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Spatial Multi-Criteria Analysis in Environmental Assessment: A Review and Reflection on Benefits and Limitations

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Anticipating and avoiding adverse environmental effects resulting from land-use changes and other anthropogenic interventions is the key objective of environmental assessment (EA). EA requires consideration of multiple environmental criteria to establish the receiving environment's sensitivity and capacity to absorb change. With the increasing availability of and accessibility to spatial data, the adoption of spatial multi-criteria analysis, also known as GIS–MCA, has become a prominent technique to support EA. Using two diverging case studies, this paper reflects upon the advantages and disadvantages of applying GIS–MCA in EA reported in literature. While the significant contribution of this approach to increasing objectivity, transparency and accountability is corroborated, it is recognised that there is no one-fits-all solution. The widespread application of GIS–MCA calls for further research on the effects that methodological assumptions and data limitations may have at various planning hierarchies and decisions, and how these can be addressed to optimise the value of this technique in EA.

Keywords: Decision support; environmental impact assessment; environmental sensitivity; geographic information systems; multi-criteria analysis; strategic environmental assessment.

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Introduction

Environmental assessment (EA) requires that the effects of development interventions are assessed in order to identify and mitigate any significant adverse effects on the environment. There are two main EA instruments: strategic environmental assessment (SEA) which focusses on the assessment of the potential effects resulting from plan, programme and, in some countries, policy implementation (Dalal-Clayton and Sadler, 2005; EC, 2001; Fischer, 2007); and environmental impact assessment (EIA) that addresses potential significant effects of discrete projects (EC, 2014; Glasson *et al.*, 2012; Wood, 2014). Both approaches entail identification of adverse effects on population and human health, biodiversity, flora, fauna, water, air, climate, soils, geology, landscape, cultural heritage and material assets, as well as considerations of any effects resulting from the inter-relationship between these factors. While SEA is commonly concerned with mitigating impacts of strategic policies and actions over wide geographical areas, EIA deals with siting and design issues at the local level. In any case, both SEA and EIA address multiple environmental aspects over defined geographical areas and, perhaps as a result of this, multi-criteria assessment (MCA) approaches implemented through geographic information systems (GIS) have become a prominent technique to support EA. Increasing availability of and accessibility to spatial data (particularly as a result of increased efforts to gather information and the growing deployment of remote sensors, social networks and citizen science initiatives leading to large volumes of data) have further promoted the adoption of spatial multi-criteria analysis in EA.

MCA techniques have the capacity to make a predictive evaluation of different scenarios, and to facilitate participatory decision-making by procuring consideration of multiple criteria and conflicting objectives and perceptions, while GIS offer a unique capability to geographically visualise problems and solutions, and to automate geospatial analysis. Their synergetic capabilities enable effective structuring of decision problems, and geographically-explicit systematic evaluation and prioritisation of alternative decisions. GIS–MCA methods facilitate analysis of complex problems involving multiple variables and value judgements or decision-maker preferences, by combining relevant yet diverse quantitative and qualitative spatial datasets into composite indices for ranking alternatives or scenarios (González *et al.*, 2011; Malczewski, 2006). The combination of objective data (i.e. environmental variables) and subjective values (in the form of values or weights that capture the relative importance of the variables and thus emphasise priority areas or key public concerns) enables a holistic view of scientific facts and public perceptions.

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The application of GIS–MCA methods in EA commonly focusses on examining the characteristics that make an area susceptible to change (i.e. starting point) or on analysing resulting impacts (i.e. end-point) (see e.g. González, 2017b; Kværner *et al.*, 2006; Marull *et al.*, 2007; Pavlickova and Vyskupova, 2015; Toro *et al.*, 2012). Appraising what makes an area sensitive to plan/programme/project implementation is essential in order to mitigate potential effects from the onset. In this context, there are two main conceptual approaches of analysis: (a) one that focusses on sensitivity, also commonly referred to as vulnerability or fragility analysis (Kværner *et al.*, 2006), which entails establishing the intrinsic susceptibility of a system to being adversely affected; and (b) that which determines the capacity of a system to absorb change from given man-made interventions, without being damaged (Gómez, 1992; Taiwo and Feyisara, 2017). Both analytical approaches are mirror images, inverse ways of achieving the same objective of determining the areas with greater and lesser likelihoods of being negatively affected. For simplicity, this paper adopts environmental sensitivity as the common term to refer to both approaches, unless otherwise indicated.

Examining sensitivity enables further insight into the baseline environment adding to the purely technical factoring of characteristics (González, 2017b), while addressing EIA and SEA Directive requirements to give due consideration to the vulnerability/sensitivity of the areas likely to be affected when identifying and characterising potential impacts (EC, 2001, 2014). In addition, it provides a robust foundation for cumulative effects assessment by addressing co-occurring sensitivities and, therefore, potential effect accumulation. Similarly, it can contribute to sustainable development by steering development to suitable areas and mitigating environmental impacts by avoidance. Nevertheless, GIS–MCA has been criticised for its limitations and implications. There are a number of MCA methods; Saaty's pair-wise comparison is one of the most widely applied (Wallenius *et al.*, 2008) but there are many others (see e.g. Greco *et al.*, 2016; Malczewski and Rinner, 2015), each suited to different problems and, more relevantly, providing different results. Notwithstanding this, the literature illustrates the growing importance of the technique in supporting EA. This paper sets to further investigate the benefits and limitations of spatial multi-criteria analysis in EA, with a focus on environmental sensitivity approaches.

