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SID 5 Research Project Final Report

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Project identification

1. Defra Project code: SP0531
2. Project title: Novel methods for spatial prediction of soil functions within landscapes
3. Contractor organisation(s):
   Cranfield University
   The Macaulay Institute
   Centre for Ecology and Hydrology
4. Total Defra project costs (agreed fixed price): £ 370000
5. Project: start date .... 01 July 2004
   end date .... 01 June 2006

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Executive Summary

7. The executive summary must not exceed 2 sides in total of A4 and should be understandable to the intelligent non-scientist. It should cover the main objectives, methods and findings of the research, together with any other significant events and options for new work.

The overall objectives have been met by this research but some of the specific objectives were amended, in agreement with Defra, as a result of research findings or lack of project resources.

The 1:50,000 scale digital soil maps were successfully generated for each catchment and maps for the Tern and Eden are presented in comparison with the equivalent NATMAP. A large amount of work was directed towards assembling data for, and running, a wide range of environmental models for the three catchments. This involved harmonising data, sharing datasets and in some instances extending existing datasets or deriving new ones. The extensive work that was required to assemble a representative range of working models to describe most of the six soil functions meant that for demonstration purposes these had to be run using existing NATMAP data. There was insufficient time and resources within the project to transfer the models to the 1:50,000 scale-equivalent data derived from the digital mapping exercise. This also meant there was no longer the need to ground-truth the predicted model outputs derived from using the derived detailed soil data.

Emphasis was given to the development of a high-level framework to assess interactions between soil functions because multi-functionality cannot be adequately assessed accurately by a single value. A prototype Evaluation Framework has been developed which allows the functional capacity of land to be interrogated on a 250 m grid. This framework utilises a wide-range of information at a catchment-scale, including the outputs from the different soil models. The framework also allows users to review whether positive or negative interactions will occur between soil sub-functions as a response to land use change. Tentative rankings have been placed on the changes in soil function that result. This Evaluation Framework is the first of its kind and offers significant potential for use as a tool to assist decision-making for land use planners and policy-makers.

The project has identified three areas of further research which have direct relevance to the proposed EU Soil Framework Directive (CEC,2006): (a) further development of the constraint analysis matrix, (b) the development of a scenario testing tool and (c) the development of a planning tool for optimising land-use allocations.

8. As a guide this report should be no longer than 20 sides of A4. This report is to provide Defra with details of the outputs of the research project for internal purposes; to meet the terms of the contract; and to allow Defra to publish details of the outputs to meet Environmental Information Regulation or Freedom of Information obligations. This short report to Defra does not preclude contractors from also seeking to publish a full, formal scientific report/paper in an appropriate scientific or other journal/publication. Indeed, Defra actively encourages such publications as part of the contract terms. The report to Defra should include:

- the scientific objectives as set out in the contract;
- the extent to which the objectives set out in the contract have been met;
- details of methods used and the results obtained, including statistical analysis (if appropriate);
- a discussion of the results and their reliability;
- the main implications of the findings;
- possible future work; and
- any action resulting from the research (e.g. IP, Knowledge Transfer).

1. Introduction

Soils provide society with a range of environmental and economic goods such as food, timber and clean water, and services such as a platform for construction, organic waste recycling and the storage of carbon that would otherwise be in the atmosphere. Provision of these goods and services are commonly described as the functions of soil. The maintenance of soil multi-functionality is key to the sustainable use of land and soils. This approach is now explicit in the European Soil Framework Directive (2006; article 1) and soil protection policy within the UK. The First Soil Action Plan for England is structured around the key soil functions and has the explicit aim of maintaining multi-functionality *"…to ensure that England's soils will be protected and managed to optimise the varied functions that soils perform for society … in keeping with the principles of sustainable development and on the basis of sound evidence."* (Defra 2004)

In the last decade, there has been a trend to complement traditional soil classification with an appraisal of the different functions (Table 1) which soils perform in ecosystems and landscapes (Blum 1993, Karlen *et al*. 1997). By so doing, the emphasis shifts from the <u>taxonomy</u> of soils to their <u>functional capacity</u> based on inherent soil properties. Such an approach will allow soils to be more widely recognised by society (Karlen *et al*. 1997), provide society and governing institutions with options and trade-offs for land use decision making (Miller *et al*. 1995) and help clarify the role of soil science in the land use decision making process (Bouma 2001).

Table 1: Functions of Soil (after Blum 1993 and Defra, 2004).

Soil Function	Description
Biomass production	Food, fibre and timber production
Environmental interactions	Filtering, buffering & transforming e.g. buffering of atmospheric inputs; biodegradation of toxic compounds
Biological habitat and gene reserve	Diversity within the soil; basis for valued semi-natural habitats and associated fauna
Physical medium	Base for built development and other human activities such as recreation
Source of raw materials	Supplying water, clay, sand, gravel, minerals, etc
Cultural heritage	Concealing and protecting archaeological remains; as a record of land use and settlement patterns

Land managers, regulators and policy makers require readily available information on the capacity of soils to perform the various soil functions at a map scale appropriate to the decisions being informed if they are to take soil function into account in their decision making.

For Great Britain soil maps are available for the whole country at 1:250,000 scale, appropriate to policy and decision making at country or national scale. Only a quarter of the country is covered by larger scale maps (1:50,000 and 1:25,000) and virtually none at the scale of 1:10,000 required for farm and field level decision support. However, Defra project SR0120 demonstrated that it is possible to derive larger scale soil map information using models and extrapolation techniques. The objective of this project was to use these techniques to provide soil information at a useful scale and to apply this information to the prediction of the soils' capacity to perform key functions.

All soils perform more than one function and the suite of functions for which individual soils are suited varies. In addition, there can be conflict between demands for different functions (Blum 1993) and objectivity is needed in establishing trade-offs between them (Miller *et al*. 1995, Karlen *et al*. 1997). An understanding of how the various functions interact in time and space is currently missing. This project set out to resolve and better understand these interactions by examining the feasibility and utility of developing a soil function/land use framework. The extent to which existing data and models could be used to predict soil functional capacity and quality across an area was also investigated. The potential impact of different management scenarios and/or environmental conditions on the delivery of multiple soil functions within these landscapes was investigated.

The approach is built on the UK's long-term involvement and expertise in the development and application of a multi-functional approach to soil protection and management (Howard *et al*., 1989; Loveland and Thompson, 2002). In addressing these issues, the project has also identified gaps in the knowledge of processes which influence soil functions and the data required to extrapolate and apply findings more widely.

2. Objectives

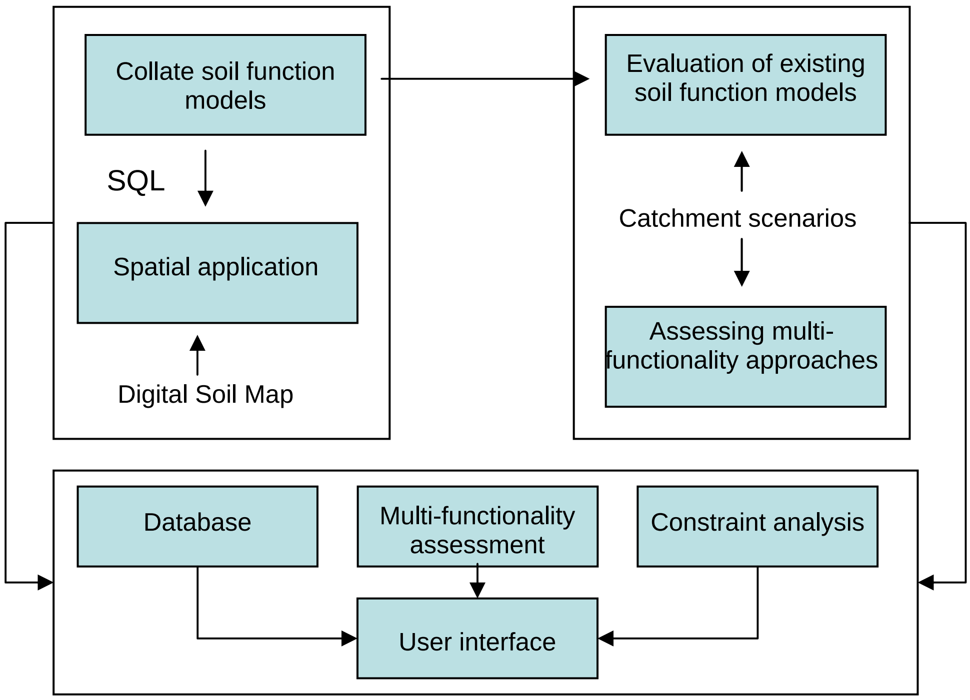
The overarching objectives as initially set out were:

- To develop and apply predictive models of the relationships between environmental data and known soil patterns to predict capacity for key soil functions within diverse landscapes for which there is little detailed underpinning soil information available. In order to reconcile sustainable land use objectives with broader issues of environmental quality, the techniques will be applied at the whole catchment scale.
- To develop a high-level framework in which the non-specialist user-community (land managers, planners, regulators) can explore questions regarding soil functionality.

Both the modelling of a large number of very diverse soil function models from variety of source and the very complex nature of modelling multi-functionality caused the project objectives to be amended in order to successfully deliver a framework for evaluating multi-functionality. As a result, three of the original activities were dropped - stakeholder meetings in each of the test catchments, the use of newly derived more detailed digital soil maps for mapping soil functional capacity and the ground-truthing of the soil function models.

Enough local knowledge existed within the project team to list the major issues associated with each of the catchments without reference to stakeholders. Work on assigning probabilities and confidence limits to the digital soil maps for the Eden and Tern catchments only become available late in the project by which time the models had been implemented using the 1:250,000 National Soil Map. The advantages of using digital soil mapping techniques to improve spatial resolution have been demonstrated. While the Identification and formalisation of requirements for ground truthing of soil functions has not been undertaken, a detailed description of each of the models used in this project was collated thus providing the basis on which ground-truthing protocols could be developed.

Figure 1: An overview of the project objectives and work packages.



The project has been addressed through three distinct work packages:

a) the spatial application of individual soil function models in three diverse catchments,
b) investigation of the feasibility of assessing multi-functionality and scenario testing, and
c) the development of an evaluation framework for a non-technical user community.

The relationship between the individual work packages is shown in Figure 1.

3. Approach and Results

3.1 Predictive models of soil functional capacity within diverse landscapes

To reconcile sustainable land use objectives with broader issues of environmental quality, it was decided to carry out this research at the catchment scale. Following discussions with Defra, three catchments were selected to reflect a diverse range of climate, soils, soil functions and land uses. To support the digital soil mapping and soil functional capacity modelling, as well as serving as background information, a wide range of soil and other environmental data were assembled for each of these catchments and are detailed in Appendix 1. The data were collated from numerous sources including the partner organisations and external sources where licensing would allow.

