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# Cross-scale analysis of social-ecological systems: Policy options appraisal for delivering NetZero and other environmental objectives in Scotland

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**Abstract:** Public policy confronts complex, contested, wicked problems such as climate and biodiversity crises with challenges of how issues are framed, analysed, codified, and interpreted. Social-ecological systems provide an analytical framework that couples the biosphere and technosphere, recognising biophysical limits and emphasising the importance of critical reflection within policy decision-making. Conducting policy-options appraisals is increasingly seen as a transdisciplinary research-policy endeavour with researchers engaging policy actors in an extended peer community (post-normal science). This paper presents a case study of analysis undertaken with researchers, policy analysts, policy makers and other stakeholders to support decisions on how to implement future agriculture support in Scotland, so that the policy programme better delivers across social, economic and environmental objectives.

The key change being considered in the future agricultural support programme is Enhanced Conditionality (EC) where the level of financial support provided to farm-businesses will depend on their undertaking agri-environmental measures that deliver against the key priorities of reducing greenhouse gas emissions and reversing biodiversity losses. The paper outlines the policy context within which the EC options appraisal takes place – highlighting how EC is a crucial component in making the wider suite of policy measures work.

The transdisciplinary approach, Quantitative Story Telling (QST) is presented, emerging from decision support, participatory research, and post-normal science for policy domains. The stages of QST highlight the importance of analysis that underpins any quantification (decision on how issues are framed and what it included in the analysis) and the expectation that research outputs with be deliberated on with, and interpreted from, stakeholder perspectives. The project specific analyses are outlined, combining top-down options appraisal of how macro-policy decisions could constrain EC and bottom-up analysis of potential uptake and effectiveness of EC measures, undertaken in inter-disciplinary workshops with domain experts from biodiversity, soils and waters. The paper highlights challenges for implementation and evaluation at meso-scale with interactions between farm-businesses and catchment, landscape and regional objectives.

The conclusions of the analysis, in policy terms, are that EC presents an opportunity to significantly realign how agricultural land management is conducted in Scotland, so that it is more effective in delivering climate change and biodiversity objectives, but there are formidable challenges in resolving the policy "sudoku". Meso-scale issues are likely to mean the need to integrate alternative modelling paradigms such as spatial, empirical agent-based modelling (ABM) into policy option appraisals. By taking multi-scale, social-ecological systems perspectives on EC it has been possible to identify key policy decisions at a range of scales on which the success of EC will depend, to have a realistic understanding of how effective the EC measures might be in heterogenous Scottish environments and what are the likely barriers to uptake. The analysis also highlighted where outcomes of the policy change are likely to be challenging to monitor-evaluate; and where there are dependencies between farm-businesses that mean EC measures need to be supplemented with mechanisms that (1) promote cooperation between land managers and (2) identify and respond to agreed local priorities. The value of the participatory QST process was in making sure the analyses being undertaken were salient and the outputs seen as credible – but the challenges of interpreting necessarily complex outputs remain. The greatest value of QST may be that it provides a structured way to navigate complexity with policy makers rather than seeking to control or eliminate it.

***Keywords:*** *Agriculture, environment, sustainability, policy, scale*

## 1. INTRODUCTION

This paper presents a case study of an inter- and transdisciplinary analysis undertaken with public policy analysts, policy makers and stakeholders to support decisions on how to implement future agriculture support in Scotland, so that the proposed programme better delivers across the social, economic and environmental objectives.

Public policy confronts complex, contested, wicked problems with challenges of how issues are framed, analysed, codified, and interpreted. The urgency of the climate, biodiversity and other crises means there are advocates for transformational change, but transformation is seen as inherently risky and opposed by beneficiaries of the existing approach. Social-ecological systems provide an analytical framework that couples the biosphere and technosphere, recognising biophysical limits and the importance of critical reflection within policy decision making. Such framing is inherently interdisciplinary (problem oriented) and can make use of computer-based analysis to make sense of systems (diagnostic) or testing alternatives (backcasting, options of how to deliver outcomes). There is also a recognition of scale as key factor in issue framing and analysis – what is observable and interpretable is scale dependent, not just geographically but via other classifications such as industry sectors. Conducting policy-options appraisals is also increasingly seen as a transdisciplinary endeavour, that is, engaging with an extended peer review with multiple, non-equivalent perspectives reflecting different interests and communities (post-normal science). Participatory processes are needed that can use context dependent knowledge to interpret the salience, credibility and legitimacy of the analysis undertaken.

