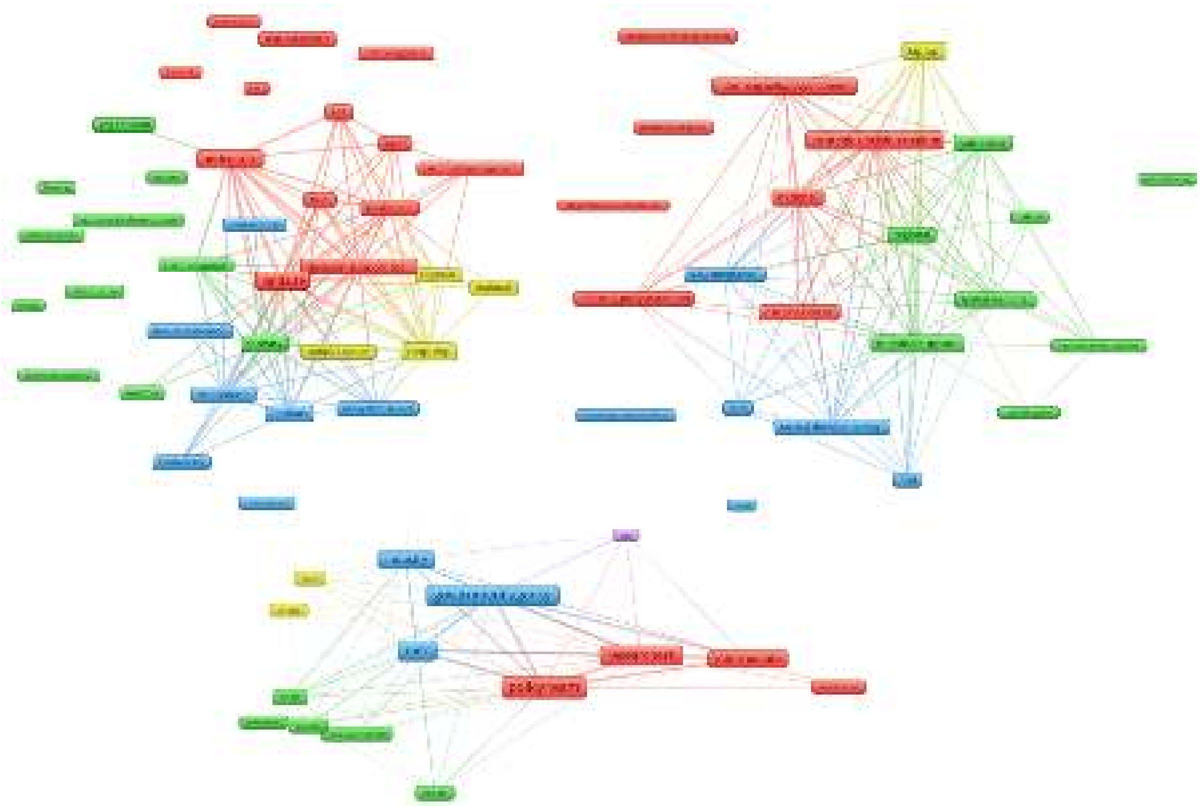
SEFARI Fellowship: Mapping Land Use and Natural Capital Models and Research in Scotland

25th April 2025



Summary

This report presents the results from an online survey commissioned by SEFARI on behalf of the Scottish Government to assess the current coverage and capabilities of the Land Use and Natural Capital modelling and tools used and in development by the research community in Scotland. The purpose is to map and categorise the modelling capabilities available and understand how this capability can be better used and enhanced.

The rationale is that there are many modelling projects supported by the Scottish Government and other funding sources, and that there is a need to explore how these research efforts can be further developed and utilised for policy and practice support. A further objective is to take stock of the modelling capabilities and explore the potential for integration of models, tools and data within integration platforms. We make eight main recommendations on how modelling for land use and Natural Capital can be supported and developed.

The report is a product of the SEFARI Fellowship Mapping Land Use and Natural Capital Models and Research in Scotland.

Results:

There is a rich diversity of research-based modelling activities covering a wider range of Land Use and Natural Capital subjects and issues that are supported by the Scottish Government. There is a high level of modelling capability that has developed in Scotland enabled by this support over several decades. The survey analysis showed:

- There were 70 survey responses, 55% were funded by the RESAS Strategic Research Programme.
- Model type categorisation:
    - There were 27 Models detailed (39%) of which 81% are spatial. 7% of these were considered as being a platform for modelling.
    - There were 26 responses for Tools (37%) of which 77% are spatial;
        - 16% are a spatial Dataset or Map (11); 7% are Tools / Platforms and 1% identified as a Platform, all of which are spatial.
    - Overall, 84% were considered as being spatial.
    - Modelling capabilities cover a broad range of themes including Land Use (48), Natural Capital (31), Ecosystems / Habitats (31), Biodiversity (21), Agriculture (47), Forestry (21), Soil (29) and Water (23). These themes cover a wide range of spatial scales from field to national.
- The primary objectives of use cover multiple application areas and are focussed on: decision support (49) and decision making (34 tactical, 24 strategic); informing policy development (39) or assessment (27); improving subject understanding (34) including complex systems (21), spatial planning (32), risk assessment (31); monitoring (12), data integration and synthesis (29) and advancing modelling capabilities.
- The main beneficiaries of models / tools are Government Agencies (54), Policy teams / analysts (51) and researchers (46).
- Gaps in capability include:
    - Energy and infrastructure coverage.
    - Focus on horizon scanning, future projections and scenario development.

Key Messages

Model type, objectives, use and useability and complexity

1. The majority (84%) of models, tools and platforms have spatial capabilities.
2. There is good coverage by models/tools related to Land Use and Natural Capital covering a broad range of relevant themes and spatial gradient from Field to Catchment, Regional up to the National scale.
3. Decision and policy support are the primary objectives for model and tool development and use.
4. There were no responses of models / tools where the primary objective was horizon scanning, future projections or scenario development. This indicates a key gap in the research capabilities. However, the research team are aware that some models and tools do have the capability to be used in these areas, but these may not have been indicated as the primary objective.
5. Respondents indicated that 30 of the 46 policy-related models are not considered easy to run because they either require training for new users, or require having specific coding skills, or they are suitable for use only by the development team.
    a. 24 of these are of higher complexity indicating that for most of these models/tools, the pathway of their adoption by policy teams needs to be via close collaboration with the development teams.
6. Advanced computing resources, in the form of High-Performance computers or Clusters, are needed for running models / tools for complex research questions and or systems at National or Regional scales that are used mainly for supporting strategic decision-making, and to a lesser extent, for informing policy development.
7. Broader model / tool usage by other people (beyond the development team) requires investment in training of potential users and/or close collaboration with their respective development teams.

Regarding potential for model, tool, data set or platform integration within a framework:

8. There are fewer barriers to integration within a framework for the easier to use, more simple forms of models and tools.
9. Some barriers to integration are practical e.g. coding language, common data frames etc., that could be overcome with specific investment to enable compatibility, such as use of Application Programming Interfaces (API's) and shared data libraries.
10. There is an opportunity within the modelling communities and those using model outputs in Scotland to develop a combined approach of having stand-alone model / tools that operate independently but have the capability to work alongside models and tools operating within an integrated framework. This flexible approach is more likely to realise a better overall potential for Land Use and Natural Capital model-based research support for policy as it will overcome the limitations of existing integrated frameworks.

Regarding value for money:

11. There is need to develop a better understanding of the relationship between the costs of model development and use and their impact on policy support and wider benefit to research beyond that information provided by this report. There is also need for

understanding how modelling as a research activity depends on other activities such as data collection and quality control. Modelling development also serves as a medium for synthesising knowledge amongst researchers and informing data collection needs, hence its value extends beyond just use of outputs.

Gaps in capabilities:

12. Consideration should be given to developing a data integration strategy to enable shared use within models, tools and platforms.
13. There is need for improved and coordinated data curation capacity (input and output data, parameter values and metadata) to be developed alongside efforts for data and model integration. This is essential for model calibration, sensitivity analysis, validation and model inter-comparison. Consideration needs to be given to the computing resource requirement to support modelling and data curation.
14. There is need to develop modelling capabilities and capacity to undertake research focussing on understanding the biophysical, economic and social aspects of the future, for example under climate change and biodiversity loss. This includes risk and opportunity assessments, cost benefits of transformations including ecosystem restoration (i.e. avoided spend).
15. There is a substantial gap in capabilities to model grassland systems, particularly the estimation of primary production under future climate impacts and the relationship between grass growth, animal offtake and greenhouse gas balances. Given the scale of grassland-based land use and the livestock sector in Scotland role in the carbon budget, this represents a large gap in our modelling capabilities. There is also a gap in capabilities to model vegetation, fungi and microbial responses to climate change and how this affects nutrient and energy flows in ecosystems.
16. The modelling community in Scotland covers a wide range of subject coverage and modelling approaches and can be agile to new challenges. A modelling capability gap exists in representing energy and infrastructure in terms of land use and natural capital.

Conclusions

The survey mapping has shown there is a rich diversity of Land Use and Natural Capital models, tools and data available within Scotland, developed and used by a knowledgeable and skilled set of modelling and research teams. This represents a strong capability across multiple research and policy interests and objectives, with wide representation across multiple spatial and temporal scales and themes of application areas.

Modelling to date has had good impact for many policy, research and application area beneficiaries. There is increasing potential for further positive impacts and expansion to a broader range of beneficiaries by developing a future modelling strategy.

This report has been commissioned partly in the context of helping to improve understanding of the potential to develop model integration approaches that make the most effective use of the current modelling capabilities in Scotland and whether this is likely to meet Scottish Government modelling support requirements.

Our analysis of the survey responses and knowledge of the modelling and output user communities leads us to conclude that there is strength in having a strategy that facilitates both:

- The development of an integration approach (i.e. platform, where technically feasible), is transparent and doesn't lead to over-simplification or use of large assumptions, is capable of representing complexity and is desirable in terms of improving the utility of model outputs for scientific and policy purposes, and;
- A continuation of the current approach to model and tool commissioning, development and application, as this enables independence, flexibility and agility.

This strategy is based on the recognition that whilst an Integration Modelling Platform (IMP) is an area of interest to Scottish Government, it is not necessarily their desired goal as there are legitimate concerns on utility. To help inform thinking on modelling development we have provided a set of recommendations on what this strategy needs to include. A key element of this is the development of an integrated approach to data collection and curation for model calibration and validation, as well as analyses. This will enable models to better utilise available data and inform what further data collection, e.g. through use of environmental monitoring requirements, that will increase model utility for policy support purposes.

This research has also highlighted that modelling is more than just models, code and data. The key ingredients are the people and their knowledge of the modelling domains, data utility and their ability to establish and maintain good working relationships with data providers and output end users. This is particularly important in respect of modelling for policy support. We have recommended the development of the modelling community cohesion through establishment of mechanisms to enable better understanding between policy, science and modellers. This includes the need to recognise the additional time and resource overhead required (including IT and computing, time for improved communication between modellers and policy teams), but which will likely increase the value for money of enhancing modelling capabilities.

As pressures and time urgency build on our land and Natural Capital assets from climate change, biodiversity loss and objectives for food, water and energy security, it is becoming increasingly important to enhance our modelling capabilities to enable model-based experimentation, learning and understanding and development of foresight. The following recommendations are based on a combination of interpretation of the survey findings and the research team's experience.

Recommendations

1. Develop a twin-track strategy for future modelling support that enables both the continued independent modelling development and application and takes steps to facilitate model and data integration (e.g. through modelling team coupling, model linkages through Application Programme Interfaces – APIs, or as part of a platform). Both approaches need to be adaptable to the needs of responsive and strategic areas of research interest and policy support requirements. This strategy needs to be flexible in response to the level of investment available. Note: many respondents had not considered model integration as a potential development or how this might be achieved but amongst those who did, overall, most had a positive perspective.
2. Improve spatial data integration capabilities and ease of access to data and alignment with data collection activities (see also Recommendation 3.4.1).
   - 2.1. This initiative should assess current approaches to best practices in spatial data integration.
3. The Scottish Government and research community should develop a data and model support strategy (as per recommendations 1 and 2) to include:
   - 3.1. Assessment of the utility of an integration platform that is specific to the needs of Scotland.

- 3.2. Develop best practices to facilitate model development, data access and sharing and potential integration approaches through:
  - 3.2.1. Enabling improved communications between modelling teams within a governance structure to facilitate improved technical capabilities through consultation with and collaboration between modelling and Government analyst and policy teams. Examples may include workshops and hackathons for specific research challenges, chat groups.
  - 3.2.2. Developing mechanisms to facilitate knowledge and data sharing (e.g. modelling workshops) and processes to reward researchers for collaboration.
  - 3.2.3. Liaison with other funding organisations (e.g. UKRI, Innovate UK) to help coordinate investment in modelling support, including PhD studentships to foster new entrants to modelling.
  - 3.2.4. Fostering an improved culture of sharing best practice knowledge and input and output data.
  - 3.2.5. Develop agreed definitions of terminology.
  - 3.2.6.Maintaining a living catalogue of models and data, (of which this survey and list of models and tools serves as a start).
- 3.3. Develop modelling teams and policy use community cohesion to better understand potential and limitations of model use. This community can then inform practical considerations of developing governance of modelling and management of additional overheads (including IT requirements), depending on the level of implementation of the proposed strategy.
- 3.4. Create a science, model and policy Advisory Group with the remit of planning for future modelling support needs and realising potential including:
  - 3.4.1. Identifying fundamental gaps and limitations in models and data for input and alignment with data collection efforts.
  - 3.4.2. Increased utilisation of machine learning and AI, IT opportunities (e.g. cloud and exoscale computing).
  - 3.4.3. Planning for emerging policy support needs (e.g. Bills and Strategies in preparation by Scottish Government).
  - 3.4.4. Exploring how modelling as an activity can help serve as a medium for improved cross-policy coherence (e.g. multiple environmental concerns that exist across multiple policy domains).
  - 3.4.5. Develop improved model use impact on policy recording, as part of the overall science-policy impact feedback mechanisms recommended by the SRP Science Advisory Board.
- 3.5. Review in detail the strengths and weaknesses of existing model integration and alignment approaches, such as model intercomparison and improvement projects (AgMIP and ISIMIP) or Integration Modelling Platforms (e.g. ERAMMP – see review included below).

4. Given the urgency of climate change and biodiversity pressures on policy development and support needs, there should be a focus of improving capabilities for foresighting to frame decisions, risk understanding, for example modelling the effects of climate change, particularly extreme weather.
   - 4.1. Such foresighting efforts need to be integrated with modelling effort to improve understanding of behaviour change.

5. We caution against commitment to using a single approach to model integration, such through using an Integration Modelling Platform, as this may be seen as placing all one's eggs in one basket. It has risks in terms of over-simplification, having large assumptions and error propagation flows, incompatibility between models and input data and is cumbersome for research and policy teams to operate.
6. The remaining period of the current Strategic Research Programme (to 2027) can be used to:
    6.1. Consult in more detail with the modelling community and the Scottish Government analytical and policy teams to better define the policy support needs and develop the modelling support strategy.
    6.2. Set responsive mode and long-term capabilities objectives, to include development by Scottish Government of example Areas of Research Interest questions the modelling needs to inform, and exploration by the modelling community of how this can be best achieved (e.g. through integrated modelling and use of systems thinking). We recommend the use of a set of example research questions that cuts across policy challenges and research domains, to explore options for utilising existing capabilities and development of new ones.
7. Investment should also made in supporting increased capabilities to use model outputs beyond Government policy and academia audiences, specifically Local Authorities, businesses and the public.
8. The above recommendations are made in the context of the need to maximise both the impact of modelling for policy support and demonstration of the value for money. We recommend that improving these is central to ensuring future investment in modelling, but recognises that the need for impact and value exists across the range of simple to complex models. We also recommend that mechanisms be developed to better quantify impact and value.

Contents

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Accompanying material:

Details of individual models and tools, as provided in the survey, are available from a spreadsheet (with filter options enabled) comprising the survey responses with personal details removed. This is available here Land Use and Natural Capital Survey Responses - Spreadsheet | SEFARI. A visual summary and analysis of all question responses is provided (Appendix D).

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Introduction

Policy makers, land managers and investors are increasingly interested in considering land use and its relationship with Nature and the services it provides in decision making. It is expected that a better understanding of how land, land use and Natural Capital function under a range of existing and future drivers (i.e. climate change), as researched through Scottish Government support and assessed through modelling, will have the potential to improve policy development. Quantifying and valuing natural assets will help drive decisions that are more environmentally, economically, and socially sustainable, and help address the climate and biodiversity emergencies. We recognise the great potential for use of integrated spatial and numerical data sets and coordinated land use and Natural Capital modelling to improve how these resources help meet demands by policy makers and analysts, planners and land managers to find solutions to complex and challenging environmental management questions.

To help develop the research to support better informed decisions, it is useful to take stock of the current land use and Natural Capital modelling research capabilities that policy and decision makers currently have access to and will need to develop further to meet the emerging challenges.

The purpose of this report is therefore to present the results from an online survey of the land use and Natural Capital research community in Scotland that use or develop models and tools related to land use and Natural Capital and receive funding from the Scottish Government. We then present a set of recommendations based on the research team's knowledge and experience to help stimulate discussion on how best to develop the modelling capabilities in the Strategic Research Programme.

The rationale for the study was to better understand the range and diversity of current models and tools and associated data used, as well as gaps and potential synergies. **The objective** of the study is to inform planning on how land use and Natural Capital modelling and tool use and development can be supported and further developed in the future to better meet policy and decision-making needs. This information can be used to better plan further data collection and model and tool development requirements.

The **context** for the study is that there are increasing pressures on land and how it is used arising from the need for mitigation of and adaptation to climate change whilst building resilience to impacts and reverse ecosystem degradation and biodiversity loss. There is a need to achieve net zero targets, as well as ensuring food security enabled by a resilient, prosperous and sustainable land use sector. Multiple policies and plans are in place or under development that aim to resolve these challenges, hence there is an increasing need for high quality support from the land use and Natural Capital modelling community.

Method

We have used an online survey using the Qualtrics platform to present 29 questions (see Appendix A) that were developed through a series of consultations with the project Steering Group (consisting of Scottish Government and Agency colleagues). The questions and the structure used in the survey were designed with the aim of capturing as broad as possible range of model and tool-based research effort, rather than the depth and specifics of each activity. The survey link was disseminated through multiple routes:

- Targeted emails to Institute CEO's, organisation leads, Scottish Government staff, RESAS Strategic Research Programme Theme Leads etc., with requests to disseminate to colleagues.

- Cascading (snowball) approach within research organisations, i.e. Heads of Department, individual researchers.
- Dissemination undertaken by SEFARI, RESAS and the James Hutton Institute research team.

Responses were targeted from researchers working with or developing models and tools (including spatial data sets) that had relevance to land use and Natural Capital and had received funding support from the Scottish Government. The definition of 'land use and natural capital models and tools' was made as broad as possible, and participants were encouraged to provide response even if they were unsure if their research came under the broad definition.

Dissemination also reached some organisations outwith Scotland, with the aim of encouraging responses from them where their work included Scotland.

Participants were given 7 weeks to respond from the initial invitation issued 3rd December 2024 and closed on the 10th of January 2025 (though it should be noted this covered the Christmas and New Year break). Whilst the coverage of dissemination was comprehensive, there may have been omissions, and it remains unknown as to how many possible respondents did not receive the invitation to participate. Despite the broad definitions above, there may have been researchers who could have provided a response but decided their work fell outside of the definition, or where unclear if their work fell within the funding source definition. With 71 survey responses there is confidence that the majority of researchers working in this area have responded and that the results presented represent a substantial portion of the relevant research.

Summary of Results

We present below the analysis as combinations of responses to individual questions to help group relevant details into subject areas that enable improved overall understanding of the current model capabilities, coverage and gaps. These groupings were developed through consultation with the project Steering Group. We present network maps based on keyword searches from the responses for grouped questions. Responses to individual questions are available in the accompanying spreadsheet (Land Use and Natural Capital Survey Responses - Spreadsheet | SEFARI).

Participant backgrounds

Q1: Who do you work for + Q3: How is your model-based research funded?

- **71 complete survey responses**, one duplicate removed to give a total of 70.
- Institutions and organisations % (Answers)
  - 59% The James Hutton Institute (41), 16% SRUC (11), 7% Scottish Forestry (5), 6% Scottish Government (4), 4% NatureScot (3), 1% BioSS/Rethink Carbon Ltd/Rowett Institute/Royal Botanic Garden Edinburgh/UK CEH/University of Oxford
- Funding source % (Answers, multiple)
  - 55% SG RESAS SRP (53), 26% Other answers (25), 7% UKRI (7), 6% Horizon Europe (6), 5% Industry/Business (5) --> *No one has chosen "Innovate UK"*
  - Other answers included:
    SG ARE, SG CivTech Challenge, Scottish Government Farming with Nature Programme, Grant/Loan, Scottish Forestry, Responsive Research Fund - ENRA 2022-2027, Not funded, Funded directly by SG resource, Welsh Government, Multi-institute, SEPA, CREW, Defra,

Scottish Alliance for Food, Trusts, National Trust for the Lake District, NGO, Plant Health Centre, Esmee Fairburn Foundation, SEPA, UK Government, government funding, CCC

Model Type

Q3-1: Category of model/tool (expert judgement) + Q6: Is your model spatial? + Q4: What type of model/tool is it?

