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OPEN LETTER

Applications of environmental intelligence for rural land management

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Abstract

Environmental intelligence brings together multiple data streams, employing human reasoning and machine learning to better understand and manage the environment. This article describes the possibilities and limitations of using environmental intelligence to support outcomes-based rural land management policy. We argue that environmental intelligence approaches are particularly well suited to planning and assessing the effectiveness of nature-based solution investments for the delivery of ecosystem services, such as flood mitigation and climate change mitigation. However the 'outcome' to be achieved, and the outcome metrics used, need to be carefully selected to ensure they are realistic, responsive to land management and rigorously measurable. Environmental intelligence in support of outcomes-based approaches must address social issues of fairness and social justice as well as environmental outcomes.

Keywords

ecosystem services, agriculture; land use; Environmental Land Management schemes, Common Agricultural Policy, evidence, environmental intelligence

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Open Peer Review

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Any reports and responses or comments on the article can be found at the end of the article.

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Introduction

Rural land can provide important economic and social benefits; not just through employment but through the provision of ecosystem services such as mitigation of flooding and drought, sequestration and storage of carbon and food production (Gawith & Hodge, 2019; Kristensen, 2016; van Zanten *et al.*, 2014). However, the provision of ecosystem services is dependent on having sufficient stocks of well-functioning natural capital that are geographically close to areas of demand for ecosystem services (see Mulligan, 2021). However these stocks, and in turn the economic and social benefits they enable, are threatened by a variety of activities such as inappropriate land management, urbanisation and infrastructure development (Kristensen, 2016; Plieninger & Bieling, 2012; Poulton & Johnston, 2021; Schulp *et al.*, 2019; Winkler *et al.*, 2021).

Macro-level policy interventions, such as publicly funded financial payments to incentivise land management actions with a public benefit, affect the stocks of natural capital (Kristensen, 2016; Springermann & Freund, 2022; Stoate *et al.*, 2009; Vejchodska *et al.*, 2022). Therefore there is an opportunity to use policy to steer rural lands towards ecosystem service delivery. However careful consideration needs to be given to which services are incentivised. The historical policy drive in Europe to intensify food, and the resulting subsidies applied per area of land under production, meant that food provision was prioritised over nature conservation and other ecosystem services. Hedgerows have been removed, ponds and wetlands drained, unproductive lands agriculturalised, and fertilisers, herbicides and pesticides overused. This has led to widespread agricultural soil degradation and a simplified rural landscape with reduced biodiversity and ecological function (Gerowitt *et al.*, 2003; Hayhow *et al.*, 2019; Mueller *et al.*, 2021; Stoate *et al.*, 2009). This has undermined the sustainability of agricultural production whilst also leading to increased offsite impacts such as increased flood risk and more carbon emission.

The European Union (via the Common Agricultural Policy) and England (via the Sustainable Farming Incentive within the Environmental Land Management schemes) are exploring policies which incentivise conservation and restoration of natural capital on farmland (Defra, 2021; EC, 2022; Herzon *et al.*, 2018; Matzdorf & Lorenz, 2010). Such approaches include action- and outcome- based measures; i.e. with payment linked to particular actions (i.e. cutting a meadow once a year after a certain date) or to the benefit provided (i.e. delivery of a species-rich wet meadow) respectively.

In this evolving policy environment, there are two key challenges for outcomes-based approaches. The first is to develop methods to identify which of the possible range of land management options or nature based solutions (NBS) work best at delivering the required outcomes in a particular location. The second is to measure how well existing land management investments deliver a variety of ecosystem services, and to do so in a simple, cost-effective and scientifically rigorous way. Environmental intelligence approaches have the potential to meet both of these challenges.