## 2. BACKGROUND

The political background for the analysis is the decision by the UK government to leave the European Union (EU), enacted in 2020. Previously, Scotland's agriculture policy had been heavily shaped by the EU Common Agricultural Policy (CAP) with decisions on both budgets, and the measures implemented, decided in EU level processes. In the post EU-exit period, Scotland has remained broadly aligned with the CAP with agricultural support divided into two Pillars – Pillar 1 with Direct Payment schemes available (subject to eligibility) to all farm business and Pillar 2 schemes delivering both enhanced payments for biophysically disadvantaged land and agri-environmental or rural development measures subject to competition for funding. Longer term there is the need for a new legal basis for agriculture support and the new primary legislation is an opportunity to reshape how to deliver the objectives of Scottish Government (SG). In 2022 SG published a proposal for a new Agriculture Bill which contained both a 'Vision for Scottish Agriculture' and proposals for agricultural support payment mechanisms (Scottish Government, 2022). While remaining committed to objectives of food security and viability for farm businesses, the Vision was much more explicit in tying agriculture policy into GHG emission mitigation (NetZero by 2024), stopping (by 2030) and reversing (by 2040) biodiversity losses and increasing the resilience of rural areas to climate change. These objectives are also guided by principles of Just Transition and specific commitments to remote and island-based communities.

Central to delivering this Vision is the use of Enhanced Conditionality (EC), see Tier 2 in Figure 1, as a mechanism to mainstream agri-environment measures for all farm businesses with 50% of current funding becoming conditional on undertaking agri-environmental measures. Tier 1 (Base Payments) would also see more demanding minimum standards. Targeted and competitive elements of funding will remain in Tier 3 (Elective Payments) for nature restoration and business development. Tier 4 (Complementary Support) will invest in skills, monitoring and land use change. This is the policy 'sudoku' discussed in the results.

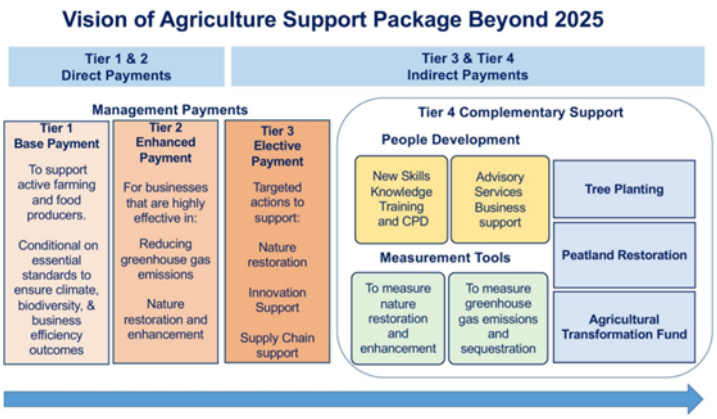


**Figure 1.** Taken from Scottish Government (2022)

At the scale envisioned in the Vision, EC is a step-change from the existing CAP Pillar 1 Direct Payments through stronger environmental requirements; or Pillar 2 agri-environment schemes as it has a bigger budget and applies to more businesses. As a "menu" type of scheme each farm business, unless otherwise constrained by EC measure targeting, will make a free choice of EC measures and their extents. That choice balances the desirability to the business of each EC measure, the resources needed to deliver the EC

measure, and the weighting per measure (ha equivalents). The mix of EC measures, and the outcomes of EC measures undertaken will vary depending on the specific environments in which they are implemented.

## 3. METHODS

The specific approach to transdisciplinarity is Quantitative Story Telling (QST).