Methodology

With the objective of undertaking an informed reflection upon the application of GIS–MCA methods in EA, this paper reviews expert opinion in published academic literature and contrasts two geographically and sectorally differing case

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studies to explore practice. Given that the application of GIS–MCA in EA is eminently practical, and that practice has outpaced research in this area, the methodology combines both literature review and practical case studies, as some recent reviews in related areas (see e.g. Smith, 2016; Babelon *et al.*, 2017). This approach provides a more comprehensive illustration of contemporary applications and perceptions (than that provided by either literature or case studies alone), to advance discussion in this research area.

To gather and examine experts' opinion, a systematic literature review was undertaken. To achieve this, the Web of Science was searched for relevant peer-reviewed publications that contained in the title the following keywords: 'geographic information systems' or 'GIS' combined with 'environmental assessment,' 'environmental impact,' 'impact assessment,' 'multicriteria,' 'multi-criteria' or 'sensitivity.' The results were exported to RefWorks and, after duplicates were eliminated, 464 publications were listed. These were scrutinised for relevant content (e.g. application of the technique to address environmental considerations) by referring to the title and abstract, reducing the initial set of relevant manuscripts, which were then reviewed in full detail. The list was further refined on the basis of their specific inclusion of an examination of, or reflection on, advantages and disadvantages of applying GIS–MCA (papers purely describing the method and analysing outputs, without a critical examination, were not included in the review). A comprehensive literature review was beyond the scope of this paper, as the focus is on GIS–MCA benefits and limitations. The reported benefits/limitations were grouped and ranked according to the number of times they were cited in the reviewed literature. The literature review not only provided an overview of reported benefits and limitations of GIS–MCA, but set a framework for the examination of the case studies.

To explore how these methods are applied in EA in practice, two case studies were examined — each of these has been developed and implemented by one of the authors. These were selected on the basis of their adoption of an environmental sensitivity analysis technique in different countries, administrations, sectors and planning stages. The first case study (conducted by A. González) refers to environmental sensitivity mapping as a support tool for SEA of land-use plans in Ireland (see also González *et al.*, 2011; González, 2017b), while the second (conducted by Á. Enríquez-de-Salamanca) refers to the analysis of reception capacity as a first stage of EIA for road planning in Spain (Carrasco and Enríquez-de-Salamanca, 2004; Loro *et al.*, 2014). The comparative examination of the case studies facilitates exploration of similarities and divergences in the contribution of spatial multi-criteria approaches to environmental sensitivity analysis as part of SEA and EIA processes. These practice-based case studies, coupled with the

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authors' own extensive GIS–MCA use and experience, add to a reflection upon the relative relevance and validity of some of the benefits and limitations identified in the literature.

Environmental Sensitivity Case Studies

Irish strategic land-use planning

The Irish planning system requires development plans to be prepared by local authorities, and these to be periodically reviewed (DEHLG, 2000). Such plans are subject to SEA under the requirements of the European Union (EU) SEA Directive (EC, 2001; DEHLG, 2004a,b); as a result of their periodic update, the forward planning sector accounts for 70% of SEAs in the country (EPA, 2016). Although various SEA approaches have been implemented since the transposition of the EU Directive, in the last decade, environmental sensitivity mapping has been widely applied in SEA processes in Ireland, promoted by existing guidance (EPA, 2015).

The spatial analysis is based on participative multi-criteria decision-making principles. It adopts a weighted overlay algorithm that avoids normalisation, whereby the sensitivity of each area directly relates to the number of sensitive environmental criteria that overlap at one location, each multiplied, where applicable, by the relative importance assigned to it (Fig. 1; see also González *et al.*, 2011).

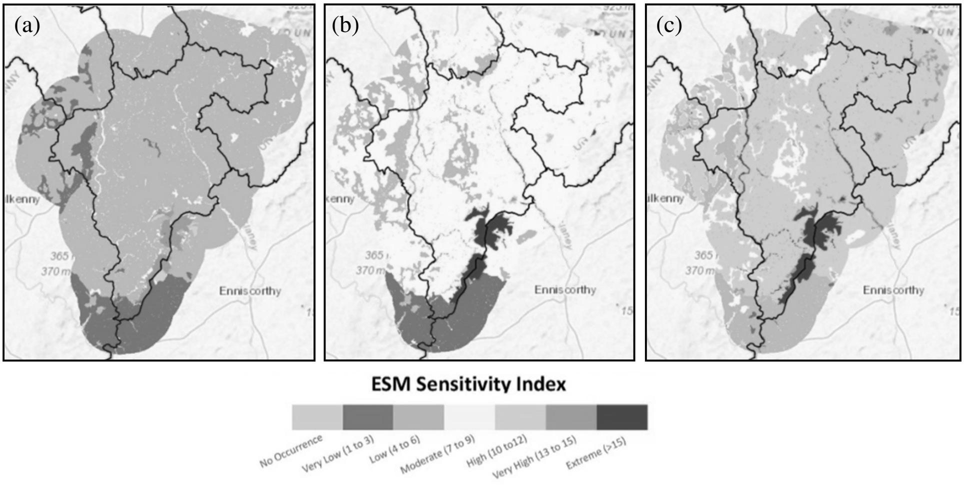

Fig. 1. Sample environmental sensitivity maps for County Offaly, Ireland, showing the effects of public values where: (a) unweighted criteria (including floods, protected biodiversity areas, cultural heritage, drinking water resources and aquifer vulnerability); (b) weighted biodiversity criteria; and (c) weighted biodiversity and water criteria.