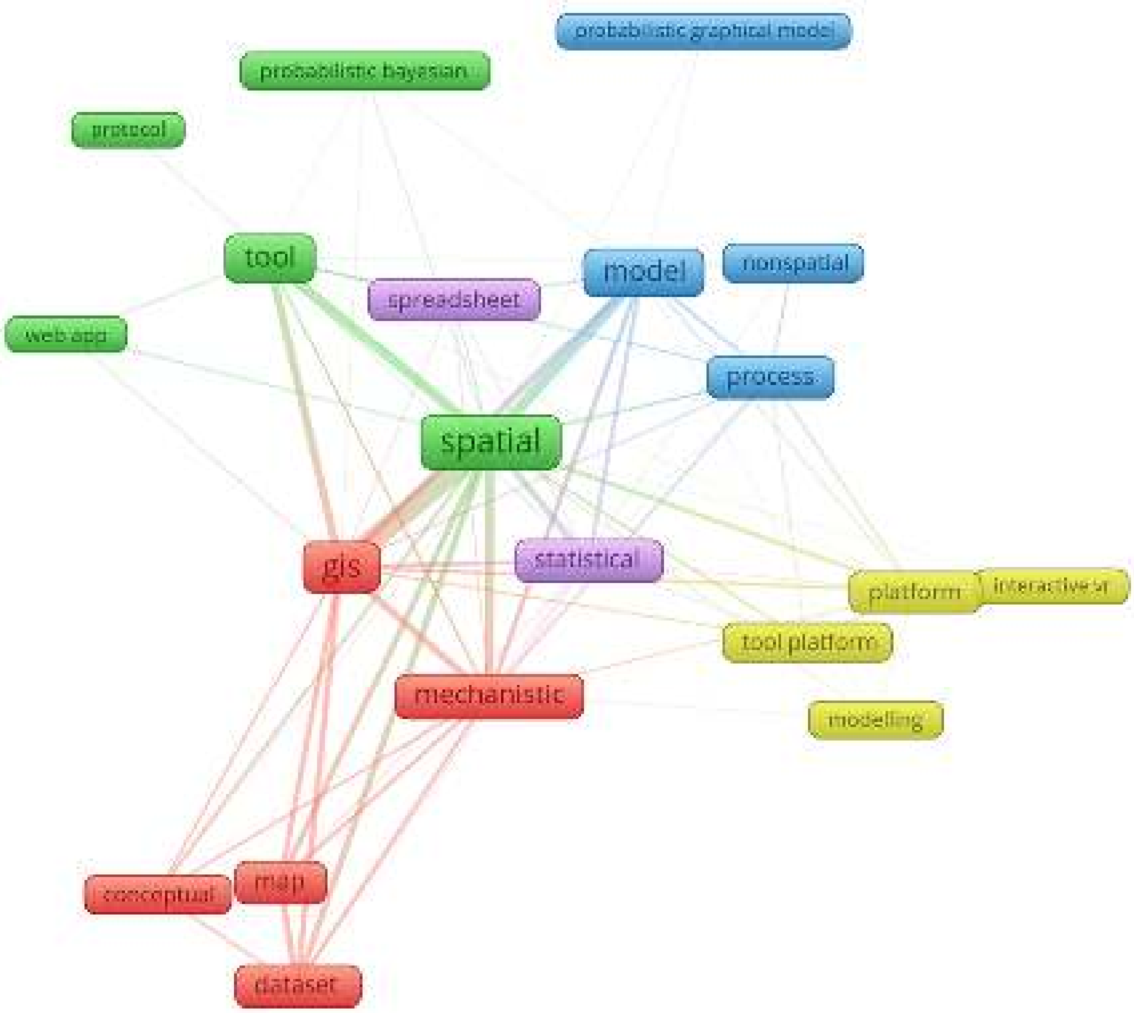


Figure 1: Network map of model type made within VosViewer (Version 1.6.20). The network map shows keywords based on the survey answers from questions 3-1, 4 and 6. The main connections are shown as lines (thicker line = more connections) and the size of the word box indicate number of occurrences of the keyword (larger box = more occurrences). Colours indicate word clusters identified by VosViewer.

The network map (Figure 1) for model type shows all the 20 keywords within Questions 3-1, 4 and 6. This combination of questions allow the visualisation of the categories (model/ tool/ platform/ dataset/ map), as well as splits between spatial and non-spatial models/tools and what type of model/tool is most prominent.

The 5 identified clusters[1] are "Spreadsheet", "Map", "Platform", "Tool" and "Model" with the main connector being "spatial".

"Non-spatial" is linked to "models" and "tools" that are mechanistic and process-based ("process"). "Spatial" is highly variable and linked to all the other keywords, beside non-spatial, with the strongest connection to "models" and "tools" that are GIS-based ("gis") and mechanistic.

Table 1: Model type (Questions 3-1, 6 and 4)

Category Q3-1		Spatial Q6	Type of model / tool Q4
39%	Model (27)	81% Spatial, 19% Not Spatial	29% GIS based 22% Mechanistic 19% Statistical or ML 14% Process-based 9% Spreadsheet 7% Platform for modelling
37%	Tool (26)	77% Spatial, 23% Not Spatial	48% GIS based 19% Mechanistic 15% Spreadsheet 11% Process-based 7% Statistical or ML
16%	Dataset/Map (11)	100% Spatial	50% GIS based 39% Mechanistic 11% Statistical or ML
7%	Tool/Platform (5)	100% Spatial	39% Platform for modelling 31% GIS based 15% Statistical or ML 15% Process-based
1%	Platform (1)	Spatial	GIS based
Total answers (%)		**84% Spatial, 16% Not spatial**	**37% GIS-based 19% Mechanistic 13% Statistical or ML 9% Process-based 8% Platform for modelling 7% Spreadsheet 5% Conceptual 2% Probabilistic Bayesian 1% Dataset**

Notes:

- The survey did not specify what a Natural Capital model or tool should be to encourage a broad representation. For processing purposes, we classified the 70 responses into the following categories based on provided descriptions and expert judgement:
  - 11 responses were for individual datasets or maps (spatial layers). However, it needs to be noted that in most cases these datasets were created using some type of conceptual, GIS-based or statistical model.
  - 27 responses were for various types of models.
  - 26 responses were classified as tools.

[1] For more information on the coding behind the clustering approach, see: VOS: A New Method for Visualizing Similarities Between Objects | SpringerLink. And the VosViewer manual: VOSviewer Manual

    - 6 responses were classified as either tools or platforms.
- Here platforms are interpreted as computing capabilities to use multiple models or as data fusion approaches, for example within a central data processing hub to enable a data management pipeline which may include integrated analytical and visualisation capabilities. However, this definition was not provided in the survey, hence respondents may have considered a platform as a tool. The terms tool or platform can thus be used interchangeably.
- Unless stated otherwise and for brevity, datasets/maps, models, tools or platforms are collectively presented in the report as models/tools. 59 models/tools were described as spatial and 11 as not spatial. Regarding the main data format(s) used by the spatial models or tools, most of them (n=34) used both vector and raster datasets, 7 used only vector and 15 only raster ones, but the format was not known for 2 models/tools. There was also one response about a broader map-based visualisation. Overall, 37% of models/tools were GIS-based, followed by mechanistic (19%) and statistical or machine learning (ML) (13%) ones. It is worth highlighting that 45 of the respondents stated that they used programming and/or coding, either solely or in combination with other software tools, for developing their models/tools, with 17 and 15 of these using R and Python scripts/tools, respectively.

Key Message 1: The majority (84%) of models, tools and platforms have spatial capabilities.

Model themes and scales.

Q13: Which broad theme(s) describe your model/tool? + Q6-2: What is the nominal granularity? + Q14: What broad category of coverage best describes your model/tool?

The network map in Figure 2 shows the main connections of answers given to Questions 6-2, 13 and 14 (Appendix A). 4 main clusters of keywords were identified with the biggest including “agriculture” and “land use”, followed by cluster 2 “natural capital” and “forestry”, cluster 3 with “ecosystems and habitats” and the smallest cluster being dominated by “mapping”.

Connectivity: The main connections are clear in the network map but strikingly some themes, categories and nominal granularities are much less connected to the main keywords. There is a clear lack of models/tools that are on an international or national granularity within the survey responses. Whilst the most common themes within the submitted models/tools are land use, agriculture, ecosystems/habitats, soil, water and forestry, there are almost no models/tools that identified as covering plant health, infrastructure, energy, net zero or farming. This may be due to how respondents interpreted how they saw their model or tool in terms of its overall theme. Our knowledge of the modelling community confirms that there are research teams using models in plant health, net zero and farming themes.

Decision support: Most models/tools are used or can be used for decision support or mapping within the field and catchment scale. However, other categories are highly underrepresented such as soil management, conservation, GHG emissions and agricultural reform support. There is a clear disconnect of models/tools covering “soils” but not being used for soil management, ecosystem services or habitat restoration. Another example of an important theme that is less represented in this survey is “biodiversity” with weak linkages to ecosystems/habitats, forestry/land use and decision support tool.

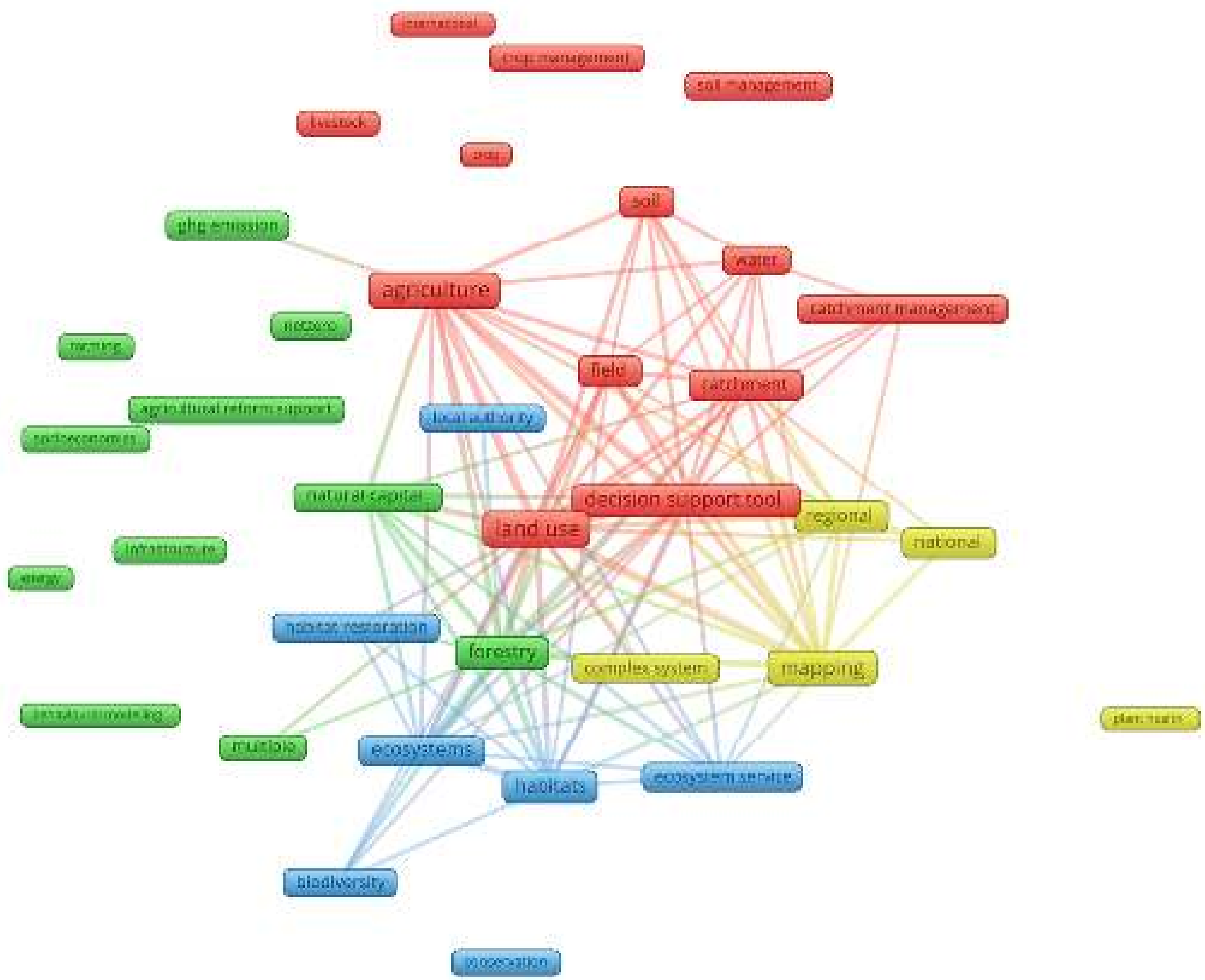


Figure 2: Network map of model themes, scales and broad category made within VosViewer (Version 1.6.20). The network map shows keywords (minimum occurrence is 3) based on the survey answers from questions 6-2, 13 and 14. The main 100 connections are shown as lines (thicker line = more connections), missing lines indicate week connection between keywords. Colours indicate word clusters identified by VosViewer.

Themes (multiple choice): (these are the most common answers based on Q6-2 and Q13)

Table 2. Broad theme and scale of application

Theme	Total	Scale							
		Crop	Field	Catch-ment	Local Authority	Regional	National	Inter-national	Multiple
Land Use	**47**	2	25	24	11	20	19	2	15
Natural Capital	**30**	3	12	14	9	14	12	2	7
Ecosystems/ Habitats	**31**	2	14	14	10	14	14	2	11
Biodiversity	**20**	-	10	8	7	8	7	-	9
Agriculture	**47**	3	22	21	11	17	15	3	10
Forestry	**21**	1	13	11	9	10	8	1	8
Soil	**29**	3	15	18	7	15	12	1	5
Water	**23**	2	15	18	7	13	11	1	7
Energy	**4**	-	1	1	1	1	-	-	1
Infrastructure	**7**	1	4	3	3	3	2	-	3

Most of the models/tools are covering categories of Decision support (46), Mapping (40), Ecosystem services (24), Catchment management (19) and Greenhouse Gas emissions (20).

- Mapping and Decision Support tools cover predominantly the themes of Land use and Agriculture followed by Natural Capital, Ecosystems/Habitats and Soil.
- Models/tools for GHG emissions and Ecosystem Services are mainly linked to Agricultural applications with aspects of Land Use and Natural Capital.
- Catchment Management models/tools are covering the themes of Land use, Water and Agriculture

Key Message 2: There is good coverage by models/tools related to Land Use and Natural Capital covering a broad range of themes and spatial gradient from field to catchment, regional up to the national scale. Gaps in capabilities are addressed in Key Messages 12-16.

Primary Objectives, Use and Scale of Application

Q5: What are the primary objectives/usage of the model/tool? (also focus on policy development or assessment) + Q15: What is the representative intended scale of application of the model/tool? + Q7: What computing resource is required to run your model/tool?

Table 2 Primary objective for model / tool use

Amount of the multiple choice from 70 responses	
Support tactical decision making	34
Support strategic decision making	24
Advancing modelling capabilities	13
Informing policy development	39
Informing policy assessment	27
Data integration and synthesis	29
Horizon scanning, future projections or scenario development	0
Improving understanding of complex systems	21
Improving understanding of a particular subject or issue	34
Monitoring current conditions	12
Decision support	49
Spatial planning	32
Risk assessment	31
Total choices from all 70 survey responses	**345**

Note: Responses to this question provided the option for combinations for ‘Support strategic decision making’ that included the term ‘e.g. future planning’ (29 responses). Respondents may have felt their selection of an option where ‘e.g. future planning’ was included covered the ‘Horizon scanning, future projections or scenario development’ option. It is worth noting however that there were no responses where this option was selected.

The network analysis on the “keywords” of Questions 5, 7 and 15 is shown in Figure 3. The network map visualises the main linkages between primary objectives/usage of the models/tools, their intended scale and the computing resource needed to run the model/tool.

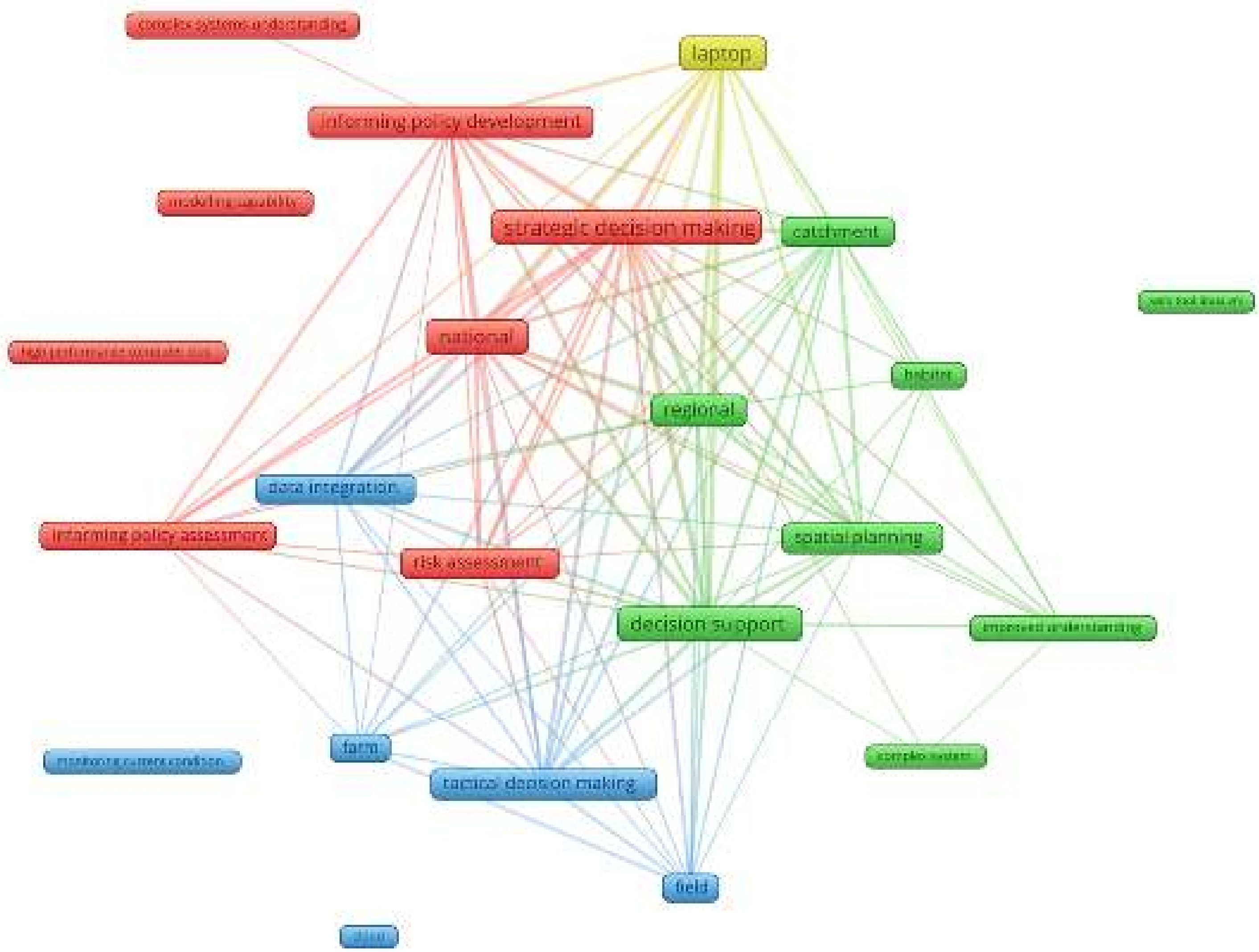


Figure 3: Network map of model objectives made within VosViewer (Version 1.6.20). The network map shows keywords (minimum occurrence is 3) based on the survey answers from questions 5, 7 and 15. The main 100 connections are shown as lines (thicker line = more connections), missing lines indicate week connection between keywords. Colours indicate word clusters identified by VosViewer.

Most of the submitted models/tools can be run/used on a laptop/PC with some exceptions that need a high-performance computer/cluster or are run on a cloud or web tool Linux VM. Most models/tools that can be used on catchment and regional scale are intended to be used for strategic decision making, decision support and to inform policy development. Improving modelling capability and complex systems understanding are minor objectives within the submitted models/tools.

- 49 out of 70 respondents chose “Decision support” as the primary objective/usage of their model/tool:
  - 9 of 49 (18%) → Dataset/Map (17%, 9 out of 54 choices within datasets/maps)
  - 16 of 49 (33%) → Model (12%, 16 out of 133 choices within models)
  - 19 of 49 (39%) → Tool (15%, 19 out of 127 choices within tools)
  - 4 of 49 (8%) → Tool/Platform (14%, 4 out of 28 choices within tool/platform)
  - 1 of 49 (2%) → Platform

Key Message 3: Decision and policy support are the primary objectives for models and tools.

Of the 70 responses, 59 indicated that the models / tools had a policy support or improved science-policy collaboration (Q24), with each providing examples of what the use and possible impacts have been.

Responses to Q24.1 provided in the accompanying spreadsheet provide examples of uses of models / tools. impacts. Impacts of model use on policy and practices remains a challenge however as recording and tracing and providing feedback to modelling teams on their impacts may not be absent or not comprehensive hence understanding if the objective of decisions or policy support have been achieved requires more detailed assessments of individual model / tool use. The development of approaches to resolve this (and as a general science-policy relationship) was a recommendation from the SRP Science Advisory Board.

Key Message 4: There were no responses of models/tools where the primary objective was horizon scanning, future projections or scenario development. This indicates a potential key gap in the research capabilities. However, the research team are aware of some models and tools that have the capability to be used in these areas, but these may not have been indicated as the primary objective.

Despite the lack of response to the primary objective for models / tools being horizon scanning, many are used for decision and policy support. The responses may reflect both a limitation to the wording of the questions and to respondents’ perspectives on ‘primary objectives’, i.e. their primary objective may have been ‘to address a specific current research question’ which may not then recognise the potential for use for horizon scanning.

This implies the need for improved definitions of terms and clarification on differences between primary objectives and potential additional use.

Q5-1: Informing policy development or assessment?
(Expert opinion based on choices made on Q5)

	Yes (46 total)	No (24 total)
Dataset/Maps	6	5
Model	20	7
Tool	18	8
Tool/Platform	2	3
Platform	-	1

Focus on policy support: Most of the respondents (*n*=46) indicated that their models/tools can be used for either policy development and/or policy assessment. This indicates that policy relevance is a driving force or at least an important consideration during model/tool development and implementation.

Computing resources: Modest computing resources, such as a PC or Laptop, are needed to run 32 of these policy-relevant models/tools, while more advanced computing resources, such as Linux Virtual Machines, Cloud computing or High-Performance Computers or Clusters or combinations of them, are needed to run 13 models/tools, most of these (*n*=11) used for Regional or National applications.