Environmental intelligence (EI) brings together multiple data streams, employing human reasoning and machine learning to better understand and manage the environment (Mulligan *et al.*, 2021). Potential data sources include monitoring data from *in-situ* sensors, airborne or satellite remote sensing, as well as outputs from spatial modelling (Table 1). These data streams can be combined with artificial intelligence methods (such as machine learning), and/or human reasoning. All EI techniques have limitations which can restrict their suitability for certain applications. However, combining different techniques can broaden the range of suitable applications. For example, combining *in-situ* sensors with satellite data and/or spatial modelling can help improve the accuracy of both approaches: *in-situ* sensors provide highly locally relevant data at particular points but lack spatial coverage whereas satellite data provides spatial coverage but lacks the local relevant and temporal detail of *in-situ* sensing.

In this article we introduce EI and discuss the possibilities and limitations of its use to support outcomes-based rural land management. We focus on the use of *in-situ* monitoring, satellite remote sensing and spatial modelling because their application in this context is further developed than airborne remote sensing and artificial intelligence approaches.

Possibilities

The importance of geography

Environmental intelligent approaches are able to incorporate geography. Geography matters because management can have different impacts within and between agricultural fields as well as across larger climate, soil, topographic and geological gradients (Soane *et al.*, 2012; Zhao *et al.*, 2020). This spatial variability means that 'rules of thumb' on how to manage for a particular outcome are rarely effective across such gradients. Environmental intelligence offers the chance to measure and account for this spatial variability in both planning and effectiveness assessments, through use of locally specific *in-situ* monitoring or area-based remote sensing or modelling.

There are two principal uses for EI in supporting outcomes-based rural land policy:

- identifying the optimal location for a management action to occur (strategic planning)
- determining how well a management action performs (effectiveness assessment)

For strategic planning, spatial modelling (often incorporating satellite data), can provide evidence to help answer a variety

Table 1. Glossary of terms used in this article.

Term	Definition
Ecosystem services	The benefits people obtain from ecosystems
Nature-based solution (NBS)	The use of nature and natural processes to provide environmental, social and economic benefits.
NBS investor	A person or organisation financially investing in NBS. This includes governments, commercial investors, landowners and farmers.
Monitoring	The process of detecting, observing and taking measurements of characteristic(s) of an area over a period of time. Monitoring can take place within the area (*in-situ*) or at a distance (remote sensing).
In-situ monitoring	Involves placing sensors within the location of interest (such as placing sensors in the soil within an agricultural field).
Remote sensing	A form of monitoring where observations are made from a distance. Two key forms of remote sensing are airborne and satellite.
Airborne remote sensing	Measurements are taken by mounting sensors on drones or aircraft to obtain observations for specific locations.
Satellite remote sensing	A form of remote sensing where sensors are mounted on satellites orbiting the planet. They can be used to observe specific areas at high resolution or larger areas at lower resolution.
Spatial modelling	An analytical approach where geographical information is explicitly included in the model.
Artificial intelligence	Intelligence as demonstrated by machines (in contrast to the intelligence demonstrated by humans and animals).
Machine learning	A form of artificial intelligence where algorithms build a model based on a sample dataset. The algorithm can then make predictions for other datasets without being explicitly programmed to do so.
Counterfactual	An alternate state used as a comparison to help understand the effect of an intervention such as a policy or particular land management practice.

of questions related to: i) the scale of investment required (e.g. EcoActuary Investment Planner, Mulligan *et al.*, 2023a; Mulligan *et al.*, 2023b); ii) the optimal location for a particular type of land management activity to occur (e.g. scenario based ecosystem service assessment tools such as WaterWorld; Co$tingNature, InVEST, ARIES, LUCI and NEVO); iii) identifying beneficiaries and potential impacts of different management activities (Table 2). Spatial modelling of this kind can therefore support NBS investors to identify the scale, types and locations of investments with the greatest 'bang per buck' i.e. those which deliver the greatest ecosystem service benefits for the least financial and opportunity costs.

For effectiveness assessment, *in-situ* monitoring can provide evidence to assess the ecosystem service benefits provided by current management practices in relation to counterfactuals or Key Performance Indicators. *In-situ* monitoring can be combined with satellite data and spatial modelling to evaluate other aspects of performance such as identifying beneficiaries (Table 2). Therefore *in-situ* monitoring alone, or combined with remote sensing and spatial modelling can provide NBS investors with a means of rigorously evaluating the outcomes achieved through specific investments.