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The sensitivity of the various criteria is harmonised on the basis of legislative environmental protection frameworks and expert knowledge in a scale of 1 (low) to 3 (high) to facilitate their aggregation (González, 2017a). The selection of environmental criteria and their relative importance are, in all cases, to be contextualised to the geographical and planning contexts, to ensure that the SEA is focussed and meaningful (Therivel, 2004). The aim of environmental sensitivity mapping is to anticipate potential significant impacts and inform the development and assessment of planning alternatives (e.g. land-use zonings), steering future development away from sensitive locations and, in this way, mitigating impacts at project level (González, 2017b).

Spanish road-route planning

Strategic planning of state transport infrastructure in Spain is done through plans that consider connectivity needs and main itineraries. These plans are subject to SEA, as per the transposition of the EU SEA Directive in 2006 (BOE, 2013). In between strategic itineraries at SEA level and road alternatives at EIA level, important decisions must be made that should take into account environmental considerations; yet this decision step is not subject to a specific EA process.

Since the late 1990s, the Spanish Ministry of Public Works has promoted the consideration of environmental criteria from the early stages of road planning, dividing the studies into stages (Arce *et al.*, 2010; Carrasco and Enríquez-de-Salamanca, 2004;

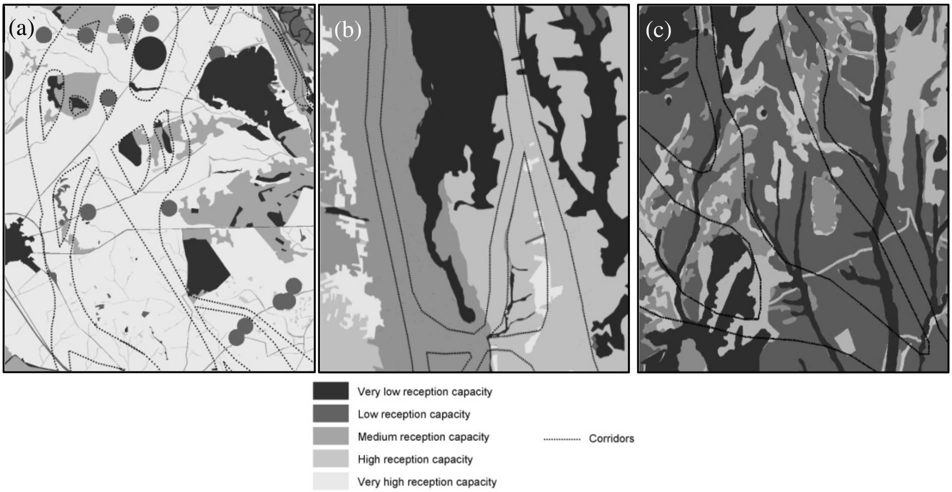

Fig. 2. Samples of reception capacity maps, and corridor definition in new motorways: (a) Palencia-Carrion, Palencia, Spain; (b) extension of A-66, León, Spain; and (c) connection between A-1 and A-2, Guadalajara, Spain.

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Loro *et al.*, 2014). In a first stage, the reception capacity of the territory (Gómez, 1992) is mapped in order to identify road corridors that avoid environmentally sensitive areas. The commonly adopted method is overlaying spatial dataset, assigning to each area the maximum restriction value due to any criteria (Fig. 2), as weighting criteria is considered to mask important territorial limitations due to a single factor (Carrasco and Enríquez-de-Salamanca, 2004). The results of this stage feed into the EIA scoping phase.

In a second stage, road alternatives are proposed within the corridors, and analysed according to technical, financial and environmental criteria in specialised studies, including EIA. The outputs of these studies are harmonised (in a scale of 1–10), and an MCA is carried out, weighting the criteria and performing a robustness analysis.

Results and Discussion

Reported benefits and limitations of spatial multi-criteria analysis in EA

The literature review identified a significant number of publications (464) that addressed GIS–MCA methods in environmental-related studies, but only 28% (130) referred to the application or applicability of the technique to EA or to the consideration of the sensitivity of the receiving environment to land-use changes. Of these, the majority (61%) merely present a methodological approach and related outputs, and do not evaluate shortcomings/advantages of described GIS–MCA methods; only 39% (i.e. 51) contain some critical examination of benefits and limitations. Arguably, this illustrates a common lack of scrutiny or appraisal of research methods in published literature. The review findings also suggest that greater attention is paid to the methods of handling information than to the quality of the information itself; in fact, in 8% of the cases (four) authors acknowledge to have handled incomplete information due to lack of data (Gorsevski *et al.*, 2012; Gumusay *et al.*, 2016; Nas *et al.*, 2010; Siefi *et al.*, 2017). The robustness of a method does not counteract the lack of input information, or its poor quality, so data considerations should be given due attention (González, 2012).

