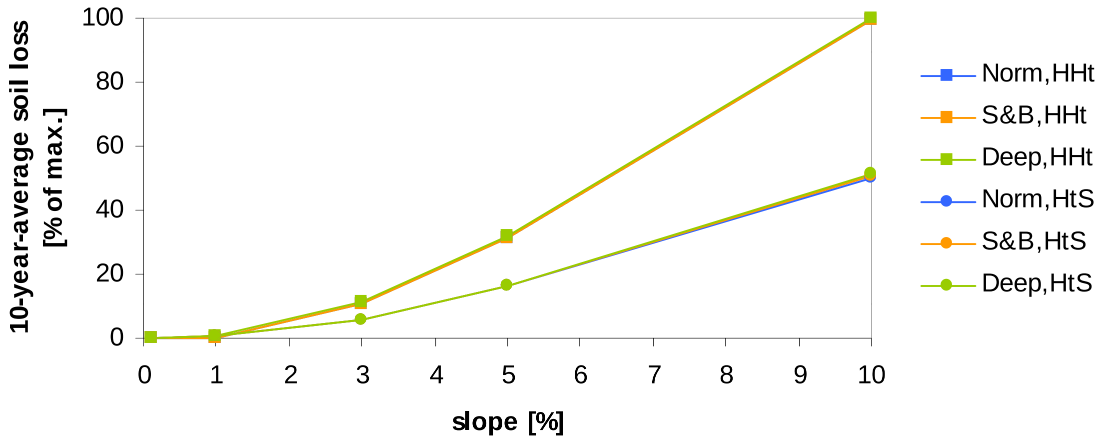

Figure 13. The effect of field slope on soil loss in surface runoff for normal practice (Norm), deep (Deep) and skim and burial ploughing (S & B) on 2 soil types.

An increase in the initial plant available P status of the soil increases both PP and DP_r output (Figs. 14-15). The increase is more noticeable at low P-status values. The differences between the HHt and HtS soil types are solely due to the differences in surface runoff and erosivity between these soils.

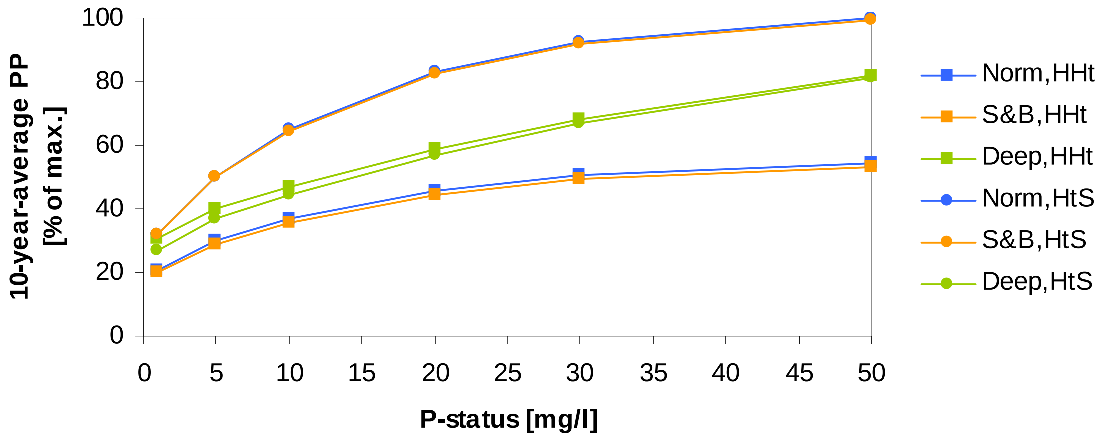

Figure 14. The effect of the initial status of plant available P in soil on PP losses for normal practice(Norm), deep (Deep) and skim and burial ploughing (S&B) on 2 soil types.

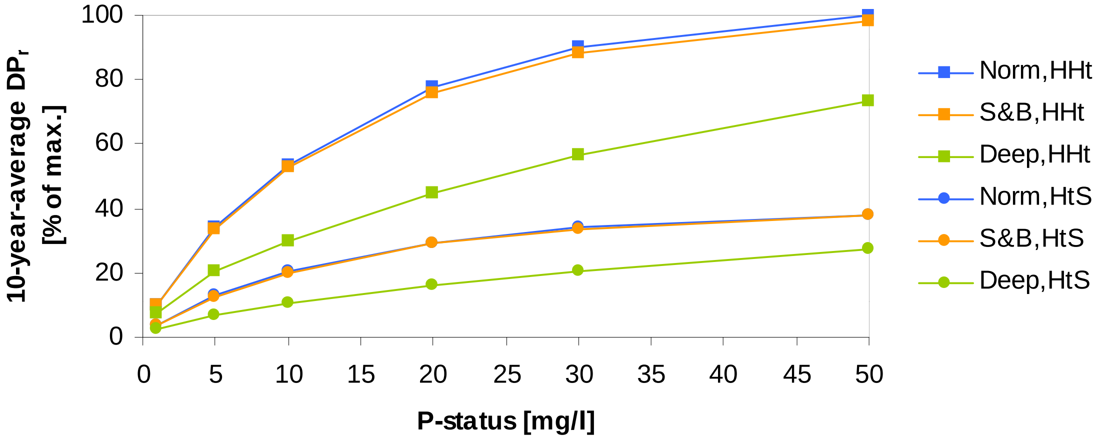

Figure 15. The effect of the initial status of plant available P in soil on DP_r for normal practice (Norm), deep (Deep) and skim and burial ploughing (S & B) on 2 soil types.

4.1.2. Scottish Results

ICECREAM simulations were performed for the Ythan, Eden, Glenstang and Burn O'Need catchments to estimate the impacts of the 4 countermeasure scenarios on soil and phosphorus losses. All results are presented for a uniform slope of 6% equivalent to 3.4 degrees and expressed as relative values compared to the highest value in each graph.

General trends for all catchments

In the Eden and Ythan catchments in eastern Scotland arable land is typically situated on freely to imperfectly draining soils and rainfall is comparatively low. The Glenstang and Burn O'Need catchments, in south-west Scotland, are dominated by livestock farming with heavier textured and imperfectly to poorly draining soils being most common. Rainfall is significantly higher than in the eastern areas (see Section 3.3. Table 5.). These differences in climate and soils lead to different rates of erosion for the dominant soil types across all catchments, as shown in Figure 16. The lowest rates are predicted for freely draining soils while imperfectly and poorly draining soils show higher rates.

The effects of crop type on soil loss were consistent across catchments with winter wheat always showing highest rates followed by winter barley and winter oilseed rape. All summer-sown crops had lower rates of soil loss, although the sequence varied between catchments depending on differences in sowing, harvesting and tillage dates as well as crop parameters such as yield. Mowing grass which is ploughed every 3 years always has higher rates of soil loss compared to permanent grazing grass and green fallow. The effects of crop type are illustrated for the Ythan catchment in Figures 17 and 18 for the dominant soil type. The consistent difference between winter and summer sown crops is due to the exposure of partially bare soil to winter rainfall and snow melt. When crops are sown in autumn they grow insufficiently to cover the soil during winter. This applies in particular to winter wheat. The fine tilth produced before sowing also erodes much more readily than a ploughed field or stubble. This is well documented in the literature (e.g. Evans & Cook, 1987; Speirs & Frost, 1985).

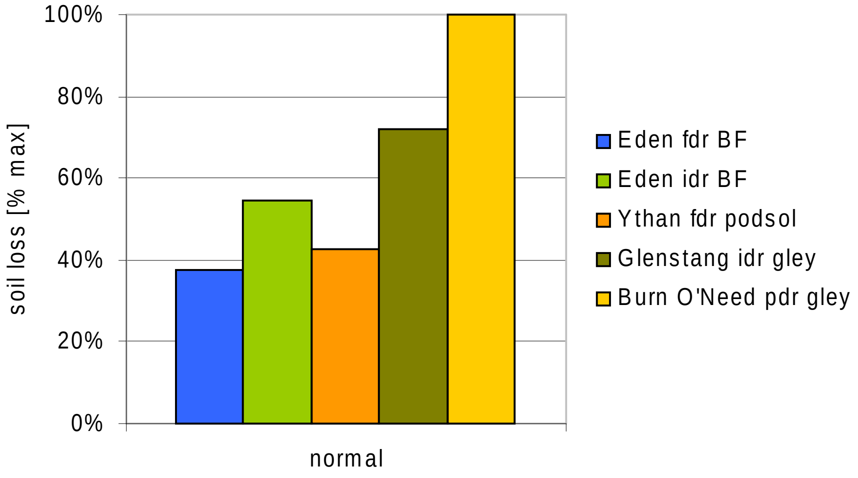

Figure 16. Soil loss on mowing grass at 6% slope on the dominant soil types of each catchment (fdr, idr, pdr = freely/imperfectly/poorly draining; BF = brown forest soil).

Losses of PP are highest on winter wheat in line with soil loss (Fig 17.). Potatoes show comparatively high losses of PP since they receive the highest rates of P fertilization of all crops studied (150-200 kg/ha of P_2O_5). In the Eden catchment potatoes and swedes receive once yearly applications of animal manure. Here the losses of DP_r are almost twice as high for potatoes compared to other arable crops, again due to the level of fertilisation (Fig 18). In the Ythan area, manure is spread onto fields of spring barley and oilseed rape but DP_r losses are similar to other crops. Generally soil loss and PP are very sensitive to slope, while DP_r varies little in response to slope.

Ploughing Countermeasures

In agreement with the Finnish results, deep ploughing of Scottish soils lead to greater changes compared to skim and bury ploughing. Any changes in soil loss due to countermeasures were always matched by corresponding changes in the volume of surface runoff.

In the Ythan catchment only one soil type dominates, a cultivated iron podsol. Deep ploughing reduces the soil loss potential since subsoil with a higher sand and lower clay content is brought to the surface (Fig. 17). DP_r is also reduced since the subsoil has a lower P status. These 2 effects combine to reduce PP. Skim and burial in comparison causes only a small decrease in these parameters.

In the Eden sub-catchment two soil types cover 63 % of the area, a freely (fdr BF) and an imperfectly draining (idr BF) brown forest soil. Deep ploughing is predicted to cause a small increase in soil loss on fdr BF while idr BF shows no change (Fig. 19). The two soils behave very differently with respect to PP losses after deep ploughing. The freely draining soil has a higher concentration of labile inorganic P in the subsoil compared to topsoil and the total P content decreases with depth by less than 50%. This leads to a marked increase in DP_r and a slight increase in PP. On the less well drained soil PP is noticeably reduced while DP_r is slightly reduced, a combined effect of lower P status of the subsoil.

The most common soil group in the Glenstang catchment, occupying 78% of the area, consists of imperfectly draining non-calcareous gleys and brown forest soils. Other soils are poorly draining and therefore deemed unsuitable for ploughing countermeasures (see Chapter 5). The dominant land use is mowing and grazing grass. Deep ploughing simulations suggest the following changes: soil loss increases for all land uses up to slope angles of 4-5%, but above this limit only for grazing grass and potatoes, while soil loss for winter barley and mowing grass decreases. PP significantly decreases for crops and mowing grass, while grazing grass shows a variable response depending on slope. DP_r is slightly lower compared to normal practice for crops and mowing grass, while grazing grass shows a small increase (5%). Skim and bury ploughing causes very little change in soil loss for all land uses. Results for PP and Dpr confirm this trend with the exception of grazing grass, which shows a 9 and 14% increase, respectively.

In the Burn O'Need catchment the most common soil group, consisting of poorly draining non-calcareous gleys, occupies 33% of the area. It is classed as not suitable for ploughing countermeasures due to soil wetness (see Chapter 5). Only 13% of the catchment has better drained soils (in the same soil group as in Glenstang) that are suitable for deep and for skim and burial ploughing. The land use is 70% grazing grass, 30% mowing grass. Although the same climate, soil chemistry and plant parameters were used in the simulations as for Glenstang, some differences in the results occur. These appear to be due to different phosphorus inputs via faeces and manure as a result of differences in livestock densities. After deep ploughing DP_r on grazing grass decreases; PP also decreases but varies with slope. Changes following skim and bury are variable but small.

Tests carried out with the ICECREAM model suggest up to 10% error on the predictions for changes in soil and P losses after deep and skim and burial ploughing. This relates to the unexpected sensitivity of the model to changes in the depth distribution of soil layers in the input files which were necessary to simulate the soil profile changes after ploughing.

Changes in the diet of dairy cows and beef cattle

Scenario 3 was only simulated for the Glenstang and Burn O'Need catchments. The countermeasure feeding regime implemented for dairy cows and fattening cattle leads to an increase in phosphorus loadings via increased manure and faeces to mowing grass and via extra faeces only to grazing grass. This is a combined effect of increased volume of manure due to more concentrate feeding (dairy cows) and fewer grass fields being available for disposal and grazing. Figure 20 illustrates the increases in DP_r and PP on the main soil group in each catchment. At the scale of the individual field DP_r is increased by 75-84% on mowing grass and 34-64% on grazed grass. The effect on PP is slightly less with increases of 57-60% and 17-45%, respectively.

Ceasing production

Green fallow simulations showed low rates of soil loss, typically below those of grazed grass but slightly higher than on rough grazing land (Figs. 17 & 18). Since no fertilisers are applied, DP_r and PP are also low.