3.1.1 Test areas

The three catchments selected are the Eden, Lossie and Tern catchments. They were selected to represent a wide diversity of soils, terrain, land use and climatic conditions (Table 2).

Table 2: The Catchments.

Catchment	Location	Primary land cover (LCM 2000)	Area (km^2)	Av. rainfall (mm $year^{-1}$)	Altitude range (m)
Upper Tern	English West Midlands	arable, improved grassland	593	694	48-376
Upper Eden	North West England	improved and acid grassland	689	1483	90-893
Lossie	North East Scotland	improved grassland, coniferous woodland, bog	270	957	3-522

The Tern catchment identified for study is upstream of the confluence of the Tern and Roden and covers approximately 593 km^2. The area is mainly under arable cultivation (cereals and roots) although some woodland persists on the driest sandy land and the wet floodplain soils of the Tern are under permanent or rough grass. Rainfall is about 650 mm per annum with a field capacity period of 145 days and an accumulated temperature of approximately 1400 day degrees above 0^oC.

The river Eden, rising on the western flanks of the Cumbrian Pennines, south of Kirkby Stephen, flows north westwards towards Carlisle before discharging to the Solway Firth. The area south of Lazonby and the Eamont confluence has been chosen for the study, which extends to approximately 689 km^2. The north-eastern part of the catchment is drained by short, relatively steep streams from the Pennines; the south-western part includes tributaries of the Lyvennet system which arise on Ravensworth Fell and headstreams of the Eden originating on Mailerstang Common and passing through Kirkby Stephen. The watershed along the Pennines scarp rises to over 1000 m OD, while the river falls to about 70 m OD near Lazonby. Rainfall exceeds 2000 mm per annum on the eastern watersheds, with a field capacity period of over 11 months and an accumulated temperature of less than 750 day degrees above 0^oC. The lower valley has about 850 mm annual rainfall, a field capacity period of 215 days and an accumulated temperature of about 1300 day degrees above 0^oC.

The catchment of the River Lossie extends to approximately 270 square kilometres. The river rises on Carn Kitty (521 metres) in the Moray Firth foothills and flows northwards to the Moray Firth. The catchment is very narrow at its estuary with two man-made canals on either side. The climatic regime within the catchment is amongst the most favourable in Scotland. Average annual rainfall ranges from 600 mm at the coast to 1000 mm at the river source and accumulated temperature values, within a Scottish context, are high (approximately 1250 day degrees above 0^oC). Annual sunshine totals are relatively high at around 1400 hours annually on the low ground.

3.1.2 Digital soil maps for the catchments

The methodology established under Defra SR0120 (New methods of soil mapping) was further developed to successfully generate the digital soil maps for the Eden and Tern catchments (detailed soil maps were already available for the Lossie) at a target resolution of 1:50,000 to provide the base information for the soil function modelling phase. Digital Soil Mapping (DSM) is the only viable approach currently available to produce soil maps at the catchment scale at reasonable costs.

DSM relies on relationships between factors such as landscape, climate and geology, for which detailed maps exist, and soil. The range of input data that have been used in this modelling exercise are soil descriptions (auger bores), climatic and geological maps as well as Digital Terrain Model (DTM) derivatives. Soil-landscape models were developed using two different data-mining tools: Bayesian Belief Networks (NETICA™ from NORSYS Software Corp.) and Decision Tree Statistics (See5/C5.0 from RuleQuest Research). Final model selection was based on the error rate calculated from the predicted versus the actual soil series for each of the training points.

Figure 2: Detailed soil map (by DSM) compared to NATMAP for the Upper Eden catchment

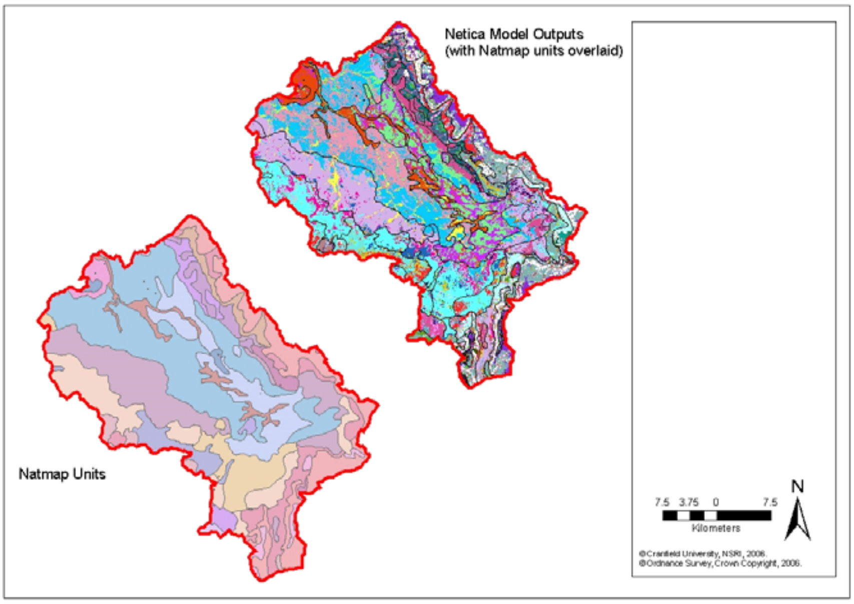
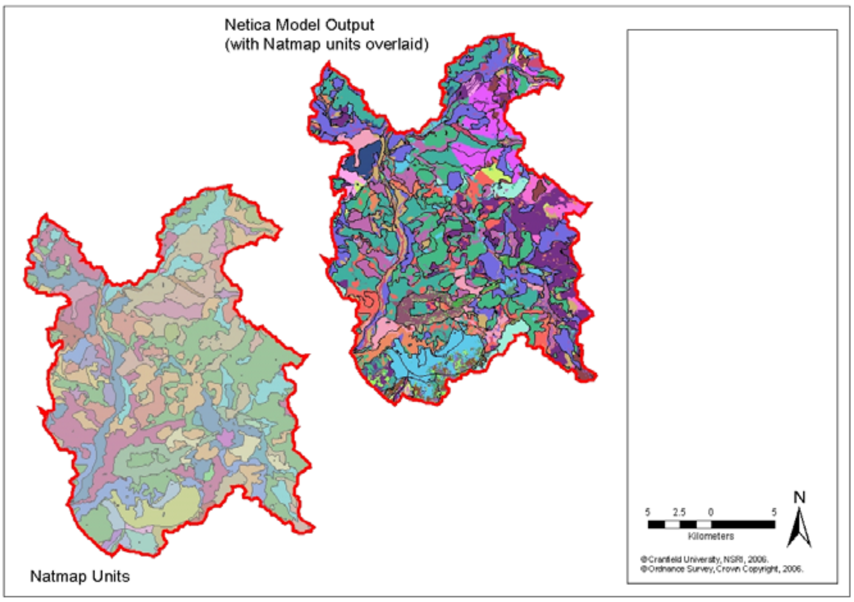


Figure 3: Detailed soil map (by DSM) compared to NATMAP – Tern catchment.



For both the Eden and Tern, the final models were developed using NETICA and enhanced soils datasets were produced for both with predictions of soil type (soil series) at each intersect of a 50 m grid. Figures 2 & 3 illustrate the increase in spatial resolution of the resulting maps compared to NATMAPand the improvement in map unit designations from soil associations to soil series.

The Digital Soil Mapping techniques used in the Tern and Eden catchments have provided more detailed soil maps that are more relevant to the thematic interrogation required to map soil functional capacity and their interactions with land use or environmental change. Hence DSM makes it possible to begin to consider different land management options for maintenance of soil functions.

When using legacy data, the number and distribution of auger bores that are available in both geographic (i.e. the number and spatial distribution of auger bores available for the project area) and thematic (i.e. the number of auger bores available to model individual soil series) space imposes inherent limitations on the resulting soil maps (Mayr et. al. in press). However, the great benefit of this type of approach to soil mapping is that data limitations are clearly identified and provides the means of identifying where additional data collection would be most beneficial, and likely costs can be estimated. Data resolution for the Tern could be further improved using targeted soil surveys.

3.1.3 Modelling soil functions in catchments

Our objective was to develop and apply a modelling approach to predict the performance of key soil functions in catchments where only sparse or low resolution soil survey data are available. To support this activity, a literature review was undertaken to evaluate current developments in soil function assessments (Appendix 2). The specific aim was to make use of the large number of readily available models which were relevant to the delivery of individual soil functions. However, no single model adequately represents all aspects of any of the six broad soil functions. Individual models address 'sub-functions' of the broad functions. For example, the biomass production function can be assessed by generalised models of agricultural production but is best represented by models which assess the individual sub-functions of horticultural and/or arable cropping, grassland and/or forestry production and now energy crop production. The list of models and the link between these and the individual soil functions is illustrated in Table 3 and Appendix 3.

This is clearly not a comprehensive list since the purpose was to establish whether such an approach showed potential for investigating relationships between soil functions within catchments. A consequence of the diverse history of the models is that there are a range of concepts applied to the assessment of individual soil sub-functions:

- *Critical loads:* defines classes of buffering capacity of soils which can be viewed as 'Functional Capability Classes' for sub-functions within the Environmental Interaction function (Hornung and Skeffington, 1993).
- *Land capability:* assesses limitations to a specific land use imposed by permanent land characteristics or properties e.g. USDA Soil Conservation Service. The degree of limitation dictates the land capability class of a soil within the range of land use options. Capability and suitability are complimentary, and overlap to some extent (Howard *et al*., 1989).
- *Soil/land suitability:* suitability is the fitness of a given type of land for a defined use (FAO, 1976). The principle is that the implementation of a specific land use proposal should not result in severe or progressive degradation e.g. The Soil Survey of England and Wales land suitability classifications for a wide range of agricultural crops (Howard *et. al*., 1989).
- *Risk analysis:* a quantitative relationship between exposure to a degrading influence and its effect e.g. soil buffering capacity for pollutants which relates to pollutant speciation and bio-availability (de Haan, 1987) and soil erosion risk models which allow the effect of potentially damaging rainfall to be assessed on a range of soil types with contrasting properties.

It is unlikely to be possible or desirable to use the same modelling concept to represent all aspects of soil functionality since some functions or sub-functions will be best suited to specific types of models. However this raises the fundamental issue of comparability between the different model/soil functions since output scales are not necessarily directly comparable or numerically equivalent.

The implementation of the models proved to be much more challenging than originally anticipated. Significant effort was required during the initial phase including a series of workshop-type sessions and consortium communications to reach a common understanding about how the models could be implemented and the practicalities of how they would be run e.g. identifying data requirements and sources, harmonising datasets, resolving the multitude of modelling concepts and establishing comparable scaling. Although this affected progress on other objectives, it was important to address these fundamental issues before moving on to the next stages.

Table 3: The list of models used by the project for individual soil functions.