Although the large volume of GIS–MCA publications may well serve as praise for the contribution of this approach to environmental disciplines, the papers that contain a critical appraisal indicate that researchers and experts consider that the application of the technique has benefits and limitations in similar measure; 32 reviewed papers highlight benefits, while 37 point to limitations (Table 1).

From this review it can be concluded that the main benefits of GIS–MCA approaches are derived from their rapid, systematic and effective assessment of multiple factors across varying geographical areas and scales, and the provision of robust and objective information in a simple, effective and understandable way for decision-makers. They are flexible, participative and adaptable methods that enable a comparative assessment of scenarios/alternatives, which can be applied for differing objectives and at different planning scales.

Table 1. Benefits, limitations and recommendations of spatial multi-criteria analysis methods reported in international peer-reviewed literature.

Benefits	References
Enhanced interpretation and understanding: Contributes to making decision processes more objective.	1–4, 8, 17–19, 21
Exploratory capacity: Enables exploration of alternatives and/or scenarios and their suitability, or of changes in individual indicators or weights.	2, 4, 13, 15, 17, 19, 28, 32, 38
Speed: Saves time and effort; rapid preliminary assessments (of extensive geographical areas).	18, 22, 23, 30, 34, 41, 43, 47
Consistency and accuracy: Systematic, robust and consistent assessments; reproducibility of results; reduction of errors; logical framework for comparing criteria.	2, 16, 18, 26, 28, 41, 43
Flexibility: Applicable to different regions, planning hierarchies, sectoral contexts and spatial scales (i.e. geographical scope, criteria and level of assessment detail).	2, 12, 15, 18, 20, 41, 46
Integration: Combination of multiple heterogeneous datasets (alphanumeric, cartographic, remotely sensed, expert knowledge and value judgements); amalgamation of all dimensions of sustainable development; possibility of combining with other methods.	3, 7, 8, 16, 18, 28, 38
Participatory decision-making: Enables incorporating value judgements and receiving feedback (from output maps); promotes collaborative processes and participation; facilitates reaching consensus; possibility to handle multiple stakeholder preferences; promotes democratic decision-making.	4, 17, 18, 28, 32, 38
Efficiency: Effective use of the information for impact evaluation; rapid integration of readily available spatial data; simplifies data handling and provides easy access to information; outputs can be easily updated upon the availability of new or better information.	2, 3, 26, 29, 45
New insights: Facilitate assessment of cumulative effects; promote spatial awareness; aggregated outputs provide a holistic view easily understood by decision-makers.	1, 2, 5, 18, 19
Information exchange and enhancement: Knowledge sharing; integration of scientific knowledge with stakeholders' values and preferences; and increased quality and quantity of information provided to decision-making.	5, 6, 18, 19
Savings: Reduction of costs of assessment and alternative selection processes.	23, 43, 45
Automation and performance: Automating geospatial analysis allows screening all possible sites and all public weights (i.e. effect of public opinion on outputs).	8, 9

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Table 1. (*Continued*)

Limitations	References
Effect of inputs on outputs: Results depend on criteria and weights, thus on data quality and expertise; common discrepancy between experts on subjective value judgements and weights; emphasis on certain criteria may lead to omission of other key important factors; compensation issues — low scores are counterbalanced by high scores.	1, 4, 8, 9, 12, 13, 15, 18, 20, 24, 26, 27, 31, 36, 37, 42, 43, 45
Data constraints: Lack of relevant environmental criteria and data; political standpoints affecting data accessibility; differing coverages, scales and accuracy; translation from vector to raster implies loss of information; influence of raster cell size on results.	8, 18, 19, 20, 23, 34, 39, 41, 49
Level of complexity: High number of criteria may lead to technically difficult overlay operations; use of a small amount of criteria may lead to excluding important factors; difficulty to quantitatively specify weights of evaluation criteria.	6, 7, 20, 23, 33, 34, 43
Modelling methods: Different approaches can lead to different outputs; temporal assessments commonly require adaptation of models; lack of scientific foundation in some methods.	2, 4, 7, 10, 11, 32
Aggregation: Criteria summation, indexes and quantitative transformation generate loss of information; indexes can be difficult to interpret.	1, 2, 4, 7
Costs: Benefits outweighed by the costs of the work; lack of financial resources.	2, 21, 34, 40
Uncertainty: Data quality issues, methodological errors and model uncertainty could imply inefficient, unreliable or inappropriate decisions; lack of research on uncertainty and conceptual/operational validation.	18, 32, 39, 42
Interpretation: People see different things on the same map; influence of stakeholders' understanding of multi-criteria analysis and concepts.	5, 7
Data management: Difficulties in defining and combining spatial units; finer spatial units require better resolution and this requires more accurate data and time.	7

