

Research article

Ecosystem accounting for biodiversity surrounding windfarms

Emma King^{a,*}, Jane C. Stout^a, Yvonne M. Buckley^{a,b}, Ian Donohue^{a,b}^a School of Natural Sciences, Trinity College Dublin, Dublin 2, Ireland^b Co-Centre for Climate + Biodiversity + Water, School of Natural Sciences, Trinity College Dublin, Dublin 2, Ireland

ARTICLE INFO

Handling Editor: Dr. Lixiao Zhang

Keywords:

Ecosystem accounting

SEEA-EA

Wind energy

Biodiversity

Natural capital accounting

Renewable energy

ABSTRACT

To ensure that climate action and biodiversity obligations are met, the rapid growth of the renewable energy industry must be accompanied by tools to monitor, protect and enhance the biodiversity surrounding renewable energy infrastructures. The United Nations System of Environmental Economic Accounting–Ecosystem Accounting (SEEA–EA) provides a statistical framework to measure and document positive and negative changes in ecosystem extent and quality. Using a spatially explicit approach, this framework can provide industries with a standardised, measurable, verifiable, and reportable approach to ecosystem management. However, accounting for biodiversity, particularly at smaller site-specific scales, is underdeveloped in the SEEA–EA. Here, we use the SEEA–EA to develop biodiversity-themed ecosystem extent and condition accounts for onshore windfarms and provide a management tool for operators, enabling them to understand the extent of the habitats present, and their ability to provide resources for biodiversity. We added a new step into the condition account process to facilitate the incorporation of variables for biodiversity. Application of the methodology highlighted considerable biodiversity potential of some habitats, particularly peatland, marsh, and freshwater systems. The spatially explicit methodology clearly identified locations where improved management could enhance biodiversity. Implementing the SEEA–EA framework is standardised and repeatable, and its flexibility allows for accounts to be built at site-scale for a variety of land-uses and habitats. The development of biodiversity-themed ecosystem accounts for the onshore wind energy industry demonstrates the utility of the SEEA–EA to inform local management decisions across a sector that is critical for climate change mitigation.

1. Introduction

Ecosystem accounting is used to assess ecosystems and their ability to provide services in a format that is similar to financial accounts (Edens et al., 2022). This approach can facilitate the systematic incorporation of natural assets into policy and decision-making, in particular by those who may not be familiar with ecological vocabulary (McGrath and Hynes, 2020). The first framework for the System of Environmental Economic Accounting (SEEA) was published in 1998 following the emergence of environmental accounts over the preceding decade (Edens and Hein, 2013). The United Nations System of Environmental Economic Accounting (UN SEEA) has, since 2012, become the international standard framework for ecosystem accounting. The SEEA–Ecosystem Accounts (EA) has been ratified as a statistical standard since 2021. The SEEA–EA differs from other accounts within the SEEA framework in that it uses a spatial approach to compile accounts, enabling combination of multiple spatially-explicit layers from geographical, environmental, and economic datasets into a single account. However, biodiversity, defined

as “the variability among organisms from all sources, encompassing all ecosystems and ecological systems to which they are part, including diversity within species, between species, and of ecosystems” (United Nations, 2011), presents a particular challenge for ecosystem accounting (Grover et al., 2023).

Ecosystem accounts can be compiled at a range of scales and are often used as a tool to measure changes in natural capital. Natural capital is the stock of natural resources, from which flow goods and services that have benefit and value to humanity (Costanza and Daly, 1992). Ecosystem accounting has primarily been conducted at national and regional scales to measure the stocks and flows of natural capital through various systems and sectors (CSO, 2018; Farrell et al., 2021). The focus on national scale accounting can be attributed to the explicit, and intentional, link between the SEEA and the System of National Accounts, which allows the extension of national economic accounts to incorporate natural capital (Bagstad et al., 2021). Existing ecosystem accounts created using the SEEA–EA methodology have been developed for several countries (Bond et al., 2013; Hein et al., 2020b) and even at

* Corresponding author.