### 3.1. QST (theory)

QST was first formalised and tested by the lead authors in the H2020 MAGIC project in which it was used to support social learning regarding water-energy-food nexus issues and governance in complexity - multiple land use sectors, multiple objectives, multiple scales (Blackstock et al., 2023; Matthews et al., 2021; Renner et al., 2020; Waylen et al., 2023). This application of QST formalised knowledge and learning from Hutton researchers in a range of fields over several Scottish Government Strategic Research Programmes. These included land use decision support (Matthews et al., 1999), soft system analysis (Matthews et al., 2002), deliberative inclusive processes (Matthews et al., 2006; McCrum et al., 2009), research communication (Matthews et al., 2008), evaluating the impact of using environmental modelling and software (Hare et al., 2003; Matthews et al., 2011), policy options appraisal (Matthews et al., 2013) and transdisciplinary working with policy teams (Matthews et al., 2015). The experiential learning was combined with insights from post-normal science that highlights the need to think differently about how scientific data is deployed to support decision-making, when facing complex, contested and urgent transformation challenges. QST responds to these challenges; it is a process designed to help scientists work with stakeholders to prompt reflection on, and potentially reframing of, sustainability problems and to develop shared understanding of the issues even when conflicting stakeholder values mean that generating a consensus is challenging.

### 3.2. What happens in a QST process?

QST is a cyclical, iterative process that balances both 'semantic' phases – work with stakeholders to understand how issues are framed (what is included and excluded) and how evidence is interpreted - and 'formal' phases – work to quantify these issues, see Figure 2. QST typically incorporates data and expertise arising from different disciplinary perspectives (e.g., social, and natural sciences) as well as from stakeholders themselves. In this diagram, the top represents both the start and potential end point of the cycle, but successive iterations are desirable (Matthews et al., 2020). The figure highlights the importance of semantic-formal and formal-semantic interfaces where translational processes are undertaken and where co-construction can be crucial.

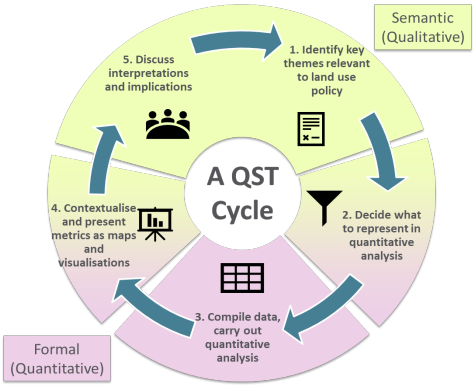


**Figure 2.** The stages of Quantitative Story Telling (QST)

### 3.3. Project specific analyses

The analysis focuses on the EC measures from multiple scales and perspectives. The analysis of EC measures is contextualised by discussion of macro level policy options. These include the implications of budgetary decisions allocating resources between Tiers and decisions within Tiers on how funds are distributed in space. Many of these decisions have not yet been made but the impacts of these different options need to be included as they dictate which farm businesses could access the resources and where environmental outcomes will be expected. Budget and regionalisation decisions also have implications in terms of redistribution with implied gains and losses for regions and sectors. The authors could draw on several of these macro-level options appraisals conducted via other projects to inform the EC analysis. The lead authors were also able to draw on analysis of the previous Ecological Focus Area (EFA) scheme that implemented a "menu" scheme for arable land, looking at patterns of uptake for the range of measures, regionally, per business type and over time.

For the proposed EC measures the authors undertook a screening process – eliciting and formalising knowledge both from previous projects looking at uptake of agri-environmental or nature restoration measures and from a wide range of biodiversity, soils, waters domain experts within the wider 2022-27 Strategic Research Programme (SRP). Their expertise spanned a wide range of spatial scales – plot, field, business, region/catchment/landscape and national/EU. The EC screening used workshop-based reviews of the EC list of measures that contains 93 proposed EC measures, 36 for GHG emissions reduction; 12 for soil health and 45 for protecting or improving biodiversity. This listing was discussed with thematic groups of researchers

over three sessions. First a scoping discussion of the policy background and measures with the thematic lead, second an initial review of the measures (~3hrs) followed by an in-depth workshop (~6 hrs). Deliberation on the issues was structured by a summary screening matrix. Comments and issues were either captured in the screening matrix or articulated within a screening synthesis document. The decision to focus on EC was made following an issues-framing workshop with SG in September 2022; and the screening insights were shared with SG for their feedback during February 2023. The researcher workshops were also influenced by interactions with other research for policy and stakeholder processes; so the EC screening also incorporated insights from SG policy and analysis colleagues gleaned from related analysis processes.