Recommendations	References
Undertake a robustness analysis to evaluate and validate the results (by examining the effects of methodological assumptions, data and value judgements on the results).	9, 10, 13, 15, 16, 25, 37–39, 46, 51
Explore the possibility of using various methods with two or three selection stages throughout the decision-making process; varying complexity of the analytical methods, from simple overlays to weighted combinations.	1–3, 5, 8, 25, 26, 46–48, 50
Make a clear distinction between constraints and evaluation criteria (also between aspirational goals and objectives).	13, 14, 16, 17, 20, 35, 42, 44
Selection of criteria, *dataand weights*, and any relevant assumptions, *must be contextualised* to the study area and to the assessment objectives.	6, 14, 18, 26, 30, 32, 36

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Table 1. (*Continued*)

Recommendations	References
Avoid obscuring findings; include individual criteria and partial suitability maps as appropriate.	7, 14, 16, 18, 25
Identify data limitations and quantify uncertainties and communicate them to decision-makers.	10, 18, 19, 39
Promote consensus on criteria and weight selection; include appropriate level and number of experts and engage public, private and academic sectors.	8, 27, 29, 40
Perform the spatial analysis at the finest resolution possible.	39
Apply the approach *as an empirical decision-support tool.*	5
Avoid aggregating impacts at different scales and on different *environmental components.*	2

Notes: [1]Aissi *et al.* (2012); [2]Antunes *et al.* (2001); [3]Basso *et al.* (2000); [4]Boggia *et al.* (2018); [5]Bojorquez-Tapia *et al.* (2011); [6]Boroushaki and Malczewski (2010); [7]Chakhar and Mousseau (2008); [8]Chang *et al.* (2008); [9]Chen *et al.* (2010); [10]Crosetto and Tarantola (2001); [11]Demesouka *et al.* (2016); [12]El Baba *et al.* (2015); [13]Eldrandaly (2013); [14]Gemitzi *et al.* (2007); [15]Geneletti (2008); [16]Gigović *et al.* (2017); [17]Gonçalves and Pereira (2002); [18]González *et al.* (2011); [19]González (2012); [20]Gorsevski *et al.* (2012); [21]Grabaum and Meyer (1998); [22]Gülci and Akay (2015); [23]Gumusay *et al.* (2016); [24]Hamadouche *et al.* (2014); [25]Hariz *et al.* (2017); [26]Hossain *et al.* (2009); [27]Jelokhani-Niaraki and Malczewski (2015); [28]Joerin *et al.* (2001); [29]Karnatak *et al.* (2007); [30]Khan and Samadder (2015); [31]Kumar *et al.* (2015); [32]Malczewski (2006); [33]Montgomery and Dragićević (2016); [34]Nas *et al.* (2010); [35]Nguyen *et al.* (2015); [36]Ozturk and Batuk (2011); [37]Perpiña *et al.* (2013); [38]Plata-Rocha *et al.* (2011); [39]Rae *et al.* (2007); [40]Riddlesden *et al.* (2012); [41]Sadek *et al.* (1999); [42]Sahnoun *et al.* (2012); [43]Siefi *et al.* (2017); [44]Silva *et al.* (2014); [45]Svoray *et al.* (2005); [46]Tavares *et al.* (2011); [47]van Haaren and Fthenaki (2011); [48]Vasileiou *et al.* (2017); [49]Webb (1982); [50]Yakar and Celik (2014); [51]Zhang *et al.* (2013).

They enable information integration and sharing, and promote spatial awareness and evidence-based decision-making. However, it is also widely conceded that GIS–MCA methods are information management tools and that their speed, economy and reliability largely depend on the complexity of the adopted method, and on the quantity and quality of the digital information available. The accuracy of outputs not only depends on the accuracy and quality of the inputted data (which often may not precisely or objectively represent a territory), but subjective public or experts' perceptions (in the form of criteria weights) can also significantly shape results and, subsequently, decisions (see e.g. Chang *et al.*, 2008; Chen *et al.*, 2010; Eldrandaly, 2013; Hossain *et al.*, 2009; Ozturk and Batuk, 2011; Perpiña *et al.*, 2013).

Planning and policy standpoints on data access and information sharing, as well as the degree of stakeholders' authority on criteria selection and weighting, can

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significantly influence assessment outputs. GIS–MCA provides a flexible framework where participants can explore, understand and redefine a spatial decision problem (Malczewski, 2006; Nyerges *et al.*, 1997), potentially enhancing both spatial decision-making and consensus reaching processes (Jelokhani-Niaraki and Malczewski, 2015). But as no agent is free from the risk of bias or manipulation (Enríquez-de-Salamanca, 2018), the observed benefits of integration and participatory decision-making can be, in fact, the detriment of GIS–MCA approaches. While the literature emphasises the need to address and communicate data and analytical uncertainty, little is said about communicating assessment bias which can equally lead to inefficient, unreliable or erroneous land management (Rae *et al.*, 2007).