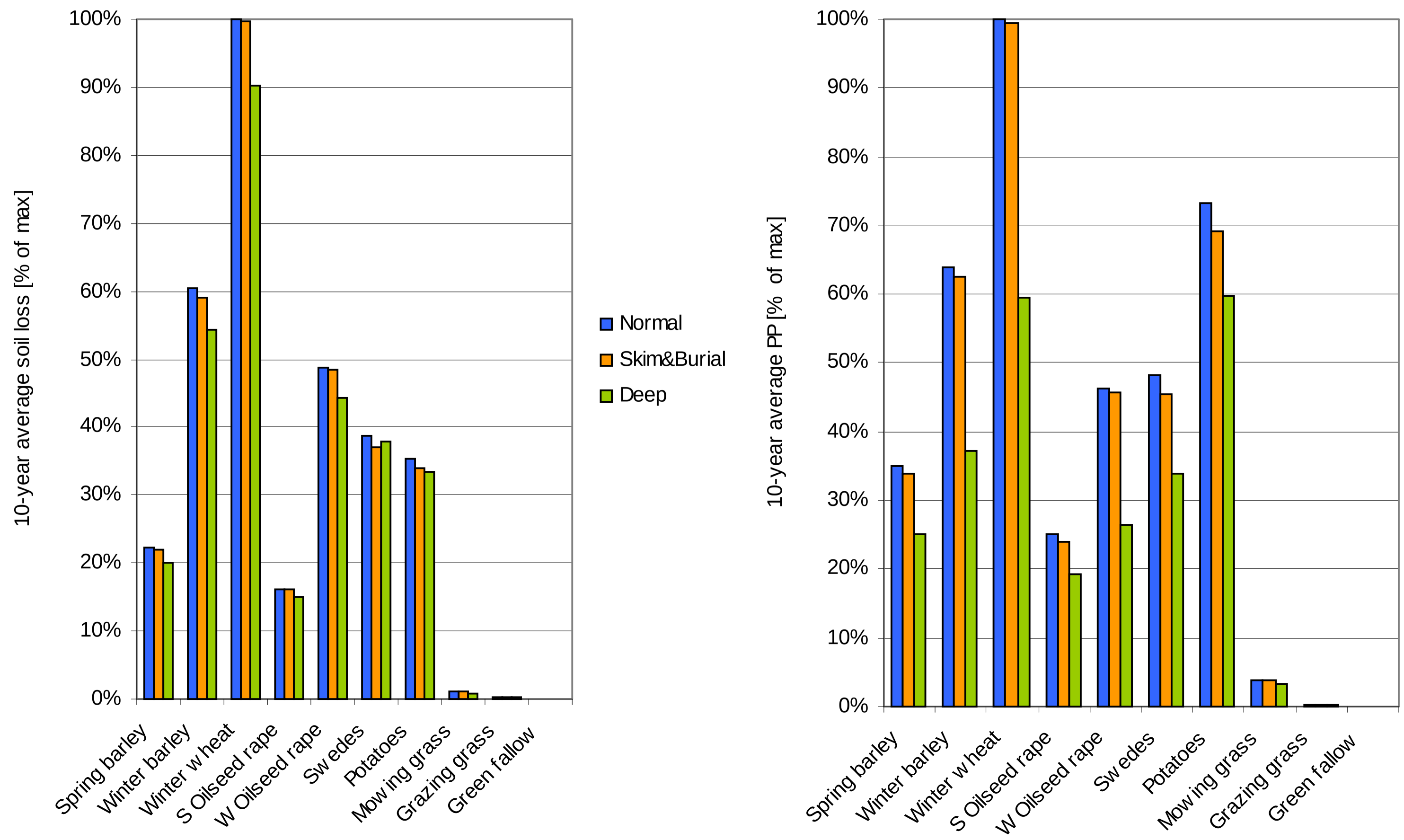

Figure 17. The effect of crop type on soil loss (left) and PP loss (right) for normal practice and after deep and skim and burial ploughing (6% slope; freely draining iron podsol) in the Ythan catchment.

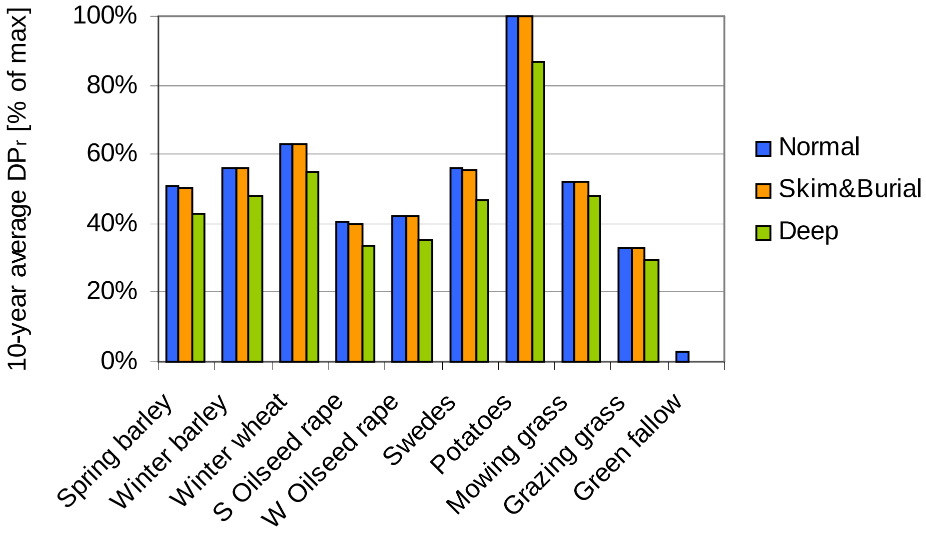

Figure 18. The effect of crop type on DP_r for normal practice and after deep and skim and bury ploughing (6% slope; freely draining iron podsol) in the Ythan catchment.

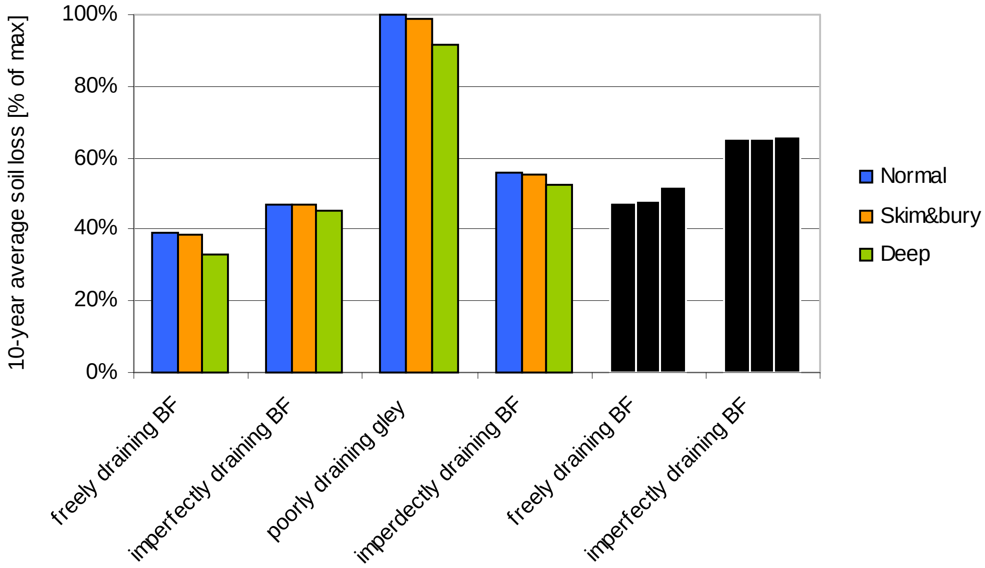

Figure 19. The effect of soil type on soil loss in the Eden catchment at 6% slope before and after ploughing countermeasures. Values are for all arable land using a weighted average of crop types including grass. The soils vary in texture from sandy loam to clay loam. The most frequent soil types are marked in black.

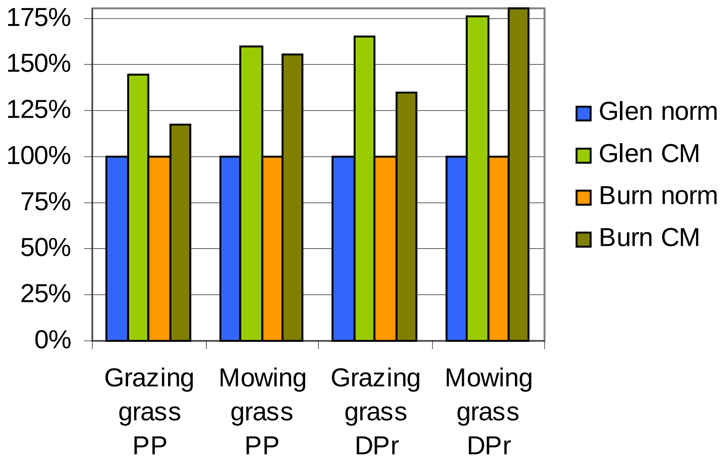

Figure 20. Changes in PP and DPr in the Glenstang and Burn O'Need catchments on the dominant soils for normal practice and after changes in the feeding of dairy cows and fattening cattle (norm=normal, CM=countermeasure). 'Normal values' are set to 100%.

Validation of modelling results

Any comparison of modelling results with real measurements has to consider that ICECREAM predicts losses of soil and nutrients at the field scale. However, it is very likely that only a proportion of this dissolved and particulate matter reaches watercourses (Sharpley & Rekolainen, 1997). Measured values, e.g. in rivers, are thus likely to be lower than modelled values unless there are significant upstream contributions. The results also represent 10-year averages for crops and soil types under standard management practices. This contrasts with measured values for soil loss, which are specific to a field and time period.

For the Eden sub-catchment in Scotland ICECREAM predicts a 10-year average concentration of dissolved phosphorus in runoff of 0.42 mg P/litre. Measured values in the Eden Water in 1996 were on average about 0.1 mg/l (SEPA East Region, unpublished). For the Ythan sub-catchment the mean predicted value is 1.3 mg/l compared to river measurements of around 0.05 mg/l (1980--1992; Macdonald *et al.,* 1995). Hooda *et al.* (1997), in a comparison of 6 Scottish catchments, observed that ditches and field drains could have much higher P concentration that the main streams. They reported that rivers in western catchments dominated by dairy farming had higher phosphate concentrations than more cereal dominated eastern catchments. This is confirmed by results for the Glenstang and Eden catchments. However, P losses in the upper reaches of the Ythan are as high as in dairy farming areas. This may be due to the large impact of pig farming.

The model predictions of 10-year average erosion rates are most likely elevated compared to actual rates in Scotland. Comparisons are limited by the lack of long-term field measurements and sole focus on arable areas. Wade (1998) measured rates of 0.08-5.5 t/ha over one year in east Scotland on winter cereals on comparable slope angles. Watson & Evans (1991) estimated a mean rate of 11 t/ha in north-east Scotland on arable sites regularly affected by erosion. In an arable catchment with a mean slope of 1 degree, Slattery (1994) estimated an overall rate of 0.22 t/ha. In comparison the predictions for the test catchments of 6.5 t/ha in Eden, 6.8 t/ha in Ythan and 1.4 t/ha in Glenstang, appear somewhat high considering that 20, 36 and 90 % respectively, of the areas is under grassland management.

4.2. Ammonia Emission Calculations

The total ammonia emissions of Finland were estimated at 34.7 kt NH_3/a in 1995 (Grönroos *et al.,* 1998b). Emissions from livestock comprise 84% of the total emissions, other agricultural sources contribute 13% (e.g. fur farming, mineral fertilisers), and industrial emissions only 3%. In livestock farming, cattle sources are most prominent. Similarly in the UK, agriculture contributes around 90% of emissions with more than half of this originating from cattle farming (Sutton *et al.,* 1995). A recent estimate of total agricultural emissions is 229 kt/a NH_3-N (van der Weerden *et al.* In press). Thus, countermeasures associated with changes in animal numbers, animal densities, feeding systems, manure storage and application practices are likely to affect ammonia emissions. The impact of Countermeasure Scenarios 3 and 4 (see Section 3.4.) on emissions was assessed for both countries.

For Finland, calculations for present emissions and changes due to countermeasures were made via a spreadsheet programme that uses municipal data for animal numbers, manure storage systems and spreading techniques to calculate the emission factors (Grönroos *et al.,*1998b).

Ammonia calculations for Scotland were made for each catchment based on Pain *et al.* (1997) using a computer spreadsheet (Excel 7.0) developed to create inventories of total emissions in the UK. Catchment specific input was based on Agricultural and Horticultural Census statistics for parishes in 1996 and information provided by local agricultural advisors and land owners:

- numbers of animals in each livestock category
- the relative output of slurry and farm yard manure
- the relative distribution of slurry and FYM onto arable land and conserved grass
- the total amount of mineral fertiliser used on crops and conserved grass.

Total figures for variables such as volume of dirty water, surface storage facilities and area of manure heaps were scaled down assuming a linear relationship with animal numbers. The relative proportion of storage types and any emissions factors were not altered. Emission inventories were created for each catchment split into: cattle, sheep, pigs, conserved grass and crops. It was not possible to calculate emissions for wild red deer, though these would be low.

Finnish and Scottish results aggregated over different areas are presented in Section 6.1.

4.3. Landscape Structure Analysis for Biodiversity

Some countermeasures include alterations in land use management that may impact on landscape structure and subsequently lead to changes in habitat and species diversity of the agricultural landscape. Under Countermeasure Scenario 3 (changes in the diet of livestock) grassland may be converted to barley production to replace grass in the diet of dairy cows with less contaminated barley concentrate. Under Countermeasure Scenario 4 afforestation is a suitable alternative land use when animal and crop production have to cease due to the high level of radioactive deposition. The changes in landscape structure resulting from these 2 scenarios were studied in two Finnish test areas, Lestijoki and Rekijoki (Luoto *et al.,* in prep.). Lestijoki is characterisized by a high proportion of dairy production with large areas of intensively managed mowing grass in rotation. Rekijoki is a typical cereal production area in south-western Finland, but with exceptionally large areas of semi-natural pastures and meadows.