Function	Component	Concept	Model	Model
Biomass production	Food production	Suitability for agriculture	Agricultural Land Classification	Defra
	Food production	Suitability for arable production	Arable Crop Suitability Model	NSRI
	Food production	Suitability for grassland	Grassland Suitability Model	NSRI
	Energy crops	Suitability for energy crops	Energy Crops Suitability Model	NSRI
	Energy crops	Suitability for energy crops	Willow suitability	NSRI
	Energy crops	Suitability for energy crops	Short Rotation Coppice	Macaulay
	Forestry	Suitability for Forestry	Land Capability for Forestry	Macaulay
	Forestry	Suitability for Forestry	TreeFit	NSRI
Environmental interactions	Buffering	Critical loads	Critical loads (acid buffering)	CEH
	Buffering	Critical loads	Critical loads (nitrogen	CEH
	Buffering	Critical loads	Critical loads for Acidity	CEH
	Filtering	Groundwater vulnerability	Groundwater Vulnerability	NSRI/Maca
	Filtering	Leaching potential	Soil Leaching model	NSRI/Maca
	Filtering	Water quality	SWATNAT	NSRI
	Storage	Critical loads	Radiocaesium transfer	CEH
	Storage	Metal binding capacity	Metal Binding Capacity	Macaulay
	Storage & filtering	Sludge acceptance	Sludge acceptance model	NSRI
	Storage & filtering	Sludge acceptance	Sludge disposal model?	NSRI
	Storage & filtering	Sludge acceptance	Slurry Acceptance Potential	Macaulay
Biological habitats	Semi-natural habitats	Suitability for semi-natural plant	GBMOVE	CEH
	Semi-natural habitats	Suitability for native tree species	Native Woodland model	Macaulay
	Semi-natural habitats	Suitability for lowland heath	Lowland Heath Regeneration	NSRI
	Semi-natural habitats	Suitability for tree species	TreeFit	NSRI
Physical medium	Housing	Suitability for shallow foundations	Housing Suitability Model	Macaulay
	Housing	Suitability for shallow foundations	Shallow foundations	NSRI
Sources of raw material	Peat	Suitability for peat extraction	national soil maps	NSRI/Maca
Cultural heritage		Vulnerability to erosion	Soil erosion model	Macaulay
		Vulnerability to erosion	Morgan-Morgan-Finney Model	NSRI

The required soil and other variables were assembled to execute the various models across all three catchments. Two key tasks were;

- *Harmonising data requirements to use models in England and Scotland.* The Soil Surveys of England & Wales and of Scotland have different soil classifications and data holdings (format and content). Models, especially those developed by either partner, tend to reflect the respective available datasets. Thus, model implementation across border for all catchments was resolved by discussion and by deriving new universally compatible datasets.
- *Providing extensive soil property datasets for dynamic/process-based models.* Several models require input variables which are not routinely available from soil surveys. Whilst data are available in paper archives these required collation, electronic capture and validation prior to use.

All models were implemented using Structured Query Language (SQL), which was selected as it allowed the maximum possible use of existing programs and routines within LandIS and the Macaulay Institute databases. The SQL scripts extracted the relevant soil properties based on the appropriate soil series for each grid cell and provided the associated soil properties to the individual soil function models. Where detailed (soil series) maps are available this is straight forward but use of the soil association map units from the national soil maps required translation into a dominant soil series for each grid cell in order that ‘SQL’ statements could be used to extract the relevant data from LandIS.

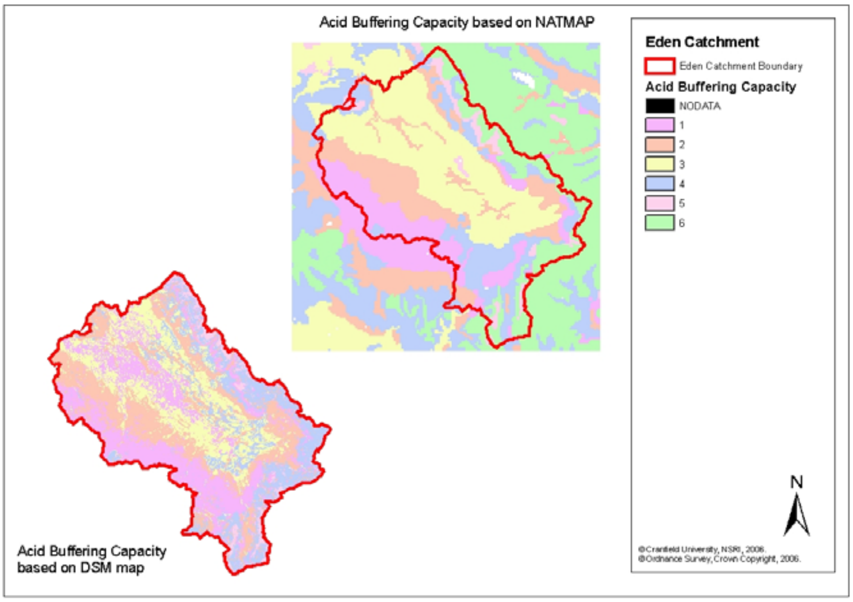
The operational scale for the models was set at a 250m grid as this was a manageable number of grids in terms of data processing and most appropriate to the scale of the input data from the soil maps. A 250m grid was draped across the soil maps for each catchment with the model application work carried out in parallel with deriving new soil maps based on Digital Soil Mapping. Underlying the soil map, for each 250m grid, were the individual soil properties that were required to run each model. Most of these data were derived from the national soil maps. In total 34 sub-functions and functions were modelled for the Eden and Tern catchments and 27 for the Lossie (Table 4).

Table 4: Framework of data and model application for each catchment.

VARIABLE	EDEN	TERN	LOSSIE	VARIABLE	EDEN	TERN	LOSSIE
LCM	✓	✓	✓	LOW_HEATH	✓	✓	
ALC/LCA	✓	✓	✓	NATIVE_WOOD	✓	✓	✓
BARLEY	✓	✓	✓	MAC_HOU	✓	✓	✓
CEREAL	✓	✓	✓	SHRINKAGE	✓	✓	
MAIZE	✓	✓	✓	PEAT	✓	✓	
POTATO	✓	✓	✓	MAC_EROSIO	✓	✓	✓
SUGARBEET	✓	✓	✓	MMF	✓	✓	
GRASS_Y	✓	✓		NVZ	✓	✓	✓
GRASS_T	✓	✓		SSSI	✓	✓	✓
GRASS_SUIT	✓	✓	✓	ANC_WOOD	✓	✓	✓
SUNFLOWER	✓	✓	✓	ARCH_OS	✓	✓	✓
WILLOW	✓	✓	✓	ARCH_EH	✓	✓	
MACLAND	✓	✓	✓	ARCH_HS			✓
ACID_NSRI	✓	✓		URBAN	✓	✓	
UKCLA	✓	✓	✓	NSI_CADMIUM	✓	✓	✓
CLNUTN	✓	✓	✓	NSI_COPPER	✓	✓	✓
MAC_CADM	✓	✓	✓	NSI_LEAD	✓	✓	✓
MAC_COPPER	✓	✓	✓	NSI_NICKEL	✓	✓	✓
MAC_NICKEL	✓	✓	✓	NSI_ZINC	✓	✓	✓
MAC_ZINC	✓	✓	✓	MAC_SLUDGE	✓	✓	✓
MAC_CHR			✓	SLURRY	✓	✓	
MAC_LEAD			✓	SWATNAT_CONC	✓	✓	
SOIL_LEACH	✓	✓	✓	SWATNAT_VA	✓	✓	
GWVUL	✓	✓	✓	CSLAMB1000	✓	✓	✓
SLUDGE_NSRI	✓	✓		CLLAMB1000	✓	✓	✓

Not all models were applied in all catchments since there were some 'duplicate' models e.g. Macaulay and NSRI used their own models for sludge recycling (MAC_SLUDGE vs. SLUDGE_NSRI) or erosion (MMF vs. MAC_EROSION) and some models were not considered applicable across all the catchments. Examples are potential for lowland heath (LOW_HEATH) and vulnerability to clay-related shrinkage (SHRINKAGE). Other models were too time-consuming to implement in all circumstances, such as SWATNAT. Figure 4 illustrates the outputs from the acid buffering model for the Eden. All models have been clearly documented complete with input requirements, methodology, output classes, limitations and literature references itemised. A complete set of the models descriptions and the respective maps can be found in Appendix 3.

Figure 4: Acid buffering using detailed soil maps for Upper Eden catchment.



It is concluded that the methodologies adopted could be applied to any part of the UK and that the required data sets exist. However models do not exist for all sub-functions, in particular those relating to aspects of environmental interactions, biological habitat and cultural heritage functions. Further work should assess the applicability of models such as SUNDIAL, STAMINA and RothC.

Further work is also required to evaluate how the outputs of the different models would be improved by increased resolution of soil information, in particular confidence errors associated with the results. Current soil series information is of insufficient spatial detail to map soil functional capacity at sub-regional level. There is only partial coverage of the country at 1:50,000 or greater while most decision-making will require information at scales larger than 1:50,000.

3.2 Modelling of multiple soil functions under different scenarios

Having compiled all necessary datasets and model predictions, both multi-functionality of soil functions and scenario testing were investigated.

3.2.1 Catchment scenarios

As a first step, a set of scenarios were identified for each of the three catchments based on a two-pronged approach:

1. Expert knowledge of the significance of current and future pressures on soils and local knowledge of specific catchment-scale issues, particularly land use and management-related, were collated from members of the project team and local experts.
2. Each partner hosted a two-day catchment visit. Day 1 was an office-based familiarisation on each catchment when the following were presented and discussed; soil mapping and available soil property data, model outputs, current and future land uses/management options, issues relating to the delivery of soil functions. Day 2 was a field reconnaissance where we examined issues identified from the previous day e.g. specific examples of potential for change under CAP reform or areas of uncertainty in soil mapping.

Potential land use and management changes were related to over-arching drivers of agricultural development and reform (e.g. CAP reform), environmental stewardship (e.g. Nitrate Sensitive Areas) and conservation management (e.g. habitat designations). The non-land based pressures of climate change and atmospheric deposition were also identified. The scenarios identified for each of the three catchments are listed in Table 5.

Table 5: Examples of potential land use and management changes for each catchment identified from knowledge and field reconnaissance.