E-mail addresses: kinge6@tcd.ie (E. King), stoutj@tcd.ie (J.C. Stout), buckleyy@tcd.ie (Y.M. Buckley), donohui@tcd.ie (I. Donohue).<https://doi.org/10.1016/j.jenvman.2025.126618>

Received 20 January 2025; Received in revised form 9 May 2025; Accepted 15 July 2025

Available online 18 July 2025

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the EU-scale through the Integrated system for Natural Capital and ecosystem services Accounting (INCA; La Notte et al., 2022). These accounts have focused primarily on provisioning and regulating services derived from natural capital stocks such as carbon, water, and timber (La Notte et al., 2021; Vallecillo et al., 2019). Given the European Union's new Corporate Sustainability Reporting Directive (CSRD; 2022/2464), many companies will now be required to incorporate sustainability and environmental matters into their annual reports, including measurements of the impact of their operations on natural capital. Ecosystem accounting approaches, such as the SEEA-EA, are, therefore, increasingly applied at local- (Driver et al., 2015), site- (Lound, 2015), and corporate-level scales (Ingram et al., 2022; Martini et al., 2024). There are benefits to businesses of utilising ecosystem accounts, as they can be applied in decision-making, reporting, and planning (Ingram et al., 2022) and are repeatable, so can be used to assess change through time.

The SEEA-EA framework comprises five core accounts – extent, condition, physical ecosystem service, monetary ecosystem service, and ecosystem asset accounts (United Nations, 2021), which can be further divided into two types – stock and flow accounts (Edens et al., 2022). Stock accounts, which consist of ecosystem extent and condition, are the most developed for biodiversity-themed accounting (Edens et al., 2022). While guidance is available on monetary (flow) accounts, the difficulty in quantifying the value of nature has limited progress for the creation of biodiversity-themed monetary accounts (Edens et al., 2022; Hein et al., 2015). Often, the first ecosystem account to be built is the extent account. This is defined as the spatial measurement of an ecosystem asset, which is the primary unit that comprises the accounts (United Nations, 2021). Ecosystem or habitat classifications are then used to delineate ecosystem assets within the accounting area. To be used in the SEEA-EA for accounting purposes, habitat classifications must represent a distinct set of both abiotic and biotic components and their interactions (United Nations, 2021). Ecosystem condition then measures the quality of an ecosystem asset in terms of its abiotic and biotic characteristics relative to a reference condition (United Nations, 2021).

Ecosystem condition is, in general, the second account developed, building on the extent account. Extent and condition can be used to determine targets for management of habitats that subsequently affect ecosystem services (Maseyk et al., 2016). Characteristics of the habitat are systematically organised and transformed through a series of stages to result in an index value that acts as a proxy for the quality of the asset. A range of criteria need to be met to select indicators that act as robust proxies of the condition of the focal ecosystem (United Nations, 2021): indicators need to be spatially explicit at the selected scale (Rendon et al., 2020), sensitive to environmental change (Czúcz et al., 2021), and relatively easy to measure (Czúcz et al., 2021). It is also important that there is a clear evidence-based link between the indicator and the service the account is compiled for (Czúcz et al., 2021; Rendon et al., 2020). Defining this link is, however, often difficult (Remme et al., 2016). As biodiversity has been poorly aligned within ecosystem accounting (Mace et al., 2011), difficulties in selecting suitable indicators can be compounded.

Once potential characteristics have been identified, an additional challenge is sourcing a dataset or finding a way to measure those characteristics in the field (Faccioli et al., 2023). Accessibility of data is a major limitation in many use-cases of ecosystem accounting (Czúcz et al., 2021; Feld et al., 2009; Remme et al., 2016; Rendon et al., 2020). In addition, indicators need to have appropriate reference conditions relative to the ecosystem and service for which the accounts are being developed (Martini et al., 2024). These can be difficult to source, particularly for heavily modified ecosystems (Rendon et al., 2020). The SEEA-EA proposes several options to help select a reference condition. For anthropogenic ecosystems, this includes contemporary, historical, least disturbed, or best attainable conditions (United Nations, 2021). The rationale behind choosing an appropriate reference is dependent on the goal of the account, the ecosystem type, and the management that is likely to be applied (United Nations, 2021). For example, an industry

may choose the best attainable condition if they plan to introduce management to enhance biodiversity, or least disturbed if it is a large natural area that will perform better with little intervention.