The changes in landscape structure caused by countermeasure implementation were studied using a spatial pattern analysis programme (Fragstats Raster Version 2.0, Mcgarical & Marks 1994) in connection with GIS-software (ArcInfo). The results showed considerable changes in landscape structure and habitat diversity. The landscape changes resulted in a more monotonous habitat structure compared to the present management, indicated by increased mean habitat patch size, reduced total habitat edge length and reduced Shannon diversity index. The degree of change was dependent on the present agricultural production structure and land use in the study sites. In Lestijoki, where dairy production and grasslands were dominant, the landscape structure changes were mostly due to conversion of intensive pastures and mowing grass to cereal production. In the other area with high cereal production and semi-natural pastures, the greatest impacts resulted from afforestation of pastures.

4.4. Quantification of other Impacts

Those impacts for which detailed modelling and calculations were not undertaken or modelling produced unsatisfactory results, were quantified by a variety of methods, explained in more detail in Salt *et al.* (1999a). Impact estimates for all combinations of farm type, countermeasure and impact criterion were converted to a common scale (Fig. 21) to enable a simultaneous assessment of countermeasures in the non-spatial Decision Support System (Salt *et al.,* 1999b). These impact scores also provide the necessary inputs for the mapping and analysis of impacts in the Spatial DSS, as explained in Chapter 8.

Greatly Decrease	Moderately Decrease	Slightly Decrease	NO CHANGE	Slightly Increase	Moderately Increase	Greatly Increase
-1	-2/3	-1/3	0	+1/3	+2/3	+1

Figure 21. Relative impact scores.

5. LIMITATIONS TO COUNTERMEASURE APPLICATION

Limitations are environmental and agricultural factors that may restrict the application of countermeasures. When carrying out a spatial assessment of countermeasure suitability over a large area, information on limiting factors has to be readily available for use in the GIS. This is in contrast to a suitability assessment for a farm or small piece of land where it is possible to collect information from a land owner or farmer. This route has been pursued in the development of a non-spatial decision support system for Scotland, the CeserDSS (Salt *et al.,* 1999b).

5.1. Finland

In none of the Finnish areas are slopes too steep to prevent the use of ploughing countermeasures. The two northern areas, Lestijoki and Taipaleenjoki, have maximum slopes of 2 and 4% respectively. The southern catchments, Ylaneenjoki and Lepsamanjoki, have slopes reaching up to 10% (Table 10). Soils with a clay content of more than 60% are regarded as being unsuitable for deep ploughing and skim and burial. There are, however, very few field parcels in each catchment with this soil type (Table 11). A higher clay content may occur in sub soils (depth>25 cm) hindering the use of ploughing countermeasures on certain field parcels. Since no spatial information on subsoil properties is available this could not be taken into account.

Table 10. Distribution of slope classes

Slope classes	Lestijoki	Taipaleenjoki	Ylaneenjoki	Lepsamanjoki
Percent	Frequency	Frequency	Frequency	Frequency
0 –0.55	799	379	645	345
0.55 - 2	305	64	650	224
2 – 4	0	12	267	274
4 – 7.5	0	0	72	110
7.5 –12.5	0	0	8	7

Table 11. Occurrence of heavy clay soils (> 60% clay in topsoil).

Catchment	Number of field parcels	Percentage of total
Lestijoki	0	0.0
Taipaleenjoki	9	2.6
Ylaneenjoki	5	0.7
Lepsamanjoki	15	1.5

The agricultural land in all Finnish test areas is intensively farmed and soils are regularly limed and fertilised with N-P-K. This makes them unsuitable for application of lime and potassium.

5.2. Scotland

In contrast to the Finnish catchments studied, there are many limitations to the implementation of countermeasures in the Scottish test catchments. This is partly due to a more varied topography with steeper slopes and greater variation in soil drainage status. There is also a strong rainfall gradient across the country. In addition, a greater range of countermeasures had to be considered for Scotland because of the importance of less intensive farming systems in the hills and uplands.

Thresholds were set for a range of environmental parameters above which a particular countermeasure would not be feasible or effective. The general philosophy was to apply stringent criteria. For instance, countermeasures involving ploughing are not recommended on wet soils to avoid problems of trafficability and limits for slope and stoniness are set to ensure relative ease of execution.
Thresholds for countermeasures involving ploughing to different depths and land use change are summarised in Table 12. Table 13 lists the thresholds for liming and potassium application. When countermeasures are applied in combination, all relevant conditions have to be fulfilled. The limitations used in the spatial assessment are very similar to those applied in the CeserDSS and are explained in greater detail in Salt *et al.* (1999b).

The slopes in each catchment were derived from the digital terrain model. Information on soil depth, stoniness, soil type, drainage status, CEC (cation exchange capacity) and pH was taken from the soil profile descriptions and chemical data leased from the Macaulay Land Use Research Institute, Aberdeen. These variables were available for most soil types. In some cases comparable data from Memoirs of the Soil Survey of Great Britain for the same or a similar soil had to be used. Soil wetness class was determined through expert judgement by an experienced soil scientist. It had to be assumed that field drainage systems are deep enough not be destroyed by deep or skim and burial ploughing since no data on their distribution exists and individual farmers would have had to be consulted.

Pasture intensification on hill and upland farms is only a feasible countermeasure where current rates of fertiliser application and stocking densities are well below the recommended maximum values for improved grassland (SAC, 1990). The following set of thresholds was compared against catchment specific estimates provided by agricultural advisors: 1.5 livestock units per ha, 80 kg/ha N and 70 kg/ha P_2O_5 on grazing grass and 130 kg/ha N and 100 kg/ha P_2O_5 on mowing grass.

The suitability of soils for application of lime and potassium is assessed on the basis of CEC and pH (measured in $CaCl_2$). Suitable soils are those predicted to respond with a 50% reduction in Sr/Ca and Cs/K ratio in soil solution. The thresholds were derived from simulations of soil chemistry with the PHREEQC model (Parkhurst 1995) using actual CEC and pH values for Scottish soils. It was not possible to generate thresholds for K application based on exchangeable K in soil since this requires measurements of soil solution K as input to the model. These are not available for the wide range of Scottish soils studied.

Rockiness as a limitation to ploughing could only be assessed for the soil surface based on soil profile descriptions and land use categories in the LCS88 (MLURI, 1988). Land Capability class, a variable used to assess the feasibility of growing barley, was taken from Land Capability maps (Bibby *et al.,* 1991).

For animal countermeasures assumptions had to be made about the availability of housing, feeding facilities and feeding regimes. It was assumed that on lowland farms suitable housing would be available to rear lambs on concentrate. For dairy cows assessments were based on a contribution of 28% to the net energy intake from concentrate feeding. Upland farms were assumed to have suitable areas to feed animals outdoors. No restrictions on the availability of clean roughage and concentrate were imposed.

Table 12. Limitations to countermeasures involving ploughing and land use change in Scotland.

Parameter	Shallow ploughing	Deep ploughing	Skim&Burial	Improve pasture	Convert grass to barley	Afforestation*
Slope	15 degrees	15 degrees	15 degrees	15 degrees	11 degrees	25 degrees
Soil depth	> 30 cm	> 60 cm	> 60 cm	> 30 cm	> 30 cm	> 30 cm
Stoniness to plough depth	< 35% by volume (moderately stony)					--
Depth of peaty surface layer	--	--	--	< 20 cm	--	--
Soil wetness class	class I, II, III suitable (soil profile should lack gley features or an impermeable horizon within 40 cm depth) class IV, V, VI not suitable					--
Soil drainage status	Excessive, free, imperfect – suitable; Poor, very poor – not suitable					
Altitude	--	--	--	--	220 m	--
Land Capability Class	--	--	--	--	4.1 or better	--

It was outside the scope of the project to include an assessment of windthrow hazard. Special software is being developed for this purpose by the Forestry Commission (Quine & White, 1993).

Table 13. Limitations to potassium and lime application in Scotland.

Soil Type	Potassium application	Lime application	K and lime application
Sandy (non-podsolic) & loamy soils	pH < 6.2, CEC < 15 meq/100g	Not suitable	Not suitable
Clay soils	Not suitable	Not suitable	Not suitable
Podsolic soils	pH < 4.4, CEC < 30 meq/100g pH < 5.2, CEC < 15 meq/100g	pH < 4.4, CEC < 20 meq/100g	pH < 4.4, CEC < 20 meq/100g
Organic soils, not waterlogged	pH < 4.5, CEC < 130 meq/100g	pH < 4.5, CEC < 100 meq/100g pH < 5.4, CEC < 70 meq/100g	pH < 4.5, CEC < 100 meq/100g
Organic soils, waterlogged	Not suitable	Not suitable	Not suitable
Slope	15 degrees	15 degrees	15 degrees

pH measured in $CaCl_2$, CEC= cation exchange capacity

6. IMPACT MAPS AND CATCHMENT INVENTORIES

The results of the simulation modelling have demonstrated that some impacts arising from countermeasures will vary greatly in relation to environmental and management parameters, e.g. the extent of soil erosion following deep ploughing is influenced by slope, soil and crop type as well as agricultural management. To illustrate the spatially variable risk, e.g. of soil erosion following deep ploughing, the modelling results produced for each catchment have been combined with the topography, soil and land use data to create impact maps using GIS techniques. In this manner a series of impact maps for the 4 countermeasure scenarios have been produced for each combination of countermeasure and model output parameter.

In order to derive the net impact of a countermeasure over a whole catchment and to enable between catchment comparisons, the changes in soil and phosphorus losses for each grid cell were summed over all cells treated with the countermeasure. This provides catchment inventories of change and also enables average rates of soil and nutrient loss across the treated areas of each catchment to be calculated. For ammonia emissions a mixture of maps and inventories are presented covering the catchment, regional and national scale.

6.1. Ammonia Emissions

Changes in ammonia emissions were assessed for Countermeasure Scenarios 3 and 4.

For Finland in Countermeasure Scenario 3 it was assumed that increased amounts of imported concentrate would be fed to all dairy cows in the whole country. Presently, the average use of concentrates is 40% of net energy intake for cows and 50% for bulls. This would be raised to 80% as a countermeasure. This change was estimated to increase the volume of manure, resulting in a 25% increase in N in manure (Wilkerson *et al.,* 1997). This leads to increased emissions during storage and spreading. Since the existing storage capacity may be exceeded, manure may have to be stored in field heaps or spread at unsuitable times. The impacts of these changes were taken into account by increasing the emission coefficients for cattle by 10%. As a result of the increased N excretion of cattle, a 25% increase was estimated in NH_3 emissions from cattle. For total livestock NH_3 emissions in Finland this means a 13% increase. Taking into account the possible increase in emission coefficients due to storage problems of manure, the corresponding increases for the whole country are likely to be in the region of 37% for NH_3 emissions from cows and bulls and 21 % for total agricultural emissions.

For Scenario 4, it was assumed that radioactive deposition takes place in central Ostrobothnia and that all cattle are moved to the southern province, Uusimaa (Fig. 2). Increasing the cattle production in an area previously dominated by cereal production, such as Uusimaa, would most likely require an increased use of concentrates. However, the possible impacts of the change in feeding systems were not considered in this context. If cattle production is increased in a region lacking infrastructure for livestock farming (manure storage facilities, application machinery), this would probably increase the emissions. It is difficult to quantify this in absolute terms, but we made an assumption that an additional 10% increase may take place. Figure 22 illustrates the regional changes in municipal ammonia emissions with a noticeable decrease in Central Ostrobothnia and an increase in Uusimaa after countermeasure implementation.