Key Message 5: Respondents indicated that 30 of these 46 policy-related models are not considered easy to run because they either require training for new users, or require having specific coding skills, or they are suitable for use only by the development team. Most of these harder to run or use models/tools (*n*=24) are also described as being of higher complexity, i.e., covering multiple entities at the same or over different spatial scales. This indicates that for most models/tools, the pathway of their adoption by policy teams would need to be via close collaboration with their respective development teams.

The results indicate that whilst most of the models can be run using existing computing infrastructure available to policy teams, those that address more complex multi-spatial issues and require access to more computing resources are best operated by the research teams.

- There does not seem to be any clear patterns of models/tools' primary usage by the intended scale of application; respondents selected a wide range of primary objectives and usage, which indicates that their models/tools can have a high degree of applicability for a wide range of purposes and at a range of scales of application.
- Most of the models/tools require modest computing resource, in the form of PC or laptops, for them to run, making them easier to be deployed outside of their development teams.

Key Message 6: Advanced computing resources, in the form of High-Performance computers or Clusters, are needed for running models / tools for complex research questions and or systems at National or Regional scales that used mainly for supporting strategic decision-making, and to a lesser extent, for informing policy development.

Main beneficiaries, complexity and ease of use

Q17: Who are the three main beneficiaries of the model's use? + Q12: How would you describe the complexity of your model/tool? + Q19: How easy is it to run the model/tool?

The network map in Figure 4 visualises the main connection between the main 17 keywords of Questions 12, 17 and 19. Most of the models/tools submitted in the survey are conceptual, are intermediate in their difficulty to run (requires training) and are dominantly for researchers, government agencies and policy teams/analysts.

Very few models/tools are simple in their complexity ("sec" in Figure 4) and easy to use which makes it difficult to use them within communities and local authorities, which is clearly shown in the missing network links. Although some models/tools are intended for the public or local authorities as beneficiaries, these models are often only intended for the use of the development team ("expert") which limits the accessibility to these models/tools.

- Most respondents indicated that Government Agencies were one of the main three beneficiaries of their models/tools' use (n=54), followed by Policy teams/analysts (n=51) and Researchers (n=46). Interestingly, Policy teams/analysts were the most popular main (first choice) beneficiary (n=26), followed by researchers (n=17) and then Government Agencies (n=11) and Industry/Business (n=9). Moreover, most of the models/tools (n=58) seem to have some form of impact on either policy or science-policy collaboration.
- However, only 11 respondents have indicated that their models/tools are simple or of relatively low complexity (i.e., single entity coverage), whilst 22 models/tools are considered by their developers/users as easy to run, with most requiring some form of training or specific coding skills for running them (n=38), while 10 respondents indicated that their models/tools can only be used by their respective development teams.

Key Message 7: Broader model/tool usage by other people (beyond the development team) requires investment in training of potential users and/or close collaboration with their respective development teams.

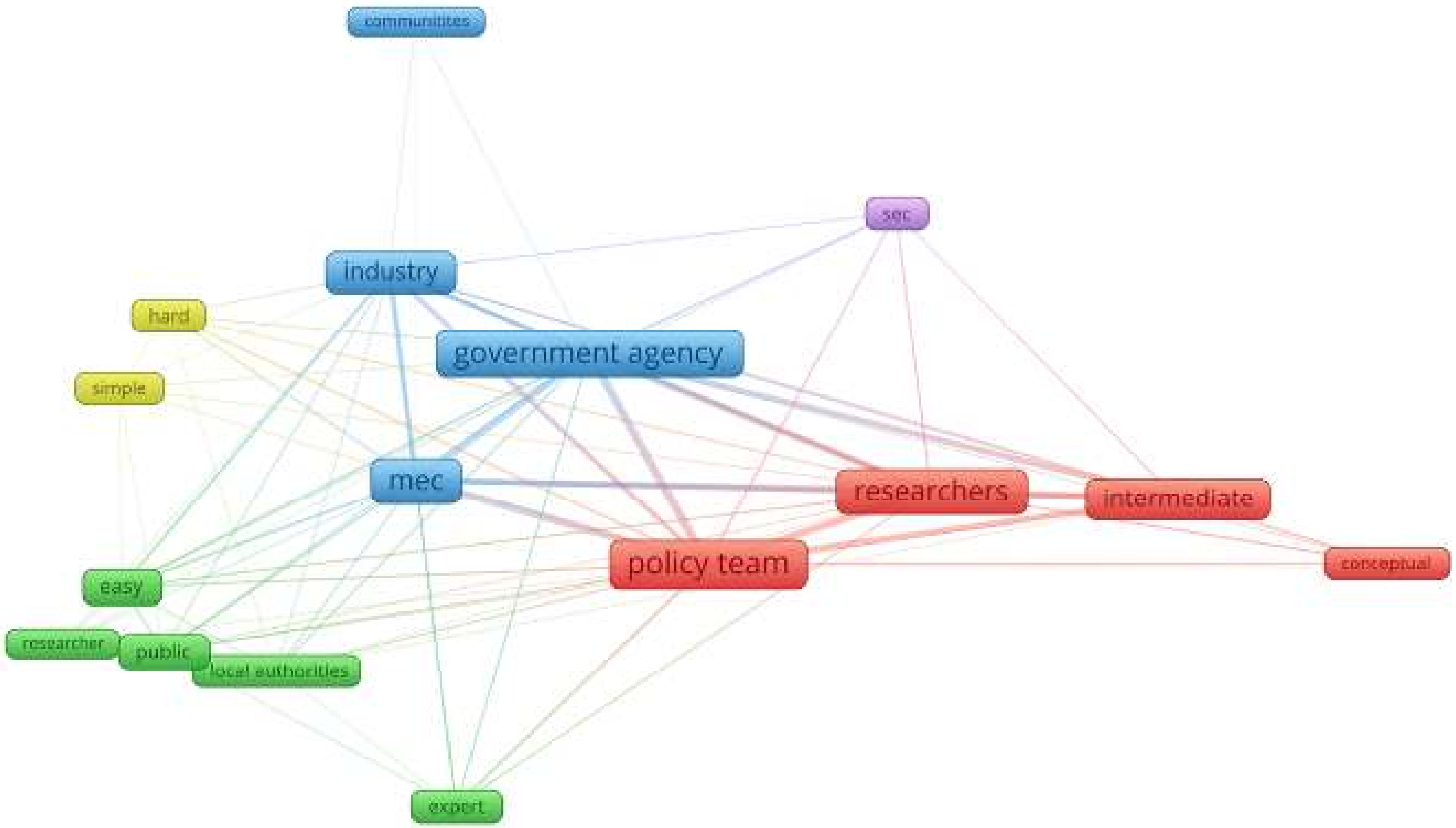


Figure 4: Network map made within VosViewer (Version 1.6.20). The network map shows keywords (minimum occurrence is 1) based on the survey answers from questions 12, 17 and 19. The main connections are shown as lines and the size of the word box indicate number of occurrences of the keyword. Colours indicate word clusters identified by VosViewer. Sec = Single entity coverage, mec = multiple entity coverage, hard = model/tool requires coding, intermediate = model/tool requires training, easy = no training necessary (e.g. API based).

Barriers to integration

Q22-2: In your opinion - are there limitations or barriers to the potential for your tool/model to be integrated into wider decision support frameworks + Q3-1: Category of model/tool (expert judgement) + Q18: Are there restrictions to model/tool usage)?

The purpose of this grouping of Questions is to help inform discussion on the potential for model/tools or platforms to be integrated into a framework. Note: it was not possible to create a meaningful network map as VosViewer was unable to appropriately utilise important words such as “no” or “not” for the restrictions and barriers.

Respondents provided a variety of answers, some lengthy and descriptive, related to the existence of limitations or barriers for the potential integration of their models/tools in decision support frameworks, such as ERAMMP or EcoservR. To summarise these responses, we used our expert judgement to identify different types of barriers or limitations and to assess their varying levels of potential integration.

- Around 40% of the respondents (n=29) indicated that their models/tools have a **high potential for integration** because no barriers or limitations were mentioned. Most of these have been described as Models (n=11), followed by Tools and Datasets/Maps (n=8 for both). However, only 12 of these models/tools are described as easy to use (10 are described of intermediate difficulty of use, i.e., training required). Six (6) respondents were uncertain or unaware of any barriers or limitations to integration, while one respondent did not provide an answer.

Key Message 8: There are fewer barriers to integration within a framework for the easier to use, more simple forms of models and tools.

- Of the remaining 34 responses, **23 models/tools needed some form of further work and/or investment that could potentially remove barriers or improve the potential for integration**. For example, 3 respondents indicated that their models/tools were coding-specific, hence potential integration would need to understand the models/tools’ code input and outputs. But this also meant that e.g., R-based tools could be more easily integrated in frameworks based on R such as EcosrvR.
- Another 3 respondents indicated that their models/tools as being application specific as the main barrier for wider integration; but they did not indicate any other limitations, which may imply that there would be good potential for integration if a decision support framework required these specific applications. Two models/tools required validation before considering the potential for integration, while 12 models required further work to facilitate the potential integration, such as harmonisation of common spatial data frames; translation of land cover/habitat types to common taxonomies/systems; solving issues related to software requirements (specific libraries, APIs) and to processing times.

Key Message 9: Some barriers to integration are practical e.g. coding language, common data frames etc, that could be overcome with specific investment to enable compatibility, such as use of Application Programming Interfaces (API’s) and shared data libraries.

- For 19 models/tools, respondents indicated barriers and limitations to integration that are more difficult to overcome, such as issues related to licencing of software and/or datasets and other permissions and co-ownership of the models/tools with other organisations.
- An important aspect was raised by 3 respondents, who indicated that their models/tools were not appropriate for model integration because they worked better as standalone applications. For example, they indicated that the value of their models/tools was best gained through the use by their respective developers as they have in-depth knowledge of the models- data pipeline and data quality issues.
- There was also critique of ERAMMP as an approach to integration related to the fact that, according to the respondent's understanding, it is not a standalone modelling framework but a soft integration of various existing tools of which different proprietors retain exclusive use, which limits the distribution of model outputs and hence, is not seen as an appropriate framework for wider integration of land use and natural capital models/tools in Scotland.
- Six respondents were uncertain or simply did not know of barriers to their models/tools' integration potential, one respondent did not find integration of their model/tool as relevant. One respondent did not provide an answer to this question.
- Most of the 34 models/tools with identified barriers or limitations to integration (n=22) had also restrictions regarding their usage, with most being accessible for academic use only (n=10), followed by restrictions due to the models/tools being licenced (n=5). Access for academic use only is also the main usage restriction for 4 of the 29 models/tools with no indicated barriers or limitations to integration, with one model/tool also indicating restrictions to use due to issues with IP. The remaining 21 models/tools with good potential for integration had no restrictions to usage.
- From a policy relevance perspective, 19 of the 29 models/tools with good potential for integration had primary objectives of either informing policy development and/or policy assessment, while 18 of them were also considered to generate a direct impact on policy and/or, their usage, lead to improved science-policy collaboration. Accordingly, 15 of the 23 models/tools with barriers or limitations to integration that can be potentially overcome with further work also had informing policy development and/or policy assessment as their primary objective, and all these models/tools were considered to generate a direct impact on policy and/or lead to improved science-policy collaboration as well.
- These models with no barriers or limitations to integration along with those with some potential for integration, subject to further work, provided good coverage of all main broad themes such as Land Use, Natural Capital, Agriculture, Biodiversity and Soil and Water, across the full gradient from field/farm to National scale.

These responses indicate that there is need for a critical review of the benefits and disadvantages of an integrated platform. See Discussion section and Recommendation 3.5.

Overview of findings on integration:

Overall, there seems to be a core number of fully or relatively accessible datasets, models and tools, with either none or relatively limited barriers or limitations to integration or with barriers that can potentially be overcome with further work and investment. These cover most themes of the Land Use and Natural Capital modelling landscape and at a range of spatial scales. These could potentially be considered for trailing and testing initial applications integration.

However, there are concerns that integrated frameworks such as ERAMMP are not suitable approaches for providing policy support, due to issues of timeframes for policy responses (see Appendix C). Integrated frameworks may be less agile than stand-alone models or tools.

There are also key fundamental issues needing to be resolved prior to framework development and use. These include agreeing the best level of granularity and that all models or tools using the same spatial scale, whilst resolving data ownership and use licensing. This implies the need for a centralised 'geoserver' of spatial data sets. Such an approach has merit in terms of enabling spatial data integration (Gagkas 2021), curation and use by both stand-alone models and an integrated platform, but raises further questions on how this would be resourced, how it would be managed (i.e. quality control, licensing and data ownership, authority on managing updates etc.) and who would oversee this resource.

Also, the survey responses highlighted that, along with the investment needed for facilitating this integration, it is necessary for policy teams aiming to use the models/tools to engage and work closely with the research teams responsible for developing these models/tools to e.g., better understand caveats and specific context of application, but also because some of these models/tools should be run by their respective developer teams.

In addition, the survey responses highlighted that some models/tools (especially more complicated and with more sophisticated functionalities) work better as standalone tools for specific applications; hence, efforts for their integration into wider decision support frameworks that include considerable overheads that might not be justified from an efficiency perspective.

Some of the responses indicate the preference towards less centralised, ERAMMP-like systems; at the same time though, respondents developing datasets, models and tools using open-source software and programming/coding seem to be quite open to the integration of their model outputs and tools within wider decision support frameworks that are based on similar, open source approaches.

This has the potential for progressing the work of integration of Land Use and Natural Capital models and tools in Scotland through the adoption of Open Science principles that promote and foster collaboration between research and policy teams and enable greater transparency and reproducibility of modelling and analytical efforts.

Key Message 10: There is an opportunity within the modelling and end user communities in Scotland to develop a combined approach of having stand-alone model / tools that operate independently but have the capability to work alongside models and tools operating within an integrated framework. This flexible approach is more likely to realise a better overall potential for Land Use and Natural Capital model-based research support for policy as it will overcome the limitations of existing integrated frameworks such as ERAMMP.

We have recommended that a more detailed assessment is made of the strengths and weaknesses of model and data integration frameworks as this is beyond the scope of this survey and its analysis. The overall impression from the survey is however that there is interest in and potential for developing the modelling framework concept, but there are concerns about how this is currently done.

Value for money

Q23: The objective of this question is to help understand value for money and where there may be need for investment in underpinning data and model development. This question is focussed on model development and application - not on the work to produce the input data. In the last 3 years - approximately how much public funding have you received to use or develop this model / tool? Please also indicate for how long the model / tool has been used in your research.

In interpreting the responses to this question, it is important to note that participants were asked to estimate costs within ranges, rather than on actual budgets and grant wards. These estimates also did not include the costs associated with the collection, quality control and organisation of the data used as model input.

- Less than £50,000: 32 responses, of which models/tools were used for:
  - Less than 3 years: 19 responses.
  - Between 3 – 8 years (previous SRP): 4 responses.
  - More than 8 years: 8 responses.
  - One response with no specified time usage.
- Between £50,000 to £100,000 and less than 3 years of usage: 5 responses.
- Between £100,000 to £500,000: 15 responses, of which models/tools were used for:
  - Less than 3 years: 6 responses.
  - Between 3 – 8 years (previous SRP): 3 responses.
  - More than 8 years: 5 responses.
  - One response with no specified time usage.
- Between £500,000 to £1,000,000: 4 responses of which models/tools were used for:
  - Less than 3 years: 3 responses.
  - Between 3 – 8 years (previous SRP): 1 response.
- One response for research that has received a combined funding of over £1,000,000 in the last 3 years.
- 13 respondents were unsure about the extent of public funding they have received for developing their models/tools.

Some models / tools have a longer history of use and impact extending back multiple decades, hence assessing their costs and value for money is problematical. An example is the Land Capability for Agriculture classification system (LCA). This was developed in the 1980's but is still currently used in informing planning decisions by local authorities and for valuing land by land agents. Recent investment by RSAS has enabled the LCA approach to be developed as a computer-based research platform enabling estimates of future land capability under climate projections.

Key Message 11: Regarding value for money, there is need to develop a better understanding of the relationship between the costs of model development and use and their impact on policy support and wider benefit to research beyond that information provided by this report. There is also need for understanding how modelling as a research activity depends on other activities such as data collection and quality control. Modelling development also serves as a medium for synthesising knowledge amongst researchers and informing data collection needs, hence its value extends beyond just use of outputs.

Identified gaps & challenges

Data as a gap in capabilities

A limitation on development and application of models is often the availability of appropriate data for calibration and validation, rather than modelling capabilities given the breadth and depth of knowledge, mathematical representation and coding skill in Scotland.

Integrated spatial data

Previous work (Gagkas, 2021) has demonstrated the importance of developing an integrated digital approach to collecting, analysing, and re-using data to provide evidence-based support in developing, testing, implementing, and evaluating policy options in the land and agricultural sectors in Scotland. This work highlighted the need for a comprehensive, Scotland-wide environmental census of the extent and condition of terrestrial ecosystems for establishing a baseline against which progress towards environmental targets and goals can be measured, and for determining whether the environment is improving, static or deteriorating further.

It also highlighted the opportunities arising from emerging spatial and other digital technologies to support the development of an integrated approach for assessing, analysing, monitoring, and modelling the state of the natural environment at high spatial resolutions and fine temporal scales.

A wealth of land and other environmental datasets and scientific evidence exist that can be used to support the development of an integrated approach for land-use statistics, by identifying and filling-up knowledge gaps to help build a comprehensive assessment of the baseline condition. Coupled with the high capacity and expertise that exists in Scotland in the environmental and digital technology sectors (Government agencies, Research/Academia, Private sector) and existing infrastructure means that Scotland is well-placed and at a strong starting position for building a new integrated digital data approach for land-use statistics.

However, successful delivery of the integrated digital data approach would depend greatly on establishing clear leadership and effective coordination between partners, identifying knowledge gaps, mapping evidence and prioritising policy needs, and identifying shortcomings in analytical resource and existing systems and related infrastructure.

In addition, developing the integrated digital approach should consider that land-use planning and land-use change decisions need to be fully integrated and joined-up across sectors and scales, meaning that the impact of these land decisions on the wider environment also needs to be fully considered. For example, how land is managed affects soil health, surface and groundwater quality, the capacity of habitats to moderate hydrological extremes (floods, droughts) and GHG emissions from land. Therefore, the integrated digital approach needs to identify linkages between sectors and natural capital assets and be flexible, adaptive and responsive to policy priorities and emerging risks related to effects of land-use change on the extent and condition of soils, water resources and on pollutant emissions and air quality.

Key Message 12: Consideration should be given to developing a data integration strategy to enable shared use within models, tools and platforms.

Data and code curation

Whilst there are several useful mechanisms for model code archiving, version management, transparency and sharing (i.e. GitHub, which many models use in varying ways for code, metadata and report archiving – see Q25), wider input and out data curation is at best *ad hoc* and highly variable between model and tool development teams and their organisations, or at worse absent. This is mainly due to the additional overhead cost of time and resources for data curation not being available in grant awards (i.e. funds may be sufficient to deliver the model and outputs, but not to enable the longevity value of the data through coordinated curation). The process of data curation tends to be considered as a secondary level priority compared to the generation of usable outputs and not always developed as part of the overall model / tool structure and data pipeline.

The issue of data curation becomes increasingly important in respect of capabilities to calibrate and validate models. The utility of models is only as good as the quality of data input, model skill through mathematical representation and coding to enable and appropriate calibration and validation.

Key Message 13: There is need for improved and coordinated data curation capacity (input and output data, parameter values and metadata) to be developed alongside efforts for data and model integration. This is essential for model calibration, sensitivity analysis, validation and model inter-comparison. Consideration needs to be given to the computing resource requirement to support modelling and data curation

Limited use for foresight

The survey has indicated that a key gap in our use of models, tools and platforms is for foresight and planning, for example land use response to climate change. Whilst there are Scottish Government Strategic Research Programme supported projects to develop and apply this capability (e.g. C5 Large Scale Modelling and C3 Land Use Transformations in Theme C), the overall focus of modelling efforts within the SRP is centred on representing and better understanding current conditions, issues and policy support needs.

Key Message 14: There is need to develop modelling capabilities and capacity to undertake research focussing on understanding the biophysical, economic and social aspects of the future, for example under climate change and biodiversity loss. This includes risk and opportunity assessments, cost benefits of transformations including ecosystem restoration (i.e. avoided spend).

Gaps in modelling capabilities

There will always be some research areas where modelling capabilities and coverage can be increased. Overall, the survey indicates that the mix of models and tools, and research teams developing and using them covers a broad range of Land Use and Natural Capital related issues. The implications are that the breadth and depth of modelling capabilities available in Scotland can be applied to fill gaps as they emerge or when new research questions arise. Responses are often rapid when required, where resources and availability of data allow, indicating that the modelling community can be agile to new challenges.

Key Message 15: There is a substantial gap in capabilities to model grassland systems, particularly the estimation of primary production under future climate impacts and the relationship between grass growth, animal offtake and greenhouse gas balances. Given the scale of grassland-based land use and the livestock sector in Scotland role in the carbon budget, this represents a large gap in our modelling capabilities. There is also a gap in capabilities to model vegetation, fungi and microbial responses to climate change and how this affects nutrient and energy flows in ecosystems.

Gaps do exist in terms of the capacity to represent complex relationships within socio-ecological systems where there is a requirement for inclusion of biophysical, economic and behavioural modelling and use of multiple data types.

Key Message 16: The modelling community in Scotland covers a wide range of subject coverage and modelling approaches and can be agile to new challenges. A modelling capability gap exists in representing energy and infrastructure in terms of land use and natural capital.

Modelling community cohesion

To improve the utility of modelling for research and policy support needs, there is need for mechanisms to enable the modelling community to develop through improved cohesion and realising synergistic opportunities. This can be achieved though engagement and communication to facilitate learning on best practices and new opportunities (e.g. use of AI and Machine Learning), knowledge of data (caveats and uncertainties) and potential for synergistic data sharing.

Whilst there will be an overhead cost of developing improved cohesion, this cost may diminish as collaboration and knowledge sharing develops. Working relationships are often best developed through informal means enabling people to work together where there are mutual benefits and willingness to collaborate, rather than through structured mechanisms.

Key messages 12 (developing spatial data integration capabilities) and 13 (data and code curation) can serve as mediums to focus modelling community cohesion.

Model Integration Discussion

The purpose of this section is to expand on the details above, by providing a broader perspective beyond that covered in the survey responses.