## 4. RESULTS AND DISCUSSION

The results of the screening process are presented in terms of the macro (wider SG policy choices); micro (farm business/land management practices) and meso (interactions between farm businesses) scales. Policy sudoku shows that decisions made between these scales condition the potential EC choices and outcomes achieved. Decisions made for up to n=19,292 farm businesses thus need, in sudoku speak "add up to", all the national and intermediary scale commitments.

### 4.1. Macro-scale issues (from macro policy options appraisal)

***Budgets.*** Analysis to date is based on current budgets, inherited from the previous EU CAP regime. While a substantial headline value (~£500 M pa) the agriculture budget has declined in value relative to other sources of farm income. This shows the diminishing leverage that agricultural support can have as it declines as a share of total income from farming. If large enough numbers of land managers do not take up the support and the proposed EC measures are not implemented, it risks leaving only a regulatory approach to deliver the transformations.

***Distribution of funds in space*** sets the budget envelope per business and thus the expectations for EC delivery. The current regionalisation model sees the 50% of businesses with the largest payments receiving 90% of the payments suggesting they should deliver 90% of EC measures outcomes. This raises question of how this 50% of the business population maps onto "need" for change – in terms of both sectoral and regional dimensions (see meso-scale issues). Larger businesses may have the capacity to do more than their current share of funding would indicate, if they can generate "economies of scale" for delivery of the EC measures.

### 4.2. Micro-scale issues (field-enterprise and farm management)

Micro-scale analysis considered field-enterprise-farm management and the detail of the EC measures. Two themes from the micro-analysis are summarised, the uptake of measures and their likely effectiveness.

***Uptake of EC measures.*** Since EC is a menu system there is the risk that unless targeting imposes mandatory choices then effective measures will deliver nothing until they are implemented at scale.

There is a prominent narrative that simplicity is a key factor for uptake. Where simplicity aligns with clarity then the screening team agreed with the narrative. The EC measures, however, demonstrated that it is not easy to specify measures that are simple while also being clear on the expected actions themselves and/or their outcomes. Most of the EC measures are strongly muti-functional, even if they were specified as delivering primarily to one objective. There were also a significant number of EC measures that were compound (offering alternatives way to deliver the same outcomes) or indeed were perhaps better viewed as alternative objectives or measure groupings (e.g., Integrated Pest Management). This implies that even with a single measure there is a potentially complex mapping between multiple actions and outcomes. A scheme with such wide-ranging objectives necessitates a trade-off between simplicity and the robustness provided by more complex measures that can be flexibly implemented and deliver a basket of ecosystem benefits. For uptake it will be important to offer measures that have a simplicity gradient – i.e., 'step on', 'mainstream' and 'stretch' opportunities.

Uptake of measures with an efficiency focus are often preferred as win-wins. That such measures are not already adopted either highlights that the 'wins' are hard to realise, or something is blocking them, such as greater risks from "optimised" management. Efficiency, while desirable at micro level, can also have negative consequences if it drives increased production rather that reduced resource use (the rebound effect in Jevons paradox). This issue links back to macro policy decisions on the total quantity of agricultural production that should be engaged in respecting economic and environmental advantages and impacts.

Evidence from the uptake of EFA measures highlights that ease of compliance with regulatory requirements and compatibility with existing farming systems is key. For EFA, fallow was a strongly preferred measure especially for businesses with livestock present. Fallow has some production systems benefit but delivers very

weak ecosystem service benefits. It will not be an option in EC, so there is uncertainty about which EC measures will substitute. The EFA analysis also highlighted the preference for margins-based measures (e.g., buffer strips). The screening agreed that margin-based measures were positive but coupling margin and within-field measures needs to be heavily weighted to promote greater uptake, to meet the challenging objectives.