The SEEA-EA has adopted the Convention on Biological Diversity's (CBD; 1992) definition of biodiversity as *"the variability among living organisms from all sources including inter alia, terrestrial, marine and other aquatic ecosystems, and the ecological complexes of which they are apart; this includes diversity within species, between species, and of ecosystems"* (United Nations, 2011). An early debate in the ecosystem accounting concept was whether biodiversity should be incorporated as an ecosystem service, an output, or as a theme for accounts (Edens and Hein, 2013), and how it has been included in previous work varies greatly (Mace et al., 2011). The complexity in defining biodiversity within the ecosystem services concept compounded confusion as to biodiversity's place within ecosystem accounting (Reyers et al., 2012). This has, in turn, slowed the inclusion of biodiversity in ecosystem accounts (Reyers et al., 2012), and there remains uncertainty in structuring biodiversity within ecosystem accounts (Remme et al., 2016). More clarity in our understanding of biodiversity's place has begun to emerge as the SEEA-EA framework is applied to different scenarios and contexts (Bond et al., 2013; Mokany et al., 2022). Today, biodiversity is increasingly recognised as underpinning many ecosystem services in a variety of ways (Harrison et al., 2014; King et al., 2021; Waldén et al., 2023). The SEEA-EA incorporates biodiversity through thematic accounts, which provide more context or quantitative data for the broader ecosystem accounts (Hein et al., 2020b; Maes et al., 2020). Carbon and water are two other examples of thematic accounts, and, of these three, biodiversity is the least developed (Lange et al., 2022). This is due largely to early deliberations on its place in the ecosystem services concept, and complexities in measuring and defining biodiversity indicators (King et al., 2021).

Development of thematic accounts provides an opportunity to spatially assess ecosystems through the lens of biodiversity in a standardised, verifiable, and repeatable format. Much of the focus on biodiversity-themed accounts has been on species-level biodiversity (Bond and Vardon, 2019; Rainsford et al., 2025). Despite the SEEA-EA adopting the CBD's definition of biodiversity, this definition is not fully recognised in the treatment of biodiversity within the SEEA-EA guidelines (King et al., 2021), in that only species accounts are exemplified for biodiversity, rather than the broader interpretation of biodiversity as defined. It is, therefore, important to expand on the current use of biodiversity in the SEEA-EA framework to encompass all elements of biodiversity given its important roles in underpinning ecosystem services (Harrison et al., 2014) and its own intrinsic value (Taylor et al., 2020). Monckay et al. (2022) provide one of the few examples of accounting beyond the species-level, with habitat-based accounts developed for the Murray-Darling Basin.

Accounting for biodiversity at the site scale has had limited implementation and uptake due to perceived barriers (van Putten et al., 2021). However, case studies incorporating biodiversity at the site-level are beginning to emerge (Driver et al., 2015; Martini et al., 2024). Ecosystem accounting has undoubted potential to become a useful management tool for industries or corporate businesses to make informed decisions or predict change to areas under their management (Ingram et al., 2022; Keith et al., 2017). Developing accounts at the site scale can structure the collation of detailed ecosystem accounts in a standardised format that aligns with reporting requirements and can show change through time (Parkhurst et al., 2024). The flexibility of the SEEA-EA approach, while maintaining its standardised format, is a key benefit of the framework, especially in how it integrates across multiple land-uses and industries. Increasingly, more case studies are emerging that demonstrate the utility of the SEEA-EA for adaptive management and informed decision-making (Parkhurst et al., 2024; Rainsford et al., 2025; Vardon et al., 2023), although few have been developed with a specific industry or environmental impact in mind. In addition, the complexity of ecosystem accounting and conflicting perspectives on

implementation are perceived by stakeholders as potential barriers to utilising ecosystem accounts (Fleming et al., 2022).

Ecosystem accounts will differ depending on how the ecosystem assets are delineated, and what habitat classification is used. The SEEA-EA recommends the use of national classification systems, which are tailored to local ecosystems and environs. However, the SEEA-EA also recommends the use of the International Union for Conservation of Nature Global Ecosystem Typology (IUCN GET) (Keith et al., 2022) if using the accounts for comparison internationally. Use of standard National Classification system(s) facilitate more detailed and specific habitat delineation, and they also align with planning surveys and national datasets. The IUCN GET is a much broader classification system, as it needs to cover global habitat types. However, it can also be useful in site-level accounting, particularly for multinational companies that may need to account for multiple sites across many countries. Therefore, the ability to switch between different classification systems would be beneficial when conducting site-level accounting. There is, however, a need to understand whether, and how, using different classification systems influences the accounting output. Additionally, ecosystem accounting has been recognised as a potentially useful management tool for industries to support decision-making (Ogilvy et al., 2022) and non-financial reporting (Fleming et al., 2022). It is important, therefore, that the accounts developed can identify differences in condition indices among different habitat types, which would help prioritise management actions, facilitate informed decision-making, and ensure accuracy in reporting.