The survey responses indicate a range of opportunities and limitations for models and tools to be integrated within a platform. Limitations included Intellectual Property restrictions, access for academic purposes only and licensing as well as technical challenges such as programming language, spatial data resolution and limited shared data libraries.

Other aspects that are important to consider, though not addressed in the survey, also include the practical research infrastructure and personal relationship elements that enable and foster the types of collaboration that would be required to continue the current strategy of model development and use or in efforts to utilise an existing integration platform or develop one specifically for Scotland. These include:

- Recognition within the funding mechanisms that increasing the utility of model and tool use through collaboration incurs additional time and resource overheads.

    - There is need for a clear strategic goal for what seeking improved model development, utility for policy support and integration is aiming to achieve.
    - This strategic goal is also needed to improve the cost-effectiveness of investment in modelling.
- There is a need for mechanisms to support relationship building to develop trust and understanding between modelling teams and facilitate synergies where useful.
    - Differences in approaches on the most appropriate modelling methods are healthy to encourage diversity, with multi-model ensembles of helping to address issues of uncertainty (as per the model intercomparison and improvement approaches, e.g. AgMIP and ISIMIP). Other approaches to uncertainty include use of Bayesian calibration.
- Developing shared data libraries can serve as mediums for improving understanding of the data and caveats on its use for modelling.

Beware of the Integronster

There is concern within the modelling community of the risks associated with excessive integration within and between models that leads to loss of overall subject or issue representation, error propagation and distortion between internal model components. This concern is best represented by Alexi Voinov and Herman Shugart's paper where they say:

"In many cases model integration treats models as software components only, ignoring the fluid relationship between models and reality, the evolving nature of models and their constant modification and recalibration. As a result, with integrated models we find increased complexity, where changes that used to impact only relatively contained models of subsystems, now propagate throughout the whole integrated system. This makes it harder to keep the overall complexity under control and, in a way, defeats the purpose of modularity, when efficiency is supposed to be gained from independent development of modules. Treating models only as software in solving the integration challenge may give birth to 'integronsters' – constructs that are perfectly valid as software products but ugly or even useless as models". (Voinov and Shugart 2013).

In laymen terms, the warning here is that whilst from a technical perspective it is possible to integrate models and tools and data within a framework, doing so is not likely to be the most practical or agile (e.g. due to the number of partners involved), realistic (assumptions made being too broad, key relationships being over-simplified) or cost-effective approach (large overheads of interactions). Some very well-funded projects aimed to develop an Integrated Framework, e.g. SEAMLESS to assess, *ex-ante*, agricultural and environmental policies across a range of scales. But this, as an example, ultimately failed to deliver the required policy support due to being too unwieldy and impenetrable to those using the outputs.

Note: To illustrate the strengths and weaknesses of an integrative platform, we provide an annotated overview of the ERAMMP platform in Appendix C.

Modularising Models – and Research Teams

The survey results indicate that the most useful step in enhancing the modelling capabilities in Scotland would arise from a mixed approach of use of stand-alone models to represent particular application areas or research issues, whilst also developing the capability to use integrated models as modules within an Integrated Framework, where appropriate and technically feasible. Utilizing

Application Programming Interfaces (API's) as connectors between models supports a 'loose coupling' strategy, where models interact through standardized interfaces without being tightly bound to each other's internal structures or data needs.

This method enhances flexibility and scalability in model integration. The API2MoL tool (Modeling Languages) for example facilitates the integration of APIs within model-driven engineering by automating the mapping between API elements and model elements, thus streamlining the development process. Examples of platforms using API's include OurSmartFarm (developed in the SRP) and the Natural Capital Model developed in the Netherlands.

We have recommended a twin-track approach for developing an integrative platform approach (where technically feasible and desirable if it improves mode utility) and on-going support for independence of model development and application. This twin-track approach implies the need for models and tools to be modular so they can be independent but also able to function through linkages such as through API's. This analogy is also applicable to the modelling teams as well.

Integration at the data level.

The capacity for spatial model and tool development and application, including improving linkages and potential for integration, may be restricted by the availability and scales of data (granularity). To facilitate improved synergies between models and increase the utility of integration, there is need for an improved capability to integrate spatial data for use by multiple models. Spatial data integration will also facilitate improved analytical capabilities.

The benefits of data integration for modelling capabilities will also be increased through improved linking to monitoring efforts, for example, using remote sensing for habitat condition, use of environmental monitoring requirements (e.g. water quality and quantity). This benefit can be further increased through the evolving opportunities from Artificial Intelligence and Machine Learning.

Ingredients for improving model – policy interactions

The purpose of this section is to explore what the requirements are for useful science-policy relationships in terms of development, use and interpretation of land use and natural capital models and tools, and how to improve them.

Whilst there is informal collaboration and cooperation amongst modelling teams, to date model development and application within the Scottish Government's Strategic Research Programme has not been coordinated or operated within a framework that would facilitate greater efficiency through knowledge, code and data sharing.

Policy to modellers:

- **Co-define Objectives**: Policymakers to work closely with modellers to set clear objectives and clarify the purpose of modelling activities.
- **Understand Modelling Limitations**: There is a need for greater awareness within policy teams of what models and tools can—and cannot—do. Understanding limitations is essential for realistic expectations and responsible use of model outputs.
    - This requires improved communication between science and policy teams.
- **Improve Communication**: Stronger, ongoing communication between science and policy teams is needed to ensure models remain relevant, understandable, and usable within policy contexts.

Modellers to policy:

- Modellers can benefit from developing a better understanding of the policy landscape and requirement for support by policy teams and analysts.
- There is need to help policy colleagues to be able to work with modelling uncertainty and use model outputs within the boundaries set by researcher caveats, especially in respect of outputs based on limited data, or their use for foresight and planning.
- Develop agile approaches to enable rapid responses to policy support requests. An example is provided by the SRP Theme C Large Scale Modelling project (developing front- and back-end protocols for rapid model application to policy questions), as well as research Institute's responses to Scottish Government call down requests.

Common features both ways include:

- Time and mechanisms for developing working relationships and establishing mutual trust and understanding in capabilities and caveats.
- To increase the value of long-term investments through the SRP, there is need for flexibility, adaptability and agility in modelling linked with well curated long-term input data infrastructures from underpinning national capacity, on-going monitoring, experimentation and field trails. Development of this will require closer communication between modellers, policy and data providers to design and implement data integration approaches.
- There is need to establish credibility and buy-in from both components on the value in relationship building.

Conclusions

There is a rich diversity of Land Use and Natural Capital models, tools and data available within Scotland, developed and used by a knowledgeable and skilled set of modelling and research teams. This represents a strong capability across multiple research and policy interests and objectives, with wide representation across multiple spatial and temporal scales and themes of application areas.

Modelling has had good impact for many policy, research and application area beneficiaries, with increasing potential for further positive impacts and expansion to a broader range of beneficiaries. This can be achieved by developing a future modelling strategy. This study context is to help improve understand the potential to develop a modelling integration platform. Our analysis of the survey responses and knowledge of the modelling community leads us to conclude that there is strength in having a strategy that facilitates both:

- The development of an integration platform, where technically feasible, that is transparent and doesn't lead to over-simplification or use of large assumptions, is capable of representing complexity and is desirable in terms of improving the utility of model outputs, and;
- A continuation of the current approach to model and tool commissioning, development and application, as this enables independence, flexibility and agility.

We provide a set of recommendations (below) on what this strategy needs to include. Key to this is the development of an integrated approach to data collection and curation for model calibration and validation, as well as analyses. This will enable models to better utilise available data and inform what further data collection, e.g. through use of environmental monitoring requirements, that will increase model utility for policy support purposes.

Modelling is more than just models, code and data. The key ingredients are the people and their knowledge of the modelling domains, data utility and their ability to establish and maintain good working relationships with data providers and output end users. This is particularly important in respect of modelling for policy support. We have recommended the development of the modelling community cohesion through establishment of mechanisms to enable better understanding between policy, science and modellers. This includes the need to recognise the additional time and resource overhead required, but which will likely increase the value for money of enhancing modelling capabilities.

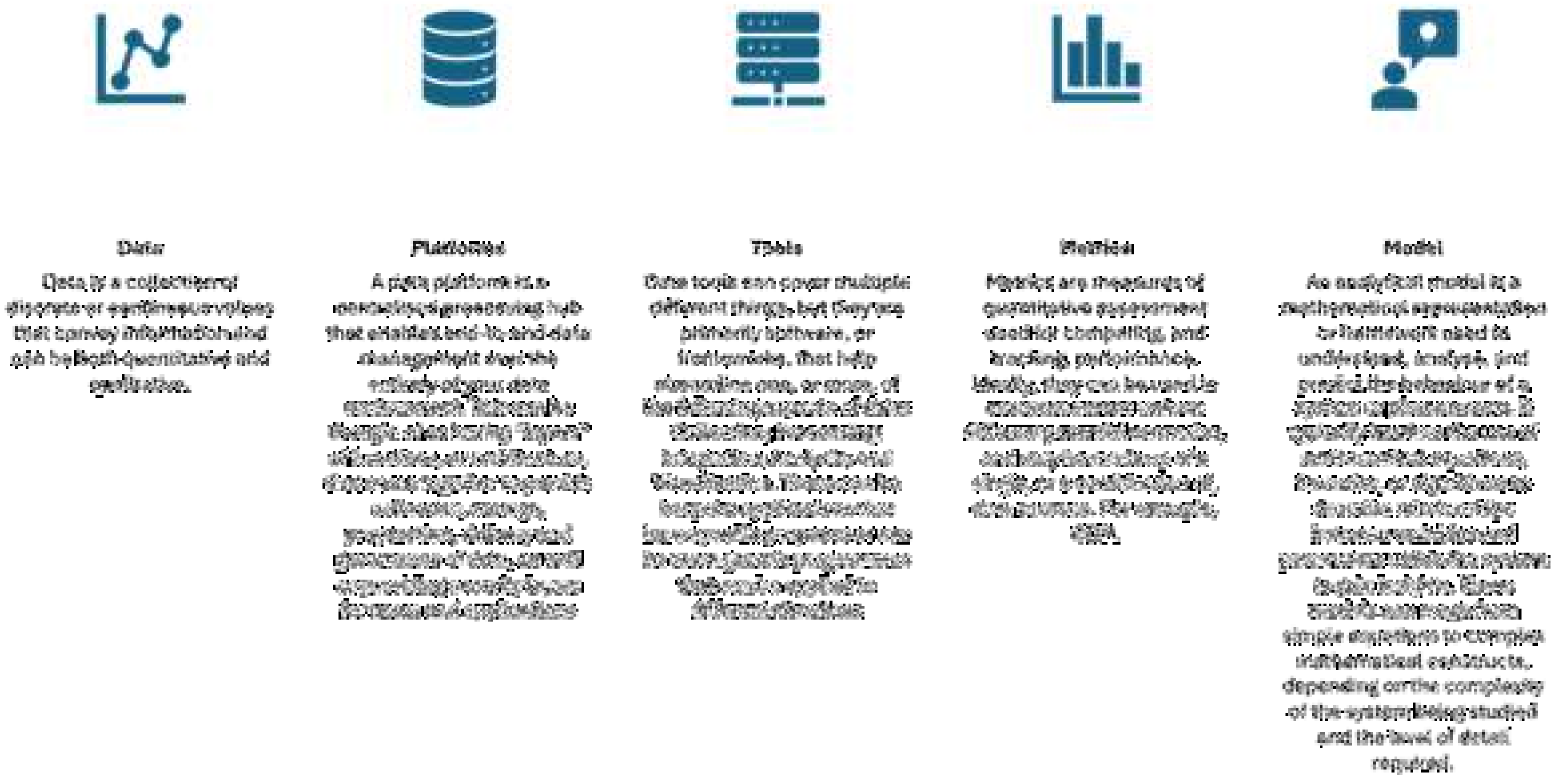
As pressures and time urgency build on our land and Natural Capital assets from climate change, biodiversity loss and objectives for food, water and energy security, it is becoming increasingly important to enhance our modelling capabilities to enable model-based experimentation, learning and understanding and development of foresight.

References

Gagkas, Z., (2021). Scoping for developing an integrated digital data approach for land-use statistics in Scotland. Report prepared for RESAS in the context of the SEFARI Fellowship on the ‘Provision of spatially referenced data relevant to land-based policy evolution in Scotland’. https://sefari.scot/document/gagkas-z-2021-scoping-for-developing-an-integrated-digital-data-approach-for-land-use

Voinov A and Shugart HH (2013) ‘Integronsters’, integral and integrated modeling. Environmental Modelling & Software 39, 149-158.

Appendix A: Definitions



The above definitions were developed by RESAS Staff (David McKean) to help separate the five main terms used by the research team and survey respondents and are provided to provide a context for the use of the terms in this report. **NOTE:** these definitions were developed after the survey invitation and were not provided to the respondents.

Appendix B: Survey questions

No.	Question
1	Who do you work for?
2	Name/Title of model/tool
3	How is your model-based research funded? [multiple choice possible]
4	What type of model/tool is it? [multiple choice possible]
5	What are the primary objectives/usage of the model/tool? [multiple choice possible]
6	Is your model/tool spatial?
6.1	What spatial format do you use?
6.2	What is the nominal granularity? [multiple choice possible]
6.3	What is the time scale of the model/tool?
7	What computing resource is required to run your model/tool?
8	What is the state of development of the model/tool?
9	What type of software or programming language is used to develop the model/tool? (e.g. R, Python)
10	Is the model/tool maintained and/or updated?
11	Did you develop the model or are you describing an existing model someone else has developed?
12	How would you describe the complexity of your model/tool?
13	Which broad theme(s) best describe your model/tool's coverage? [multiple choice possible]
14	What broad category of coverage best describes your model/tool? [multiple choice possible]
15	What is the representative intended scale of application of the model/tool? [multiple choice possible]
16	What type of classification systems do you use for land use or NC representation? [multiple choice possible]
17	Who are the three main beneficiaries of the model's use?
18	Are there restrictions to model/tool usage?
19	How easy is it to run the model/tool?
20	What evidence do you have of model quality? [multiple choice possible]
21	Does your model or research tool generate outputs that can be used as metrics or indicators against which real-world progress can be measured?
22	In your opinion, are there limitations or barriers to the potential for your tool/model to be integrated into wider decision support frameworks? Please indicate what the barriers may be.
23	Note: This question asked about funding for the research, with the understanding that details would not be provided in published reports
24	What impact can/could your model/tool generate? [multiple choice possible]
24.1	Can you provide a direct example of the model's impact? This could be a decision made using the model/tool or other demonstrable impacts of model use.
25	What documentation or metadata does the model/tool have? What do you use to record this? [multiple choice possible]

Appendix C: ERAMMP Integrated Modelling Platform (IMP) review.

IMP description from Harrison et al. (2023). The updated and annotated summary below builds upon a review undertaken as part of a previous SEFARI Fellowship (Gagkas 2021).

Drivers/Rationale:

The rationale for setting up ERAMMP came from the realisation by the Welsh Government (WG) that the environment supports significant economic sectors, including agriculture, fisheries, tourism, and forestry, that are of importance to other policy areas including health and well-being, energy, and infrastructure. Therefore, WG decided that it was necessary to build a robust monitoring and modelling programme in order to develop policies that build social, economic
and environmental resilience and to evaluate programme implementation (Gagkas, 2021).

It is important to note that ERAMMP is wider than the Integrated Modelling Platform, it also builds on baseline data (e.g., Countryside survey) and utilises annual survey data.

WG recognised that their pre-existing data and models were unable to provide the necessary systemic evidence-base to support the design of their new agricultural and environmental policies. An integrated and long-term perspective to policy design is also required by WG to meet current legislation is that puts an emphasis on addressing multiple outcomes in a holistic way.

Therefore, WG, commissioned the co-creation of an integrated modelling platform (the ERAMMP Integrated Modelling Platform or IMP) for Wales that could provide business-critical evidence to support the development of new policies focused on agriculture, land-use and natural resource management under a range of Welsh economic, regulatory and trade futures. The aim of the platform was to allow emerging policy ideas to be explored, stress-tested and iterated prior to final design and implementation. IMP modelling is **business-critical** to the WG, directly influencing decisions in active policy areas.

Obstacles:

Reasons for past lack of uptake of integrated models in decision support:

- Opaqueness of integrated models.
- Inadequate transparency in assumptions.
- Limited stakeholder engagement in the modelling process and lack of flexibility to address evolving policy needs.
- Hard-wired, inflexible system architecture limits their ability to address rapidly evolving policy needs in near real-time.

IMP co-creation:

The IMP was developed following the principles of co-creation taking an iterative approach involving the modelling consortium and Government experts. The co-creation approach started with discussion of the type of policy questions to be asked and which models to incorporate. Together, these aspects shaped the requirements of the integrated model.

The iterative co-creation approach used to develop and apply the IMP attempts to overcome criticisms of the utility of integrated models for decision support by building trust and understanding in the model and its outputs.

The development of policy questions was also an iterative and emergent process, with questions being framed very broadly initially and becoming more refined over time as understanding grew between the modelling team and Government experts of what is possible to represent in the integrated model in relation to specific policy teams.

Criteria for model selection:

Discussions on which models to incorporate in the integrated modelling framework involved the modelling team providing a transparent, honest and open understanding of the capabilities and limitations of available models to WG, including their suitability to the Welsh context and policy questions. The modelling team provided this information to WG for a wider list of available models than were ultimately chosen to include in the platform as part of the commissioning process for the IMP. Several criteria were used to select the most appropriate models to include:

- well-tested in previous research and policy applications.
- appropriate for multi-scale spatially-explicit policy assessment studies.
- produced a wide range of policy-relevant outputs.
- responsive to a wide range of environmental, policy and market drivers.
- use readily available public data as inputs.
- enable quantification of uncertainties for the estimations.
- suitable for integration, in that points of contact exist between the models.
- easily adapted to ensure the modelling framework could be iteratively customised to changing WG needs.

It's worth noting that most, if not all, of these model selection criteria can be mapped to the Land Use and Natural Capital mapping survey questions and respective responses.

IMP components & architecture:

IMP and its modelling framework comprise eleven component models (covering agriculture, forestry, land use decisions, biodiversity and ecosystem services related to carbon, water quality and air quality). These models cover agriculture, forestry, land use allocation, biodiversity, and a range of ecosystem services (including water quality, air quality, greenhouse gas emissions/carbon sequestration) and their valuation. This integrated approach recognises that policy effects in one sector have indirect effects in other sectors. In this way, the IMP explicitly accounts for biophysical and socio-economic interactions between sectors.

A useful characteristic of the IMP is that it operates at various spatial resolutions depending on what scale is most appropriate for the indicator being simulated (e.g., sub-farm, farm, catchment). The model is parameterised at a sub-farm level with biophysical constraints (e.g. climate, elevation and soils) and constraints based on environmental designations, and these are used to ascertain the most ecologically optimal configuration of each farm under a wide array of possible farm types. It is unclear though how the IMP deals with spatial scale in semi-natural habitats.

The IMP uses a soft-coupling approach to model integration. This involves passing large "data cubes" between the modelling teams. Data cubes are multi-dimensional arrays of values that maintain a consistent internal structure between model runs, growing in size as more data become available. This approach has been essential to maintain flexibility and allow institutions to use their own proprietary software within a collaborative project. WG therefore has direct access to best-in-class models without the need to develop their own in-house modelling capability. The data cube approach also facilitates fast querying of model outputs and provides the potential benefit of plug-and-play, allowing models to be updated, added or swapped in and out with minimal disruption.

The IMP advances existing integrated models by choosing a soft model-coupling approach that provides a customisable modelling framework that is sufficiently flexible to adapt to changing WG needs. This soft-coupling approach is key to the flexible integration, as 'people' (academics and WG working in partnership) are the enablers of fast model adjustment to evolving WG business-critical policy questions. This retains the active expertise in the model components within the IMP, rather than transferring the components to a central or external (to WG) modelling team. It also enables delivery at a pace that allows adaptation of WG policy thinking as model outputs emerge.

However, this approach means that essentially the WG modelling team doesn't have control over the IMP, so this depends on continued collaboration (and funding) between the WG and IMP consortium.

IMP components:

1. Scenario settings.
2. Ecological Site Classification model: tree species suitability and forest productivity.
3. CARBINE forest sector carbon accounting model: estimates productivity and carbon storage potential of forestry.
4. Agricultural model (SFARMOD): estimates the current and future profitability of various agricultural activities within each full-time farm holding in Wales using user-specified management and policy options.
5. Land allocation model (LAM): current and future profitability to simulate potential farming system change.
6. Farm emissions model (FARMSCOPER): determines emissions for predicted land allocations established for each farm.
7. Ecosystem services models (soil and biomass carbon, water quality, air quality).
8. Biodiversity models (plants, birds, woodland habitat connectivity).
9. Health impacts.
10. Valuation of ecosystem services (carbon, water quality, air quality).
11. User interface.

Baseline evaluation and quality assurance (QA):

Complexity of the modelling chain and the range of component models, resulting to some extent by the chosen architecture for integration, means there is no single activity for baseline evaluation and QA; instead, a range of activities is used to add to overall level of QA:

- Academic peer-review.
- Documentation of assumptions.
- Sensitivity testing (only models specifically developed for IMP).
- Model validation (where possible).
- Expert assessment.

Is the IMP a dynamic modelling approach?

No - The IMP is not a dynamic model, it broadly represents "short-term" and "long-term" consequences of Government policy designs, hence it does not consider and cannot model a wide array of factors that influence farmer and land manager decision-making (e.g., farmer behaviour, socio-cultural context, non-agricultural income).

An alternative approach could be to adopt a systems-based approach that can guide evidence-based environmental policy and management and enable policy analysts to understand complex interactions and relationships more easily, such the approaches described in Glendell et al. (2025) and DEFRA's approach (https://www.gov.uk/government/publications/integrating-a-systems-approach-into-defra/integrating-a-systems-approach-into-defra). An example of using a systems thinking approach for land management scenario testing is described in the study by Stewart et al. (2021), which included translating a logic map produced using participatory analysis coupled to probabilistic/Bayesian graphical modelling, to assess the impact of different land interventions on the overall utility of the British uplands and the provision of specific ecosystem services.