The nature of the change implied by the EC measure was also seen as crucial. The more transformative the less likely the EC measure would see uptake; with increasing challenge as measures moved from land management through land use and to land cover. The last was associated with permanent loss of productive capacity with consequences for land values that might underpin the financial viability of the business. Land tenure was also seen as a significant limitation on uptake, as rented, seasonal and communally managed land is unlikely to be used for these transformative measures.

Uptake of EC measures was also seen to depend on there being funding to make them viable in terms of both the capital investment (e.g., creating wetlands) but also their maintenance over time (with some evidence that such funding can be harder to secure). This is reflected in the language used – with revenue measures described as manage, improve, enhance etc and capital described as create (and restore). Uptake of the 'create or restore' EC's will depend on decisions taken regarding the Tier 4 Agricultural Transformation Fund as the EC budgets are unlikely to cover the large-scale capital works needed.

***Effectiveness.*** The other micro-scale theme is the effectiveness of the proposed measures and the likelihood of achieving the outcomes expected. Here the screening drew heavily on experimental and systems analysis researchers with expertise in ecosystem processes and their interaction with land management. Even with the long (n=93) list of measures, there was some concern about missing topics where land use and management affect the environment (e.g., water quality and aquatic ecology). There was also concern that actions to improve the resilience of production or ecosystems to climate change were limited.

Effectiveness is important in operationalising EC since it can underpin decisions on the weighting given to any measure, i.e., land managers would have to do less of the most effective measures to achieve the threshold. This may mean that they choose to do smaller areas of the most effective measures (a narrow and deep approach) or more extensive areas of less effective measures but which in aggregate still deliver the necessary changes. The screening also highlighted measures (such as soil pH and compaction management) that were perhaps better considered as management requirements for all land (Tier 1 - basic standards).

The heterogeneity of Scotland's biophysical environments means that the specification of EC measures so that they are universally beneficial is challenging. In assessing effectiveness, the screening team agreed a standard that *measures should in aggregate deliver benefit*. This standard reflected the view that for nearly all measures it was possible to envisage circumstances in which there would be either minimal benefit or some disbenefit. The circumstances in which such disbenefits occur could be specified based on research-based knowledge but two challenges remain. Incorporating such knowledge into the measures specification could make them too complex and the data on which to make operational implementation decisions may be lacking or cost prohibitive (e.g., subsoil condition data).

Effectiveness was also seen to depend on implementing *the right measure in the right place*. Since many of the measures will be new to land managers, this emphasises mainstreaming the knowledge of what makes each measure effective and meshing this with the experiential knowledge of land management and environmental conditions on each farm business. This implies the need for investment in Tier 4 Skills and Advisory Services and potentially in peer-to-peer learning e.g., in Tier 3 – Elective Payments.

### 4.3. Meso-scale issues (catchment-landscape-region)

Meso-scale issues are perhaps the most challenging in making the EC effective. Geographical meso-scale perspectives highlight where issues of interactions between farm-businesses can have profound impacts on the outcomes. Evaluation of outcomes also raises a series of meso-scale issues both spatial and temporal.

***Interactions.*** Important meso-scale issues arise when interactions between farm-businesses make a difference to the outcomes. Examples include the need for some measures to be undertaken by enough farm-businesses in an area to generate a concentration e.g., presence of habitats or positive management, that means species can be conserved or restored. Issues here include how to geographically encourage uptake by increased weighting or supporting coordinated EC choices between farm businesses either via farm networks or third parties such as catchment partnerships. Cooperation and coordination are also essential where there are teleconnections e.g., in natural flood management measures where benefits must be measured at locations beyond the boundaries of farm-businesses. There is also potential to add value by layering individual measures to reinforce each other and deliver greater benefits – e.g., hedge restoration, coupled with improvements (width

increases), better management (less disturbance) and with margin management that see less (or no) crop protection products in the vicinity. The challenge for such interactions is in quantifying the extra weighting this should attract and enacting this in IT systems accessed by land managers.