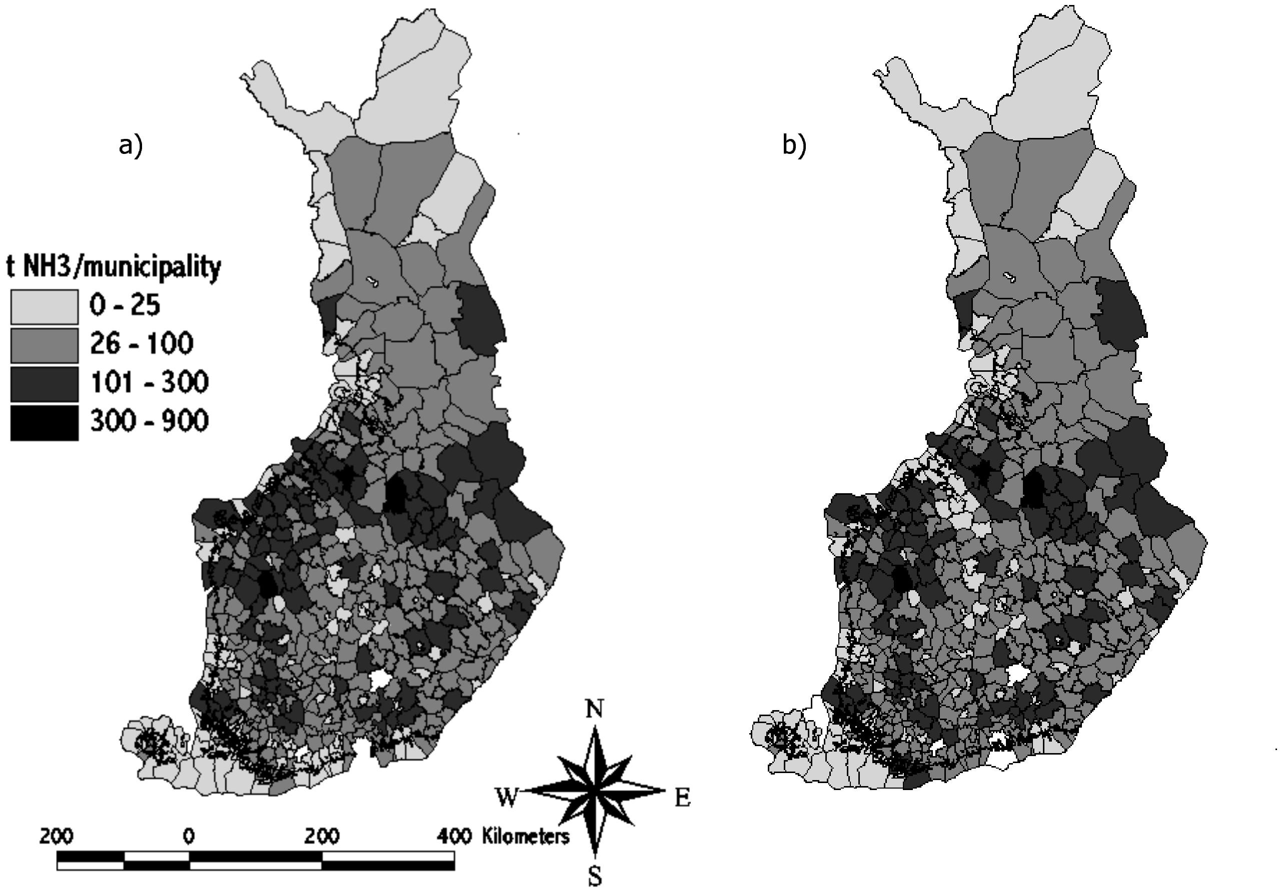

Figure 22. Ammonia emissions (t per year) for the municipalities in Finland in 1995 (a) and for Countermeasure Scenario 4 (b).

For Scotland the impact of Countermeasure Scenarios 3 and 4 on ammonia emissions was assessed at the catchment scale only. Estimates of baseline ammonia emissions for the Scottish areas are presented in Table 14.

For Countermeasure Scenario 3 the impact of changes in concentrate feeding to dairy cows was estimated assuming a 27% increase in N excretion (Wilkerson *et al.,* 1997). Additional emissions due to lack of storage capacity for additional manure were not considered. At the level of the catchment, changes in the diet of cows lead to a predicted rise in ammonia emissions of around 15% (Table 15). Higher levels of concentrate feeding to lambs during indoor fattening would have much smaller effects given the shorter period of approx. 3 months over which the alternative diet has to be supplied. Earlier or later sale of young animals would result in very small changes in ammonia emissions from a farm.

Table 14. Estimates of ammonia emissions from different land uses for Scottish catchments under current practices (kg NH_3-N per year)

Catchment	Dairy cattle	Beef cattle	Sheep	Pigs	Conserved grass	Tillage crops	Total	Total
	kg/year	kg/year	kg/year	kg/year	kg/year	kg/year	kg/year	kg/ha+year
Glenstang Burn	14255	8962	675	0	1069	34	24994	28
Burn O'Need	15148	8013	2144	0	1154	0	26459	12
Eden Water(1)	0	6798	2095	0	492	1990	11375	5.2
Lugate water	0	7451	1508	0	563	0	9522	2.9
Water of Tarf	0	153	123	0	0	0	276	0.06
River Ythan (1)	0	4919	847	36970	482	562	43781	31
Lusragan Burn	0	437	102	0	20	0	559	0.80
River Noe	0	0	255	0	0	0	255	0.14
River Erradale	0	0	120	0	0	0	120	0.09

1) Only a sub-section of these catchments was assessed

Table 15. Changes in ammonia emissions resulting from countermeasures (kg NH_3-N per year)

	Change dairy cow diet		Cease animal production		Cease arable production		Afforestation	
	Emission increase		Emission reduction		Emission reduction		Emission reduction	
	kg/year	%	kg/year	%	kg/year	%	kg/year	%
Glenstang Burn	3849	15.4	24960	99.86	34	0.14	24994	100
Burn O'Need	4090	15.5	26459	100	0	0	26459	100
Eden Water(2)	0	0	9385	82	1990	18	11375	100
Lugate Water	0	0	9522	100	0	0	9522	100
Water of Tarf	0	0	276	100	0	0	276	100
River Ythan (2)	0	0	43219	98.7	562	1.3	43781	100
Lusragan Burn	0	0	559	100	0	0	559	100
River Noe	0	0	255	100	0	0	255	100
River Erradale	0	0	120	100	0	0	120	100

The most drastic changes in ammonia emissions occur under Countermeasure Scenario 4, where animal production ceases. The greatest reductions occur in catchments with significant numbers of cattle (Table 15). In contrast, cessation of arable production has only a small effect.

For both Finland and Scotland, it is concluded that the predicted changes in ammonia emissions will have only a small effect at the national level. However, locally important impacts may arise if livestock production is intensified or transferred to a different region. The severity of environmental impacts such as acidification and eutrophication of soils and surface waters, will depend on the sensitivity of local ecosystems.

6.2. Impact Maps for Soil and Phosphorus Losses

The changes in soil and phosphorus losses predicted for all countermeasure scenarios were mapped for the 4 Scottish and 4 Finnish catchments included in the ICECREAM modelling exercise. Selected impact maps, based on 10*10 m grid cell size, are presented.

Figure 23 shows the predicted change in soil erosion following deep ploughing of arable and rotational grassland in the Ythan sub-catchment. Since 90% of the area is dominated by one soil type, the spatial differences in soil loss are mainly driven by the slope angle which ranges from 0 to 40 % in this area. For all land below 13 degrees slope the modelling results are mapped as a weighted of arable crops and grassland. Land between 13 and 15 degrees slope is mapped as mowing grass and steeper land as grazing grass.

Changes in particulate phosphorus losses in surface runoff (PP) are illustrated for the Eden sub-catchment (Fig. 24). The map highlights the differential effect of the two most common soil types. In the eastern part of the area PP loss decreases after deep ploughing, while in the western part it increases. As explained in Section 4.1.2., the dominant freely draining brown forest soil in the western half of the sub-catchment has an unusually high labile P status in the subsoil which causes this effect.

The impact of drastic changes in land use involving conversion of large areas of grassland to barley cultivation (CM Scenario 3b) is illustrated for the Glenstang Burn catchment (Fig. 25). Losses of particulate P in runoff increase over the whole area modelled in accordance with differences in slope since one soil type dominates.

The feeding of increased amounts of imported concentrate to dairy cows (CM Scenario 3a) and the associated increased need for manure application to mowing grass explains the increased loss of dissolved phosphorus (DP_r) in runoff illustrated for the Burn O'Need catchment (Fig. 26). The large areas not modelled represent mainly built up areas and woodland in the south-west and areas of peat in the north-east.

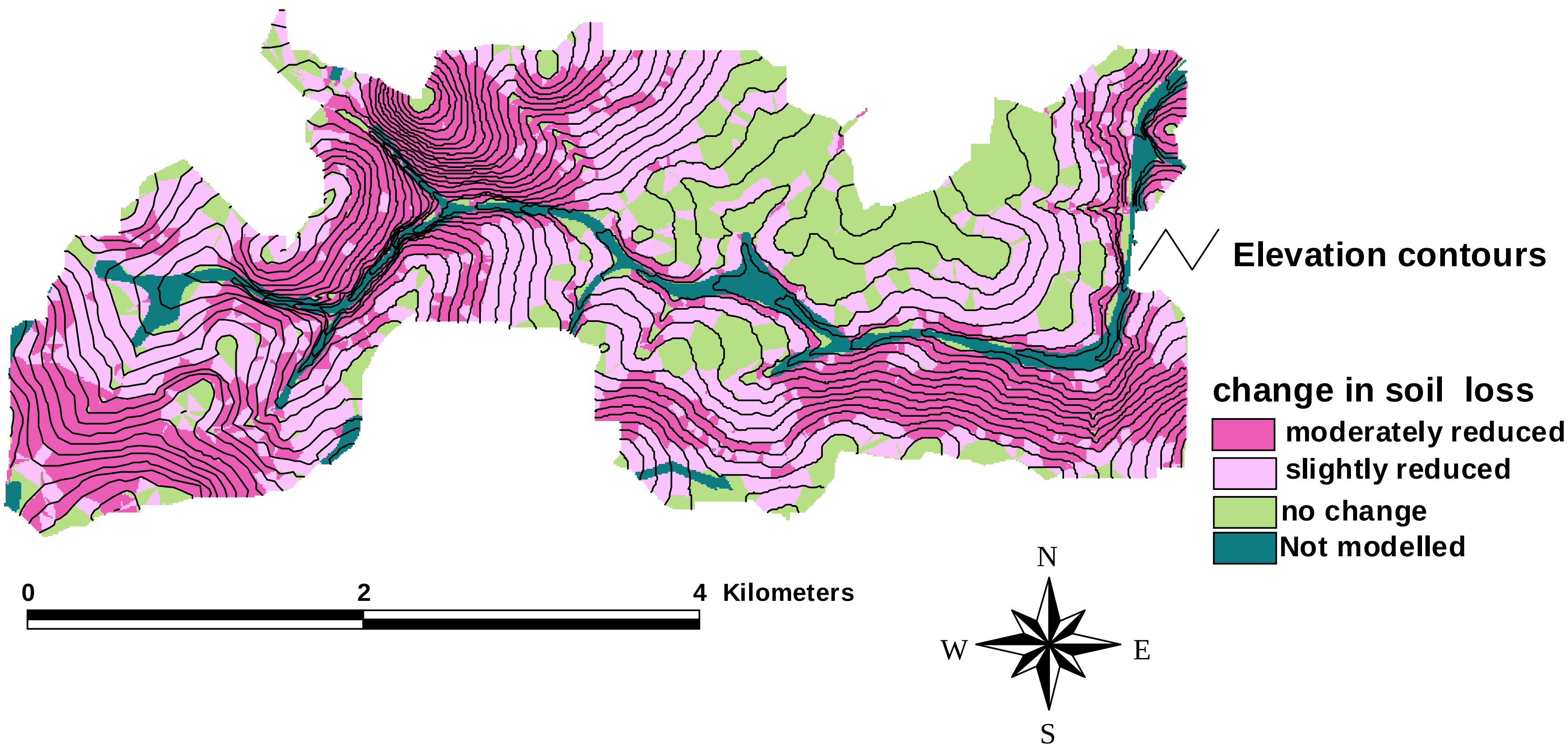

Figure 23. Soil erosion risk in the upper Ythan catchment (north-east Scotland) following deep ploughing. Contour interval 5 m.

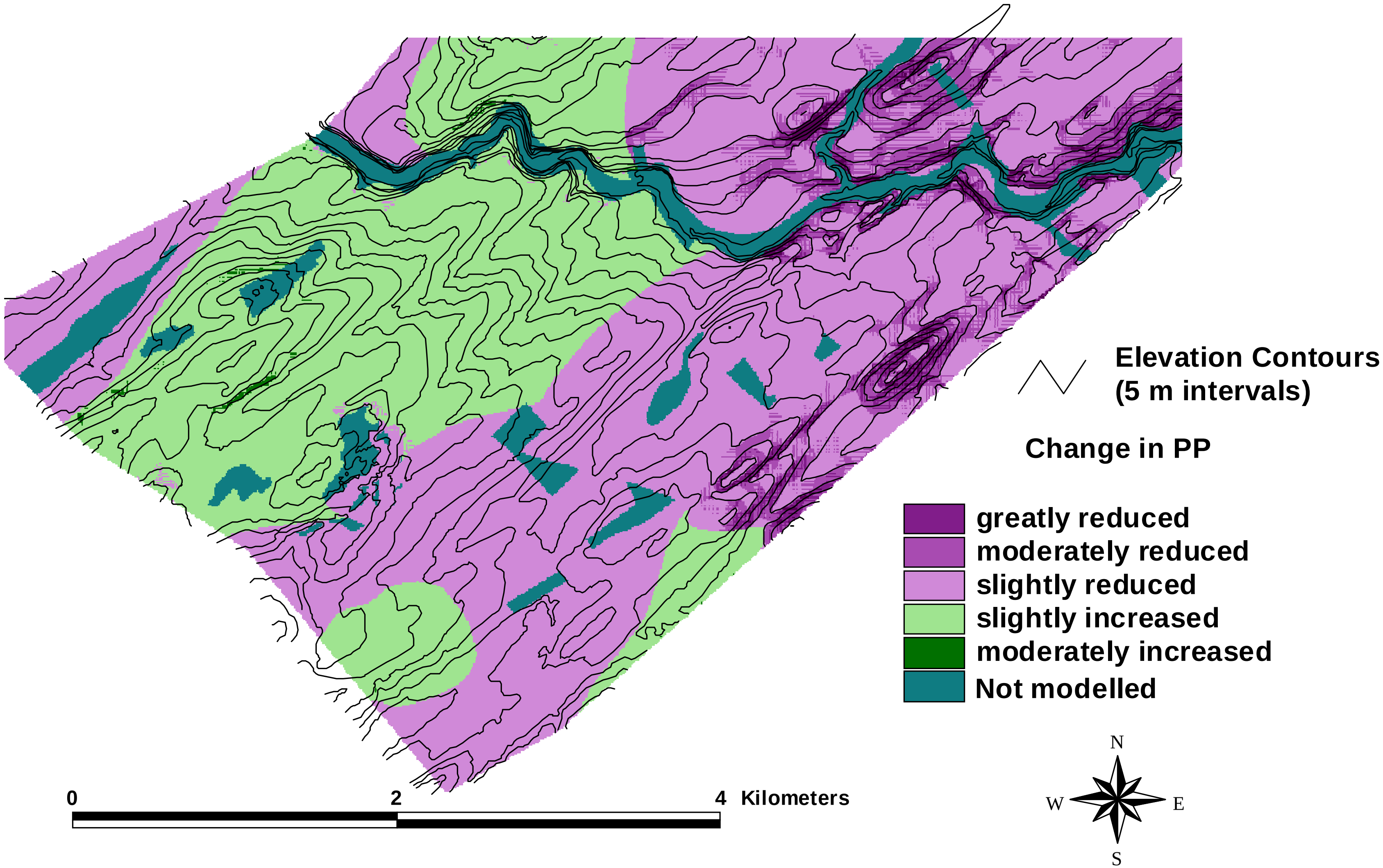

Figure 24. Risk of particulate phosphorus loss in the Eden Water sub-catchment (south-east Scotland) following deep ploughing.