Eden	Tern	Lossie
- Increased afforestation (coniferous and broadleaf)	- Increased broadleaf afforestation	- Woodland restructuring
- Increased dairy stocking density in lower catchment	- Lowland heath regeneration	- Habitat restoration
- Construction of wind farms.	- Urban development	- Expansion of natural pine woods
- Increased use of forage maize	- NVZ restrictions	- Flood management
- Restoration of heathland habitats		- Construction of wind farms
- Increased slurry disposal		- Decrease in sheep density
- Expanded conservation designations (NP, SSSI, AONB)		- Expansion of horticulture
- Decrease sheep density in uplands		

3.2.2 Evaluation of existing models

There was considerable discussion over how to implement change scenarios across the models of soil functionality. For example, impacts on soil functions could be assessed by changing the input variables (soil or other environmental) for the individual models to values that might be expected under the changed condition. However, not all of the available models are capable of scenario testing. Table 6 summarises the direct links between the individual models and potential scenarios. Only eleven models were directly sensitive to land-use change with the possibility of at least some soil properties to be changed under different managementscenarios. Ten models could be regarded as sensitive to climate change since they include droughtiness, field capacity and soil wetness class. Other models could be used if they include variables such as soil organic carbon, rainfall, temperature, growing season length that vary with changes in climate. However, all such parameters (and the statistical or mathematical bases of their relationships) require updating to be useful for climate change scenario testing; this was beyond the scope of this project.

In conclusions, most land function models are rule-based rather than process-based and therefore have no capacity to deal with feedback mechanisms. Models applicable to soil functionality tend to be static and, as such, have limited capacity to support scenario testing. Many of the models make use of derived climatic parameters such as *field capacity days* that often indicate only relative differences between locations and can not be easily disaggregated to study impacts of climate change.

There is a need for simplified models that could be implemented using currently available soil information through the adaptation of current models and/or development of new models from first principles. This phase of the project highlighted the lack of soil functional capacity models suitable for scenario testing. Few if any models address *spatial dynamics* (i.e. there is no interaction between individual grid points), *temporal dynamics* (i.e. changes in soil properties due to land use or climate change through time). There is inadequate understanding of the interactions between different soil functions and sub-functions.

3.2.3 Assessing current approaches to soil multi-functionality

Before tackling the development of a high-level framework for decision makers, we first assessed the different approaches that have been applied to the concept of soil multi-functionality with a view to identifying the most appropriate for application in our framework. The relative importance of soil functions varies depending on the soil in question but all soils perform more than one function. As a result, there is competition between them (Blum 1993) and a need for objectivity in determining any trade-offs between them (Miller *et al*. 1995, Karlen *et al*. 1997). The range of uses to which a given soil may be put depends upon its inherent properties and those of the site in which it occurs. Some soils may be suitable for a wider range of uses than others; however, certain uses can alter the properties of the soil to the extent that the range of possible uses can change. The multi-functionality concept involves preserving the properties of a given soil which are important for the widest possible range of functions so as to keep options open for future generations. Thus, multi-functionality is a complex concept and recognizes the various functions which soils can perform and stresses that the exploitation of one function of soils by man should not impair the operation of other functions. While this is the aim and a fundamental principle of soil protection policy, it is a challenging ideal that may not be achievable (i.e. the use of a soil as a foundation for buildings or roads sterilises it for other functions).

Table 6: Responsiveness of models to land use change or climate change for scenario testing.

Model	Land use change	Climate change
Agricultural land classification systems		Y
Arable Crop Suitability Model		Y
Grassland Suitability Model		Y
Energy Crops Suitability Model		Y
Willow suitability	Y	Y
Short Rotation Coppice	Y	Y
Land Capability for Forestry		
TreeFit	Y	
Critical loads (acid buffering)	Y	
Critical loads (nitrogen deposition)	Y	
Critical loads for Acidity Buffering	Y	
Groundwater Vulnerability Mapping		
Soil Leaching model		
SWATNAT	Y	
Radiocaesium transfer		
Metal Binding Capacity	Y	
Sludge acceptance model		Y
Sludge disposal model		Y
Slurry Acceptance Potential		Y
GBMOVE	Y	Y
Native Woodland model		
Lowland Heath Regeneration		
Housing Suitability Model		
Shallow foundations		
Soil erosion model	Y	
Morgan-Morgan-Finney Model	Y	

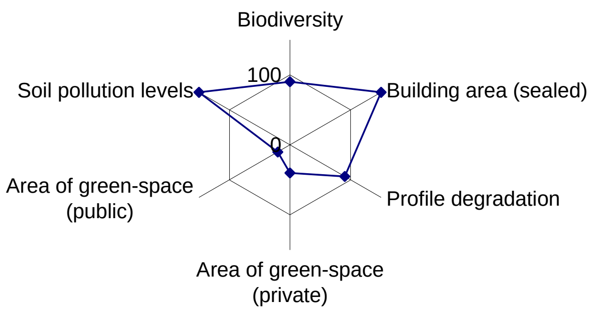
Various approaches to multi-functionality were reviewed and four examined in detail for potential application in the framework:

(a) Tabulated approaches
Tables presenting the functional capability classes for a range of functions or sub-functions based on soil type or individual parcels of land are constructed. Bastian (2000) used this approach to undertake an assessment of selected landscape functions / natural potentials in natural landscape units (microgeochores) in Western Lusatia (Saxony, Germany).

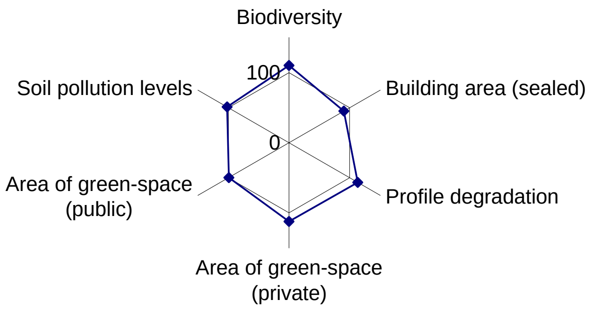
(b) Graphical approaches
Bar chart and AMOEBA models have been used in the past to illustrate multi-functionality. Loveland and Thompson (Environment Agency, 2001) proposed a bar chart approach to compare national indicators for soil quality using both single and multi-state indicator models. Soil functions have been compared using the AMOEBA model by Ten Brink *et al*. (1991) and are particularly suitable for assessing changes over time. Simplified AMOEBA diagrams are presented in Figure 5, where six indicators are initially in an 'imbalanced' state such that the soil can only support a limited number of functions, and an 'equilibrium' state where the soil is capable of successfully performing a wide range of functions. Wood (2005) proposed this approach for indicators in the built environment. This approach requires a score or weight to be applied to each function (in this case on a scale of 0-100). This is generally achieved through stakeholder engagement and based on the value that the stakeholders (including market forces) place on the soil 'goods and services' under consideration. Consensus may be difficult. It is possible to use soil suitability models to guide weighting but the output of many of these is ordinal and non-linear. Stakeholder participation in natural resource management not only facilitates complex valuation, but it allows integration and communication between stakeholders leading to a clear definition of shared problems (Bouwen and Taillieu, 2004). The diagrams can become cluttered and difficult to read if sub-functions are shown, for example, biomass production divided into ability to provide a wide range of individual crops and trees. In most cases, a soil is able to support these to different extents and it therefore becomes difficult to allocate one score for each broad function.

Figure 5: An illustrative AMOEBA model of sustainability indicators in the built environment (Wood, 2005).

Imbalanced



Equilibrium



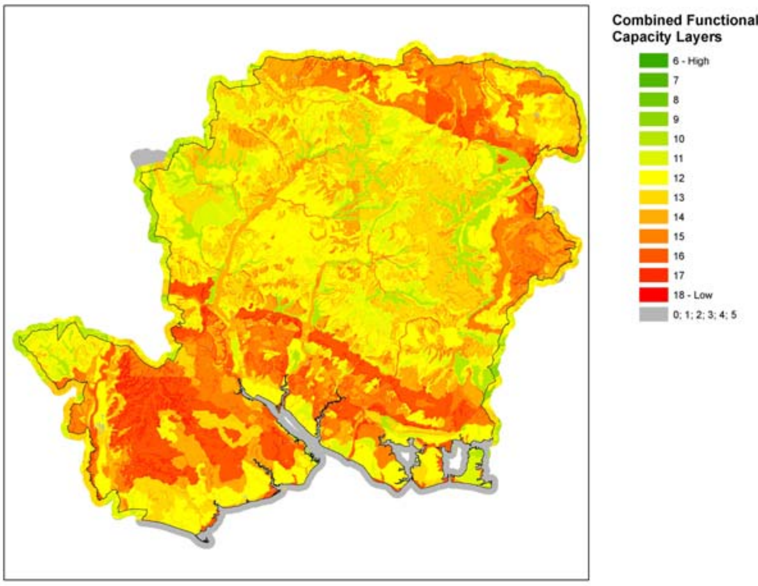
(c) Index approach

Any given soil performs a number of functions to varying capacities and the aim of sustainable management is to maintain or optimise this multi-functionality. It is possible to develop a single index which expresses the multi-functional capability of a soil. Such an index could be seen as providing an integration of the functional capability across all the various functions or sub-functions. It could be seen as identifying a means of ranking soils and identifying elite soils from a functional standpoint. Recent definitions of soil quality are based upon consideration of the capacity to carry out soil functions. Such an approached was tested by Thompson and Truckell (2005) for Hampshire (Figure 6) but found to be vulnerable to misinterpretation; other examples include Steadman *et al* (2004) in a Strategic Environmental Assessment (SEA) for future aggregate extraction in the East Midlands Region and the City of Berlin in their Urban and Environmental Information System (UEIS, 2002).

(d) Capability approach

This approach is analogous to land capability assessments (LCA) for agriculture such as Agricultural Land Classification (ALC) in England and Wales (5 grades, 7 classes) and LCA in Scotland (7 classes). In Scotland, the LCA grades the quality of land for agriculture ranging from Class 1, the best and most versatile land, to Class 7, the least productive. In order to apply this approach to soil function mapping, we assumed that land that can perform all soil functions to a high standard is the most flexible from a planning perspective. This equates to Class 1 land, the most flexible/functional land. As functional quality declines and land loses its functional flexibility it may eventually be only capable of performing one function adequately. This would, in theory, equate with Class 7 land. However, the functional capability of some sub-functions of the same primary function can be in conflict, for example, the capability for growing trees for timber can be different to that for the production of arable crops. Therefore, Functional Capability classes are best used at the primary function level as an overall indicator of multi-functionality. This approach can then be combined with an analysis of the interactions between sub-functions in order to determine the most appropriate use of the land. Defra project SP0550 “Agricultural Land Classification field data reuse” also proposed this approach.

Figure 6: Aggregated soil functional capacity map from the NSRI Hampshire Project (Thompson and Trackell, 2005).



In this project, we addressed issue of comparability of models by scaling model outputs from 0 to 1. Although it is appreciated that there is non-linearity within individual and between model outputs, this simple approach served as the starting point for implementing both the index and capability approach as part of the evaluation framework

The main challenge in developing a system of functional capability classes is defining and setting the limits to the classes. This involves, first of all, identifying the parameters that will be used to define the classes for each function or sub-function and then setting the class limit values for these parameters to define the boundaries between classes (Table 7).