Limitations

Difficulty in measuring outcomes

Assessing outcomes, while laudable, can be difficult to do in practice. The difficulties with outcomes-based approaches include:

Time: some outcomes take a long-time to accrue. For example, it takes a long time for carbon to accumulate in soil (Cooper *et al.*, 2021; Oelbermann & Voroney, 2007; Smith *et al.*, 2020). This means it is not possible to rigorously and reliably measure change in soil carbon stocks in the short-term (i.e. within 5 years).

Cost: some outcomes are difficult and expensive to measure. For example the impact of land management on biodiversity is difficult to assess as it requires a highly manual and thus relatively expensive approach.

Confounding effects: some outcomes are prone to impacts of time-varying factors beyond control - such as weather extremes or nearby changes to land use or management. This makes longitudinal (before and after) analyses of change difficult. For example, biodiversity is strongly influenced by

Table 2. Examples of policy questions answerable with environmental intelligence. All examples provided relate to flood mitigation to help illustrate the range of insights that can be supported.

Policy Support	EI	Example Questions	Examples
Planning	Spatial modelling incorporating satellite data	What level of investment - in regards to cost of, or area covered by, a particular land management action - is required to meet a specific nature conservation, climate mitigation, flood risk mitigation or other policy goal?	Over what area would regenerative agriculture need to occur to reduce flood damages by 25% to an asset at risk downstream?
		Where should a land management action occur in order to have the greatest 'bang-for-buck'?	Where is the optimal location to plant 10,000 trees in a catchment in order to minimise the financial losses at a downstream asset at risk due to flooding?
		Which land management activity has the greatest benefit for the least capital and maintenance costs?	Should I invest in leaky dams, retention ponds or regenerative agriculture if I want to maximise downstream flood mitigation benefit with the least capital and recurrent cost?*
		Who will benefit from a particular management practice?	Which buildings and other infrastructure are afforded flood protection by practising regenerative agriculture at a given farm?
Effectiveness	*In-situ* monitoring	How does this management practice perform against the counterfactual (eg conventional practice) or a particular KPI?	How much extra water is stored within soil for a particular event relative to the conventional practice, and what proportion of river flow at an asset at risk does this represent?*
	Spatial modelling incorporating *in-situ* monitoring	Who are the beneficiaries of a management practice?	How many, and who downstream, benefit from the observed increase in soil water storage?

* For worked examples see Mulligan *et al.*, 2023b

offsite factors and climatic variability which makes robustly measuring biodiversity outcomes challenging.

Starting conditions: if outcomes are designed to reward improvements in a particular outcome (i.e. incentivise restoration) then this disadvantages those who already have good starting conditions. If, for example, an increase in soil carbon is used as an outcome it will disadvantage those with already high levels and thus less potential for improvement.

Scientific and practical

Each EI approach has limitations when it comes to supporting rural land policy. The key limitations for each approach are:

In-situ monitoring can be limited by: cost of commercial equipment; cost and logistical complexities associated with equipment deployment, and maintenance and data management of large networks of sensors. Low cost, open-source monitoring initiatives such as FreeStation (www.freestation.org) have been designed to overcome these limitations and used to evaluate a variety of flood mitigation NBS (Mulligan *et al.*, 2023a).

Spatial modelling can be limited by: lack of input data (either due to unavailability or high cost); incomplete understanding of the biophysical process of converting natural capital to ecosystem services; insufficient information to parameterise models on how management practices impact natural capital and ecosystem services.

Satellite data can be limited by the spatial resolution of data. Open-access satellite data are usually of moderate resolution (30m to 1km pixel resolution) which makes them more suitable for applications beyond the farm scale. Although very high resolution satellite data are available the cost of use can be prohibitive for many within-farm applications.