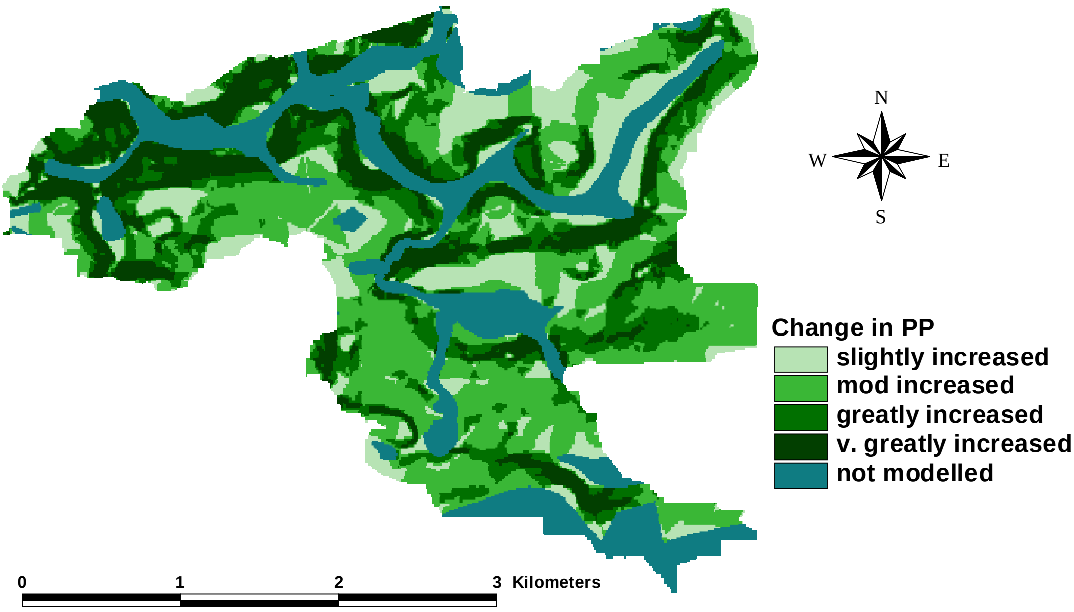

Figure 25. Risk of particulate phosphorus loss in the Glenstang Burn catchment (south-west Scotland) under Countermeasure Scenario 3b.

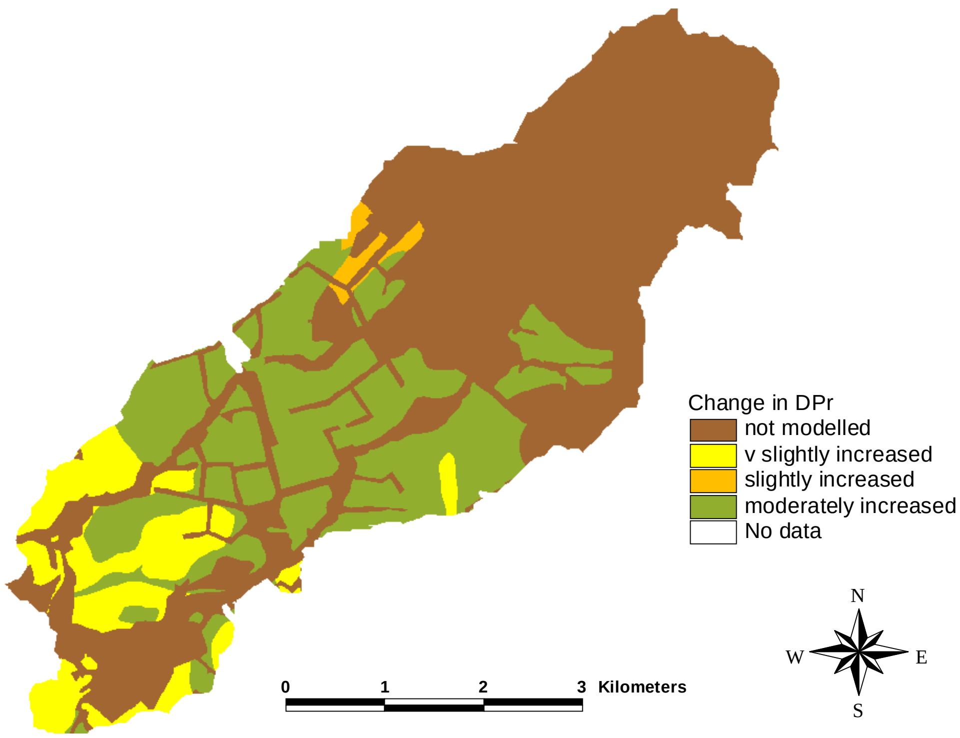

Figure 26. Risk of dissolved phosphorus loss in the Burn O'Need catchment (south-west Scotland) under Countermeasure Scenario 3a.

6.3. Catchment Inventories - Finland

The aggregated effects of the 4 countermeasure scenarios at the catchment scale are presented for the particulate P fraction (PP) and dissolved P fraction in surface runoff (DP_r). The results are 10-year-average values (1981-1990) based on field-scale model simulations (see Section 4.1.1.), scaled up to the catchment. The 4 catchments are abbreviated: Yläneenjoki (YLA), Lepsämänjoki (LEP), Lestijoki (LES), Taipaleenjoki (TAI). The results are expressed as percentage values relative to the catchment with the highest value.

The original values for PP and DP_r show remarkable differences between the catchments (Fig. 27). The highest value for PP in the Lepsämänjoki catchment is explained by the steeper slopes and the more erodible soil types. The low values for Lestijoki and Taipaleenjoki are in addition linked to the dominance of grasslands that are less prone to erosion compared to arable land. The high DP_r values for Lestijoki and Taipaleenjoki catchments are also related to the fact that grassland receives surface applied fertilization in Finland while for cereals and root crops fertiliser is injected into the soil.

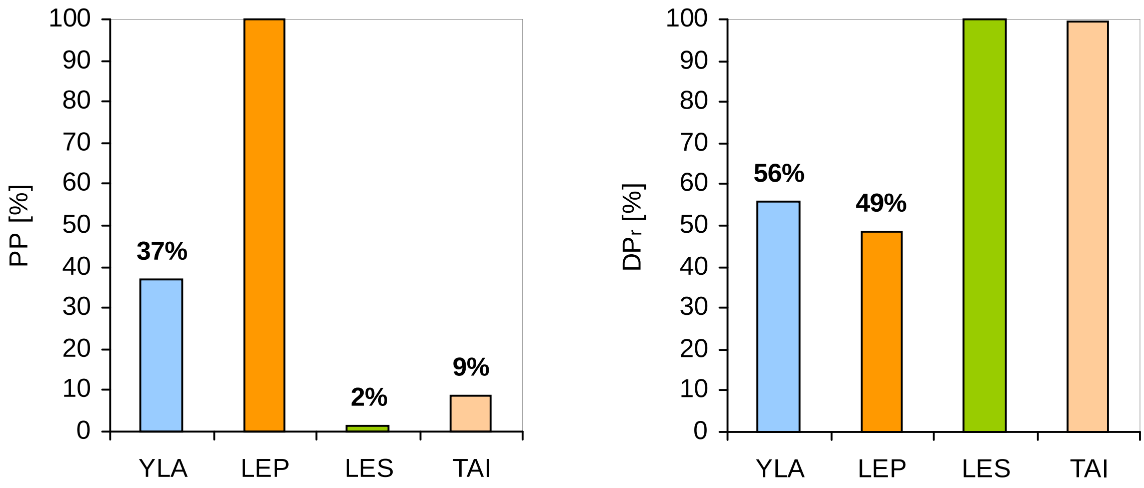

Figure 27. Aggregated 10-year-average losses of PP and DP_r under normal practice.

Deep ploughing reduces the total PP losses in every catchment (Fig. 28), because poor subsoil with low phosphorus content comes to the surface following the reversal of the soil layers. For DP_r the results are not as simple because deep ploughing reduces DP_r for the southern catchments, but increases it slightly for the northern catchments. The is related to the soil types and the dominance of mowing grass in the northern catchments. Skim and burial ploughing changes the PP and DP_r output only slightly, the maximum change being less than 3 % of the original value.

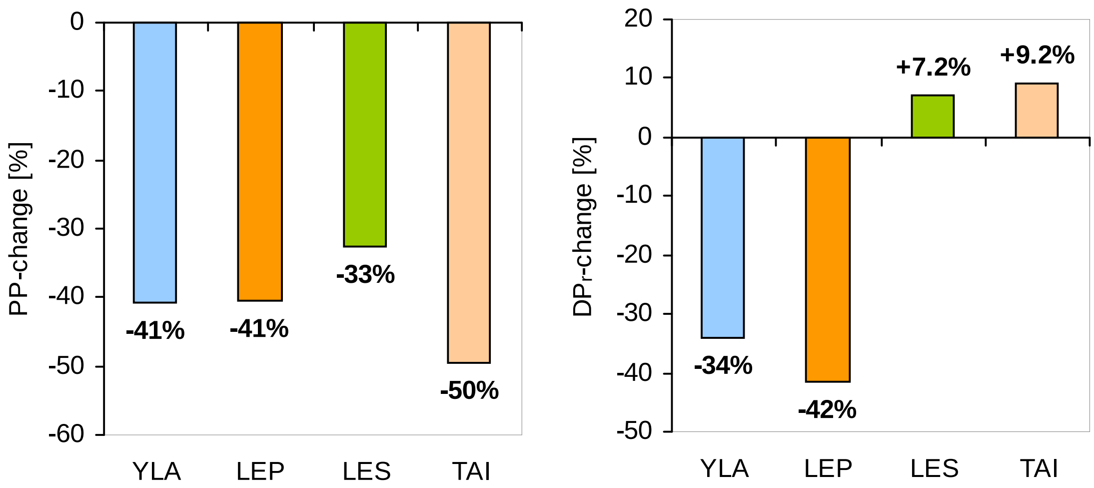

Figure 28. Relative changes in 10-year-average aggregated losses in PP and DP$_r$ after deep ploughing compared to normal practice.

In Countermeasure Scenario 3, 50% of the grass fields are converted to barley and P-fertilization is also increased. This results in increased PP values, with the largest impact occurring in the catchments with the originally highest proportion of mowing grass and the largest grass fields (Fig. 29). Spring barley is more susceptible to soil loss than mowing grass and it receives injected fertilization instead of surface application. This explains why the PP values rise whereas DP$_r$ values decrease, again in direct relation to the number and size of the grass fields prior to implementing the countermeasure.

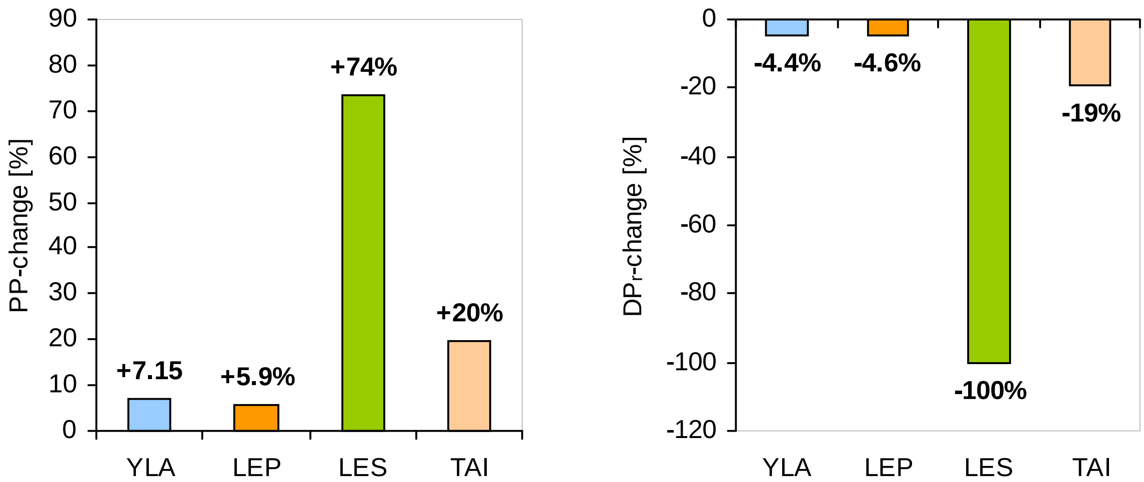

Figure 29. Relative changes in 10-year-average aggregated losses of PP and DP$_r$ following changes in dairy livestock feeding compared to normal practice.