The findings of the literature review also point to a degree of discrepancy between experts. For example, one of the key reported benefits of these methods is their contribution to objective decision-making, yet some authors also consider them counterproductive, as results inevitably depend on subjective selection of criteria and value judgements, which may favour vested interests. This conundrum is central to MCA techniques; experience- and knowledge-led bias is, to a degree, desirable in order to capture local contexts and individual perceptions. The involvement of experts, stakeholders and the general public contributes to increased awareness, improved stewardship and contextualised evidence and experience-base (Adger, 2006; Dietz and Stern, 2008; González, 2017b; Gupta, 2008). GIS–MCA techniques must be acknowledged for what they are, a decision-support tool that enables capturing key scientific issues/concerns and factoring in expert/stakeholder values in the assessment. Cogent understanding and effective application imply that the interpretation of mapped outputs must have due regard to the objective criteria and subjective values inputted in the assessment (González, 2017b). Moreover, in the quest for the previously argued transparency, reporting and disseminating the underlying criteria and weights (e.g. in the form of intermediate thematic maps) is necessary (Table 1). Transparent science–policy communication also helps addressing the issue of potentially obscuring individual criteria by aggregating multiple datasets into a composite index (Boggia *et al.*, 2018; González, 2017b; Marull *et al.*, 2007).

Another observed discrepancy is that of costs versus savings. The costs of implementing these techniques depend largely on data availability and may affect the effectiveness of GIS-based analysis techniques (Craglia *et al.*, 2012; Vanderhaegen and Muro, 2005). However, things are changing, and open data initiatives are rendering large, wide and varied socio-economic and environmental datasets publicly available to the benefit of informed and evidence-based assessments and planning processes (Hardy and Maurushat, 2017; Kitchin, 2014). Technological

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advancements are also helping overcome the need for expertise to compile data and run assessment models, and advanced online GIS–MCA tools are starting to emerge (see e.g. González, 2017b; Grêt-Regamey *et al.*, 2017). Technological innovation will continue to reduce costs and facilitate the uptake of ever perfecting GIS–MCA methods across a wide range of disciplines.

A number of authors take a step further and make a series of recommendations to enhance the applicability of GIS–MCA. The need of robustness analyses to examine the effects that criteria and weights may have in the final output is considered essential. The results of such analyses and any data or model uncertainties (e.g. errors and assumptions) should be communicated at critical decision windows. Experts also point to the need to contextualise criteria and public values, and to ensure that these are not data-dependant (i.e. that, ideally, the analysis is not constrained by data availability). A tiered approach to the assessment, which may entail different GIS–MCA methods, may help overcome data issues and better inform different decision stages. It is recommended that obscuring content in the output maps (e.g. through criteria integration or overall indexes) is avoided by providing individual or partially combined criteria in intermediate maps that enable scrutinising the underlying data and considerations; this will not only ensure transparency and help with understanding, but also more efficiently inform decision-making.

Comparative observations on environmental sensitivity analysis

The methodological approaches of the case studies examined in this paper were developed and applied independently, without previous information exchange between the authors, so the remarks and conclusions of each case study, as presented in this paper, are not conditioned by the results of the other case study. Yet the authors make a joint reflection on the state-of-the-art and related recommendations. Yet, environmental sensitivity is, in both case studies, understood as the intrinsic susceptibility of the receiving environment, in other words, its limited capacity to cope with man-made interventions. Although both cases adopt a tiered approach, where environmental sensitivity and reception capacity mapping and analysis represent an initial stage in EA to then inform the development of alternatives, the adopted MCA method and participatory nature differ (Table 2). The Irish approach uses weights to incorporate public degrees of concern associated with planning alternatives, fulfilling the participatory requirements of the SEA Directive (EC, 2001) — acknowledging the effect of such weights on results (Fig. 1; González, 2017b). In contrast, the Spanish method adopts the precautionary principle and avoids weighting in order to prevent masking important

Table 2. Differences between environmental sensitivity analysis in Irish strategic land-use planning and Spanish road-route planning.

Aspect	Ireland	Spain
MCA method	Weighted overlay $$\mathrm{ESI} = \sum_1^n \mathrm{Sc}_j W_j,$$ where ESI refers to the environmental sensitivity index that captures the overall sensitivity of the area, which relates to the total number (n) of criteria that overlap at that location; Sc_j is the scientific sensitivity score for criterion j according to legislative resource protection measures or scientific expertise values on risk (ranging from low to high — i.e. from 1 to 3); and W_j is the public weighting of subjective nature on the importance of criterion j (can be neutral or weighted — i.e. 1 or 2).	Overlay assigning the most restrictive value $$\mathrm{RC} = \mathrm{Min}_1^n\ \mathrm{RC}_j,$$ where RC is the reception capacity of the territory for the transport corridors according to the total number (n) of criteria used, ranging from very low (1) to very high (5). RC_j is the RC of each criterion. Criteria are valued according to their RCs. Partial maps of environmental, socio-economic and physical objectives are elaborated overlaying related criteria and assigning the most restrictive RC to each area, and with them an overall map.
Weighting	Participatory, stakeholder-driven.	Not applied at this stage.
Assessment level	SEA (current data constraints limit applicability at EIA level).	EIA, at the initial stages of the process (previous to the scoping phase).
Sectoral application	Currently for land-use planning; potential to be applied to other sectors associated with the zoning of lands such as renewable energy, forestry, etc.	Transport sector, for identifying strategic itineraries at SEA level or for developing alternatives at EIA level; these applications differ in scale and level of data detail.
Data sources	Publicly available national datasets covering all SEA thematic areas, commonly obtained from governmental sources.	Publicly available datasets obtained from governmental sources (national, regional and local), and thematic maps made specifically for each study.

limitations (Carrasco and Enríquez-de-Salamanca, 2004). Assigning higher importance to certain environmental criteria is a way of prioritising the conservation of some areas and, in the context of land-use planning, steering development away; however, this is not always possible for transport corridors.