Definition: *Systems thinking is a set of synergistic analytic skills used to improve the capability of identifying and understanding systems, predicting their behaviours, and devising modifications to them in order to produce desired effects. These skills work together as a system*.

Finally, within the IMP, each model has its own temporal structure, and time is only synchronised across the modelling chain to represent the "short-term" defined as the consequences of the policy design if farms remain in their current farm type and the "long-term" defined as consequences if farms transition to more profitable farm types through conversion or sale and purchase. Therefore, it can be argued that the IMP's temporal structure is simplistic, and improved approaches are needed for better testing of future/temporal scenarios that are wider to farming applications.

References

Gagkas, Z., 2021. Scoping for developing an integrated digital data approach for land-use statistics in Scotland. Report prepared for RESAS in the context of the SEFARI Fellowship
on the 'Provision of spatially referenced data relevant to land-based policy evolution in Scotland'.
https://sefari.scot/document/gagkas-z-2021-scoping-for-developing-an-integrated-digital-data-approach-for-land-use

Glendell, M., Hare, M., Waylen, K.A. et al., 2025. Systems thinking and modelling to support transformative change: key lessons from inter-disciplinary analysis of socio-ecological systems in applied land systems research. Discov Sustain 6, 231. https://doi.org/10.1007/s43621-025-00987-3

Harrison, P.A., Beauchamp, K., Cooper, J. et al., 2023. An adaptable integrated modelling platform to support rapidly evolving agricultural and environmental policy, Environmental Modelling & Software, Volume 169, 105821. https://doi.org/10.1016/j.envsoft.2023.105821

Stewart, G.B., Glendell, M., McMorran, R., Troldborg, M., Gagkas, Z., Ovando, P., Roberts, M., Maynard, C., Williams, A., Clay, G., Reed, M.S. (2021) Uplandia: making better policy in complex upland systems., Defra and Natural England Report, 68pp.: https://eprints.ncl.ac.uk/274791

Appendix D: Qualtrics report with survey metrics and plots

The following are the responses to the survey as output by the Qualtrics platform used:

SEFARI Fellowship: Mapping Land Use and Natural Capital Models and Research in Scotland - Supplementary

Q1: Who do you work for?

Q2: Name/Title of model/tool?

NatureScot
AECOM EcoUplift Tool
Farm Biodiversity Scotland
NatureScot's Natural Capital Tool

The James Hutton Institute
AgMetrics
Bio4Ag
Climate indicators
DNDC
Daisy
Decision Support System for Agrotechnology Transfer (DSSAT)
DeeRMAP
ECOFOREST
FARMTREE-landscape tool
HortiSuit - biophysical & socio-institutional suitability mapping for market gardens
Hydrology of soil types (HOST)
InVEST
Land Capability for Agriculture
Land Capability for Agriculture Platform
Land Capability for Forestry
Land Systems team integrated administrative, and research based spatial data
LandSFACTS
Landscape Zonation Tool
Lemmings tool
Map of soil texture in Nitrate Vulnerable Zones
Mycobacterium avium paratuberculosis environmental prevalence BBN
NIRAMS
Natural capital valuation framework in participatory process
New national warning system for forecasting PVY risk in Scotland
OurSmartFarm
Peatland condition mapping
Pick-a-Mix
Protocol for Rapid Adaptation of Legacy Models for Responding to Urgent Policy Queries

RAG-P tool for phosphorus application to land
Runoff risk
SLM-OT (Sustainable Land Use - Options Tool)
ScenInvest
Semi-empirical modelling of greenhouse gas emissions on peatlands/parameterisation of land surface models
Soil erosion risk
Soil leaching potential
Soil phosphorus sorption capacity
Soil series models for digital soil property mapping
Topsoil and subsoil compaction risk
Virtual Landscape Theatre
Who's Benefit? Woodland carbon investment benefit flows in Scotland
probabilistic decision support tools based on Bayesian belief networks

SRUC
Anaerobic digestion model
Efficiency Models
Manure management methane emissions forecasting tool
Marginal abatement cost curve for UK agricultural GHG emissions
Ownership Typology
Peatland GHG abatement cost model
SAEM
Scottish Agricultural Economic Model (SAEM)
Scottish Cattle Performance Model
Spatial BBN Natural Capital model
Wales Economic and Environment, Field to Farm Model

Scottish Forestry
Assessing long-term resilience of Scottish spruce forests to climate change and novel pests
Improved preparedness for Phytophthora prevention in Scotland
Phytophthora climate risk tool
Phytophthora ramorum scenario modelling
Scottish Forestry Land Information Search

BioSS
EcoSISTEM framework (applied to Peatlands)

AECOM
EcoUplift

University of Oxford

FABLE Calculator

Scottish Government
LAND Database
Land removed from agriculture identifier
PeatSCOPE
The Importance of Natural Capital to the Scottish Economy - model

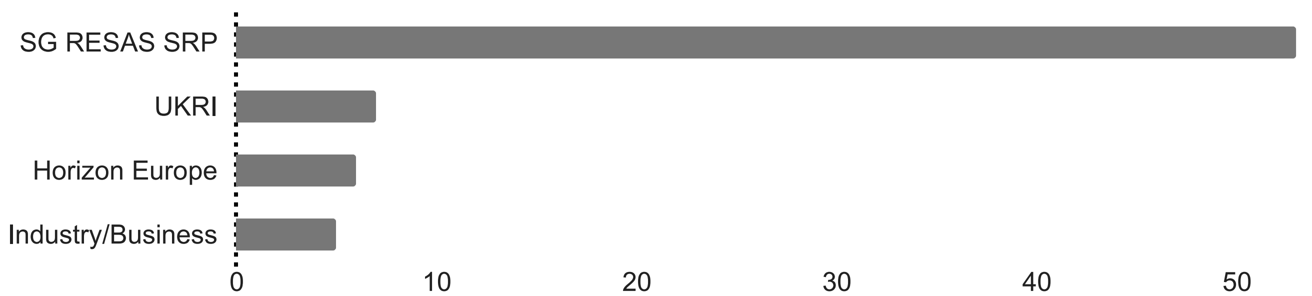
Royal Botanic Garden Edinburgh
Niche Models for Climate Refugia - Temperate Rainforest

Rethink Carbon Ltd
Rethink Carbon

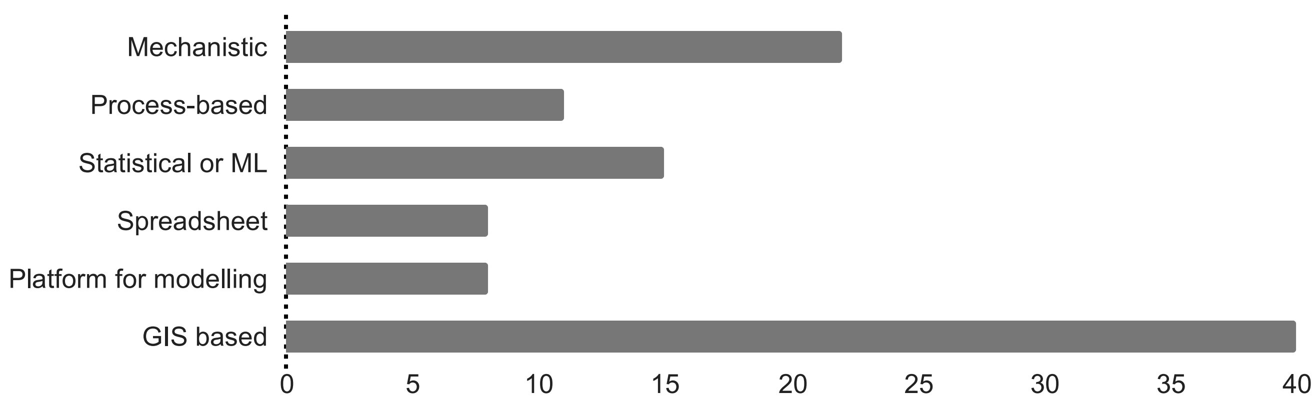
Rowett Institute, University of Aberdeen
STRAVVS (Simulating Transacting Rural-Area Ventures in Value Systems)

UK Centre for Ecology & Hydrology
UKCEH land-based GHG mitigation scenario modelling tool

Q3: How is your model-based research funded?



Q4: What type of model/tool is it?



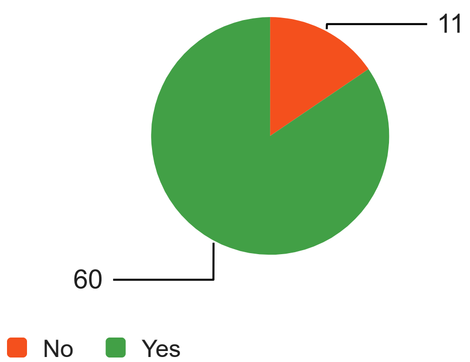
Q5: What are the primary objectives/usage of the model/tool?

Field	Choice Count
Support tactical decision making e.g. current management of a resource	34
Support strategic decision making e.g. future planning	53
Advancing modelling capabilities	13
Informing policy development	39
Informing policy assessment	27
Data integration and synthesis	29
Horizon scanning, future projections or scenario development	0
Improving understanding of complex systems	21
Improving understanding of a particular subject or issue	34
Monitoring current conditions	12
Decision support	50
Spatial planning	33
Risk assessment	31

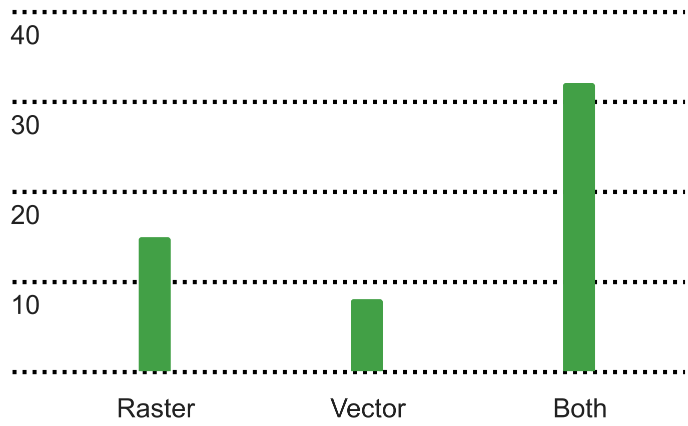
Q5: Other objectives/usage of the model/tool are:

Support identification of Nitrate Vulnerable Zones (NVZs) in Scotland
Policy options appraisal
Community engagement, citizen science, engagement, funding opportunities (grants)
Public consultations

Q6: Is your model/tool spatial?



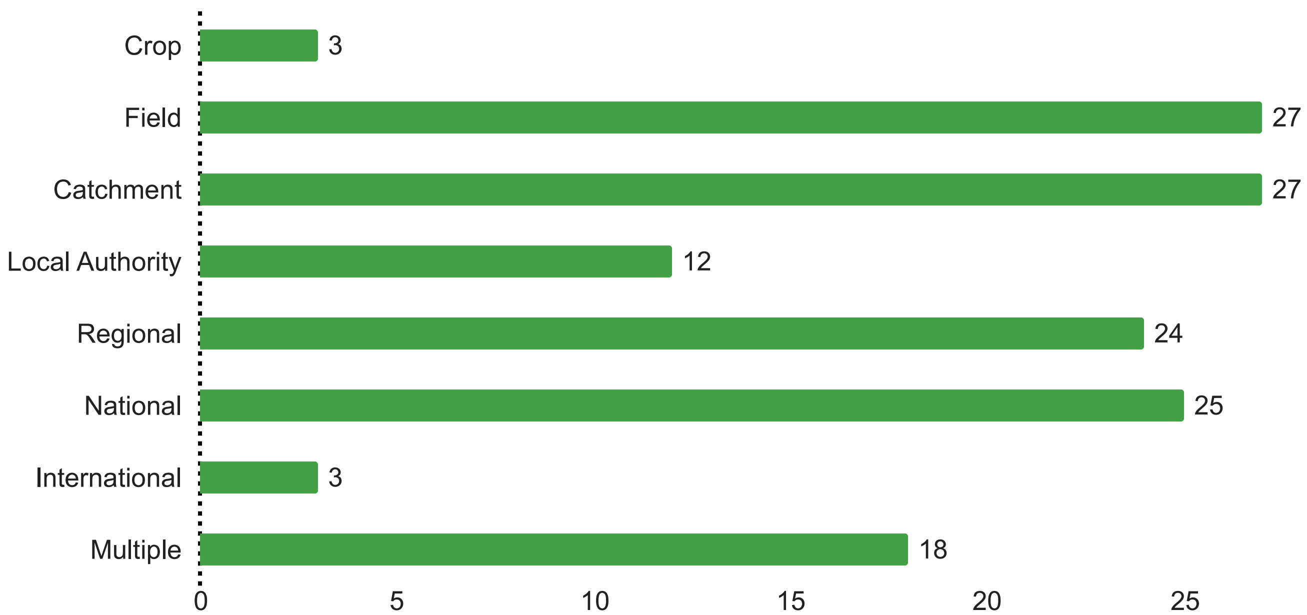
Q6-1: What spatial format do you use?



Q6-1: Other answers:

The model is flexible, depends on the input data structure. We usually we use it at the country level (4 countries in the UK), but will soon use it for part of Scotland, with rasters.
Based on LPIDs and aggregated to holdings and then to BRNs. Model outputs are spatial or can be aligned to systems, size, tenure, farm-type, etc
It can be applied spatially based on CPH or BRN
The model is not necessarily spatial, but can use space as a constraint for a location (e.g., raster or polygons) or distance (e.g., vector of transport links)
Spatial grid
Map-based visualisation
Both raster and vector data are used, and in some models triangulated irregular networks for terrain data

Q6-2: What is the nominal granularity of the model/tool?



Q6-2 -Further explanation:

The habitat and baseline mapping outputs themselves are detailed to field level (granularity of 5m x 5m in some areas) but the model outputs are best interpreted at landscape scale.

Business level (BRN) model that utilises spatial environmental data and RPID LPID data, as well as RESAS JAC and FBS data. Results can be aggregated upward to any spatial scale

It is based on LPID fields but also a series of other spatial layers. The model itself is farm level - but the input data is mostly spatial / economic / farm level survey or census data

Agricultural holding

The semi-empirical models, by their nature are local (field). Land surface models can be run at any desired scale. We are also working with process-based models eg. DigiBog

1km grid cell

Unique soil and climate combinations (1:250,000 soil series and 1km climate grid)

Investors: individual investors/companies/agencies Biophysical: multiple scales

100m grid cell at Scotland scale

Smallest basic unit: a polygon, which usually is a field or 100m grid cell. Rules can be applied at any other aggregated scale.

2 km grid cell

Field-Holding-Business and then aggregated to any other spatial unit.

1 km grid cell

Farm

inferential/historical model is on the level of a peatland restoration site. Predictive model's granularity is adjustable (currently developing on 1x1 km grid basis)

Downscaled to 5m grid cell for microclimates in forests/woodlands

The model is at the unit of a producer, so initially a (farm) business, but these can be aggregated up to regional/national

Soil type/climate cell

1 ha

It depends on input data. 10 m possible.

50m grid cell

Aligned to a 2m grid cell

100m grid cell

Any available raster spatial resolution possible, typically 100m grid cell. Vector resolution also flexible, used down to 1:10000

1km grid cell

Regional Economic Partnership level data mapped

At all scales depending on model being adapted

Depends on spatial layers selected by stakeholders

10m grid cell

Flexible spatial resolution

Users can create plans at their own chosen scale. Public datasets are integrated at the scale they were produced at, for example ranging from Ordnance Survey data at 1:1,250 all the way up to soil datasets created at 1:250,000 for example. Individual field boundaries can be identified from layers such as Open Street Map or habitat mapping. Analysis can be run at a catchment scale or even national park/local authorities. Our tooling is primarily Scotland based, however we expect to roll out into England in 2025, and have tested out datasets and analysis in California.

1 km grid cell

Postcode

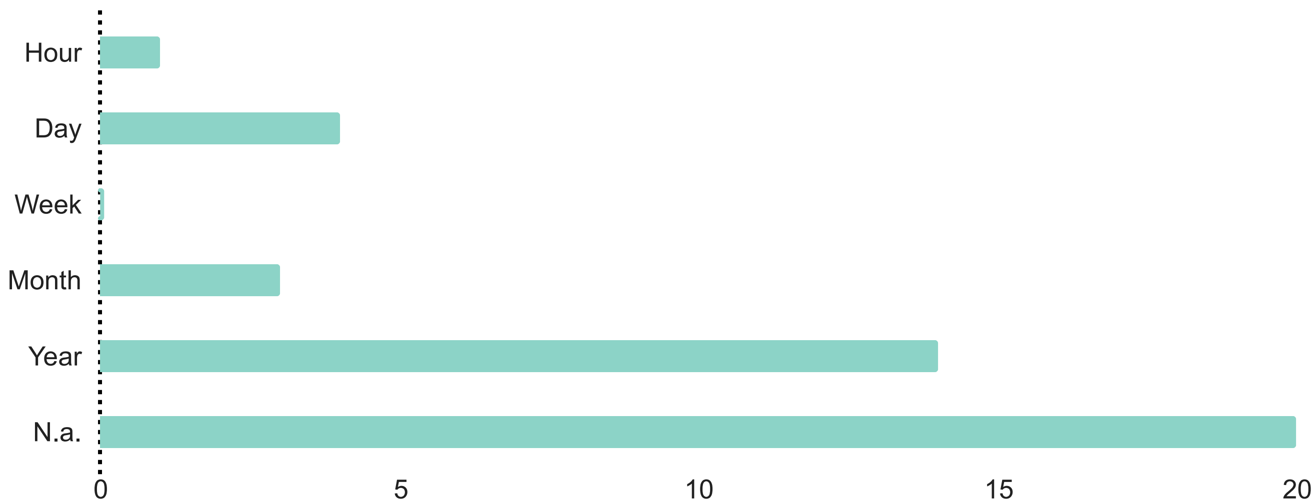
Scale and spatial dependent upon model purpose and area. Spatial scale of input data from 1:1,000 to 1:50,000; spatial resolution of imagery for textures from 0.1m grid cell to 250m grid cell.

25km grid cell

10 m resolution rasters analysis one or more DMG areas at a time

It depends on the input data and study area used. 100 m for regional/national landscapes common. 25 or 10 m possible for smaller areas.

Q6-3 - What is the time scale of the model/tool?



Q6-3 - Other, please explain:

It is based on a specific year of data and is non-dynamic (i.e. it does not predict on-the-ground changes over a period of time), rather it utilises policy scenarios to assess uptake of policy decisions and the income foregone / additional costs of compliance on the population of support recipients

It utilises a baseline year to run policy 'what if scenarios' to assess the level of existing compliance and estimate compliance costs of policy proposals

It is a monthly dataset over different time periods (from 1960 to 20790

Makes daily estimates of soil water balance, field capacity days that are aggregated to 30-year annual means. Median value of LCA classes are calculated for 30-year periods

Multiple - depending on modelling component

Can be Year, or group of years.

Time series yearly from 2000

Daily data but also presented monthly and annually for period 1991 - 2021

Modelling returns responses almost immediately. Underlying data on which modelling is done updated monthly where updates exist (some satellite derived data only updates annually) Unsure what being asked for.

The time-step is dependent on the system being modelled, but we have picked a month for agricultural processes

Model is based on 'snap shots' of natural capital assets, but could use future or past conditions if spatial data was available. It is not temporally dynamic.

not a dynamic model, so depends on input data

2018-2023

Month and year at present

Annual and monthly summaries based on daily estimates

all time scales depending on the model being adapted

Baseline mapping

time step (i.e. could be anything: 1 year, 10years etc)

any (year to group of years)

Updated as and when farmers enter habitat data

flexible

Unclear on what aspect this questions is aimed at... Data analysis and reporting is run in minutes. For example 25,000 hectares can be analysed in under 1 minute. 450,000 hectares takes between 20 and 30 minutes. The tool can be used to map current land use and future land use scenarios, varying from future cropping year on year, or projects spanning up to 100 years. The 125 + datasets in the platform have different update frequencies. Some are biannual for example, and data such as habitat is updated yearly.

Spatial risk frameworks cover a ~ 10 year period, non-spatial tools horizon scanning novel risks require annual update.

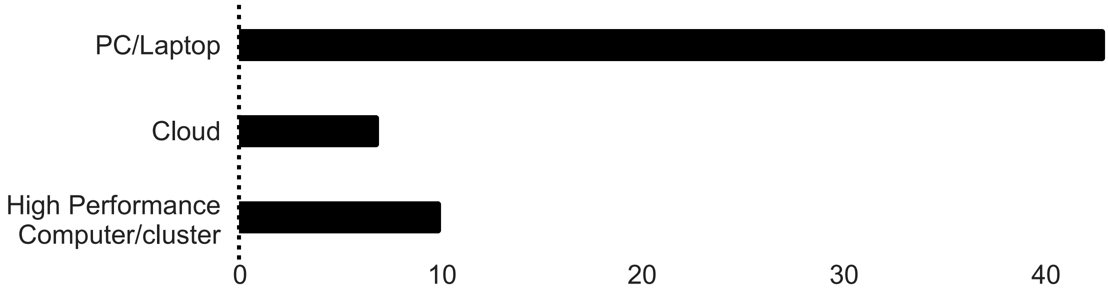
growing season (annual)

Imagery or other data (e.g. terrain cover, feature photographs) are provided as snapshots in time to be consistent across data sources (e.g. season of year; year of image to enable comparisons between years)

Not dynamic. Represents likely distribution in different seasons.

Not a dynamic model. But depends on what spatial thematic data are loaded into it for integration.