In Countermeasure Scenario 4 the introduction of green fallow in the Lestijoki catchment greatly reduces both PP and DP$_r$ losses (Fig. 30). The change from barley to grass in Lepsämänjoki decreases PP output but increases DP_r output mainly for the reasons mentioned above. The effect of higher P-fertilization is not as marked as the effect of changes from cereals to grass.

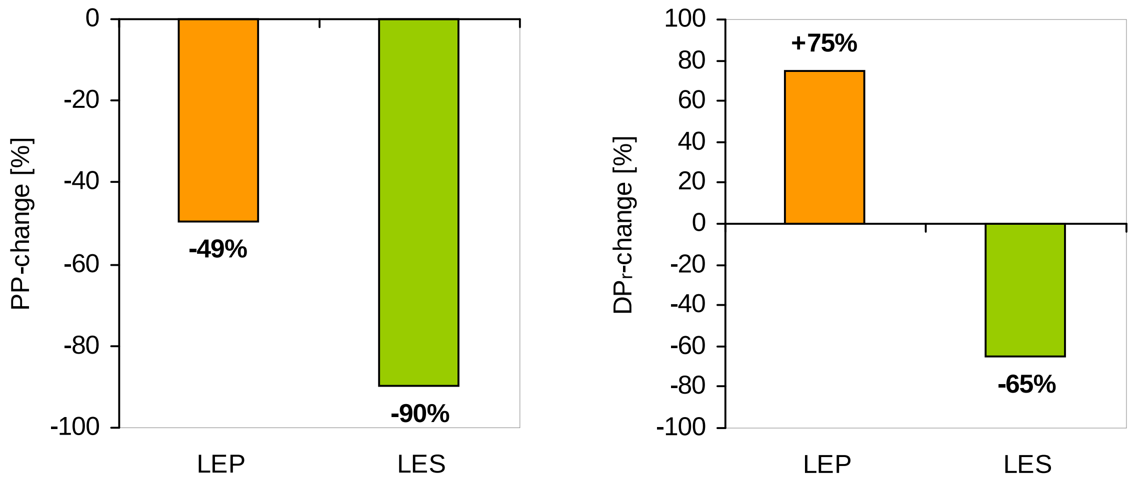

Figure 30. Relative changes in 10-year-average aggregated losses of PP and DP_r following land abandonment in Lestijoki and transfer of livestock to Lepsämänjoki.

6.4. Catchment Inventories - Scotland

The effects of the 4 countermeasure scenarios are presented for the particulate P fraction (PP) and dissolved P fraction in surface runoff (DP_r). The results are 10-year-average values (1986-1995) based on field-scale model simulations (see Section 4.1.2.), scaled up to the catchment level. The 4 catchments are abbreviated: Eden (EDE), Ythan (YTH), Glenstang (GLE), Burn O'Need (BUR). In the Glenstang and Burn O'Need catchments 22% and 87%, respectively, of the land, were classed as unsuitable for ploughing countermeasures and calculations of inventory changes are restricted to the suitable areas. Catchment inventory changes are summarised in Figures 31-33.

The most significant change associated with deep ploughing in all catchments is a reduction of 23-33% in PP. This can be explained by the generally lower total P status of the subsoil in all major soil groups. DP_r shows very variable behaviour across different soils and crops. In Ythan DP_r is 14% lower after deep ploughing since the subsoil of the dominant soil type has a lower labile inorganic pool of P. In contrast, in the Eden sub-catchment there is little overall change in DP_r. This hides marked opposite trends in the 2 main soil types. The imperfectly draining brown forest soil has a lower labile P (P_{lab}) status in subsoil compared to topsoil, which is typical of most soils while the freely draining brown forest soil has higher P_{lab} values in the subsoil. All P_{lab} input data are derived from acetic-acid extractable P data and it is known that in some Scottish soils Ca-bound P is readily extracted by this method from sandy subsoil fractions. It is uncertain how plant available this fraction is (Williams & Saunders 1956).

Deep ploughing in the Glenstang area has no net impact on DP_r at the catchment level, since small changes for individual crops are compensating each other. The only soil suitable for ploughing countermeasures is an imperfectly draining gley with a low labile P status and an even distribution of

P_{lab} down the profile. The same soil type was also modelled for the Burn O'Need area, but here there is a more noticeable change of -10% in DP_r. in response to deep ploughing. It appears that due to the low labile P status of the soil, external applications of P have a disproportionate effect. Small differences in the P application via animal faeces may partly explain the catchment differences, while differences the greater proportion of grazing grass in Burn O'Need also plays a role.

Differential responses of soil and crop types to deep ploughing are also the reason for little apparent change in soil loss in the Eden, Glenstang and Burn O'Need areas. In contrast, soil loss in Ythan decreased by 10% due to the lower erodibility of the subsoil of the dominant soil type which occupies 90% of the area.

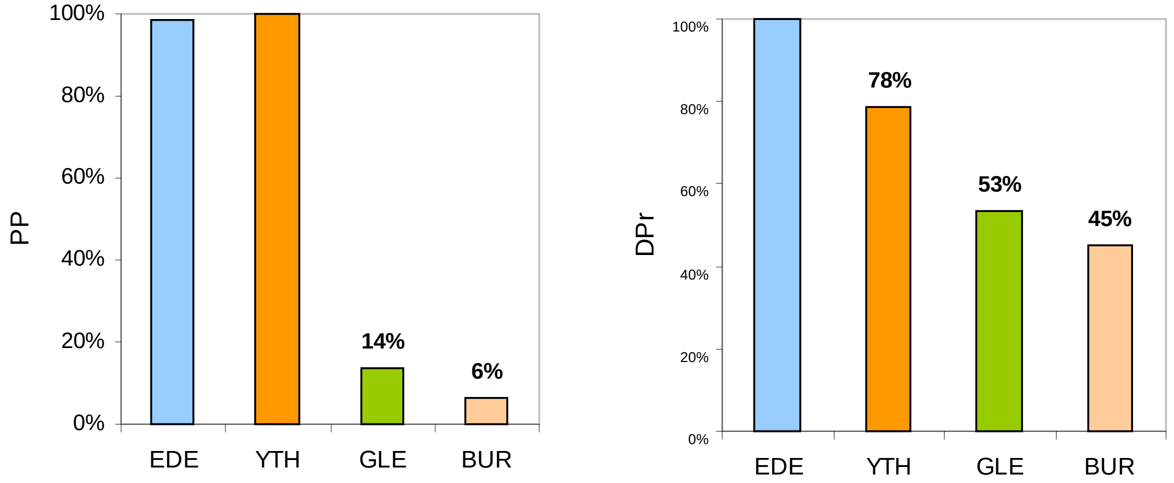

Figure 31. Aggregated 10-year-average losses of PP and DP_r under normal practice.

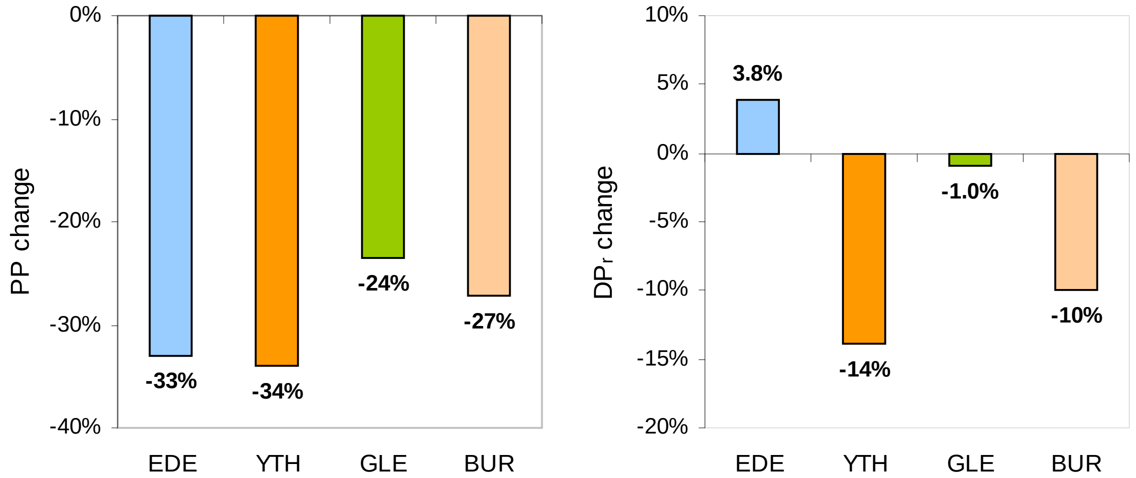

Figure 32. Relative changes in 10-year-average aggregated losses in PP and DP_r after deep ploughing compared to normal practice.

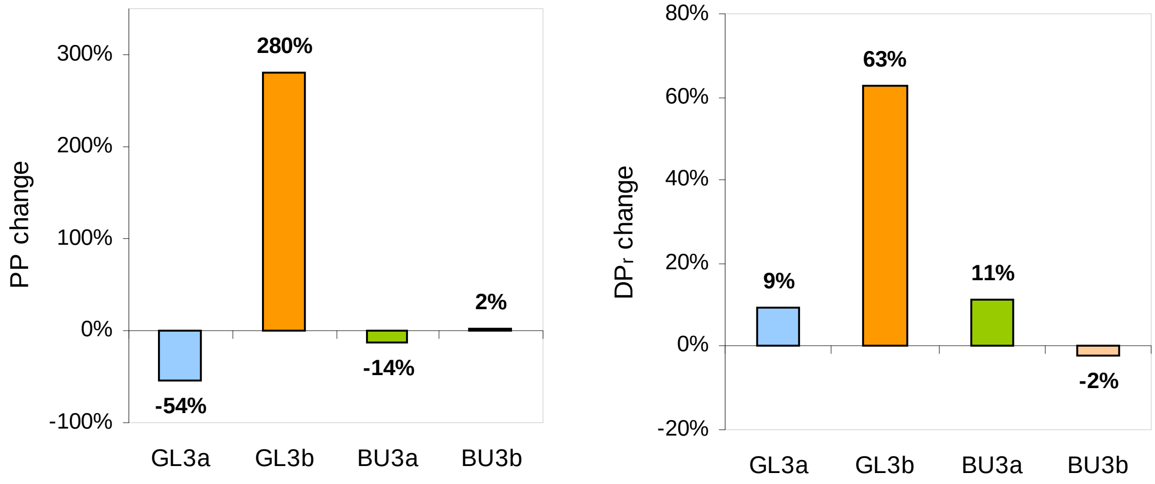

Figure 33. Relative changes in 10-year-average aggregated losses of PP and DP_r following changes in livestock feeding.

The complex changes in land use envisaged under Countermeasure Scenarios 3a and 3b have very different impacts on the two catchments. Under Scenario 3a the introduction of areas of green fallow leads to a significant decrease in PP (Fig. 33). The difference between the catchments is explained by the fact that more green fallow would be created in Glenstang. Both catchments show a small increase in DP_r, most likely in response to the additional manure applications to mowing grass. Under Scenario 3b the increased cultivation of barley leads to a large rise in PP and DP_r in Glenstang while Burn O'Need shows no change compared to the original losses. This results from the suitability of the Glenstang area for winter barley cultivation, while in Burn O'Need spring barley is a more suitable crop. Rates of erosion and hence PP losses, are much higher on winter compared to spring barley. The same applies to DP_r but to a lesser extent.

The cessation of both animal and crop production in all Scottish catchments leads to drastic reductions in soil and phosphorus losses, ranging from 84-99%, as arable and improved pasture land are converted to green fallow.

7. SUITABILITY MAPS

Selected suitability maps have been produced for one Scottish catchment, the Lugate Water, to illustrate how land suitability for countermeasures may vary spatially. The whole catchment is a less favoured area with sheep and beef farms. Suitability assessments were made for pasture improvement, pasture intensification, potassium and lime application based on the limitations given in Section 5.2.

Soils that are predicted to respond effectively to K treatment are a humus-iron podsol, peaty podsol, peat and a non-calcareous gley. The suitable areas marked in Figure 34 occupy slopes up to 15 degrees (26%). The same soils, with the exception of the gley, also fulfil the criteria for liming (see Fig. 35). Since it may be difficult to spread lime or K fertiliser with commonly used spreaders on vegetation dominated by dwarf shrubs such as heather, the appropriate land use types are classed as 'suitable, with technical difficulties' as opposed to grass-dominated vegetation which is classed as 'suitable'.

All improved grassland in the catchment is suitable for pasture intensification since current stocking densities and fertiliser application rates fall below the thresholds specified in Section 5.2. (Fig. 36). There is further scope for pasture improvement, i.e. converting rough grazing to improved grassland in small areas as shown in Figure 37. These areas are occupied either by brown forest soils or non-calcareous gley soils. The other soils in the area are limited by stoniness, depth of peaty topsoil or poor drainage.