The onshore wind energy industry in Ireland provides an excellent case study to test the flexibility of the SEEA-EA, as wind turbines are co-located across many land-use types and habitats on the island (Hallan and González, 2020), and operators require tools to facilitate management decisions incorporating the biodiversity that surrounds their wind turbines (Gorman et al., 2023). Further, previous case studies have demonstrated the ability to develop ecosystem accounts at larger scales in the Irish landscape (Farrell et al., 2021) and planning for onshore windfarms in Ireland typically utilises a specific national habitat classification system (Fossitt, 2000), which provides the opportunity for comparison against the SEEA-EA recommended typology (Keith et al., 2022).

Here, we develop a workflow to specifically address the challenges of scale, incorporation of biodiversity, and data availability for thematic natural capital stock accounts using the SEEA-EA framework, building on the decision-methodology developed for site-level ecosystem accounting (Gorman et al., 2024). We apply this framework to build site-scale ecosystem accounts for seven exemplar windfarms across Ireland. The accounts were built primarily to identify areas of natural capital that enable biodiversity enhancement or protection across multiple habitats and land-uses. We use our results to compare ecosystem accounts based on two different standardised habitat classification systems (that is, the Irish Fossitt classification system and the SEEA-EA-recommended IUCN global ecosystem typology) to understand the extent to which these different systems affect condition scores. We compare condition scores among habitats to assess the ability of the SEEA-EA to measure biodiversity condition among habitat types. Finally, we discuss the limitations of our approach, and of ecosystem accounting in general, and make recommendations on the application of ecosystem accounting at local-scales.

2. Methods

2.1. Indicator development

In the SEEA-EA, the Ecosystem Condition Typology (ECT) is “a hierarchical typology for organising data on ecosystem condition and characteristics” (Czúcz et al., 2021). This typology was developed to standardise and structure the selection of variables included in the ecosystem accounts. To select variables, relevant literature on

biodiversity indicators and scorecards for similar habitats were reviewed. These scorecards were typically developed for existing projects that tested indicators to measure condition of specific habitats in Ireland, typically for results-based payment schemes. The scorecards reviewed included those described by the Wild Atlantic Nature Project (2024), Pearl Mussel Project (2018), FarmPEAT (2024) and McLoughlin et al. (2020). The variables selected should have a clear biophysical link to the goal of the accounts being developed (Czúcz et al., 2021a). Here, our goal was to develop biodiversity-themed accounts that can be used to inform management decisions for the Irish wind energy industry. Thus, the variables need to have a biophysical link with the potential for the ecosystem to provide habitat for biodiversity.

A literature review of biodiversity indicators and a review of available datasets was conducted to provide a list of 34 potential variables that could be included in the condition account. A workshop was held with five independent expert ecologists to discuss the suitability of potential indicators prior to inclusion. In the ECT, there are typically six classes (ranging from physical state to landscape/seascape state) across three groups (that is, Abiotic, Biotic and Landscape). All potential indicators for the Biotic grouping, ‘Functional state characteristics’, could also be seen as other characteristics (structural or compositional state). Thus, no functional indicators were selected for the biodiversity accounts.

For variables that require data to be collected in the field, index scorecards were developed (Appendix A). The scorecards needed to be practical for use in the field and also for stakeholders to be able to easily use and input the data into the accounting framework. Therefore, the condition variables in the score cards needed to be easy to record, easy to interpret, standardised across habitats of the same type, and in units that are easy to follow.

2.2. Implementing the SEEA-EA

The first accounts built were the extent accounts using area of each habitat. Ecosystem assets were delineated and placed into the best-fitting habitat type, and this was based on the SEEA-EA definition of ecosystem types (that is, represents a distinct set of abiotic and biotic components and their interactions). Each ecosystem asset was assigned a habitat type from the Irish national classification system *A Guide to Habitats in Ireland* (Fossitt, 2000) at the most fine-scale (Level 3), and a Functional Ecosystem Typology from the IUCN GET classification. As we only gathered data from one set of surveys, the standard SEEA-EA extent account format was modified to account for one observation period rather than changes over time. That is, accounts were created using only ‘opening values’ as no ‘closing’ data were collected.