Regardless of the merits of EI, a key challenge with its uptake, as any new technology, is that it requires a change to business-as-usual. It demands a change in working practices and additional time, effort and cost. Financial barriers are however reducing due to the development of low-cost, open-source monitoring hardware and free-to-use spatial modelling software. The organisational hurdles, of changing established ways of working, remain the greater challenge.

Discussion

Environmental intelligence approaches can support assessment of outcomes-based land management. However, the ability to use outcomes-based incentivisation depends on

the possibility of developing reliable indicators (measures) of outcomes and the length of time to achieve measurable outcomes.

Tension between biophysical and policy timescales

Some outcomes cannot be achieved within the timescales required for outcomes-based incentives. For example, the lag between when a management action is started and a rigorously observable change in soil carbon occurs makes change in carbon storage a poor choice for an outcomes-based approach. As policy-relevant outcomes need to be achieved quickly, a more suitable outcome is estimating the carbon fluxes of agricultural soils i.e. to estimate the carbon removed (sequestered) from the atmosphere by the soil every year. If there is a net sequestration, rather than net emission over the course of the year, then this is evidence that the management practice is working and in the long-term soil carbon will increase.

Potential to reinforce geographic inequalities

Many ecosystem service outcomes are assessed based on the number of people or the monetary value of assets benefiting from the service. This means that greater value is given to natural capital that is close to (and therefore benefits) lots of people or valuable assets. To illustrate this point take the example of improved water storage in soils and the ecosystem service of flood mitigation - if the number of people protected or the monetary value of the assets protected from a flood are used as an outcome then it puts a greater value on natural capital that influences more affluent or populated areas at the expense of natural capital that may be benefiting fewer people or assets with less monetary value. Thus, multiple values need to be considered in order for investments and incentives for more sustainable land management to be socially just (Hakkarainen *et al.*, 2020; Kenter, 2018).

Conclusions

Environmental intelligence approaches can help deliver outcomes-based rural land management by providing context specific evidence for planning and evaluating NBS investments. We provide a series of recommendations to those considering developing or applying such approaches:

- Metrics for outcomes-based assessment need to be simple, low-cost, easily collected, rigorous and informative of the outcomes that matter.
- Metrics should be comparable between farms, between data collectors and verifiable or independent of those receiving the incentive.
- Incentivise conservation as well as restoration by considering those that have managed natural capital well and already have intact natural capital on their land.
- When evaluating outcomes, give consideration to the choice of outcome to ensure that they are realistically achievable within the necessary time period and that they are socially just.
- Consider whether measuring outcomes is the best approach, particularly in those situations when the cost of time and resources associated with evaluating outcomes is great. If it is well known that a given management action is environmentally the right choice then it might be more cost-effective and reasonable to incentivise a verifiable practice rather than an outcome.

Ethics and consent

Ethical approval and consent were not required.

Data availability

No data are associated with this article.

Author contributions

Caitlin M. S. Douglas: Conceptualization, Writing - original draft; Writing - review and editing

Mark Mulligan: Conceptualization; Writing - original draft; Writing - review and editing

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✔ **Dr. Kumar Ashwini**
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The article is well-written and explains the role of EI in land development in rural areas. Nowadays ML is key to understanding environmental degradation in every aspect whether it is related to climate, land, surface water, air, etc.,
So this review paper highlights these issues and their role with EI.
The paper can be accepted for indexing.

Is the rationale for the Open Letter provided in sufficient detail? (Please consider whether existing challenges in the field are outlined clearly and whether the purpose of the letter is explained)
Yes

Does the article adequately reference differing views and opinions?
Yes

Are all factual statements correct, and are statements and arguments made adequately supported by citations?
Yes

Is the Open Letter written in accessible language? (Please consider whether all subject-specific terms, concepts and abbreviations are explained)
Yes

Where applicable, are recommendations and next steps explained clearly for others to follow? (Please consider whether others in the research community would be able to implement guidelines or recommendations and/or constructively engage in the debate)
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Earth Science, Application of ML in forcasting LST, LULC, River Morphology,

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.