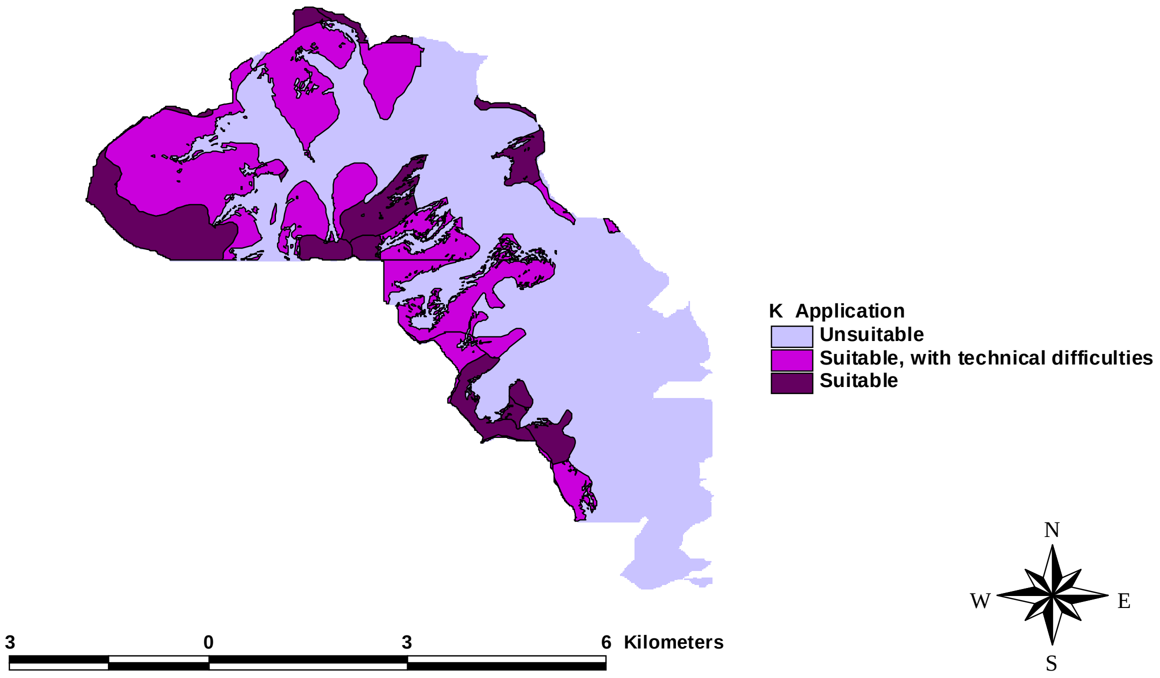

Figure 34. Land suitability map for soil application of potassium in the catchment of the Lugate Water, south-east Scotland.

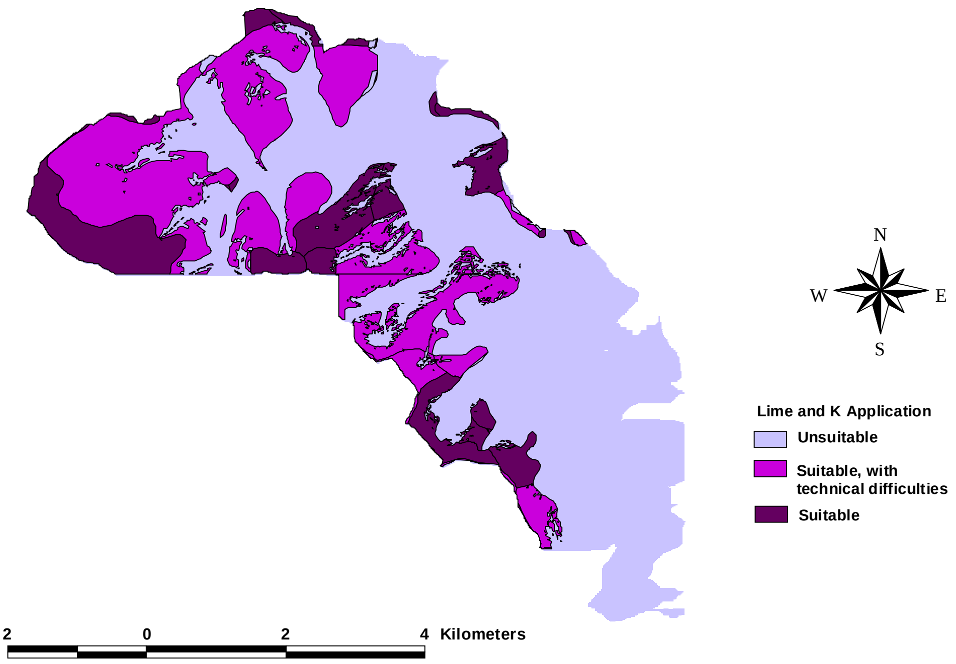

Figure 35. Land suitability map for soil application of lime and potassium in the catchment of the Lugate Water, south-east Scotland.

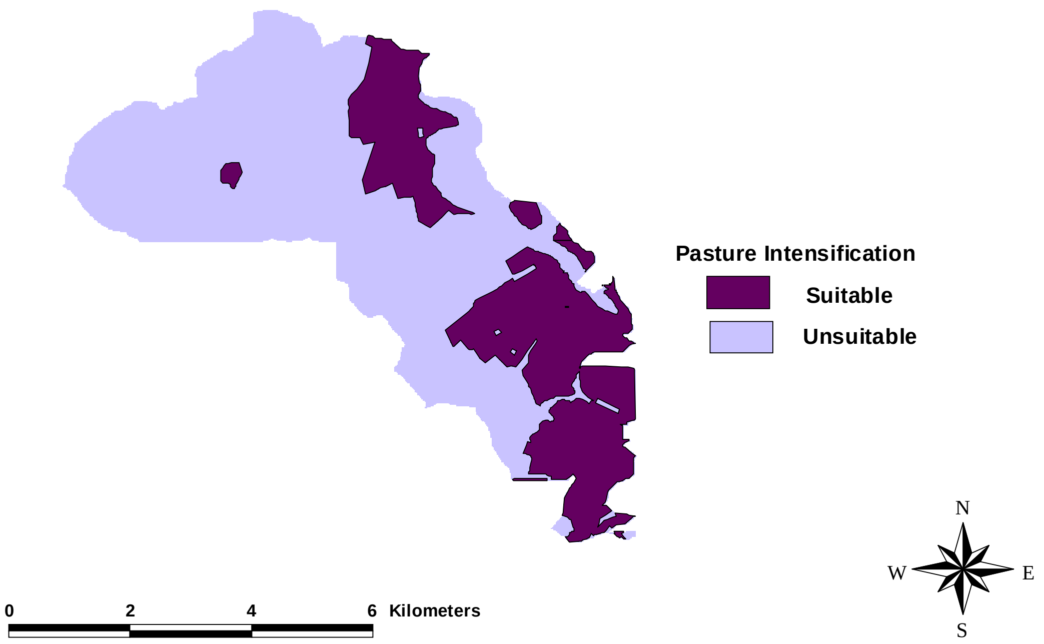

Figure 36. Land suitability map for pasture intensification in the catchment of the Lugate Water, south-east Scotland.

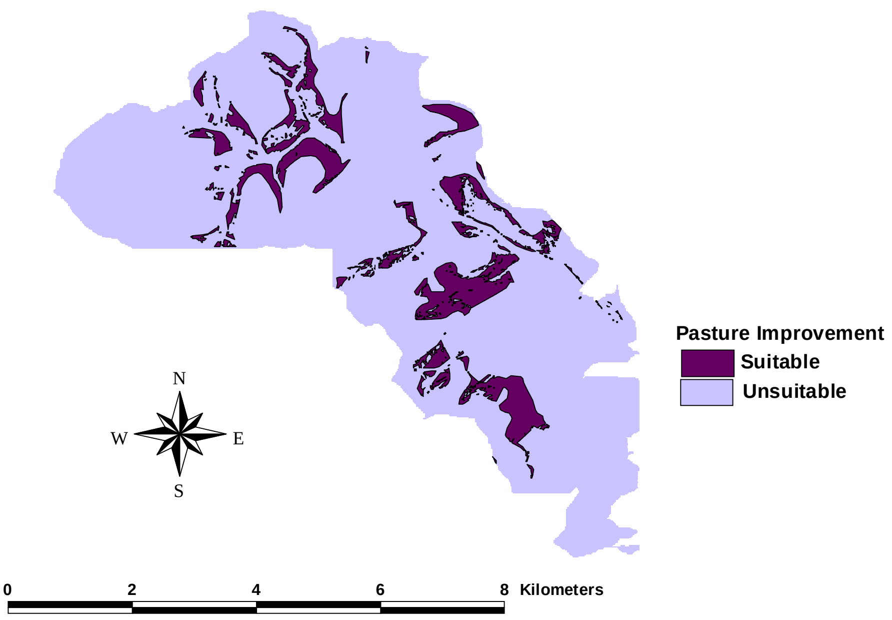

Figure 37. Land suitability map for pasture improvement in the catchment of the Lugate Water, south-east Scotland.

8. SPATIAL DECISION SUPPORT SYSTEM

The formal integration of the spatial assessment of land suitability for countermeasure application and the assessment of potential environmental impacts into a GIS-based Spatial Decision Support System (SDSS) represents a potentially powerful tool for planning and evaluating countermeasures at the local, regional and national level (Salt & Culligan Dunsmore, submitted). This should encourage better decision-making strategies by improving the way in which substantial data sets are integrated and assessed (O'Callaghan, 1995). The system can be further enhanced by including Multicriteria Decision Making (MCDM) methods to help solve often conflicting and multiple objectives in selecting remediation options (Jankowski, 1995). The integration of GIS and MCDM has for instance been used in agricultural land use (Jansen & Rietveld, 1990) and ecological planning (Grabaum & Meyer, 1998). Within the CESER project, we have designed and partially implemented such a system for the Scottish study sites, primarily intended for the optimisation of countermeasure strategies at the regional scale.

The GIS software package used to develop the SDSS is ArcView™ , version 3.1 (ESRI, 1997), a widely available PC-based system. The flexibility and user friendliness of the SDSS are key components in ensuring its success as a decision-making tool. In keeping with this objective, the inner workings of the spatial assessment process are shielded from the decision-maker by the use of a flexible, user-friendly interface, created using the programming language available in ArcView™ called Avenue (ESRI, 1997). The output from the system is in the form of a suitability map for a particular countermeasure or a thematic map depicting the 'most suitable' countermeasures for a given area, based on the outcome of the environmental impact assessment.

As illustrated in Chapter 6, the environmental impacts quantified for each study catchment are combined with the topography, soil and land use data to create spatial data coverages depicting the magnitude of 'impact risk' posed by each countermeasure. For each combination of countermeasure and assessment criterion (see Table 2 and 8), an individual impact map is generated. These impact maps form the basis of the suitability scores which are calculated using a Multicriteria Decision Making methodology (see Section 8.1.). Due to a number of modelling, time and data constraints, it was necessary to pre-process these maps for the CESER project. However, future systems could be linked dynamically to the environmental models used to assess the relative impacts of different countermeasures.

The impact maps used by the SDSS are raster-based maps resulting from the land suitability and environmental impact assessment undertaken for each combination of countermeasure and assessment criterion. Land suitability is determined using the set of limiting factors of the physical environment that exclude the implementation of the countermeasure (see Chapter 5). The defined thresholds of implementation are used to eliminate or 'mask out' cells from within the study areas that are deemed unsuitable. For example, deep ploughing on land that has slopes of greater than 15 degrees is not recommended. Therefore, all cells with a slope greater than this value are excluded from the spatial assessment in the SDSS.

The values on the impact maps range from between –1.0 (greatly decreases impact on criterion) and +1.0 (greatly increases impact on criterion) with a score of zero indicating that no impact at all has been incurred (see Fig. 22, Section 4.4.). Both qualitatively and quantitatively assessed impact maps are portrayed in this way. It is necessary to first normalise the results from the quantitatively assessed criteria, such as the soil loss figures generated by the erosion model in ICECREAM, to fit this impact scale.

8.1. Multicriteria Decision Making (MCDM)

Multicriteria Decision Making (MCDM) is the methodology chosen to assess countermeasure suitability within the SDSS. MCDM is a well-known branch of decision-making techniques that logically structure and evaluate problems with multiple attributes and objectives. It has been endorsed by the International Commission on Radiological Protection for use in the appraisal of radiological protection problems (Merkhofer & Keeney, 1987). A recent example is the RESTRAT project where it has been used to evaluate restoration options for small but highly contaminated areas, such as radioactive waste disposal facilities (Hedeman Jensen, 1999) . MCDM is based on the evaluation of a two dimensional matrix in which one dimension consists of alternatives and the other of criteria (Voogd, 1983). Alternatives are the different possible choices or scenarios from which the decision-maker must choose. Criteria, on the other hand, are the means by which the alternatives are assessed. The MCDM ranking technique used in the SDSS is compensatory in that it allows for a poor performance by a particular alternative on one or more criteria to be ‘compensated for’ by a good performance on other criteria (Jankowski, 1995). The ability to make ‘trade-offs’ in criteria performance, within the bounds of certain thresholds, is viewed as a key component of the assessment methodology, as it accurately simulates the real-world decision making environment in which losses in the one arena can be justified by the gains made in another.

In the SDSS, the assessment criteria are made up of a mixture of environmental and agricultural parameters (see Table 2, Section 3.1.). Normally, within a two-dimensional assessment matrix, the alternatives would be the different countermeasures that can be applied to a contaminated area following radioactive deposition. However, when working with spatial data coverages in a raster environment, this approach must be altered slightly. A suitability assessment must be carried out for each possible countermeasure and the results compared between countermeasures for every spatial unit. Therefore, an extra dimension must be added to the matrix to account for the spatial variability of the data being evaluated. The third dimension, in theory, are the countermeasures, while the individual raster cells are treated as the individual alternatives. The raster cells contain layers of data about a particular area in space. For each raster cell within the study area, this information is used to assess the cell’s suitability for the application of each individual countermeasure. By comparing impact scores for raster cells across countermeasures, the ‘optimal’ countermeasure for each area is identified (Fig. 38). This is the countermeasure with the lowest overall impact on all environmental and agricultural criteria.