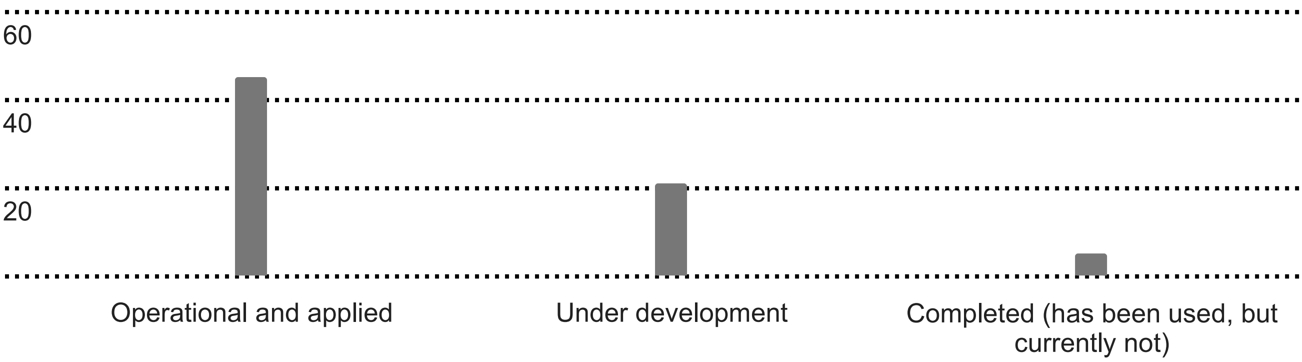
Q7: What computing resource is required to run your model/tool?



Other answers included:

- It also uses proprietary @RISK software to estimate existing levels of uptake and provide distributions of likely additional costs of compliance
- Depends on scale/resolution
- Any of the above
- Linux VM
- Can run on laptop or HPC for larger simulations
- Any of above - depend on analysis
- Don't know - was developed by the Met Office and tool is now live as a web resource
- Don't know
- As the user its just you own computer/laptop/phone. Behind the scenes AECOM use a computer cluster (many remote machines)
- Web-based: runs faster on a Linux server
- Can also run on PC
- Depending on model being adapted
- Linux VM, HPC
- Linux VM
- Windows, ArcGIS Pro
- PC with high specification graphics cards
- Web tool: runs faster on Linux server
- Fast PC/laptop ok. As it is a web tool, best performance on a Linux server to which users connect.

Q8: What is the state of development of the model/tool?



Q9 - What type of software or programming language is used to develop the model/tool? (e.g. R, Python)

The models are all written in R and once launched, the scripts will all be available to download on Github (or equivalent)

Spreadsheet-based

Python

STATA, spreadsheet-based

Spreadsheet-based

STATA

GIS tools

R, Fortran

R

Fortran

C

Python

netLogo; R

R, QGIS

Python

C++ (an ArcGIS/python interface exists as well: "SLM-OT")

Python

Databases, GIS tools and scripting langs R etc

R

Don't know

R

Fortran

Python, STATA, QGIS, ArcGIS

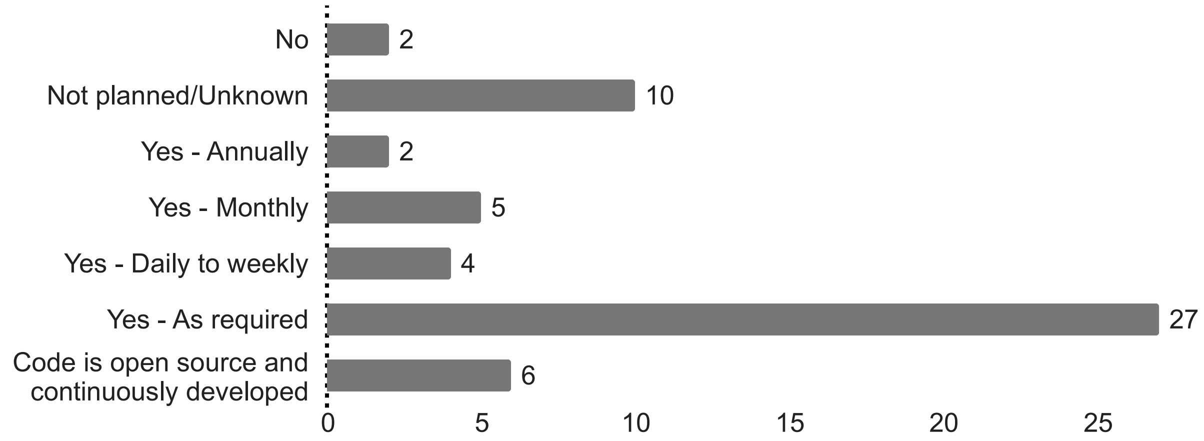
ArcMap, R

Python

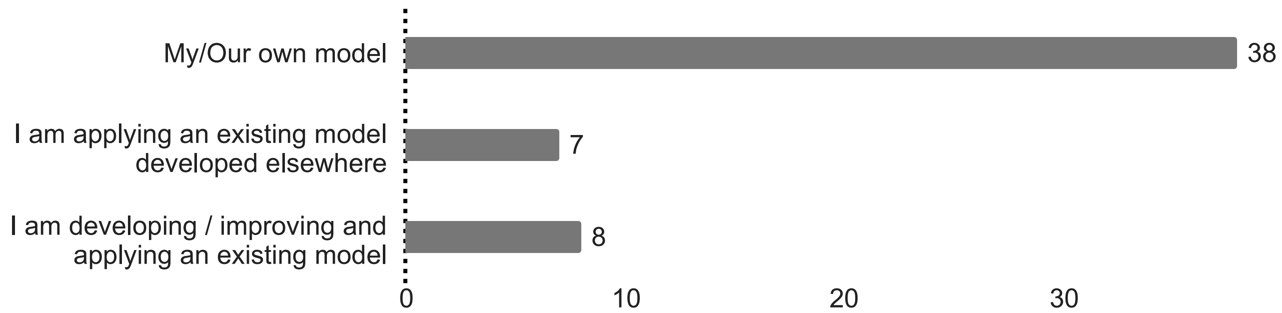
netLogo

R, spreadsheet-based
ArcGIS
ArcGIS
ArcGIS
ArcGIS
ArcGIS
Genie, R
R Shiny
Python
R
Don't know
QGIS
MATLAB
Python, PostGreSQL, .Net
Python and ArcPy
R and Python
Genie, rSmile (R API)
Python
ArcGIS Enterprise
xl plus VBA macros
Excel
Depending on model being adapted
ArcGIS pro
Python
Python
C++
Python toolbox in ArcGIS Pro
JavaScript/Typescript
Julia
React, NextJS, NodeJS, PostGIS, Typescript, various AWS services
R
R
Not sure
VRML
Python
Python and Node
DEXi and R
STATA
ArcGIS

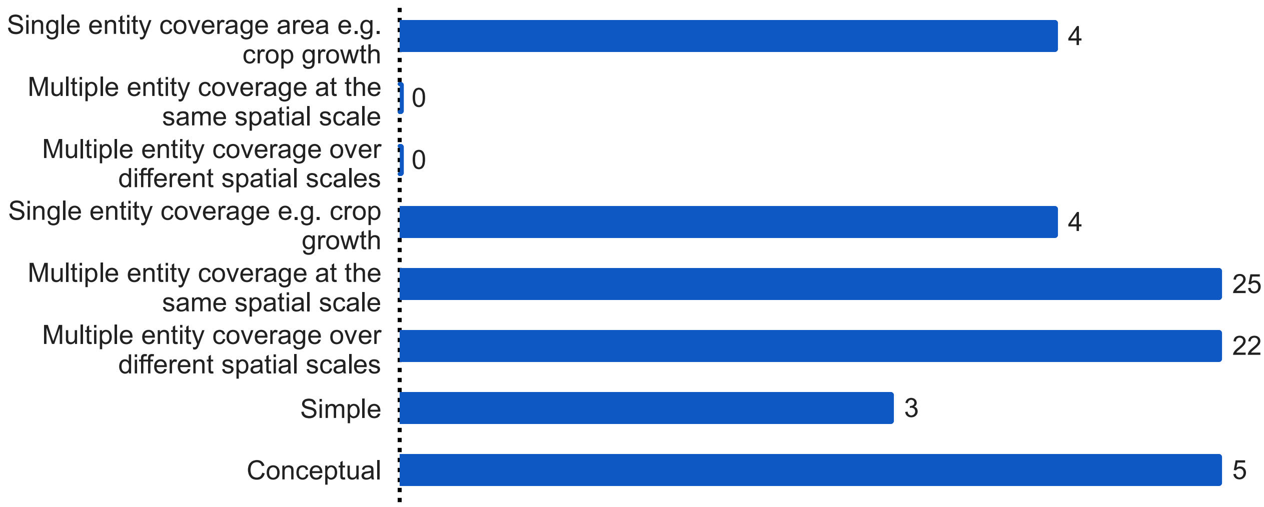
Q10: Is the model/tool maintained and/or updated?



Q11: Did you develop the model or are you describing an existing model someone else has developed?



Q12: How would you describe the complexity of your model/tool?



Q12: Expanded explanation

The interface and user journey from the tool is very simple and easy to use, but the models behind it (ecosystem service, habitat network models etc.) are rooted in more complex science. There is also complexity in the sense that there are multiple outputsn for the user to engage with (habitat layers, ecosystem service model outputs, opportunity area outputs etc.) but these have been deliberately designed to be as simple to navigate as possible. The should not require technical expertise to operate.

Farm level model - based on population data

Multiple entity coverage over different spatial scales. Can be used in more complex or simplified mode (limited compulsory inputs)

I would probably class this as Intermediate - Multiple entity coverage at the same scale (1 km2 grid). The model integrates inputs on climate (rainfall, temp, evapotranspiration, deposition), land use (land cover, crop types, livestock), and soils (HOST, field capacity etc.) to model the soil water balance and runoff (one entity) as well as nitrate mass balance and leaching (second entity, the main model output). The model only has about 7 parameters

Depending on model being adapted

depends on the conceptualization of the system by the participating stakeholders

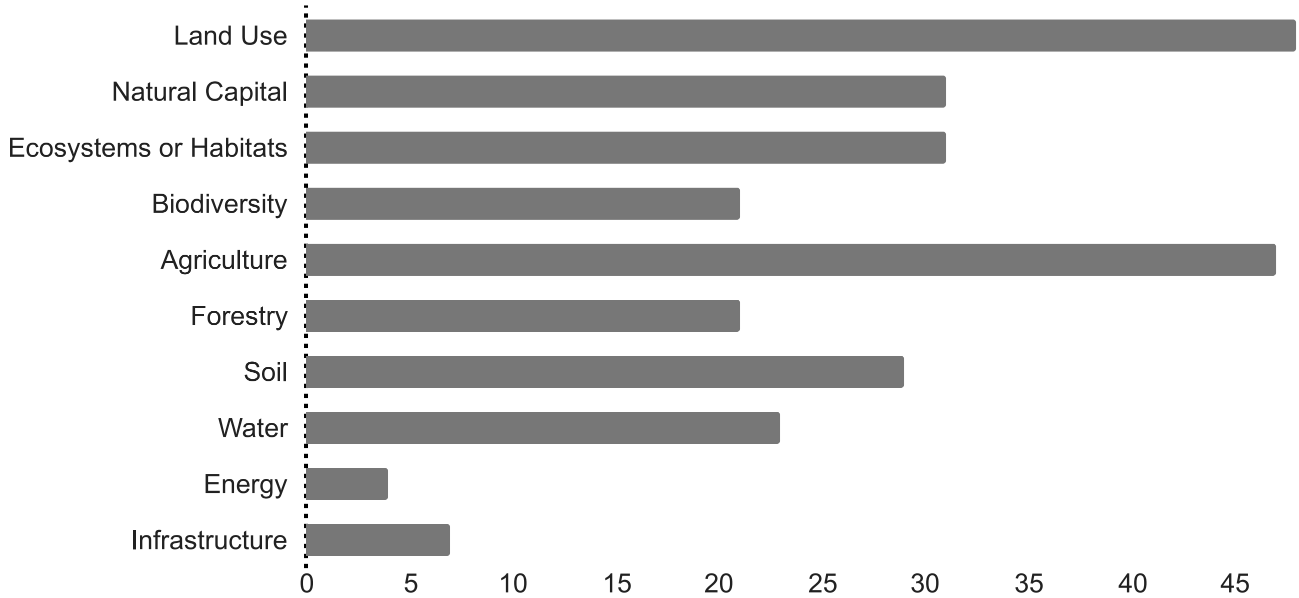
Risk frameworks for different diseases at different stages of the invasion range. More than one tool is developed as part of this project.

Couple of elements - one is using updated information to understand how well original modelling performed and one is to test a variety of control measure scenarios to inform policy.

Multiple entities are used within the virtual reality models, with several for the same spatial location (e.g. soil, land cover, Land Capability for Agriculture) and associated images (e.g. ground photographs, sensor measured data), and icons to represent features.

Intermediate: Multiple data sets used but an easy to use user interface to choose them and to give them different importance

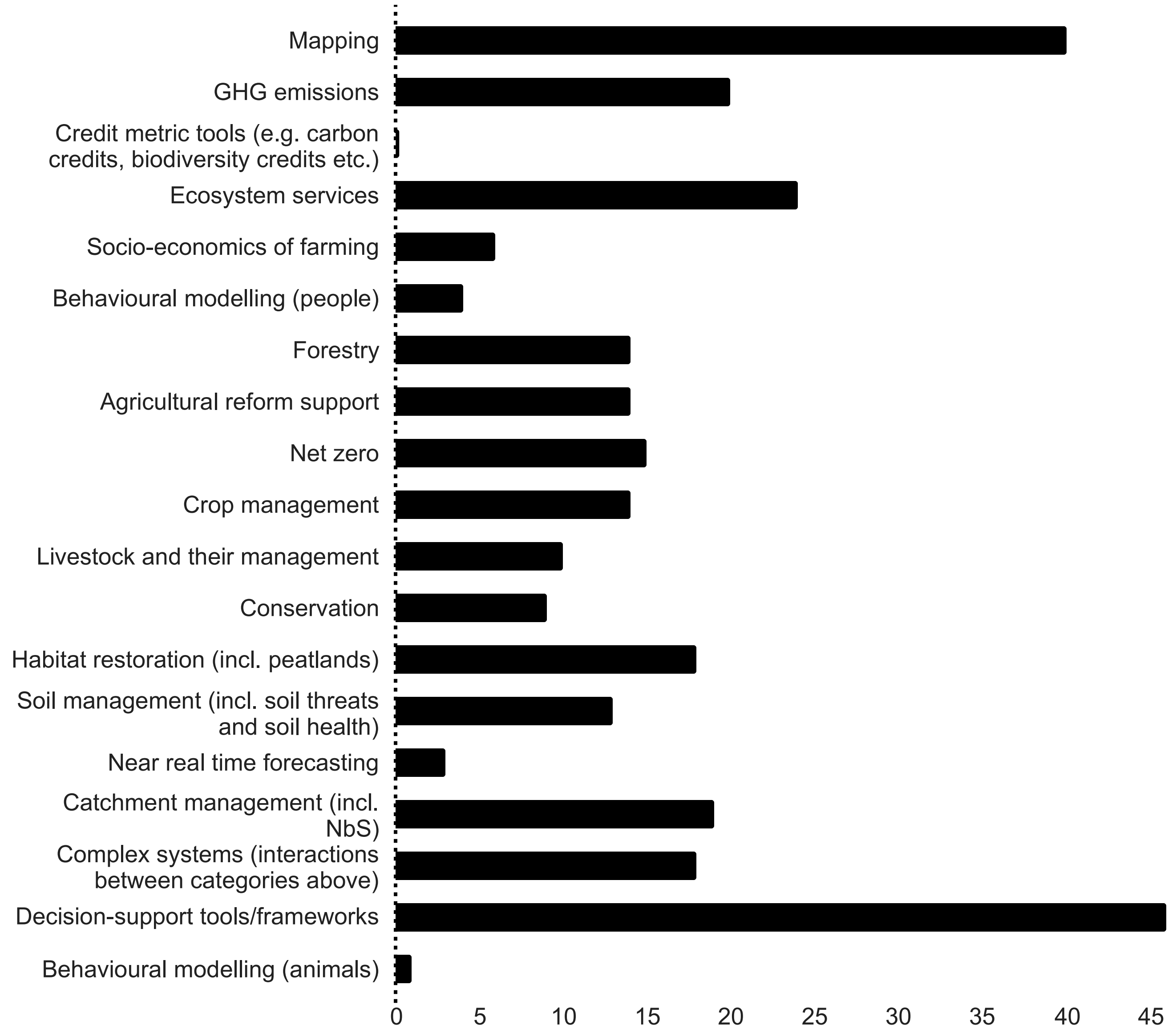
Q13: Which broad theme(s) best describe your model/tool's coverage?



Q13: Other answers:

Policy
Peat soil
It could be integrated with any of the above
Tree health
Plant health
Food
suite of multiple models, each with a different focus
GHG
spatially explicit simulator for plant species dynamics - currently applied to Peatland vegetation dynamics
Peatland
Plant health
Plant health
The range of virtual reality models cover most categories, or have been used in experimental or spatial planning frameworks.
Deer Management
Multiple themes: the focus is forest expansion but the spatial criteria pertain most of the themes above. Also it is flexible enough so that more layer can be added

Q14: What broad category of coverage best describes your model/tool?



Q14: Other answers:

It could be used for any of the above

Sorry, wasn't sure what categories were most appropriate here. Ultimately the model simulates nitrate leaching. This is/can be used to inform and support NVZ and hence can have implications on management of crops and livestock (stricter restrictions on nutrient application in NVZs)

Plant health subject to international treaty so is it about statutory regulation

Plant disease modelling

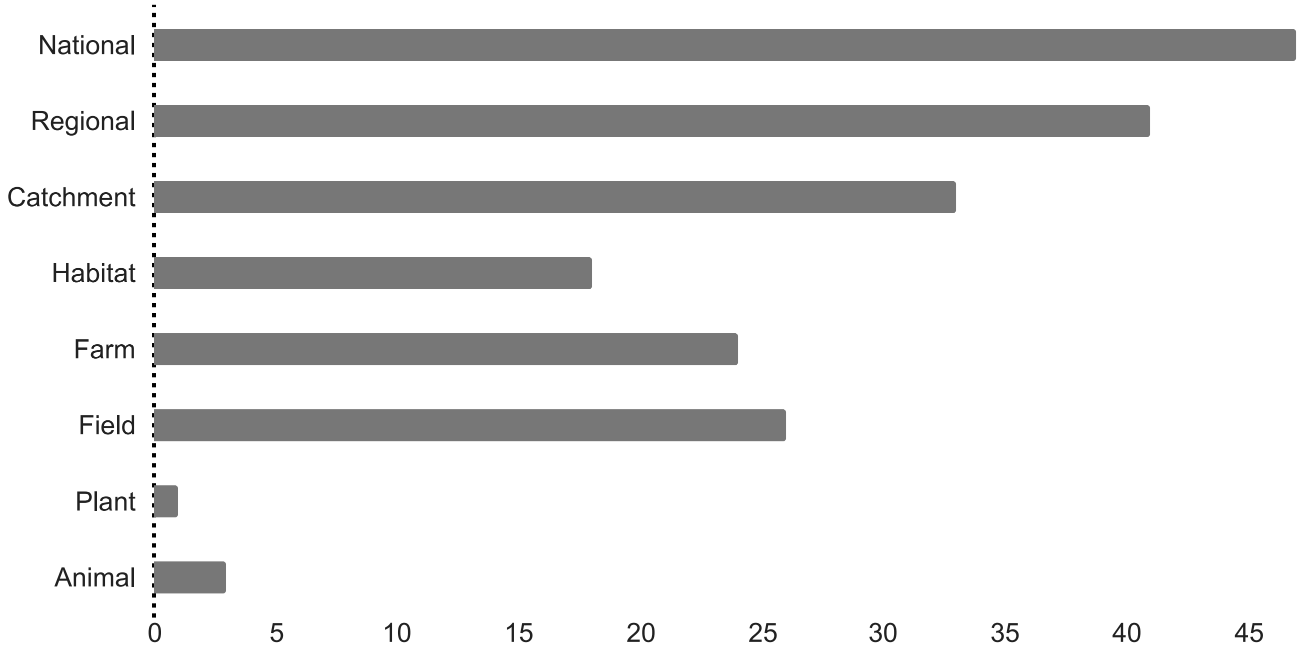
socio-economics of economic reliance on nature

Community engagement

Epidemiological control modelling

Models have been created for particular purposes with aspects of several categories represented, or used in narratives about landscape change, including citizen led planning. Themes in addition to those listed are renewable energy, aquaculture, offshore coastal environments, sea floor environments, urban squares and greenspaces, ecosystems threatened by plant disease

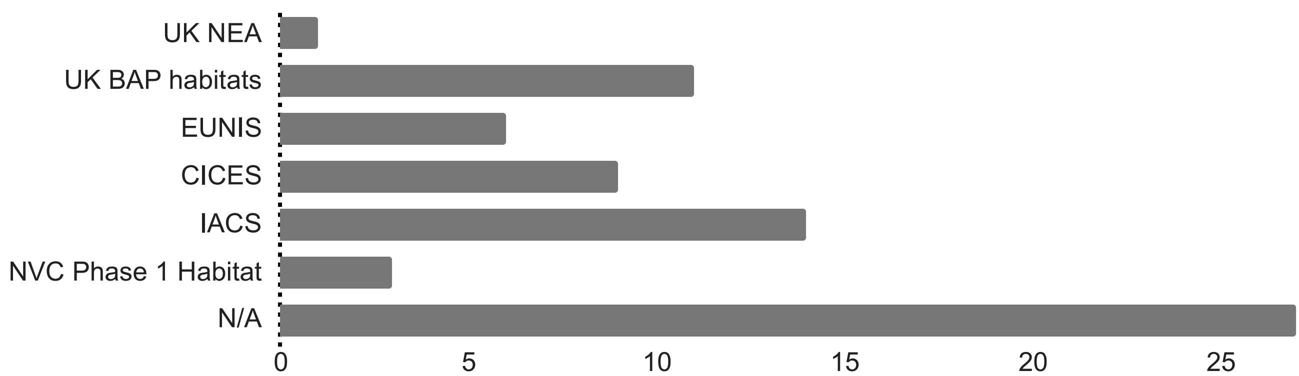
Q15: What is the representative intended scale of application of the model/tool ?



Q15: Other responses:

temperate European peat area
It can also be deployed on different scales
1 km resolution
For forests/woodlands at protected site (e.g. NNR) scale
National application is possible, but would limited due to data processing requirements
Currently set to three case study areas, 2 x catchments, 1 x biosphere and Shetland.
Depending on model being adapted
Sub-sea marine environments (e.g. lochs), urban feature (e.g. internal and external buildings.