Table 7: Capability-type approach to multi-functionality assessment

	Number of functions performed			
	All (6)	Most (4-5)	Some (3)	Few (1-2)
Well	1	2	3a	4
moderately well	2	3a	4	5
poorly	3b	4	5	6

The simple definition for the proposed classes are:

- Class 1: The land is capable of performing all six primary functions to a high standard
- Class 2: The land is capable of performing most primary functions to a high standard or all functions moderately well.
- Class 3a: The land is capable of performing some primary functions to a high standard or most functions moderately well
- Class 3b: The land is capable of performing all primary functions but poorly
- Class 4: The land is capable of performing most primary functions poorly, some moderately well and a few well
- Class 5: The land is only capable of performing a few primary functions moderately well and some poorly
- Class 6: The land is only capable of performing a few primary functions poorly
- Class 7: The land is capable of only performing one primary function

For demonstration purposes, results from the Index approach for each primary function were taken as a starting point for the capability evaluation. The index values for each primary function were categorised using a simple 3 fold classification that described the functional capacity (i.e. functioning well – Index value 0.66-1.0; functioning moderately well – Index value 0.33-0.66; and functioning poorly – Index value 0-0.33). The terms 'well', 'moderately well' and 'poorly' are at this stage based solely on value judgements of the model outputs rather than on strict, rigorously tested thresholds. It took many years of progressive improvement to develop the existing ALC/LCA systems, so it is unrealistic to expect that level of accuracy here. This exercise is an attempt to test principles in order that a judgment can be made regarding the applicability of the soil functional capability concept. Class 3 has been split in order to maintain the distinctions made in the original ALC/LCA classification.

The current techniques described above represent only very simple approaches to the assessment of soil multi-functionality. The wide variation in output from the available models makes the approaches difficult to implement. None of the approaches allows interactions between the various soil functions to be addressed and their value for scenario testing and the assessment of multi-functionality is limited. New methods are therefore needed if this is to be achieved.

Both the assessment of individual models used in the project for their capacity to undertake scenario testing as well as the assessment of current multi-functionality approaches highlighted the shortcomings and hence limitation for scenario testing. None of the above methods provides a formal framework in which the user of land or those with an interest in its use can ask questions about the sustainability of current or possible future patterns of land use. Secondly, the interactions between soil functions are not adequately addressed in any of the multi-functionality approaches.

However, in order to demonstrate the limitations of current multi-functionality assessment approaches, both the index as well as the Capability approach was implemented in the Framework (Section 3.3.3.). Both the tabulated and graphical approaches were dismissed as not appropriate for this study as they are difficult to implement spatially.

Before any scenario analysis can be undertaken, an understanding of the interactions between soil functions has to be developed. The initial requirement was to take the current model outputs and compare the current conflicts between the soil functions in a spatial context. These issues were discussed at a project meeting in July 2005 and agreement reached that the project would put scenario testing to one side and focus on the examination of current conflicts between soil functions using the evaluation framework. A simplified capacity-type approach would be adopted which address conflicts between soil functions through a matrix evaluation would exercise. The evaluation framework is described below.

3.3 The evaluation framework

The framework developed in this project is the first to be developed for application at catchment scale. Three guiding principles were used in the design of the evaluation tool.

(a) all soil functions need to be considered, even if they are currently not all adequately addressed,
(b) a framework should be developed that suits the models/data being used rather than an idealised framework to which models and data are then hopefully fitted, and
(c) the questions raised by Loveland and Thompson (2002) in their report on soil indicators are key:
  - what do you want to do with this soil?
  - what functions is this soil performing?
  - what functions could it perform?
  - are these the functions we want it to perform?
  - is this the best use of this soil?

The concept of soil quality – 'the capacity of soil to function' (Karlen *et al.,* 1997) – is one mechanism by which the various functions of soil can be judged holistically. The capacity-type approach offers a way of simplifying soil maps, and data, for the user in terms of functions. Although the concept handles each function separately it portrays the flexibility and/or multiple functions that soils perform, thus providing guidance for stakeholders to optimise across functions. Such a framework provides a way of communicating soil functions to a wide audience, including planners and policy makers, by demonstrating how soils deliver soil functionality. The framework is based on a Pressure-Impact assessment. Although it is very difficult to generalise about the impact of a given pressure on a particular soil function, in most cases, current knowledge allows the likely direction of the response to a given pressure to be identified by using evaluation matrices which allow such relationships to be identified and visualised.

In order to evaluate soil functions and their interactions an evaluation framework was developed (Figure 7). The framework consists of a user interface, a database, two multi-functionality assessments and a constraint analysis. The framework was populated for each of the three catchments separately and the results of the analysis presented at three hierarchical levels. At the highest level is the overall assessment of the ability of a parcel of land to undertake the six primary soil functions and their sub-functions. An important conceptual difficulty is how to decide if a soil is performing well at the primary function level when there are conflicting results from individual sub-function model output. The degree to which this dichotomy affects any decision on the ability of a soil/land to perform an overall primary function can depend on the number and range of sub-function models incorporated into the overall assessment. Because of this, it is generally more useful to assess the primary functions in terms of their sub-functions. For example, within the environmental interactions primary function we have incorporated sub-function models which reflect the capacity of soils to buffer a range of pollutant inputs, such as acidity, sulphur, nitrogen and metals, rather than a consideration of a single capacity to buffer the whole range of potential pollutant inputs. Similarly, within the biomass production function, sub-functions are defined for the production of a range of arable crops, grass, energy crops and timber.

3.3.1 The user interface

A user interface was developed in Microsoft ACCESS. Within the interface the user can select individual grid cells as well as different activities. This could be developed further with input from potential users e.g. implementation within GIS, addition of a land use filter. Currently, the Framework is a stand-alone package, but it is envisaged that it could and should be linked to the GIS for future development. Figures 8 & 9 are screen-shots from the interface.

Figure 7: Evaluation Framework

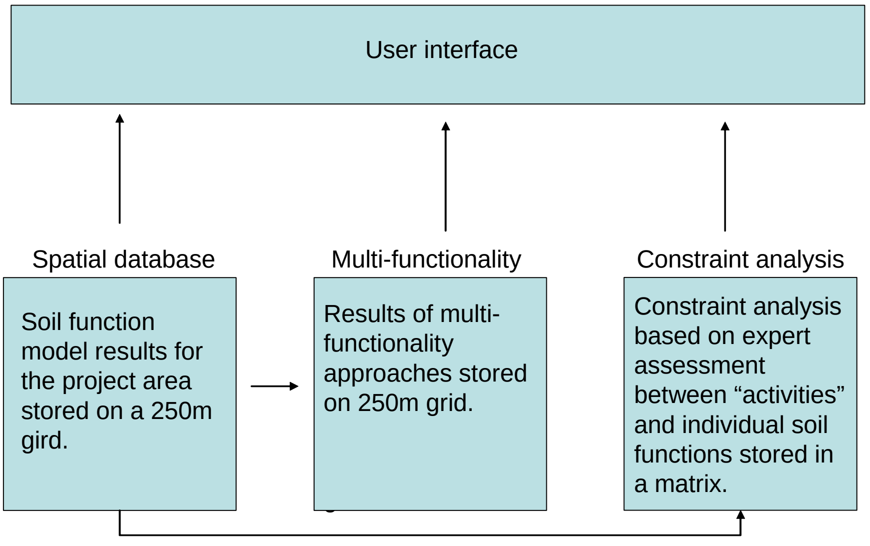


Figure 8: The user interface of the evaluation framework.

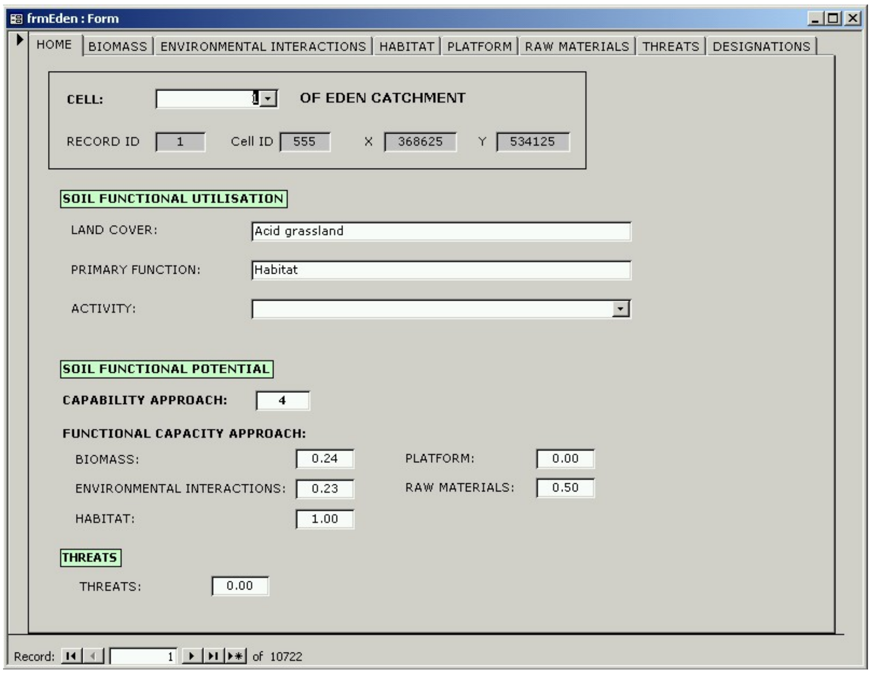
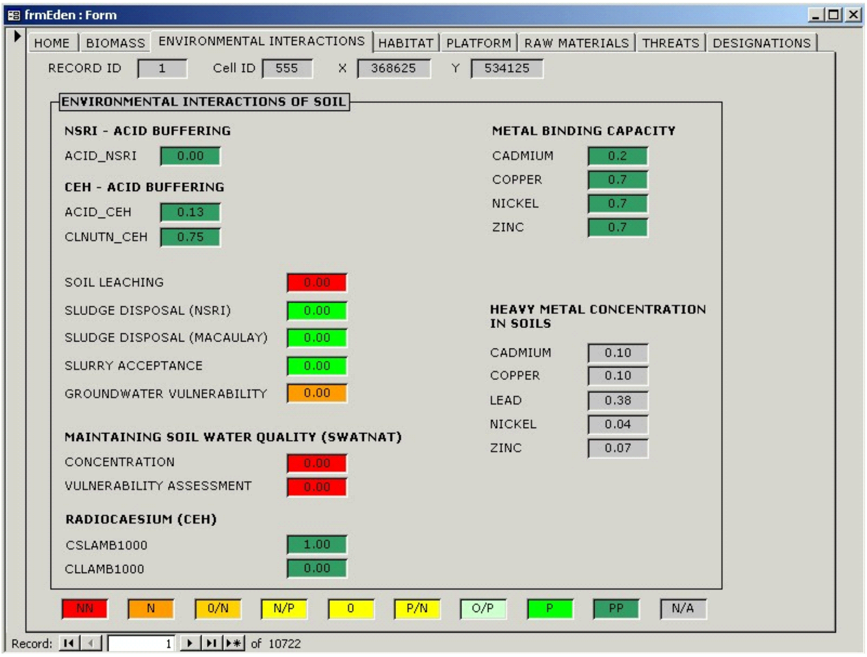


Figure 9: The outputs of the constraints analysis for environmental interactions which alerts the user to potential conflicts between different soil functions.