In the SEEA-EA framework, developing ecosystem condition accounts is a three-step process producing three accounts: the variable account, indicator account, and ecosystem condition account. The variable account is produced from inputting biodiversity characteristics. An additional step that is not in the SEEA-EA framework was added for the biodiversity accounts produced here, in which the variable was rescaled to an interval index between 0 and 3, where 0 indicates poor condition and 3 indicates best-attainable condition (Fig. 1). The addition of this step was to address directionality, non-linearity of the relationship of the variable to condition and, specifically for biodiversity accounts, issues surrounding specificity required of reference conditions (Rowland et al., 2021). These variables were then scaled using reference conditions to produce the indicator value I , as:

$$I = \frac{(V - V_L)}{(V_H - V_L)}$$

where V is the standardised variable value, V_L is the lower reference value, and V_H is the upper reference value. The indicator value I is therefore a continuous measure between 0 and 1, with zero indicating poor condition and one indicating best attainable condition.

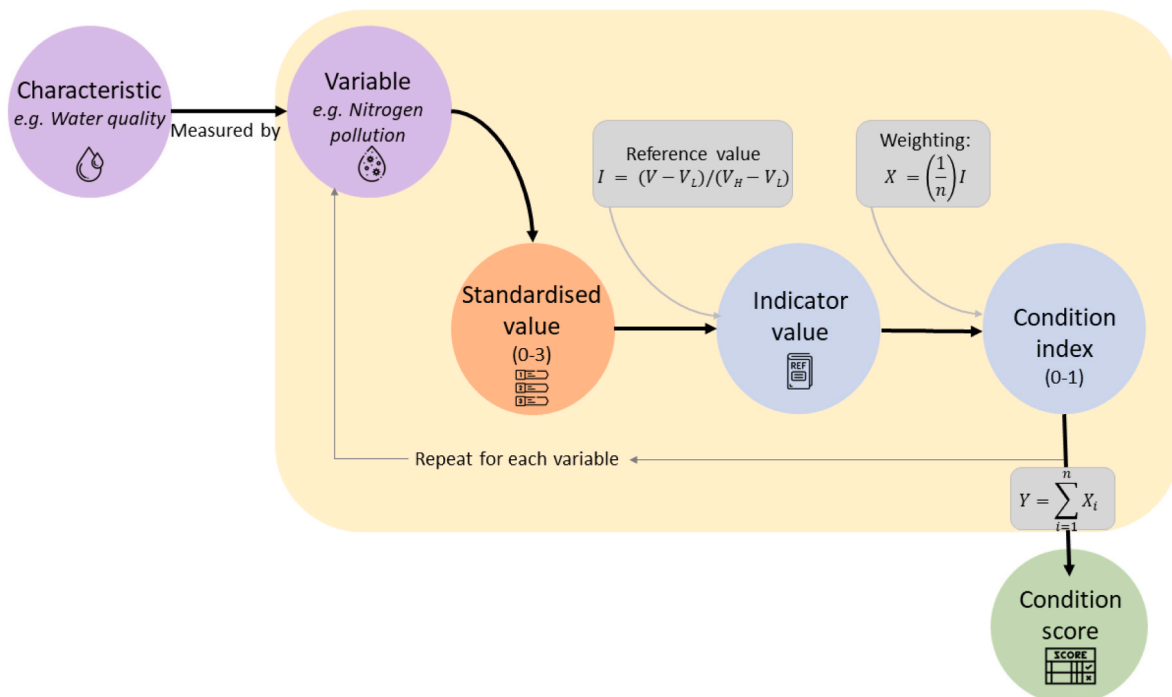


Fig. 1. Outline of steps involved in developing a condition score for condition accounts. Characteristics, such as water quality, are measured by variables, which are quantitative metrics to describe characteristics. They must be unambiguous and have well-defined measurement units. Variables are then rescaled to a standardised value on a 0–3 scale, allowing for non-linear relationships between variables and condition. Following this, they become indicators through rescaling against a reference value (V_L : lower reference value, V_H : upper reference value). They are then weighted depending on the relative importance of each indicator to the overall condition score (n : total number of indicators). This process is repeated and the condition indices for each variable are summed to produce the condition score for the ecosystem asset.