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Land-use planning is concerned with zoning lands for future developments, and commonly deals with discrete geographical areas defined by administrative boundaries (while giving due consideration to transboundary effects). Road planning, in contrast, is concerned with linear corridors that often cross administrative units. This has implications for data gathering and stakeholders' consensus, and affects the scope and applicability of sensitivity studies. The use of constraints or exclusionary criteria to avoid sensitive areas is useful to find locations for specific elements or to delimit territorial units (see e.g. Gemitzi *et al.*, 2007; Gigović *et al.*, 2017; Gorsevski *et al.*, 2012; Nguyen *et al.*, 2015; Sahnoun *et al.*, 2012; Silva *et al.*, 2014), but may not be for linear infrastructures, which cannot be interrupted. In the latter, high-sensitivity areas usually cannot be automatically excluded, since they should be crossed; an example is the presence of other linear elements of high environmental value such as rivers. When exclusion criteria are not applied, the risk of affecting sensitive areas increases, which justifies the application of the precautionary principle. Nevertheless, this is also a key consideration at strategic planning level as the lack of knowledge on project type and detail inhibits making absolute sitting decisions. Identified high-sensitivity areas are to be treated as a warning of potential land-use conflict rather than as definitive no-go locations (González, 2017b).

For spatial analyses to be effective and meaningfully inform alternative development, assessment and selection, they require contextualised current, comprehensive and detailed data. While both sectors typically prioritise the protection of sensitive habitats and species — under the requirements of the EU Habitat Directive (EC, 1992), water-related sensitivities may not be as relevant to transport corridors as they may be to land-use planning — particularly in the context of avoiding development on these natural features. Scale issues play a significant role in shaping assessments (González, 2012; João, 2007), and the planning levels of the case studies emphasise the need for varying resolution in the data. The Irish approach adopts a 100-m pixel raster resolution, while the more detailed analytical requirements of the Spanish case study rely on vector datasets at scales between 1:10,000 and 1:25,000. While raster data commonly entails less precision, it provides sufficient detail at SEA or strategic planning level (Antunes *et al.*, 2001; Geneletti *et al.*, 2007; González, 2017b; Marull *et al.*, 2007); it is typically of limited use in EIA and project planning, where more accurate evidence is needed. The assessment scale has, in turn, data requirement implications; while the Irish raster approach allows the use of available spatial datasets (typically collated at national level at a scale of 1:50,000 or smaller), in the Spanish vector approach detailed datasets are only partially available. Data availability has significant implications for GIS–MCA outputs, and may lead to important omissions. In the

Table 3. Benefits and limitations of GIS–MCA methods in Irish strategic land-use planning and Spanish road-route planning.

<table>
<tr><th></th><th>Ireland</th><th>Spain</th></tr>
<tr><td rowspan="2">Benefits</td><td colspan="2">• Enhanced interpretation and understanding through a simplified combination of multiple considerations to better inform land-use planning and road corridor sitting.
• Speedy preliminary assessment of large geographical areas in the early stages of EA, to avoid significant impacts from the onset.
• New insights and increased quality and quantity of information provided to the decision-making process.
• Integration of multiple objective and subjective criteria.
• Increased efficiency, transparency and consistency of assessments, as well as efficiency in conveying large volumes of information.</td></tr>
<tr><td>• Exploration of land-use alternatives and the effects of weights.
• Participatory decision-making by enabling the incorporation of value judgements.
• Flexibility to be applied across regions and to other sectors, at SEA level — as long as data are available.</td><td>• Exploration of road corridor alternatives.
• No influence of weights.
• Detailed and objective results.
• Flexibility to be applied to other regions and sectors, at EIA level — as long as data are available.</td></tr>
<tr><td rowspan="2">Limitations</td><td colspan="2">• Results (outputs) depend on criteria and weights (inputs), thus on data availability and quality, as well as expertise/concerns of those participating.
• The different approaches (modelling methods) adopted in the case studies would, inevitably, lead to different outputs.
• Difficulties with data management when combining multiple spatial units and scales; various planning hierarchies and sectors require specific criteria and scale of data.</td></tr>
<tr><td>• Data constraints (i.e. small-scale data available only) limit applicability to SEA.
• Influence of weights may require statistical sensitivity analysis.</td><td>• Lack of incorporation of weights limits participative decision-making.
• Need for detailed local data, and specific maps to inform road layouts.
• Not possible to differentiate constraints and evaluation criteria.</td></tr>
</table>

Irish case, the reliance on publicly available datasets results in relevant considerations being overlooked (e.g. there is no national dataset available for landscape sensitivity). Such limitation can be addressed through data gathering efforts, particularly at project level as in the Spanish case study.