***Evaluation.*** Typically, it is possible to verify actions taken but much harder to monitor their outcomes, yet ultimately outcomes will have to be used to justify the use of public money. Often it is only possible to measures the outcomes at a scale above the farm business, for example if using indicator bird species. Even if positive outcomes can be verified at this larger scale, then there are complex issues of attribution (which actions by whom) and dangers of either free riding (being credited for outcomes generated by others) or blocking (where potentially beneficial actions are not effective due to the actions of others, perhaps even outside the EC scheme). Temporal interactions can also be complex with lags meaning that beneficial actions may not have verifiable outcomes within the lifetime of the scheme (e.g., buffered fields release N long after inputs have reduced). Measures may require commitments to continued actions; but political circumstances mean that multi-annual financial commitments are hard to make and sustain.

## 5. CONCLUSIONS

### 5.1. Potential of enhanced conditionality

The Vision document recognises that current support system has not yet delivered enough progress on NetZero and other environmental goals. However, these goals need to be met while maintaining a viable agri-food system, as an important component of rural economic activity and social fabric. Debate is appropriate over the degree and rate of change, but a fundamental transformation of the agri-food system is required to meet objectives. EC is inherently uncertain and risky, but the *status quo* is not an option.

EC measures could play a decisive role in the delivery of multiple Scottish Government objectives, but they are part of a complex policy sudoku. Policy sudoku provides a potentially useful conceptual framework for considering, across scale, how EC interacts with other agricultural support sectors, regions, land managers and the geography of Scotland. The fundamental challenge is to get a mix of EC and other Tier measures (see Figure 1) that deliver the national policy commitments.

The menu-based approach implies that there will be more uncertainty about what EC will initially deliver. The uptake and implementation of EC measures will need to be closely monitored, and the scheme adapted over time to ensure that it progressively delivers more outcomes that contribute towards the overall objectives. EC is thus likely to have higher implementation costs but to deliver more than existing Direct Payment schemes. The bounds of this uncertainty were usefully explored in the research combining the macro policy options analysis (top down) and micro level measure screening (bottom up). The screening deliberations also highlighted the emerging issue of the meso-scale, which remains extremely challenging for policy making.

The challenge of anticipating meso-scale issues of interactions and intermediate objectives could be addressed with empirical, spatial agent-based modelling (ABM) (Polhill et al., 2019). Used in a hindcasting approach, ABM can assess how robust the delivery of outcomes can be to the policy configurations, EC measure weighting, budgets and intermediate objectives. This remains however a significant challenge in terms of developing models, supplying them with data, and using them in QST for policy making.

### 5.2. Why did we need to do QST?

QST reflects post-normal ideas about the role and relevance of science, and the scale of current sustainability challenges. As a result, QST processes are not typically concerned with refining specific aspects of scientific evidence, but instead questioning whether an existing science-policy consensus ignores existential threats by taking a too narrow view of the challenges faced. Many analytical tools and methods are available to probe different aspects of land use transformations, but these tools rarely enable a systemic overview of interlinked issues. It is also rare to reflect on the application of these tools and the accompanying knowledge co-production processes. As such, many existing tools do not enable a full appraisal of the system, nor evaluate the evidence created for its utility in policy-making processes. Conversely, systemic approaches can generate overwhelming complexity that can defy interpretation and discourage policy actors from engaging with the issues.

In this application, QST engaged the policy actors who selected the entry point into the policy sudoku; and were therefore invested in interpreting the results arising from the macro level policy appraisals and micro level screening workshops. The results illustrated decision points and the potential outcomes of choices made; without avoiding the challenges ahead. Thus, QST can provide a process to navigate cross-scale complexity.

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**REFERENCES**

Blackstock, K.L., Waylen, K.A., K.B., M., Juarez-Bourke, A., Miller, D.G., Hague, A., Wardell-Johnson, D.H., Giampietro, M., 2023. Implementing post-normal science with or for EU policy makers: Using Quantitative Story Telling to discuss the Common Agricultural Policy and Sustainable Development Goal 2. Sustainability Science.