The software comprises a number of individual sections addressing very different aspects of multi-functionality. These are the *functional potential* and *utilisation* of soils, *threats* to soil as well as current *designations*. Interactions between different soil functions are accounted for using *constraint analysis*.

a) Identification of functional potentials of soil

The following functional potentials have been modelled (where possible) at the sub-function level using primarily rule-based soil suitability models:

- ***food and fibre function:*** to establish the potential for soils to support individual production systems i.e. arable, forestry, energy crops or trees (suitability).
- ***biodiversity function:*** to establish which soils have the potential to support natural habitats i.e. woodlands and other semi-natural habitats.
- ***environmental interaction function:*** to establish which soils have the potential to deal with pollution through buffering, adsorption or degradation (e.g. radionuclide and N deposition).
- ***platform function:*** to establish which soils have potential to deliver suitable land for construction, infrastructure or recreation , i.e. the most appropriate land for housing (suitability).
- ***raw material function:*** to establish the potential for peat extraction.
- ***cultural heritage function:*** there are no appropriate models available but soil erosion has been used to identify if buried cultural heritage could be exhumed and damaged.

b) Identification of soil functional utilisation

Current land cover (based on CEH Land Cover Map 2000) is a surrogate for functional utilisation. Within the framework, as a pragmatic approach current land use is taken as the dominant functional use associated with a particular land use. However, although soils might be actively managed for a particular function, passively they perform several other functions. These passive forms of utilization are as important as active utilization.

c) Soil threats

Currently only erosion is modelled as a soil threat.

d) Designations

This section contains existing designations of land (SSSIs, common land, etc.) which restrict land use and management (i.e. soil functional utilisation) rather than having a direct impact on soil functional capacity. In addition English Heritage provided information for the construction of a heritage constraint layer that identified areas where land use practices could harm buried cultural heritage.

3.3.2 Database

The database was populated from spatially coherent information gathered for each catchment. The extensive database includes basic soil information, auxiliary data and all model results on a 250 m grid cell basis. The auxiliary data comprise model threats, such as soil erosion risk, together with information on designations provided by Defra (MAGIC), English Nature, English Heritage, Scottish Natural Heritage and the Royal Commission on Ancient and Historical Monuments and the relevant County Councils.

The use of a database was successful in integrating all available information and facilitating its application within the framework. Other datasets could be incorporated into the database with ease although additional constraint analysis would be required. The approach allowed the integration of a wide range of spatial datasets developed by other organisations. Extension and dissemination of the framework would however require careful consideration of data accessibility and licensing arrangements.

3.3.3 Multi-functionality assessment

Methods and results
To achieve a value for mean functional capacity, output from each primary function models was summed and the total divided by the number of models. Although this might appear simplistic, it removes any value judgements on the relative contribution or worth of individual sub-functions.

a) Scaling
In order to overcome the differences in classification systems (numerical, categorical, and number of output classes) all functions have been scaled between 0 and 1 based on expert judgement. The scaled outputs were the starting points for implementing both the index and capability approach as part of the evaluation framework.

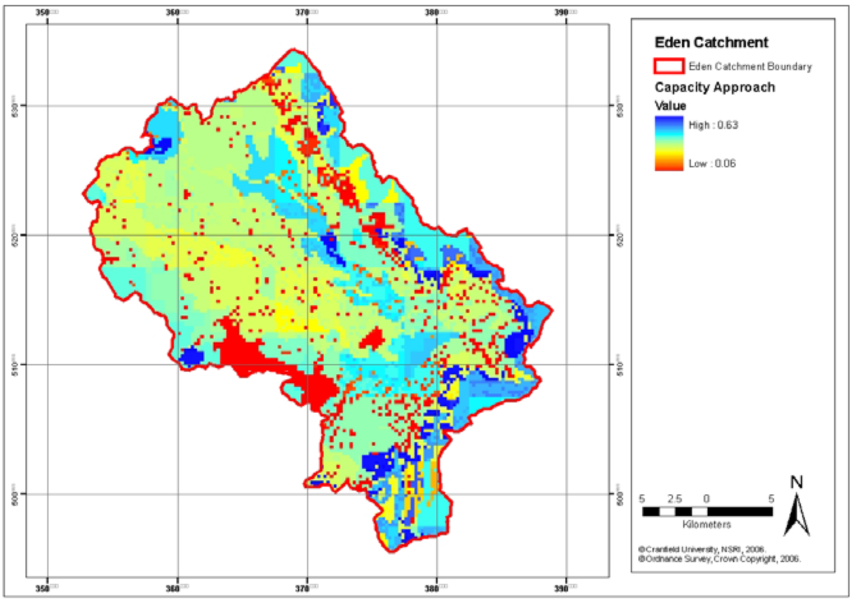
b) Index approach
The index approach introduced in Section 2.1.5 has been implemented in the Evaluation Framework in the following way:

$SQ = (fQb + fQenv + fQh + fQf + fQher)$,

where:

SQ = soil quality index, Qb = quality with respect to biomass production, Qenv = quality with respect to environmental interactions, Qh = quality with respect to habitat maintenance/ biodiversity, Qf = quality with respect to foundations, Qher = quality with respect to heritage. Results of this approach for the Eden are shown in Figure 10. Results for the Tern and Lossie are illustrated in Figures 12 & 13 at the end of this report.

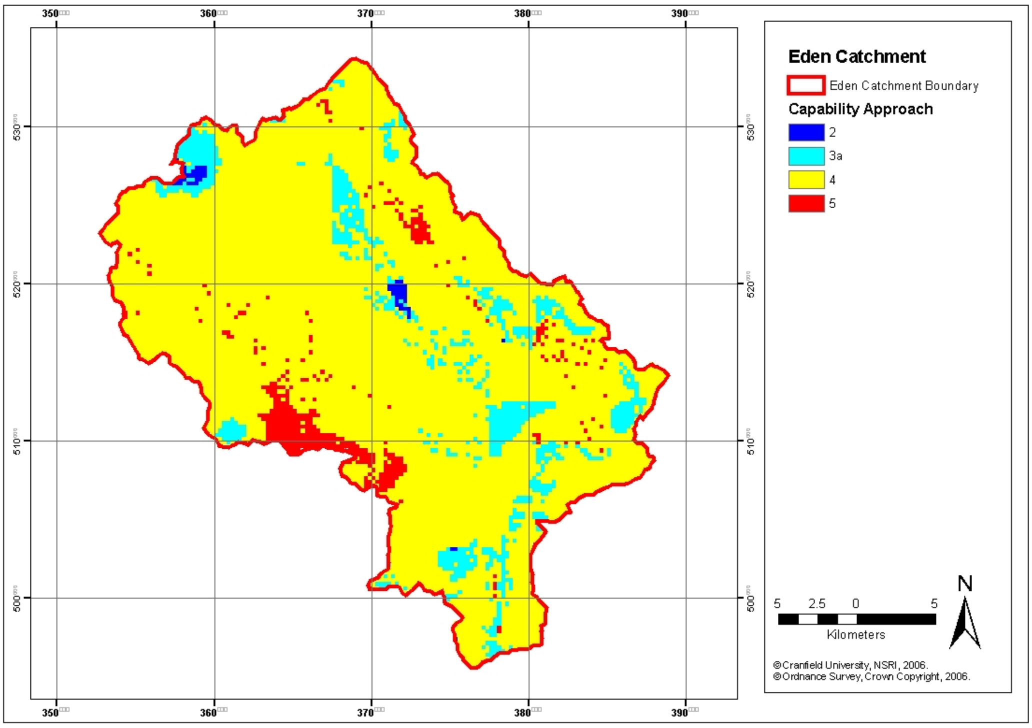
Figure 10: Map of the overall soil functional capacity derived from the index approach.



c) Capability approach
The capability approach introduced previously has been implemented in the Evaluation Framework. In the current context soils have been assigned to a series of Functional Capability Classes (from Class 1 to 7, with Class 3 subdivided). The Functional Capability Classes are defined in terms of soils' capacity to perform each of the key functions. The terms 'well', 'moderately well' and 'poorly' are at this stage based solely on value judgements of suitability model outputs rather than on strict rigorously tested thresholds, however, this approach could be developed further to allow the use of sub-classes that may indicate the functions performed least well by a particular soil. The main challenge in developing a system of functional capability classes is defining and

setting the limits to the classes. As implemented, this approach differs from the land capability approaches in that the soil is assessed on the current land use (and, hence soil properties) rather than the potential of a parcel of land. For example, on arable land biodiversity is often relatively low but if the land is left to revert to semi-natural vegetation, biodiversity would substantially increase. Whether the land ever returns to a natural state depends on the degree of disturbance it has experienced. While this method can be implemented on its own, it can also be linked with the Index approach to provide a semi-quantified basis to the definition of well, moderately well and poorly suited. Results of this approach for the Eden are shown in Figure 11. Results for the Tern and Lossie are illustrated in Figures 14 & 15 at the end of this report.

Figure 11: Map of the overall soil functional capacity derived from the capability approach.



Both the index and capacity approach are high-level approaches for assessing the multi-functionality of a particular soil and are suited to the production of mapped output. A provisional scaling has been applied to all model outputs. Further checking and correlation of output will lead to improvement and refinement, and further discussion among the partners and potential stakeholders is justified. Some of the models derive simple classes from an internal manipulation of numerical data. In these cases the models could be modified to allow access to the internal numerical calculations in order that more sensitive model outputs can be made available. The index model does not allow assessment of the relative contributions of individual soil functions as a particular score can represent a range of functional capacity profiles. The capability approach is more balanced but the functional capability classes are difficult to define. Neither of the two models addresses the interactions and interference between functions that result from exploitation of one particular function and this limits its value in scenario testing.

3.3.4 Constraint analysis

The analysis of multi-functionality clearly highlighted the need to adequately account for the interactions between land use that exploits one soil function and the other soil functions in scenario testing. This was recognised by the project team and considerable effort was invested in addressing the problem. The constraint analysis only addresses soil interactions as any other constraints are not within the remit of this project.

Despite very extensive discussions some functional interactions have still not been fully resolved. The interactions frequently involve very complex issues which can be approached from various directions whilst the predictive models available to the project were often not sufficiently sensitive to fully resolve the issues. The constraint analysis provides the opportunity to examine the impact on functional capacity of a wide range of ‘activities’. Within the framework, the constraint analysis is used to provide a qualitative assessment of the effects on all other soil functions of maintaining a selected activity. The qualitative assessment is very simple and uses a ‘traffic light approach’ of positive impact (green), negative impact (red) and no or uncertain impact (amber).