The case studies validate some of the benefits and limitations reported in literature (Table 3), particularly those related to modelling methods, effects of input

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on outputs and data management and constraints; but also some of the benefits such as their contribution to enhanced understanding, their flexibility to combine subjective and objective criteria in a participative and exploratory way or their potential to increase the efficiency, transparency and consistency of the assessments (Carrasco and Enríquez-de-Salamanca, 2004; González *et al.*, 2011; González, 2017b). In all cases, GIS–MCA approaches must be understood as operational tools to support decision-making, rather than end solutions; they are tools to systematically and transparently identify viable alternatives that are then to be subject to a detailed EA, rather than for selecting alternatives and obviating the scrutiny that EA implies and requires.

Additional insights on benefits and limitations

The direct involvement of the authors in the above case studies enables a reflection on the benefits and limitations of GIS–MCA approaches reported in literature (Table 1). Feedback from the case studies supports the widely reported benefits of enhanced understanding and better informed decision-making (Table 3). Maps have the capacity to convey large volumes of information efficiently. But such information dissemination needs also to be transparent if decisions are to meaningfully avail of evidence and be accountable. While the need for transparency is well acknowledged in EA (Morrison-Saunders and Bailey, 2000), there is no sufficient attention drawn to such consideration in GIS–MCA literature. In fact, there is ongoing criticism of spatial MCA outputs obscuring detail by amalgamating multiple criteria and values, using cryptic indexes (Boggia *et al.*, 2018), which may lack a scientific foundation (Malczewski, 2006), and which may be difficult to interpret given the limited stakeholders knowledge and understanding of GIS–MCA methods (Chakhar and Mousseau, 2008). Only some authors (e.g. González *et al.*, 2011; Joerin *et al.*, 2001) recognise that such methods can contribute to improving assessment transparency. This is supported by the Irish stakeholders who indicated that a systematic approach, with clearly drawn rules and criteria, provides the opportunity to support unambiguous, comparable and accountable assessments (González, 2017b).

A given GIS–MCA method may, in principle, be applicable to varying planning and sectoral contexts, or differing geographical regions and scales. However, as the comparative examination of the case studies has shown, the various planning hierarchies and sectors have specific assessment requirements with regard, among other things, to criteria and scale of data. It is recognised that applicability is often hindered, for example, by their inability to incorporate and address local knowledge, data and issues (Bagstad *et al.*, 2013; González, 2017b). Therefore, the

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advantage of flexibility, which is widely acknowledged in literature, is only achievable if relevant data are available at the appropriate scale for the geographical area under assessment. In general, sacrificing local detail by broad generalisations increases the applicability of a method but limitations remain. For example, the Irish GIS–MCA method for land-use planning SEAs is applicable across all administrative areas in the country as it relies on national datasets; however, it can only be applied in EIA if sufficient high-resolution good quality data were available — and this is not the case for many relevant environmental datasets. Similarly, the Spanish method could be scaled up nationally and it could well be adopted for informing transport planning in Ireland or elsewhere, but its transferability to other sectors, such as forward planning, is constrained by sector-specific criteria and data considerations. It needs to be recognised that each method will derive in different results and, perhaps more importantly, that "different approaches will be more appropriate in distinct geographic and decision contexts" (Bagstad *et al.*, 2013, p. e35). There is no universal one-fits-all GIS–MCA solution. Each approach has its merits and shortcomings, and these must be given due consideration when determining their suitability for the assessment at hand.

Conclusion

Although there is abundant literature on GIS–MCA methods, many scientific publications purely describe case-study-based applications of various approaches without any appraisal or reflection on advantages/disadvantages. This paper addresses this general shortcoming by combining the findings of a literature review with contemporary case studies linked to the authors' extensive experience using this technique, to advance understanding and discussions in the area.

The wider literature and practice recognise the contribution of GIS–MCA approaches to informing planning and to steering development away from environmentally sensitive areas. And the intrinsic spatial nature of EA and planning has lent these processes to the uptake of spatial multi-criteria analysis. However, examination of reported limitations of applying the technique puts urgency on addressing and resolving these if the technique is to succeed in supporting accountable decisions. While acknowledging that there is no one-fits-all solution, one of the strengths of GIS–MCA is its flexibility to be adapted to different assessment objectives, sectors and territorial characteristics. Yet this flexibility is often compromised by sector- and plan-specific considerations and, more importantly, by data limitations. Therefore, the research community may need to put less emphasis on reinventing the wheel and on fine-tuning existing methods and

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algorithms, and place more focus on applying currently available robust methods across sectors and geographical areas to start examining their true applicability and transferability. Similarly, while some data access and quality limitations have been resolved, more effort is needed on auditing datasets and exploring the effects of data resolution and omissions across disciplines and assessment scales (e.g. SEA versus EIA). Some issues (e.g. effects of value judgements on outcomes or map interpretation capacity) will endure but can be undoubtedly addressed by ensuring transparency and by supporting science–policy communication.

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