Hare, M., Letcher, R.A., Jakeman, A.J., 2003. Participatory Modelling in Natural Resource Management: A Comparison of Four Case Studies. Integrated Assessment 4(2) 62-72.

Matthews, K.B., Blackstock, K.L., Waylen, K.A., Juarez-Bourke, A., Miller, D.G., Wardell-Johnson, D.H., Rivington, M., Hague, A., Fisher, D., Renner, A., Cadillo-Benalcazar, J., Schyns, J., Giampietro, M., 2020. Report on EU sustainability goals: insights from Quantitative Story Telling and the WEFE nexus. MAGIC (H2020–GA 689669) Project Deliverable 5.1, 31st July 2020: Online: https://magic-nexus.eu/documents/deliverable-51-report-eu-sustainability-goals, p. 136.

Matthews, K.B., Buchan, K., Miller, D.G., Towers, W., 2013. Reforming the CAP With area-based payments, who wins and who loses? Land Use Policy 31 209-222.

Matthews, K.B., Buchan, K., Sibbald, A.R., 2002. Using soft-systems methods to evaluate the outputs from multi-objective land use planning tools, In: Rizzoli, A.E. (Ed.), pp. 247-252.

Matthews, K.B., Buchan, K., Sibbald, A.R., Craw, S., 2006. Combining deliberative and computer-based methods for multi-objective land-use planning. Agricultural Systems 87 18-37.

Matthews, K.B., Miller, D.G., Wardell-Johnson, D., 2015. Practicing and evaluating outcomes of working across the science policy interface, In: Weber, T., McPhee, M.J., Anderssen, R.S. (Eds.), 21st International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand: Gold Coast, Australia, p. 7.

Matthews, K.B., Renner, A., Blackstock, K.L., Waylen, K.A., Miller, D.G., Wardell-Johnson, D.H., Juarez-Bourke, A., Cadillo-Benalcazar, J., Schyns, J.F., Giampietro, M., 2021. Old Wine in New Bottles: Exploiting Data from the EU's Farm Accountancy Data Network for Pan-EU Sustainability Assessments of Agricultural Production Systems. Sustainability 13(18).

Matthews, K.B., Rivington, M., Blackstock, K.L., McCrum, G., Buchan, K., Miller, D.G., 2011. Raising the bar? - The challenges of evaluating the outcomes of environmental modelling and software. Environmental Modelling and Software 26(3) 247-257.

Matthews, K.B., Rivington, M., Buchan, K., Miller, D.G., Bellocchi, G., 2008. Characterising and communicating the agro-meteorological implications of climate change scenarios to land management stakeholders. Climate Research 35(1) 59-75.

Matthews, K.B., Sibbald, A.R., Craw, S., 1999. Implementation of a spatial decision support system for rural land use planning: integrating GIS and environmental models with search and optimisation algorithms. Computers and Electronics in Agriculture 23 9-26.

McCrum, G., Blackstock, K.L., Matthews, K.B., Rivington, M., Miller, D.G., Buchan, K., 2009. Adapting to climate change in land management: the role of deliberative workshops in enhancing social learning. Environmental Policy and Governance 19 413-426.

Polhill, J.G., Ge, J., Hare, M.P., Matthews, K.B., Gimona, A., Salt, D., Yeluripati, J., 2019. Crossing the chasm: a 'tubemap' for agent-based social simulation of policy scenarios in spatially-distributed systems. Geoinformatica 23 30.

Renner, A., Cadillo-Benalcazar, J.J., Benini, L., Giampietro, M., 2020. Environmental pressure of the European agricultural system: Anticipating the biophysical consequences of internalization. Ecosystem Services 46 101195.

Scottish Government, 2022. Delivering our vision for Scottish agriculture - proposals for a new Agriculture Bill: Online, p. 54.

Waylen, K.A., Blackstock, K.L., Matthews, K.B., Juarez-Bourke, A., Hague, A., Miller, D.G., Wardell-Johnson, D.H., Kovacic, Z., Voelker, T., Guimaraes-Pereira, A., Giampietro, M., 2023. Post-normal science in practice: Reflections from scientific experts working on the European agri-food policy nexus. Environmental Science and Policy 141 10.