Constraint analyses have previously been used to evaluate soil functions by Packer (1993) and Bastian (2000), and biological indicators of soil quality (Black *et al.*, 2006). The matrix presented in Table 8 is a 'matrix' of how the individual sub-functions interact and provides a

Table 8: Constraint matrix for biomass production (extract).

Function	Sub-function	Short rotation coppice	Agricultural production	Arable production	Grassland production	Energy crops	Commercial coniferous forestry
Biomass production	Short rotation coppice		0	0	P	P	N
	Agriculture production	0		0	P	P	N
	Arable production				P	P	
	Managed grassland	0	0	0		P	
	Energy crops	0	0	0	P		N
	Commercial forestry	0	0	N	N	N	
Environmental Interactions	Critical loads (acid)	P	P	PP	P	P	NN
	Critical loads (nitrogen)	P	P	PP	P	P	P
	Critical loads (radiocaesium)	P	P	PP	P	P	N
	Critical loads (metal)	P	P	PP	P	P	N/P
	Groundwater quality		N	N	N	N	N
	Slurry/sludge recyclng	P	P	P	P	P	
	Surface water quality	N	N	NN	N	N	N
Habitat and biodiversity	Acid grasslands	NN	N	NN	NN	NN	NN
	Native woodland		N	N/P		NN	NN
	Lowland Heath		N	NN	NN	NN	NN
	Trees			N/P		N	
Platform	Urban development	0	0	0	0	0	0
Cultural heritage	Protection of artifacts	N	N	NN		N	N
Environmental Interactions	Surface water quality	N	N	NN		N	N
Raw materials	peat	0	0	0	0	0	0

An interaction can be strongly positive (PP), positive (P), negative (N), strongly negative (NN) or neutral (0).

viable means of overcoming most of the inherent difficulties in assessments of the multi-functionality of soil. The basis of the interactions matrix is to identify the sub-functional responses to a specific land use or activities on the land surface. The horizontal axis of the matrix lists all the sub-functions or activities that we might wish to maximise by specific land management decisions. The vertical axis reviews any likely changes to soil properties caused by that sub-function or activity, and assesses the impact of those changes on the ability of the soil to fulfill the other sub-functions. It also takes into account whether a specific land management activity precludes the use of that land concurrently for another sub-function, for example, if the land is used for timber production it cannot be used for arable agriculture at the same time. Hence the evaluation matrix is not symmetrical. For example, when arable production is the desired function, this has a neutral effect on suitability for future housing whereas when housing development is the desired function it has a strong negative effect on potential arable production. In effect, the desired soil function is itself a driver. Some of the models, for example, groundwater vulnerability which is used as a measure of groundwater protection, are based on inherent soil characteristics such as depth or clay content that are not changed by land use. These are essentially 'passive' as they are not impacted on by most other land-based activities. Other models, however, are land use dependent, for example, the acid buffering capacity of land is determined by the chemical properties of soil and these can be altered by land management.

A matrix of all sub-functions for which models were acquired has been developed (Table 8) and incorporated into the framework. This evaluation matrix specifies the effects of managing land for the benefit of one specific sub-function on the other sub-functions of that primary function and also on sub-functions within the other five primary functions. For example managing the land for intensive dairy production might not adversely impact on many of the other biomass sub-functions but will impact negatively on capacity to preserve semi-natural habitats such as acid grassland or heathland. This level of detail will inform debates on land use conflicts. This methodology is flexible as it can be readily expanded as models are developed for new sub-functions or a better understanding of the interactions between land uses becomes available. The interactions between sub-functions have been classified into a very simple scoring system as a prototype for this kind of cross-function analysis. An interaction can be strongly positive (PP), positive (P), negative (N), strongly negative (NN) or neutral (0). In some cases the sub-functions are not defined sufficiently tightly and a mixed response is possible depending on local factors (N/P), for example where the desired function is arable production, the impact on native woodland could be positive or negative depending on whether the woodland prefers acid or base-rich conditions. This type of matrix approach can be used to investigate the relationships between the functional potential and functional utilisation or extended to capture expert knowledge and investigate different scenarios of change in pressures/drivers on individual soil functions.

The interactions matrix has been derived by the 'expert judgment' of experienced scientists from different disciplines within soil science (e.g. ecology, hydrology, classification, chemistry) who have used their best estimate of the likely interactions between the various sub-functions. This process was informed by the field visits to each of the three study catchments. In some cases uncertainties remain in the precise nature of the pressure or the response of soils to some of the land uses or activities. This is one of the major problems with such an approach and was outlined earlier. Even within a group of 'experts' there was considerable debate about the interactions between various sub-functions and a wider group of experts may disagree with the current assessments. Throughout the discussions various difficulties arose. The timescale over which the interactions should be considered is an issue. The lack of feedback mechanisms in the models is a constraint and the models used did not always express the sub-functions adequately. For example, the sub-function of protecting groundwater quality was characterised by Groundwater Vulnerability assessment which incorporates one generalised model to deal with many common pollutants often with contrasting characteristics rather than assessing individual potential pollutants. Where uncertainties over interactions arose, these have been left blank in the matrix but the issues and reasons for the uncertainties are reviewed in a parallel worksheet. Interactions and feed-back mechanisms between different factors makes the analysis within the framework complex as some of the interactions are not yet fully understood and require further work.

The evaluation matrix was regarded as a successful first attempt at assessing interactions between different functions. By its development and population, it has highlighted several issues that will need to be addressed to fully implement the evaluation framework. These include the timescale over which the interactions should be considered, lack of feedback mechanisms in the models, capacity to address spatial interactions between models and the fact that the models do not always express the sub-functions adequately.

Preparing the constraint analysis has demonstrated how little information is available on the likely interactions between sub-functions. The robustness of the matrix must be established to support further development of the framework and use by decision-makers. This would include resolution of interactions, wider consultation on interaction outcomes and complete documentation of the thought process. Further discussions would both improve and expand the current state of the matrix.

Detailed documentation of the decision processes that have been used would be beneficial and help guide future work. This documentation, if drafted in non-technical language, could be used within the evaluation framework to explain to users of the framework the issues involved in changing functional capacities.

The matrix does not fully account for the possibility of changes to the soil that may occur over time or from current land use. Heathland converted to arable cultivation may not readily revert back to heathland if cultivation ceases. Within the approaches adopted here, there has been a tacit assumption that the current land use impacts on or prohibits other functions.

3.3.5 Spatial application

Although the framework stores the results of all the models and assessments for each of the catchments on a 250m resolution, scenario testing can currently only be assessed on a cell-by-cell basis due to the complex interactions involved. However, the complexity involved in such an assessment was precisely the reason why the Evaluation Framework was developed. Spatial applications could be developed in future work using the Framework by focussing on specific questions that could be illustrated on a map e.g. "Show me the area for which biomass has a very high potential and is not restricted by more than one constraint" using multi-criterion analysis.

4. CONCLUSIONS

The project was successful in developing a high-level framework in which the non-specialist user-community can explore questions regarding soil functionality. The main results of this project are the evaluation frameworks compiled for each of the catchments. They contain the results of applying a wide range of soil functions models as well as two multi-functionality assessments and the constraint matrices. They also provide the foundation for developing spatial planning tools based on multi-criteria analysis.

This project has successfully established that soil functional capacity models can be used to assess the provision of soil functions at the catchment scale and to investigate conflicts in the delivery of soil multi-functionality. However, the application of this approach is highly dependant upon the availability of suitable models and their required input data. Digital soil mapping and use of existing soil property information for soil series could together provide much of the required input soil data for regional scale application but further models are needed to cover all soil functions and sub-functions.

The evaluation framework was developed to synthesise and use the wealth of information gained on soil multi-functionality and represents a significant developmental advance. The framework provides a user-friendly environment in which soil multi-functionality can be explored interactively for individual parcels of land. It allows options for land management and land use change to be explored when attempting to optimise a specific function. Alternatively when land use changes are imposed it enables potential conflicts between functions to be identified. It also allows threats or rehabilitation potential to be incorporated at a later stage.

The Evaluation Framework, on its own, will not identify optimal or preferred land-use between the likes of food production, habitat or housing. The Framework can, however, be used as a tool to alert decision-makers/planners to conflicts between different land uses and the delivery or potential to deliver different soil functions. Another approach would be to integrate the information generated by the Evaluation Framework into a performance/efficiency assessment, for example by using “data envelopment analysis” (DEA). DEA is a performance measurement technique which can be used for evaluating the relative efficiency of decision-making units.

5. Recommendations

5.1 Soil information

The mapping of soil functional capacity, in one form or another, is of relevance to national and local Government land use and management decision-making at many spatial scales ranging from national down to site level. It fits closely with the current focus on ecosystem services within Defra and the Environment Agency. Current soil and climate data are not resolved spatially beyond the regional or sub-regional levels and certain specific properties are lacking completely from current data bases. It is recommended that consideration be given to these inadequacies as they undermine the effectiveness of the approach to the making of properly informed decisions at these larger scales.

5.2 Soil function mapping

There is a requirement for a new set of models which overcome the limitations of existing model which are either too static or too complex. There is a need for simplified models that can run on currently available soil property datasets and be simple enough to be run spatially. This may be addressed through either adaptation of current models and/or the development of new soil functions models based on first principles.

Models or predictive tools are needed for all soil functions. Notable current gaps are for aspects of environmental function (e.g. DOC production), biological habitat (e.g. functional aspects of soil biodiversity) and the protection of cultural heritage. Additional models were identified during this project which could be included in a second phase of this work, for example, soil habitat model of CEH (GBMOVE), and concrete and pipeline corrosivity models of NSRI, SUNDIAL etc.

It is recommended that the results from other recent studies are incorporated, such as SP0538 “Impacts of climate change on soil functions” and CC0375 “The development of soil properties datasets and tools for supporting climate change impact studies”.

The integration of datasets such as BGS Mineral Assessment Reports and aquifer maps depicting aspects of the superficial and solid geological layers would add value in a number of functional assessments.

5.3 Evaluation framework

Further work to improve the index and capacity approach to multi-functionality is recommended. This should address the value of including additional concepts such as threats, rarity and resilience.

Further testing and evaluation of the evaluation framework in other areas with special references to the scaling used to unify the various model outputs is recommended.

The matrix should be expanded to allow for different interpretational aspects for each interaction. Development of the matrix should fully capture the information embedded in the constraints analysis by documentation of the decision-making process.

Development of the evaluation framework as an operational tool will require a user guide with explanatory text for each interaction stating assumptions, rationale for negative/positive impacts and outlining potential differences in interpretation in simple, non-scientific language.