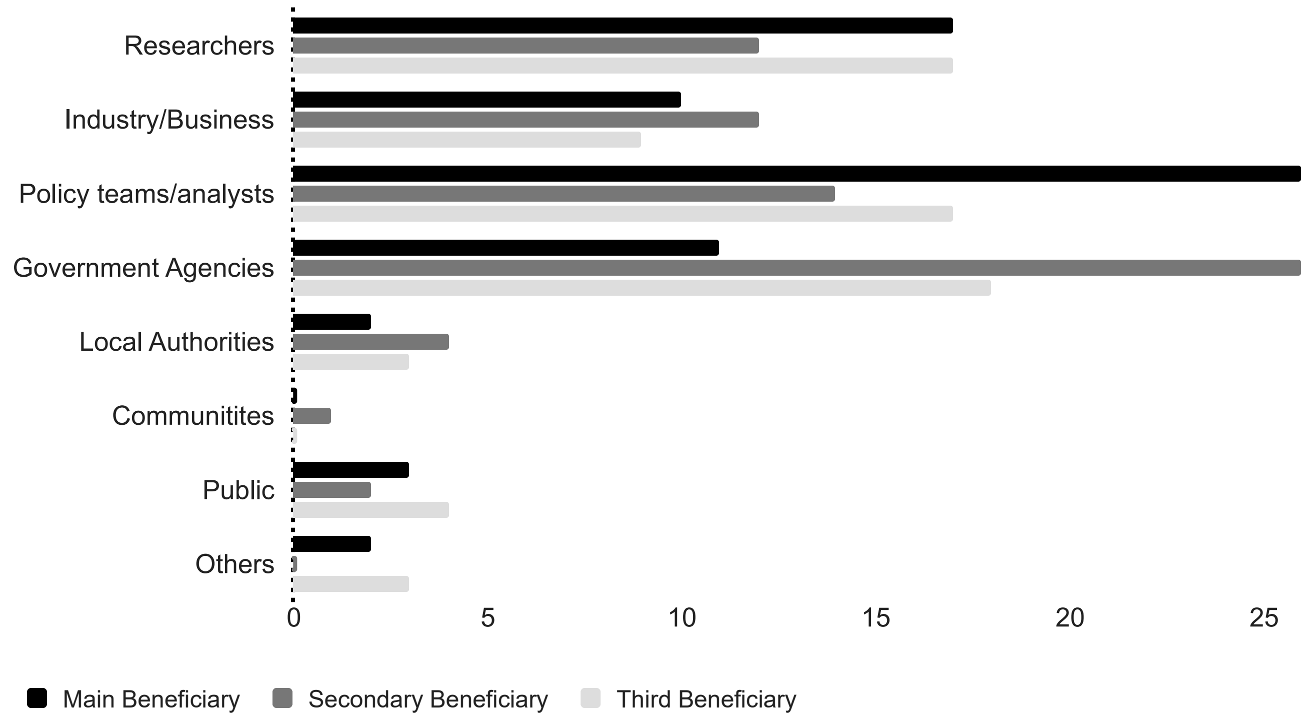
Q16: What type of classification systems do you use for land use or NC representation?



Q16: Other responses:

crop type or cultivated land cover type
crop types as in the GHG inventory
Welsh Section 7 Priority Habitats
bespoke system for land use on peatland (in development)
Based on original Land Capability for Agriculture classification system
to be decided
but could any (for the model itself)
LCM, livestock; technically any classification system could be used by the tool
NIRAMS used to use IACS data for land use, but is now using AGCensus data and LCM
Peatland quality/emission category mapping
Copernicus land cover data
We do not at present, but would likely use LCA or IACS
IPCC land use categories for GHG inventory reporting
don't know - tool was developed by Environment Systems
We make use of CEH Land Cover to understand land use, and IACS LPIS data to understand ownership type/extent (but not land use)
James Hutton Institute LCA and Ordnance Survey land use tier A
UK CEH land cover maps
Depending on model being adapted
depends on the stakeholder requirements
UKCEH LCM
as the user wishes
could be any (model has no hard coded data in it)
Whole Farm Plan Habitat & Feature Key
individual species are represented
Depends on the crop - IACS is probably closest
Land Cover of Scotland; Open Streetmap; Ordnance Survey
Broad categories: cropland, intensive pasture, extensive pasture, semi-natural woodland, plantation forest, urban, peat (degraded / restored), other land.
Developed own, from NatureScot's SLAM map

Q17: Who are the three main beneficiaries of the model's use?



Q17 - Main Beneficiary

Field	Choice Count
Researchers	17
Industry/Business	10
Policy teams/analysts	26
Government Agencies (SEPA, NatureScot etc.)	11
Local Authorities	2
Communitites	0
Public	3
Others	2

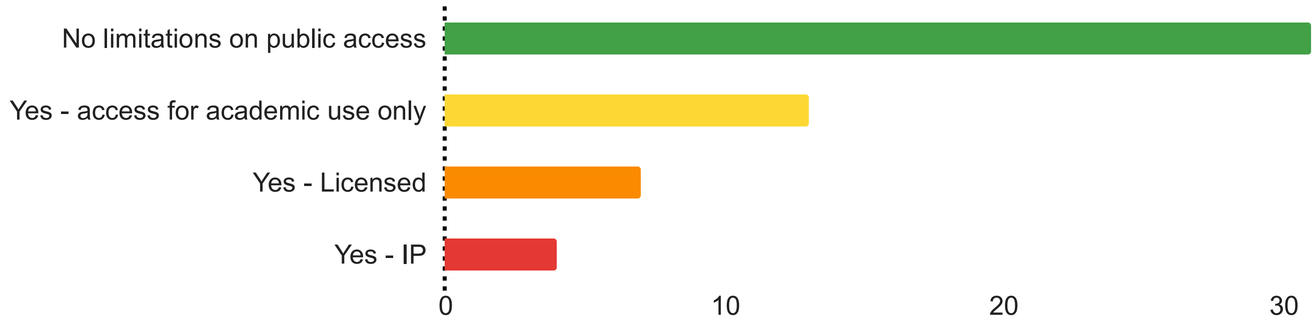
Q17 - Secondary Beneficiary

Field	Choice Count
Researchers	12
Industry/Business	12
Policy teams/analysts	14
Government Agencies (SEPA, NatureScot etc.)	26
Local Authorities	4
Communitites	1
Public	2
Others	0

Q17 - Third Beneficiary

Field	Choice Count
Researchers	17
Industry/Business	9
Policy teams/analysts	17
Government Agencies (SEPA, NatureScot etc.)	18
Local Authorities	3
Communitites	0
Public	4
Others	3

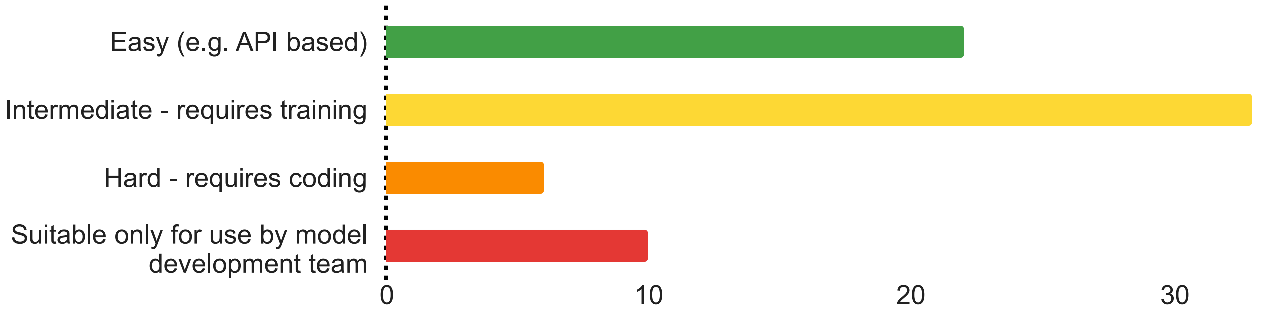
Q18: Are there restrictions to model/tool usage?



Q18: Other answers:

Inputs might be licenced.
The model is in-house only at this stage as has been developed rapidly in response to policy needs (Whole Farm Plan assessment as well as EFA extension assessments). Methods and results are being written up and will be in the public domain
unsure as yet
used for mediated modelling
latest code not yet released
The model itself is public access but some of the data sets used are licensed (eg. agCensus)
Don't know - ask PHC
still in development. Might change
access on request
For use by SASA to deliver risk forecasts to the potato industry
Can be shared within SG and with SG's partner organisations
happy to share but will need some training and possibly adjustment to make it easier to use
Integrated into internal Scottish Forestry application
protocol needs a skilled team to implement as well as open models and data
accessibility depends on datasets being used
Needs to be a registered farmer/crofter on SG RP&S system
No limitations but some intepretative guidance is required
Restrictions are in the software/hardware environment. Some data used will be licenced (e.g. Government Geospatial licence with Ordnance Survey, aerial imagery licenced from from Bluesky)
Currently academic use only but plans to make publicly available
on request
yes- if for profit

Q19: How easy is it to run the model/tool?



Q20: What evidence do you have of model quality?

Model is peer reviewed, citation or link:

The models are based on EcoServGIS (report can be found here: https://www.nature.scot/doc/naturescot-research-report-954-ecoserv-gis-v33-toolkit-mapping-ecosystem-services-gb-scale). Modifications have been made where there is new scientific information (from either peer reviewed literature or subject matter expert knowledge).

https://zenodo.org/records/7657945#.Y_OwnSbP2Uk

https://doi.org/10.1016/S1161-0301(02)00107-7

https://doi.org/10.1016/S1364-8152(00)00003-7

https://doi.org/10.1016/j.envsoft.2010.04.006

Model is due for peer review

Some aspects of the model are included in the UK's GHG inventory, undergoes international expert review https://unfccc.int/sites/default/files/resource/arr2022_GBR.pdf

Jones, R. J. A., Spoor, G. & Thomasson, A. J. 2003. Vulnerability of subsoils in Europe to compaction: a preliminary analysis. Soil and Tillage Research, 73: 131-143.

https://www.sepa.org.uk/media/344293/sepa-p-report.pdf

Lilly, A., Hudson, G., Birnie, R.V. and Horne, P.L. 2002. Inherent geomorphological risk of soil erosion by overland flow in Scotland. Scottish Natural Heritage Research, Survey and Monitoring Report No.183.

Lewis, M.A., Lilly, A and J.S. Bell. 2000. Groundwater vulnerability mapping in Scotland: Modifications to classification used in England and Wales. In: Groundwater in the Celtic Regions: Studies in Hard Rock and Quaternary Hydrogeology. Eds. N.S. Robins and B.D.R. Misstear Geological Society Special Publication No. 182. pp 71-79.

Bibby, J.S., Douglas, H.A., Thomasson, A.J. and Robertson, J.S. 1982. Land capability classification for agriculture. Soil Survey of Scotland Monograph. The Macaulay Institute for Soil Research. Aberdeen.

https://naturalcapitalproject.stanford.edu/research https://doi.org/10.1016/j.geodrs.2024.e00833

https://www.frontiersin.org/articles/10.3389/fenvs.2022.976933/full

https://doi.org/10.1016/j.agsy.2012.08.003

Hawes, C., Young, M.W., Banks, G., Begg, G.S., Christie, A., Iannetta, P.P.M., Karley A.J., Squire, G.R. (2019). Whole-Systems Analysis of Environmental and Economic Sustainability in Arable Cropping Systems: A Case Study. Agronomy, 9 438 https://www.mdpi.com/2073-4395/9/8/438

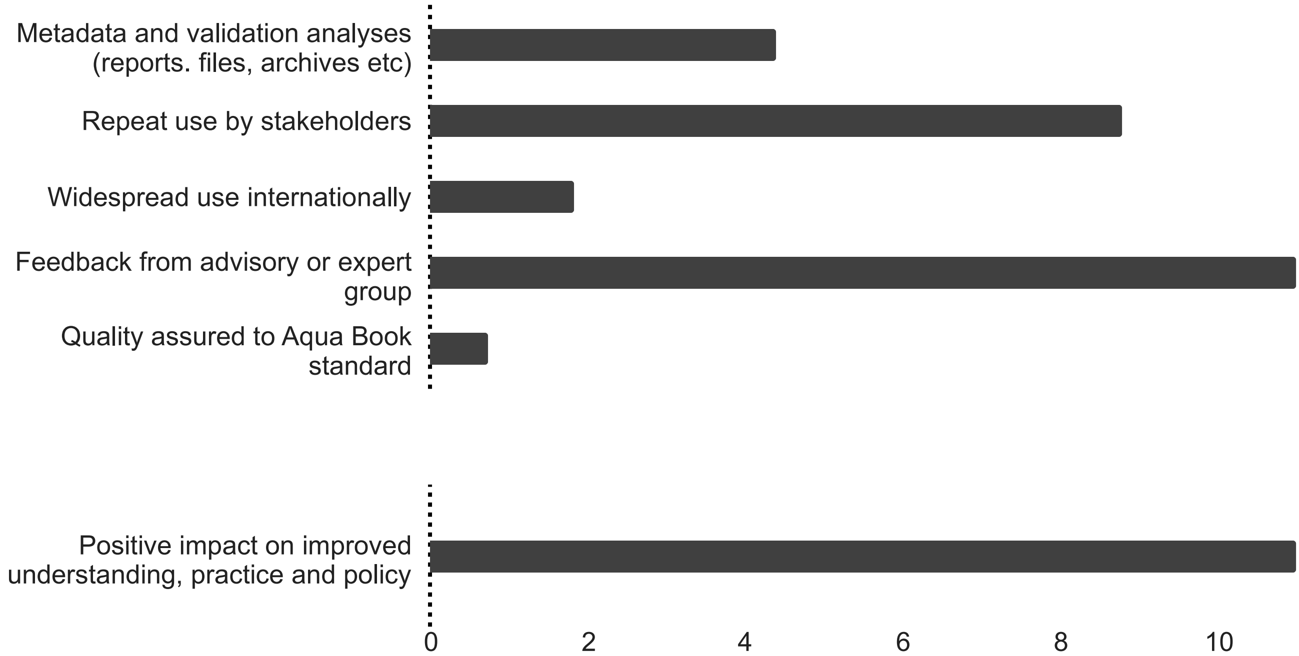
https://www.sciencedirect.com/science/article/pii/S0308521X23000690

Bibby, Heslop, Hartnup 1988 Land Capability Classification for Forestry in Britain. Soil survey monograph, Macaulay Land Use Research Institute

based on Boorman, D.B., Hollis, J.M and Lilly, A. 1995. Hydrology of soil types: a hydrologically-based classification of the soils of the United Kingdom. Institute of Hydrology Report No.126. Institute of Hydrology, Wallingford.

Boorman, D.B., Hollis, J.M and Lilly, A. 1995. Hydrology of soil types: a hydrologically-based classification of the soils of the United Kingdom. Institute of Hydrology Report No.126. Institute of Hydrology, Wallingford.

https://link.springer.com/article/10.1007/s11625-022-01242-8



The model has been used in UK policy maing for 15 years (Defra, CCC, SG)

This has been used in developing the economic business case for the Agricultural Reform Programme

The model has informed WG on the economic consequences of policy decisions since 2021/22 and outputs were used in the 2024 consultation (that resulted in 5,000 pairs of wellingtons being left at the Senedd)

The model has been used to provide ongoing assessment of cattle performance metrics in Scotland and forms the analytical basis for choices around 410 day calving interval conditionality for the SSBSS, of estimates of changes to payment rates for SSBSS, for emission reduction potential from herd performance improvements and of the potential economic impacts on small herds

M&E within JHI-C3-1, and feedback from policy teams

upcoming CxC report on understanding variation in peatland restoration cost

Was used in developing risk assessment for Private Water supplies

https://soils.environment.gov.scot/maps/capability-maps/national-scale-land-capability-for-agriculture/

https://eprints.ncl.ac.uk/274791

Used by stakeholders in practice and policy such as spatial planning of renewable energy, programmes of public understanding of issues (e.g. offshore wind energy systems; public awareness campaigns for responsible access to woodlands to reduce risks of spreading Chalara ash die-back).

Key in implementing rules around slurry applications in NVZs

Embedded in UKCEH flood estimation software

Q20: Other answers:

Whilst the model is developed within SRUC, Dr Andrew Moxey has been involved in the design and quality assurance of the model and its outputs

this is difficult to answer. the parent models are all widely published, but the extensions/adaptations to produce valid outputs for peat soils is still in development. Present models struggle with peat.

New platform currently in development

still in development

its 1st application for a "final" output is currently underway

paper including the latest model development is in progress

The model output has previously been used by SEPA for a number of ND/NVZ reviews. There are a few reports and publication describing the model: (1) Dunn SM, Vinten AJ, Lilly A, DeGroote J, McGechan M. Modelling nitrate losses from agricultural activities on a national scale. Water Sci Technol. 2005;51(3-4):319-27. PMID: 15850205. (2) CREW report https://www.crew.ac.uk/sites/www.crew.ac.uk/files/calldownservice/CREW_nvz%20report.pdf.

Still under development, but will be peer-reviewed (2025)

the model is still in development. Unit testing gives confidence about the model structure, but we are still working on validation against empirical data

Modelling approach has been applied in other circumstances

based on validated models as input layers

None really at the moment!

Trained, tuned and tested using 25 years of data

None

https://www.crew.ac.uk/publication/assessing-climate-change-impacts-water-quality-scottish-standing-waters https://www.crew.ac.uk/publication/developing-probabilistic-risk-model-estimate-phosphorus-nitrogen-and-microbial-pollution

protocol still in testing stage - will go for live testing with SG in 2026

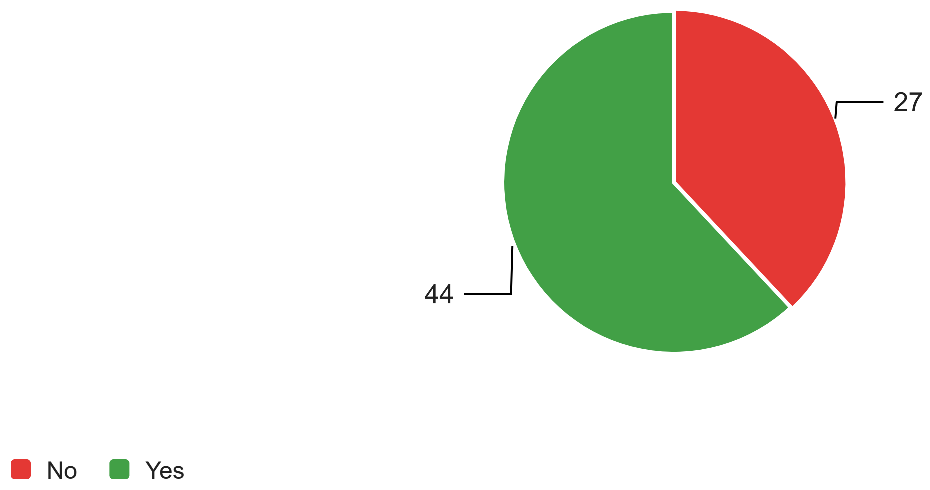
Model has gone through initial stakeholder testing successfully

Our model is not yet published, but the embedded model has widespread use internationally (https://naturalcapitalproject.stanford.edu/software/invest)

not published yet

This is only an interface to an underlying published model
validation on progress
Expect it will be peer-reviewed
Combination of other models
Working on publication
Tool currently under development, based on a published DEXi MADM model but incorporating datasets from the CSC long term platform, technical notes and monitoring protocols the content of which has been variously published and/or discussed at site visits with stakeholders over the past 14 years
validated with game keepers
many of the spatial layers in input originates from peer-reviewed outputs of from agencies. So, multiple papers and reports

Q21: Does your model or research tool generate outputs that can be used as metrics or indicators against which real-world progress can be measured?



Q21: If Yes, please provide examples:

Confused a bit by what is meant by real world progress but out models do produce biophysical values from ecosystem service models which could be re-rerun over time once change has happened to see the impacts on those values.
GHG mitigation in agriculture
Prediction of uptake of policy decisions
The model uses population data and links to other official data - the model therefore estimates animal / cph /brn level metrics that can be monitored
monetary and non-monetary value and biophysical indicators of ecosystem services under different land uses
the empirical model outputs are the underlying data for emissions report as per UK Tier 2 emission factors for peatlands and also underpin the Peatland Code emission factors.
Yield, Biomass, SWC, N losses

Yield, Biomass, N2o, N leaching, SWC

Opportunity to conduct on the ground assessments of changes in land capability for agriculture

e.g. connectivity and carbons sequestration perfomance is expected

The tool is used to evaluate the contents of various datasets within farms. So in theory can be used to monitor the progress of various initiatives, e.g., woodland area, within agricultural land over time.

Not sure I understand this. The model simulates nitrate leaching to groundwater and can be/has been calibrated to nitrate monitoring data in groundwater across Scotland (SEPA groundwater monitoring network). The water balance module has also been to some extent calibrated against river discharges in HMS catchments. But not sure if this is what is being asked here.

Inputs to impact models or further analysis

We could compare distribution of Statutory Plant Health notices issued to control the disease with high risk areas identified by the models, and explore correlation between disease outbreaks and climate suitability predicted by the model.