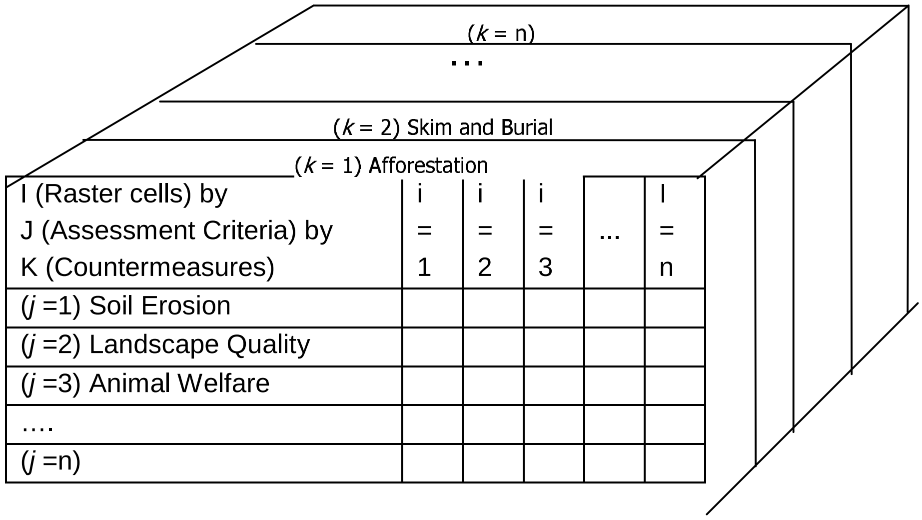

Figure 38. Model of 3-D data structure used for determining the 'optimal' countermeasure for each raster cell, where alternatives = (*i*) , criteria = (*j*) and countermeasures = (*k*)

8.2. Ideal Point Analysis

Owing to the vast amount of data that must be processed when performing a suitability assessment of this nature, the specific types of MCDM assessment methodology that can be used are significantly restricted. Many MCDM techniques are computationally impossible to apply to this situation in which each raster cell is considered to be an alternative. For this reason, Ideal Point Analysis, which is based on a single calculation of the weighted absolute distance between the ideal set of scores and the actual scores for an alternative, was chosen for the assessment.

Ideal Point Analysis (also called Goal Programming) measures the deviation between the scores for each set of 'alternative' solutions and the 'ideal' set of solutions (Zeleny, 1976). The alternative which minimises the distance between itself and the ideal is deemed the optimal solution (Carver, 1991). This is described mathematically in Equation 1 (Zeleny, 1982). The variables h_j and q_{ji} , which are the ideal point values and alternative scores, must be standardised to allow for comparisons to be made across criteria scores. This can be undertaken using Equation 2, which normalises the 'distance from the ideal' such that the highest distance is to equal a score of zero. The variable p symbolises the metric parameter, which varies according to the assessment's compensatory level. In most cases, it will be equal to one, two or infinity. Should p be equal to infinity, then the Chebyshev metric or minimax will be used to calculate the distance calculation and the results are considered to be that of a non-compensatory assessment (Pitel, 1990). The decision-maker must also define weights for each of the assessment criteria. These weights, which are represented as γ_j in Equation 2, follow the 'rating system' in which the number of points allocated to each criterion is representative of that criterion's relative importance within the decision-making process (Nijkamp, 1990).

$$\min\ d = \{ \sum_{j=1}^{j} \gamma_j^{\ p} \ (|h_j - q_{ji}|)^p \}^{1/p} \qquad (1)$$

$$q_{ji} = \max_j \rho_{ji} - \rho_{ji} \ / \ \max_j \rho_{ji} - \min_j \rho_{ji} \ . \qquad (2)$$

where:
d = distance score to be minimized
h_j = standardized ideal point value for criterion, j.
q_{ji}= standardized value, p_{ji}
γ_j = weight for criterion, j.
p = metric parameter (usually 1, 2 or ∞)

8.3. The Countermeasure Evaluation Process in the SDSS

The MCDM-GIS countermeasure selection process is spatially specific and begins by asking the user to select the co-ordinates of their study area, the resolution at which they would like to work and one of the 4 deposition scenario options (see Table 1, Section 3.1.). Then, based on the farm types that occur within the boundaries of the assessment area and the deposition scenario selected, the user is presented with a list of countermeasures that can be applied. From this list, the user can opt to either undertake a suitability assessment for a single selected countermeasure or run an assessment that includes several countermeasures.

After this, the user is then asked to define the weights and ‘ideals’ for each of the assessment criteria. The ideal values use the same scale as the impact maps, shown in Figure 22. The ideal value for the criterion ‘soil erosion and sedimentation’, for example, would most likely be the objective ‘greatly decrease’ or the value –1, while for a criterion such as ‘animal welfare’ the ideal objective might be for it to ‘greatly increase’ or the value +1. The weights, on the other hand, range on a scale of one through ten and should be used to reflect the decision-makers own biases and objectives in the decision-making process. For example, a farmer might rate product quality and animal welfare highly in order to reflect a personal objective to ensure his/her own economic welfare.

Once the alternatives, weights and ideals have been defined, the MCDM programme is called to calculate a final score for each alternative (raster cell) based on its specific distance away from the ideal criteria vector. The resulting scores for the alternatives are then stored as a raster map for further analysis and display. Once this process has been completed, there should be a raster map for each countermeasure evaluated. Each cell within these coverages will contain a value relating to its calculated suitability. By comparing the values of each of the raster cells across the countermeasure suitability coverages, a map depicting the ‘most suitable’ countermeasures for the study area can be created. As the scores are normalised, the coverage with the highest score for each cell is deemed to be the ‘most suitable’ countermeasure for that cell. An overview of this process is illustrated in Figure 39.

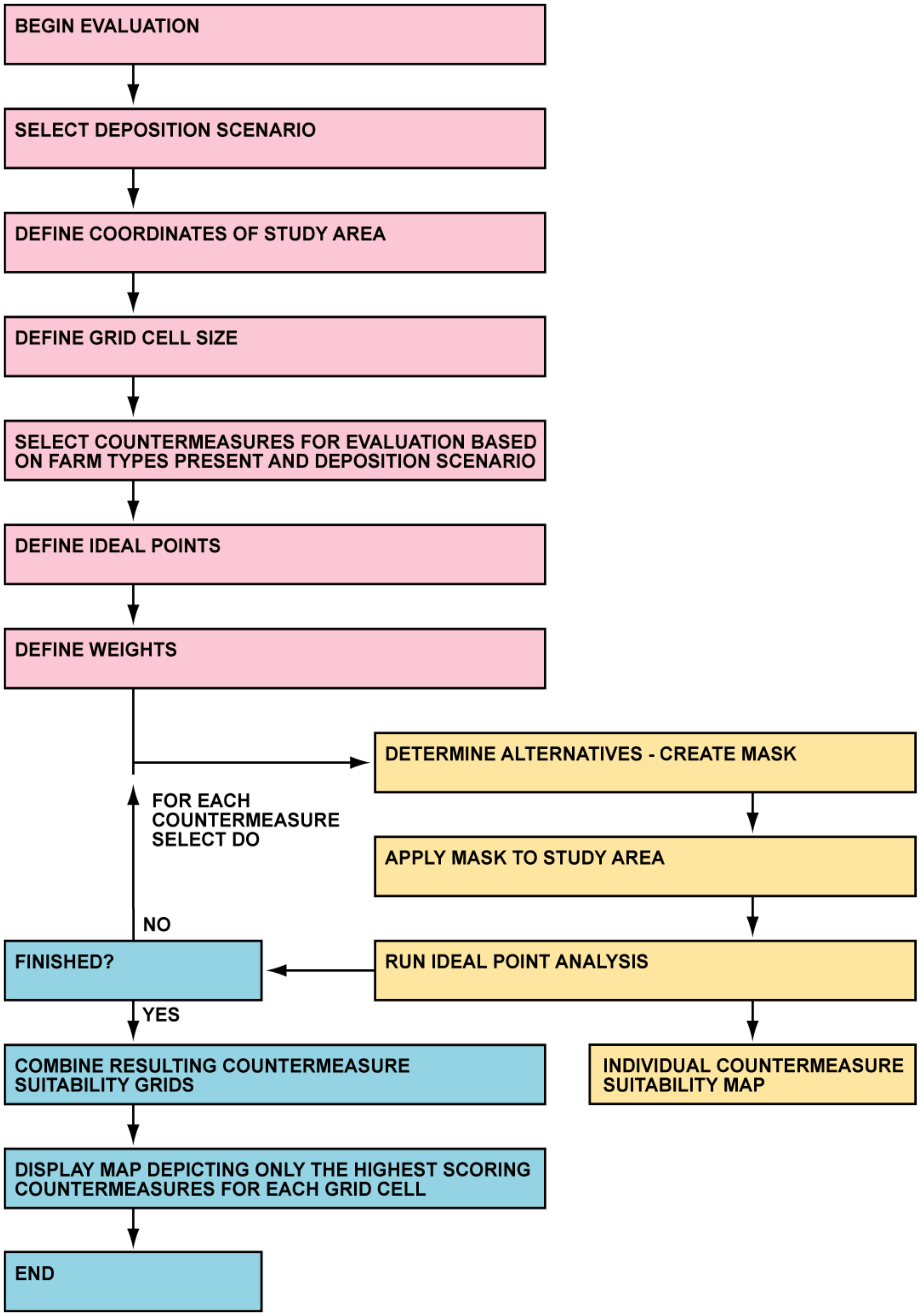

Figure 39. Overview of the countermeasure evaluation process in the SDSS.

9. SUMMARY AND CONCLUSIONS

The planning of a remediation programme following radioactive contamination of agricultural land can be optimised through a spatial assessment of land suitability and potential side-effects on the environment and food production. This can take into account geographical variability in factors such as climate, topography, soils, land use and agricultural practices that may lead to restrictions in the implementation of countermeasures. The same factors will determine the likelihood and extent of detrimental or beneficial effects on ecosystems and agricultural output.

In the CESER project a set of methods have been developed to make quantitative estimates of the side-effects of countermeasures encompassing numerical techniques such as simulation modelling, as well as empirical methods and expert judgement. These methods have been used to quantify impacts on the quality of water, soil, air and landscape, biodiversity and agricultural products. For selected impacts, mathematical modelling has been combined with impact mapping and catchment inventories in a GIS. The merit of mapping spatially diverse impacts is that decision makers can identify more and less sensitive areas and fine tune the application of countermeasures accordingly. The spatial aggregation of impacts over whole catchments or regions provides an opportunity to evaluate the net effects of a countermeasure and compare diverse areas within a country.

The results highlight the differential impacts of deep ploughing on soil erosion and losses of phosphorus in surface runoff. Depending on the type of soil and land use, these parameters may increase or decrease in the long-term and changes are most pronounced on steeper slopes. Thus it is possible to selectively treat those areas where the countermeasure will not lead to a deterioration in environmental quality or may even have beneficial side-effects. Skim and bury in comparison presents a much lower long-term risk in terms of soil erosion and nutrient losses.

Increased feeding of concentrate to dairy cows leads to several side-effects which are linked to greater manure production and land use change. Ammonia emissions will increase significantly in areas dominated by dairy farming resulting in potential environmental impacts on the local environment. The negative impacts on particulate and dissolved phosphorus losses in surface runoff are smaller when the extra concentrate is imported as opposed to increasing local cereal production. Conversion of grassland to barley production will have impacts on landscape structure and biodiversity which depend on the original agricultural production structure. Complete abandonment of agriculture will have some environmental benefits but these may be offset by negative effects on landscape and biodiversity if large scale afforestation is undertaken.

Within the context of the project it was not possible to quantify and map all impacts from a wide range of countermeasures in the same detail but the feasibility of the spatial assessment approach has been demonstrated. This shortcoming does not solely arise through time constraints but also lack of suitable models and limited understanding of the underlying environmental and biological processes. There is scope for major improvements in the accuracy of the modelling and analyses of the errors involved.

A PC-based Spatial Decision Support System has been designed to provide a formal methodology for the spatial assessment of countermeasures in a GIS environment. The system will perform a deposition scenario specific assessment of land suitability and side-effects of countermeasures. It will also display a map of overall countermeasure suitability based on effectiveness, technical feasibility and minimisation of environmental and agricultural impacts. A Multicriteria Decision Making method called Ideal Point Analysis has been included to allow decision-makers to compare and evaluate the advantages and disadvantages of different countermeasures based on their own objectives and preferences. Due to time constraints it was not possible to complete a fully working prototype of the SDSS.

The main weakness of the currently proposed system is it's inflexibility. All impact maps for the case study areas are pre-processed and cannot be altered. Equally the deposition scenarios, selectable countermeasures and environmental and agricultural limitations are fixed. Future improvements could be to dynamically link the SDSS to environmental models and allow the user greater freedom in setting the conditions for the assessments. In addition the assessment process could be greatly enhanced by including cost-benefit analysis, as shown in Salt *et al.* (1999b) and Wilson *et al.* (1999) for a non-spatial DSS.

The combined use of impact modelling and GIS has successfully demonstrated how geographic variability can be taken into account in the practical implementation of countermeasures. A fully developed Spatial Decision Support System will provide decision-makers with a powerful tool for planning and optimising remediation in agricultural systems by maximising land suitability and balancing environmental and agricultural side-effects against economic costs and benefits.

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