5.4 Planning tool

Although the current evaluation framework is a significant development, it does not yet provide the means for true spatial analysis of soil functions. Recent developments in modelling might provide the basis to develop a spatially dynamic planning tool e.g. multi-criteria analysis. Such techniques should be a component of any further developments of the evaluation framework before the evaluation framework is used as an operational decision support tool.

We recommend the Envelopment Analysis technique which measures the efficiency/performance of soil multi-functionality. The technique is widely applied in different sectors and may offer a way to assess whether proposed changes in land usage will have an unacceptably high cost with respect to any of the important narrower measures of efficiency.

6. Future next phases

The project has identified three areas for further research:

- **Constraint analysis**
  Further development of the constraint analysis matrix is required to address all soil functions adequately, make better use of model outputs (inc. scaling outputs) and expert knowledge. Additionally, the analysis matrix would incorporate full documentation of the interactions and undertake stakeholder consultation with respect to the interface design. This is the foundation of a truly multi-functionality approach and as such would have a range of potential uses. Two priority applications are identified:
- **Scenario testing tool**
  Using the constraint analysis as a scenario testing tool by incorporating the Evaluation Framework within a GIS. This would require developing dynamic models that could be applied in a spatial context. The primary issue would be to match models with data availability and as such requires a much simpler approach to support scenario testing (e.g. NIRAMS) compared to some of the very detailed mechanistic models developed currently.
- **Planning tool**
  Using the constraint analysis as a planning tool by using multi-criteria analysis to represent interactions within areas. In combination with value functions this approach could be developed in cooperation with stakeholders to make more informed decisions on land-use allocations in order, for example, to improve water quality or habitat and biodiversity issues.

Appendices

- Appendix 1: Data
- Appendix 2: Literature review
- Appendix 3: Model descriptions and maps

Figure 12: Map of the overall soil functional capacity derived from the index approach for the Eden catchment

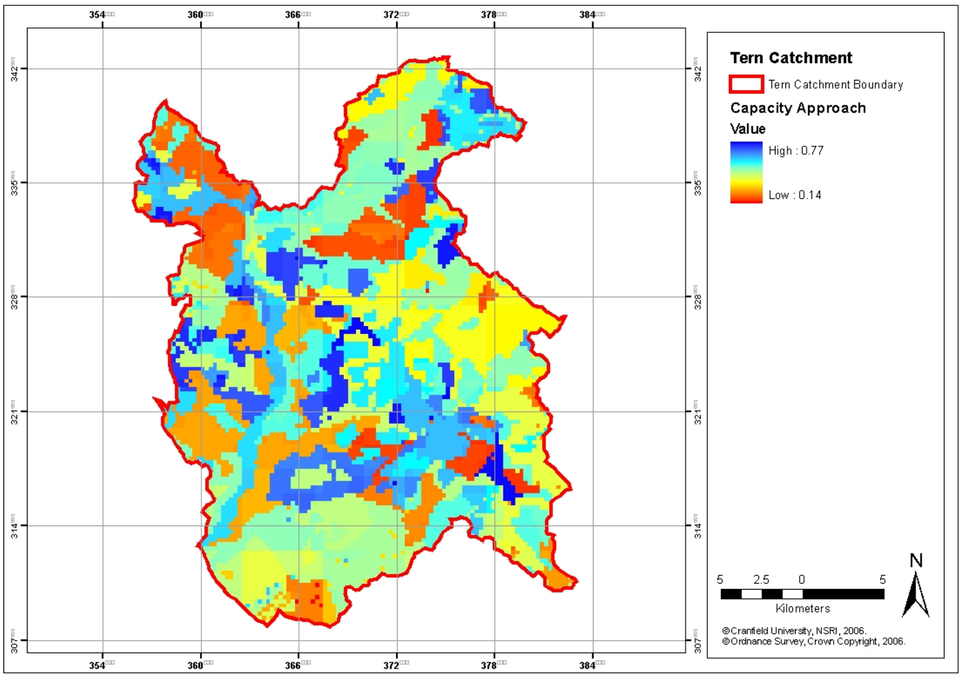


Figure 13: Map of the overall soil functional capacity derived from the index approach for the Lossie catchment

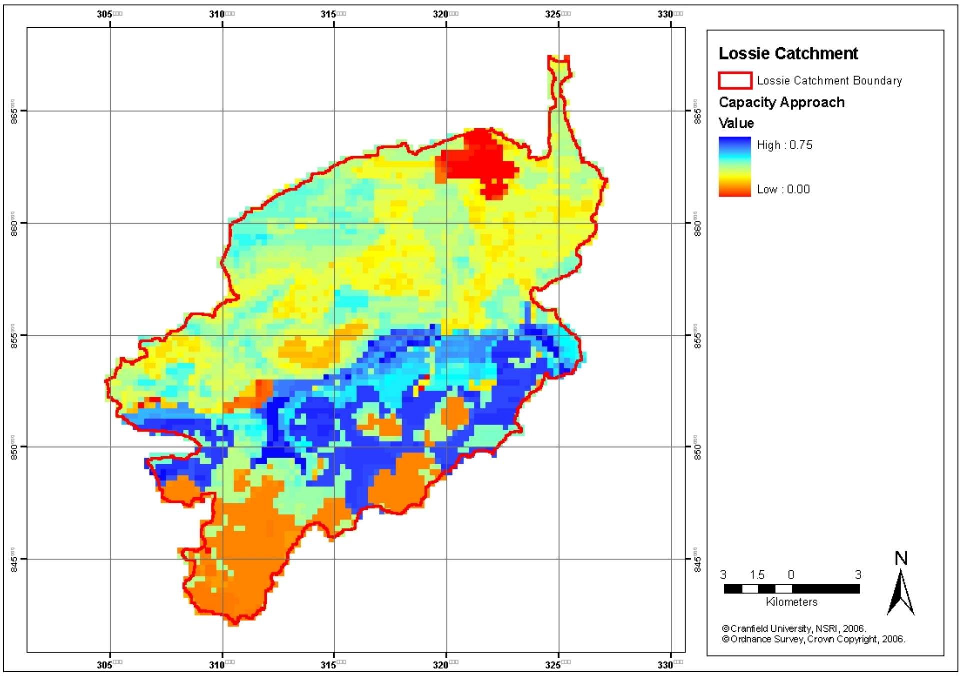


Figure 14: Map of the overall soil functional capacity derived from the capability approach for the Tern catchment

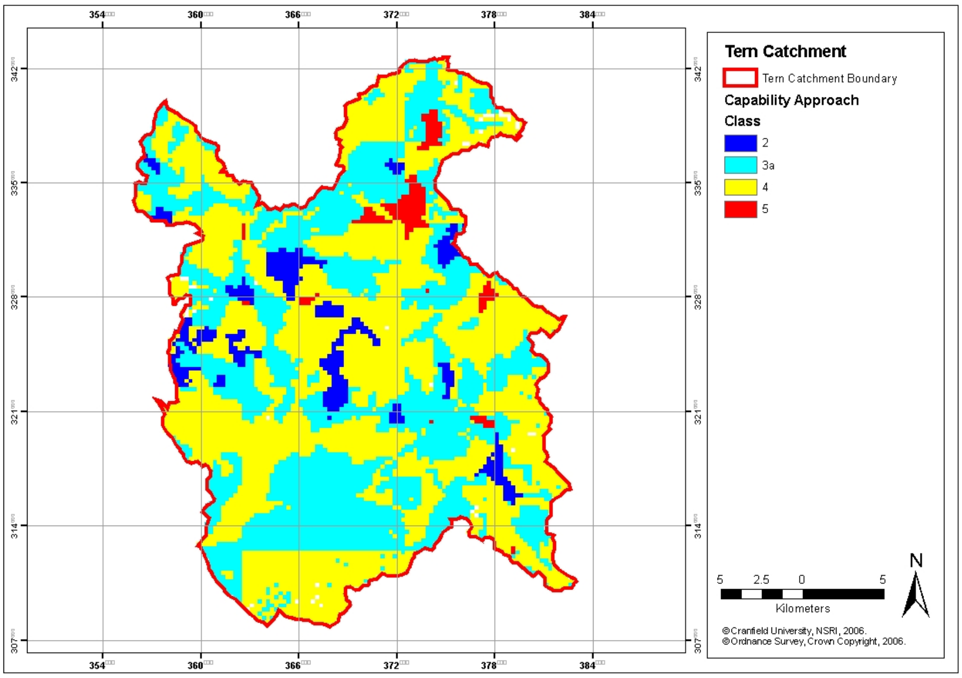
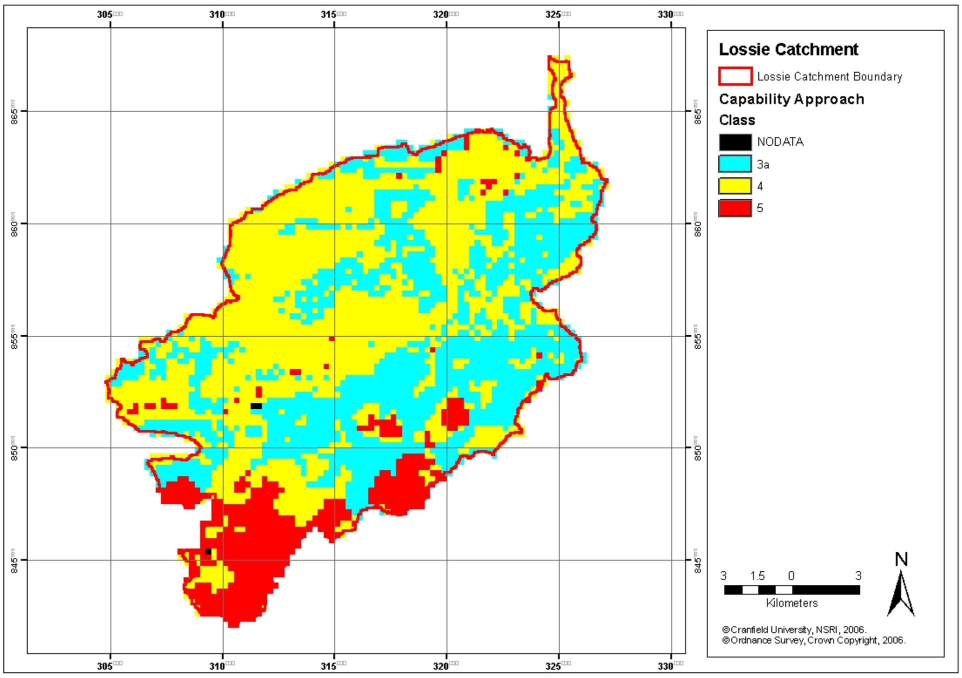


Figure 15: Map of the overall soil functional capacity derived from the capability approach for the Lossie catchment



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9. This section should be used to record links (hypertext links where possible) or references to other published material generated by, or relating to this project.

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