Can compare predictions of beetle distributions with what we then observe

the predictive use of the model can provide ballpark estimates/ ranges of peatland restoration cost in clusters of environmental conditions. The validity of such predictions can be checked against historical data

It predicts suitable refugia under climate change, which can be monitored

The outputs will support decisions that allow land managers to progress towards biodiversity/carbon/ecosystem service goals

The model measures material flow, so production of agricultural commodities can be compared to, e.g., farm economic data

GHG scenario estimates can be compared against annual GHG inventory values

Can compare risk against actual topsoil compaction

It can be used to produce maps of baseline soil properties by linking the spatial model to soils databases.

tool shows how much degraded peat is in a parcel of land so can be used to assess whether restoration can be done in areas

Compared to realised disease outcomes

Identifies how much land has been deregistered with the Rural Payments and Inspections Division from year to year and since 2012 and gives a picture of what this land has become (whether it has remained as it was or whether it has been developed and thus potentially permanently removed from agriculture)

Yield, Biomass, SWC, N leaching

nutrient concentrations and probabilities of exceeding a threshold

Reliance in % or monetary terms of different industries on natural capital/specific ecosystem services

Depending on model being adapted

expected to be able to provide what-if scenario figures in terms of market garden production for different ways of providing an enabling environment for such producers

Could be used/updated to show progress in peatland restoration

Habitat assessment provides a RAG rating for biodiversity (poor/moderate/good)

species distribution/abundance at peatland site

Woodland Carbon Code and Peatland Code carbon figures and financial forecasts, grant funding opportunities, natural capital baseline

Compare observed disease spread with that predicted by the frameworks

Testing control scenarios to understand if current measures had impact and could be compared against in future

Relative crop yield, pest & disease, input use (fertilisers, pesticides, soil management)

Is part of the Carbon Budget Delivery plan

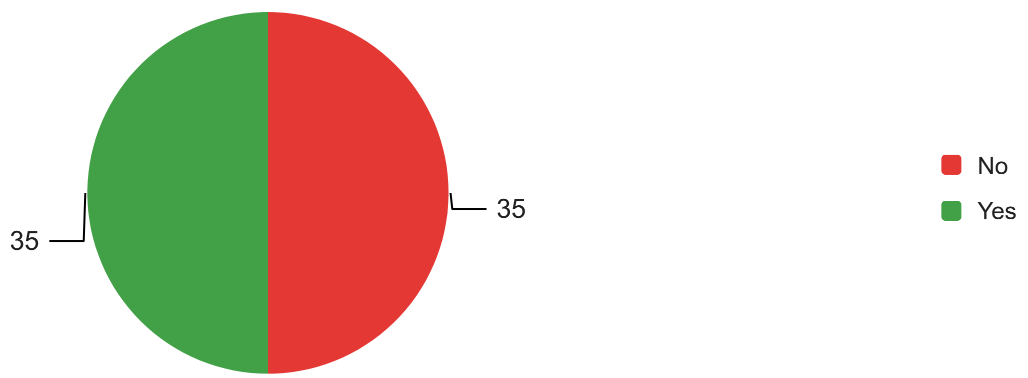
Will estimate manure methane emissions at farm to national scale based on local tempertures

Sustainability metrics will be provided based on soil health, biodiversity and crop systems indicators. These can be used in an iterative process for bespoke cropping system design to improve on the sustainability outcomes. Technical information will be provided for the management options that the user selects and protocols for measuring impact on biodiversity and soil are provided to facilitate outcomes based monitoring.

Efficiency, viability, greenhouse gas, nitrgoen use efficiency

Outputs include predicted land use, GHGs and land available for biodiversity. See https://link.springer.com/article/10.1007/s11625-022-01242-8

Q22: In your opinion, are there limitations or barriers to the potential for your tool/model to be integrated into wider decision support frameworks?



Q22: Yes, please provide more information:

the conceptual work for ERAMMP this model was done through an ongoing contract with Welsh Govt (2020-2026 through various commissions) to provide economic evidence for the Sustainable Farming Scheme policy scenarios. The model does not align to ERAMMP for a variety of reasons (spatial scale, baseline year, assumptions, data integrity, etc). Any type of integrated model must be done using the same spatial scale as a starting point. The model could have wider models attached - or the processes used in this model could be adopted in other models to improve representativeness. Diseconomies of scale and scope are observable, as is time to respond to policy needs from these wider modelling frameworks (i.e. in Wales our model is considerably more policy agile than ERAMMP - same in Scotland); to develop a module for EFA analysis in the timeframe given in 2024 would be impossible under a framework model.

The WG commissioned this work separately from ERAMMP despite it having an economic famr level optimisation model integrated. This model uses field and farm level data as the decision making unit which ERAMMP does not. There have been various meetings on model commonalitites and methods but the issues around data integrity, assumptions, baseline dates, etc means that the models are independent - although this model does feed payment rates into the ERAMMP model. This model's outputs were used in the WG consultation exercise rather than ERAMMP

Data sharing issues (APHA) may prevent integration - but metrics for cph / BRN / spatial region / farm system can be used if those are the scales of models

Would require writing codes to integrate the model simulation outputs.

Programming would be needed to integrate the model outputs.

There would be a considerable overhead in integrating an already complex framework into another framework. The value of the LCA framework is best gained through use by the developers as they have in-depth knowledge of the models, data pipeline and data quality issues.

Yet to be understood.

It is not an assessment tool, but identify zones for potential land use change

It is a land use change modelling tool. So Ecoserv might not be appropriate, but might be ok with ERAMMP.

To be honest, I don't really know. Some of the input files for the model are currently derived (e.g. potential evapotranspiration is derived based on Penman Monteith, so to be integrated into a wider framework, then it is perhaps necessary to use consistent PET models across all the models/tools integrated into the framework) and developed quite specifically to the type of land use data used (e.g. fertiliser application rates and N uptake are assumed and linked to the land use categories in LCM and agCensus, so modifications would have to be made if the model was to be applied using a different land use data set (consistent with whatever is used in the framework). Such modifications can be done (we did this when recently modelling future N leaching risk based on some future land cover projections, CRAFTY) but it obviously would take time

While some added value datasets could be provided most analyses are bespoke interpretations of policy led requests - no issue to share but no benefit to us of using the listed tools other than as sources of data

Needs further development e.g. QA and introduction of predictive measures, and ability to update as currently ends in 2021

Need more data to validate the model

There may be commercial limitations, technically this should not be an issue however.

Likely it is large and slow to run, but in principle there is nothing preventing inputs/outputs being shared between models for, e.g., different scenarios

Would require resources and ongoing maintenance funding to integrate current model/tool into wider decision support frameworks and keep it up to date

The model could be integrated into other tools/model, this would require common spatial data frame, i.e. matching pixels. The model provides a similar output to EcosrvR, but differs in building up from a different set of underlying natural capital asset data (e.g. soils, slope, climate).

Some barriers due to the need to understand each other code, but not too difficult, especially for other tools based on R, like EcorvR

Unsure, as not certain of what use an ownership model would be in the case of tools you gave as an example (ERAMMP link not working btw). But the use of licesnesed data within the model would be an issue.

Permission would need to be sought from SASA

Q22: No, please provide more information:

Our tool is completely open access and has been designed to integrate into other frameworks/tools

Approach is based on decision rules that combine numerical and spatial datasets so there shouldn't be an issue integrating it within other frameworks.

It could be added on to agricultural activity projections at any spatial scale.

Difficult to say. The main idea of our model is to deliberate scenarios and potential values emerging. These scenarios could be used and integrated in EcosrvR.

I cannot answer this as I have no working knowledge of either, however such frameworks tend to not work well for peat soils.

My database essentially spatially aligns useful agricultural/environmental data to agricultural land parcels. In theory this is an operation that only needs to be done one time before doing a plethora of other analyses; it feels like the starting point for data integration that would precede a wider decision support framework.

Don't know - ask PHC/researchers

It would require diagnosis of data input alignment and harmonisation of processes but overall it could be possible

I'm not aware of any barriers, but would need to learn more

It would probably need coding for data exchange but theoretically possible

Modelled digital soil property maps can and have been integrated within land management and environmental risk assessment frameworks, incl. recently EcosrvR.

Environment Systems were open to collaboration and integration into other tools/frameworks

Doesn't appear relevant

Happy to share but may need a bit of work to integrate.

Outputs can be used within wider frameworks

The protocol should be able to support these frameworks

Depends on how open these frameworks are

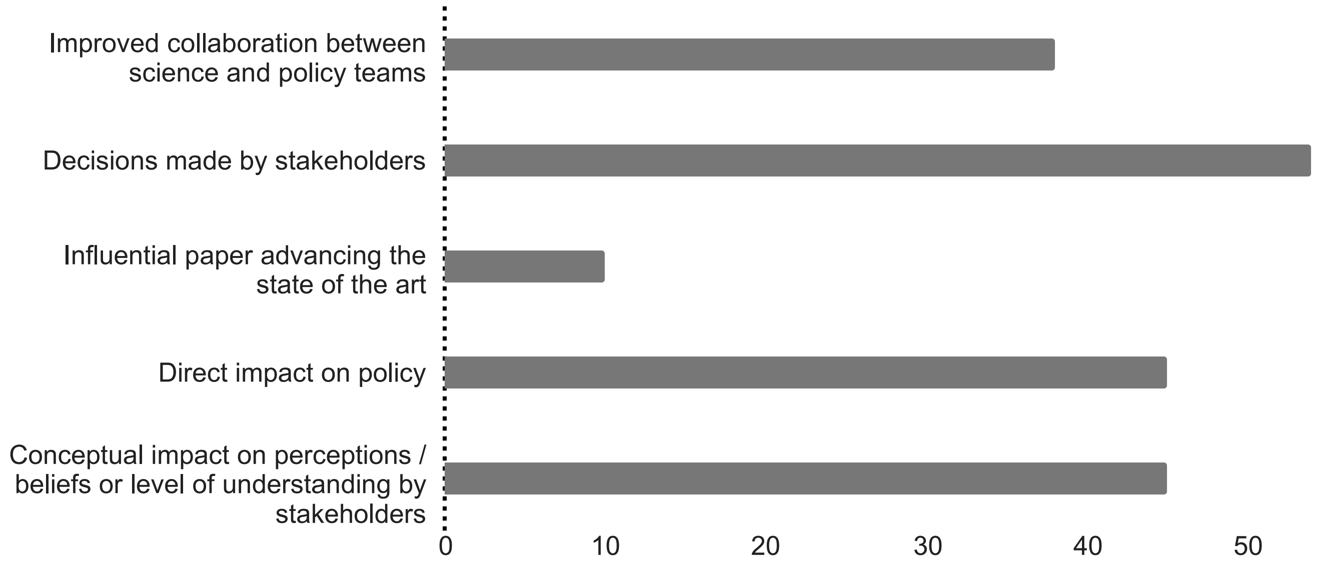
Don't know

Don't know

I'm afraid I don't have the technical knowledge to be able to answer this question, but all the content of the Bio4Ag tool and its outputs are publicly available and I don't see any reason that they couldn't be integrated or used to inform other frameworks

Suitable for integration.

Q24: What impact can/could your model/tool generate?



Q24: Can you provide a direct example of the model's impact?

Our tool is still in development so can't comment fully on this, but from our prototype testing we were informed that it helped our users engage with the community about the benefits nature, and influenced their decisions around where to support nature recovery.

Tool was developed to assist SEPA in issuing Waste Management Licencing exemptions for the application of certain wastes to agricultural land, in relation to risk to water quality from diffuse pollution. Unaware if SEPA implement the tool in their systems.

Informing carbon budget development in the UK and Scotland for more than 15 years, over 20 reports, papers (examples: 10.1016/j.jclepro.2024.142287, 10.1016/j.jclepro.2018.01.252, 10.1007/s10584-010-9898-2)

The model has been used in the Agricultural Reform Programme - in particular to justify the economic case in the 5 case model of the Greenbook

Use in Welsh Govt consultation on SFS

New 410 day calving interval for SSBSS, and associated estimates of payment rates, etc. Multiple presentations to ARIOB and papers launched by Cab Sec.

Model is underdevelopment. We have a framework and selected tools for implementation. first test will be made in 2025. Goal is to produce scenarios and a series of changes in ecosystem services and natural capital conditions that can be discussed with stakeholders, measured in biophysical and monetary units (where possible) and deliberated to find solutions tat minimise conflicts. Ideal application is at landscape and catchment scale.

see earlier response re the empirical models and their application in emissions reporting. the land surface models in question contribute to IPCC level compilations as their parent (trunk) versions are embedded in Earth System models. The contribution here is to produce better peatland representations in the land surface models for improved Earth System model runs.

The dataset has been used in the SG Strategic Research Programme: project JHI-D5-2 Climate Change Impacts on Natural Capital

The model is used in the current SRP and has been used to analyse the impact of soil degradation on spring barley yield across Scotland

The model can be used to inform about the impact crop management and climate change could have on crop productivity and N losses

The LCA platform is new and outputs only just starting to be used, but has already attracted a lot of attention from policy teams and interest from land agents

Not yet

The model supported the identification of farms that have both peatland and agricultural grazing activity, which helped inform discussions on targeted place-based grazing policy within government.

Focused discussions with NatureScot on the 1st set of results of the model.

Paper in progress on SSP1 scenarios (NetZero), example here:
https://storymaps.arcgis.com/collections/20665a1964b54e429d32ca61f897bd47?item=1

The model is/has been used as an additional strand of evidence for designation and reviews of NVZ, particularly in data sparse areas.

2008 Brian Pack review, 2013 CAP greening decisions, 2015 CAP regionalisation decisions, 2016 Areas of Natural Constraints, 2018 Driven Grouse regulation, 2021 CAP stakeholders review of 2015 reform impacts, 2023 Enhanced Conditionality review, 2023 Land Reform Bill BRIA, 2024 ARP Tier 1 review of regionalisation options.

Will be used to review of Phytophthora action plans - i.e. guide policy decisions about future control and management of these diseases

Diversification of forestry planting

Influence the way farmers control Johne's Disease on farms

Inform GHG inventory reporting

Still in development, but upcoming report has a potential to influence decision making

The model is still under development, but there are requests to use the outputs when complete to prioritise investment in conservation action

AECOM have used it internationally to inform planning decisions to protect species (e.g. pangolin). So far over 60% of Local Authorities have been onboarded to the tool and are able to use it to develop Nature Networks. Private energy companies have also started using it to bring wildlife connectivity into their thinking on their estate.

Not yet

Model has been used by CCC in determining the 6th and 7th Carbon Budgets, which then focuses policy attention on certain issues- the GHG emissions estimates from modelling of degraded and restored organic soils under different land uses has been used to justify policies and funding for peatland restoration in Scotland and the UK.

Used by SEPA during farm visits. Maps available on Scotlands Soils Website (https://soils.environment.gov.scot/)

https://www.fas.scot/downloads/managing-soil-phosphorus/

Used by SEPA. Used in project to assess cost of erosion to Scotland (23. Rickson, R.J., Baggaley, N., Deeks, L.K., Graves, A., Hannam, J., Keay, C and Lilly, A. (2019). Developing a method to estimate the costs of soil erosion in high-risk Scottish catchments. Project UCR/004/18 CRF CR/2015/15. Final Report to the SG.)

Used to develop a risk assessment for Private water supplies (https://www.daera-ni.gov.uk/sites/default/files/publications/daera/Private%20Water%20Supplies%20Technical%20Manual.pdf)
Embedded in the national planning guidelines
Previous applications of the modelling approach have been used for land use opportunity mapping in St Helena and Montserrat. The impact on decisions is unknown.
Not yet
Used as input to RIVERTOOL to support Scottish Forestry in their zonation for riparian forest grants
National mapping of wetland areas (CREW, https://www.crew.ac.uk/publication/moderating-extremes-water-availability-review-role-functioning-wetlands), map provided to NatureScot to be used for restoration screening purposes.
No, model was not funded after initial development as was not financially viable without continued SG funding
Still ongoing ...
It will be rolled out to the potato industry next growing season.
The modules developed for NatureNetworks are being used by Local Authorities to design their NatureNetworks
Results of original analysis shared with Cab Secs. Analysis ongoing. Model will automate future analysis.
The platform can assist farmers with their decision-making to improve productivity and reduce environmental impact
Another version of this modelling approach was tested by SEPA in the river Eden within the OnePlanet regulatory framework https://doi.org/10.21203/rs.3.rs-4172006/v1
Outputs have helped raise awareness amongst policy and public of what climate change looks like in terms of indicators that land managers use for decision making
The tool is used on a daily basis by our operational staff to assist in decision making processes for a wide range of forestry operations.
Impossible to make a direct link
Showing which industries, regions, jobs are supported by natural capital and to what degree - this also makes the case for working towards and which areas/industries to focus on when mitigating and adapting to climate change to protect people's livelihoods and prosperity of the economy.
Not yet
proof of concept testing with stakholders has been passed
It has been used in work by SSEN to better understand peatland across a planned area of development. It is also being used by NatureScot within the Peatland Action programme as part of their decision-making process on peatland restoration.
to be included in a future paper
Used to identify where to improve woodlands corridors and impact of LUC scenarios on them
Interface to facilitate the setting up of NetZero land use change scenarios (submitted paper), considered by Lake District National Park
The tool will enable farmers/crofters to better understand the condition of their habitats and how they might be improved for biodiversity.

The model can inform management of peatlands under different climate and management scenarios e.g. active drainage/blocking of drainage or removal of certain species. The model is able to account for specific topology of a site and therefore given appropriate data could inform local management or be used to understand how broad characteristics across sites influence management decisions We believe the model is unique in that it provide species level data unlike most vegetation models, this can be useful in informing local management of peatland sites where certain species may be of interest. The framework could also be used to carryout similar analysis of other systems

A 450,000 hectare data analysis project was carried out with the SG, to provide evidence of the outputs of the Rethink Platform. A study area previously analysed by SG was used to see how well the Rethink Platform could replicate the results. The output was found to be consistent and accurate, and provided a tool to speed up analysis whilst providing opportunities for sharing the analysis in new, interactive ways. The tool has recently been used as part of a catchment scale project to analyse multiple farms within the catchment for current conditions, opportunity areas and natural capital. Our aggregation tools enabled metrics such as the Woodland Carbon Code to be run at scale, identifying the overall carbon sequestration and potential income across multiple stakeholders. Working collaboratively has opened up opportunities that were not possible as single entities.

Spatial risk frameworks will inform Scottish Forestry Action plan for specific pests/diseases and will be taken to UK Plant Health Risk Register to inform UK level risk assessments

Will inform how Scottish Forestry revise the Phytophthora ramorum action plan with statutory implications

We consulted stakeholders (farmers, agronomists, policy advisers) during tool development to get their feedback on its utility; a potential use was foreseen in understanding what it is feasible to measure in farms and the extent to which mixed cropping practices can affect desired outcomes (for biodiversity etc)

Example impacts - Reducing risks of spread of plant disease - very positive public responses to session explaining evidence of Chalara ash die-back in woodlands, with apparent increases in awareness of risks and approaches of responsible access being mindful of cleaning shoes, tyres ('Boots, Bikes, Buggies'). Understanding of renewable energy - Increases understanding, over a 15 year period, of the background to offshore wind energy development in Aberdeen Bay, changes in spatial plans, prospective environmental impacts, and expectations of future developments. Co-constructing future land uses - citizen development of options for land uses in rural and urban areas, providing evidence of attitudes towards the introduction of renewable energy systems, woodland expansion, flood risks, and features in urban greenspaces.

Used in Carbon Budget Delivery plan

Helped make SG aware of the different emissions between regions of the UK via poster: https://sefari.scot/sites/default/files/documents/DFletcherRESAS-ve.pdf

DEXi-CSC model framework was used to design a regenerative arable crop system, balancing trade-offs between conflicting management goals at the Centre for Sustainable Cropping long-term platform. The effect on field-scale system properties has since been used to demonstrate the successes and weaknesses of the approach to stakeholders and has influenced adoption of whole-systems design approaches at other long-term research sites (e.g. Leeds University and Rothamsted). The audience is currently researchers (through peer review publication) and industry (through in-person site visits). Once the front end is built, it will be possible to extend current impact to a much wider group of stakeholders including national and EU farming communities, policy makers and as an educational tool.

Identifying best practice in carbon emission intensity, efficiency and viability https://soils.environment.gov.scot/resources/forests-and-woodlands/

The model has been embedded in soil erosion risk assessments both in Scotland and Ireland (4. Mellander, P.; O��Uallachain, D.; Baggaley, N.; Wilkinson, M.; Lilly, A.; Stutter, M. (2023) Specific Management And Robust Targeting of Riparian Buffer Zones Specific Management and Robust Targeting of Riparian Buffer Zones (Smarter_BufferZ Project) (2017-W-LS-16)EPA Research Report Prepared for the Environmental Protection Agency by Teagasc & James Hutton Institute)

This map was developed to show the distribution of the particular soil texture classes as they are described in the Nitrate Vulnerable Zone Action Programme.

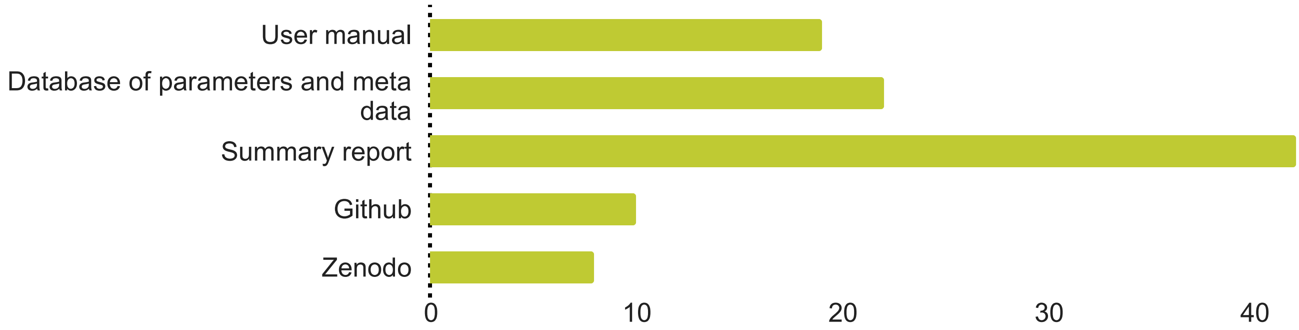
Embedded in UKCEH Food estimation software to predict low flows

FABLE for Wales informed the Welsh climate change action plan, specifically around the role of healthy diets.

Used by Trees for Life to interact with deer managers

RIVERTOOL (the river-focussed version of ECOFOREST) was used by Scottish Forestry to make a zonation for riparian woodland grants. It was also used by the RIVERWOOD partnership to explore where to fund riparian reforestation.

Q25: What documentation or metadata does the model/tool have? What do you use to record this?



Q25: Other - please specify:

Report
Unkown
In development
Developing ODD
No documentation
User manual
Unsure
Help internal information
Website
Published paper
In development
Planned
Published papers and reports
AgMetrics website
User manual and videos
Application protocol
Story map
No documentation
Quick start guide
GitLab
Published paper
https://axial-trail-391808.web.app/
Presentation and training videos
Story map