The SEEA–EA proposes several possible reference conditions that can be used for anthropogenic or highly-modified ecosystems. Best-attainable condition was selected as it aligns most closely with the goal of the ecosystem accounts for our purposes. That is, to provide good management tools in a highly modified environment. In the SEEA–EA, best attainable condition is defined as ‘the expected condition of an ecosystem under the best possible management practices.’ One of the end-uses of our ecosystem accounts is to identify areas where management can be implemented and the intensity of interventions to be recommended, and to form baseline accounts so that future accounts can inform how habitats are responding to interventions. The reason for choosing this reference condition compared to the other available options (e.g., pristine, historic, least-disturbed) was that windfarms are, and are often located in, highly modified environments that will likely never be hotspots of biodiversity. However, these landscapes can still facilitate biodiversity and provide resources and, importantly, can help reduce habitat fragmentation.

Once variables were scaled against the reference condition, they become indicators in an indicator account. The final condition account was created from aggregated condition indices, with an equal weighting (together equating to one) across the Ecosystem Condition Typology classes. Following the SEEA–EA recommendations, equal weighting was used across all ecosystem classes. Condition accounts were not created for buildings and artificial surfaces (BL3), spoil and bare ground (ED2), or urban and industrial ecosystems (T7.4) of the Global Ecosystem Typology (Keith et al., 2022) owing to the lack of biodiversity indicators for these anthropogenically-created habitats. Interactive maps displaying condition indicator scores were created using the ‘mapview’ (Appelhans et al., 2023) and ‘leaflet’ (Cheng et al., 2024) packages in R version 4.2.2 (R Core Team, 2022), and made available via the ‘shiny’ (Chang et al., 2024) package (see Supplementary Material for an example interactive map).

2.3. Site selection

Our case study windfarm sites were selected as representative of onshore windfarms across Ireland and the habitats and land-uses in which they are typically co-located. Seven sites in the Republic of Ireland were used as exemplars for which stock accounts were developed. Land-use in Ireland is dominated by grasslands, followed by peatlands, croplands, and forest (CSO, 2022), and this was replicated in site selection. Windfarm sites were also selected to represent a mixture of sizes (5–36 turbines; 65–2187 ha) and ages of operation (established 2002–2018). There are two common land management types for windfarms in Ireland – ‘wholly-owned’ and ‘herringbone lease’. In the case of wholly-owned windfarms, the entire site, incorporating the windfarm infrastructures and surrounding land, are owned and managed by the windfarm operator. For sites under herringbone lease, the area under management by the operating company is the footprint of the windfarm infrastructure, whereas the surrounding land is typically owned by separate landowner(s).

Environmental Impact Assessment Reports (EIARs) and other relevant ecological information were provided by windfarm operators. Sites were then chosen to maximise representation of the range of windfarms in operation in Ireland (that is, in terms of habitat type and land use, lease type, age, number of turbines, and geographic location).

2.4. Data collection (extent & condition)

Initial site visits were conducted between June and September 2022. Prior to this, habitat maps were drafted in ArcGIS Pro (ESRI, 2023) using boundary and turbine location data provided by the site operators and aerial imagery to assign broad habitat types. Onsite, a walkover survey was conducted, in which each habitat polygon was mapped if greater than the minimum mappable area of 400 m² (following Smith et al., 2011). The polygon was assigned to an Ecosystem Functional Group

(EFG) from the IUCN's Global Ecosystem Typology (Keith et al., 2022) and a Fossitt Code (Level 3; Fossitt, 2000), a standard scheme for describing habitats in Ireland (Appendix B). Some habitats did not fit into one Fossitt Code so were placed into a combination of two Fossitt habitat types. Land use was determined based on the dominant habitat type identified on the site, e.g., agriculture, commercial forestry, and peatland. Habitats were mapped in the field directly onto the preliminary maps using ERSI ArcGIS Field Maps software (ESRI, 2023). Data were input into ArcGIS Pro and the habitat polygons were digitised and the area of each was extracted, as was the total area of each habitat type (Fig. 2).

Both remote and field-based data collection were used to build condition accounts. The condition scorecards were used in the field to collect data on habitat condition where applicable. Remote data sources were manipulated and analysed in ArcGIS Pro to extract data relevant to the specific habitat area.

2.5. Statistical analyses

Generalised linear mixed models (GLMMs) were used to assess how condition scores varied among habitat types to understand the ability of the SEEA-EA to measure biodiversity condition of different habitats. The categorical main fixed effects comprised land use (defined as agriculture, commercial forestry, or peatland) and habitat type. Condition score was the response variable, and windfarm site was included as a random effect. A null model, which contained no fixed effects, was used to determine the random effect structure. Separate models were built using the IUCN habitat type and Fossitt Level 3 habitat type.

Weighted Effect Coding (te Grotenhuis et al., 2017) was used to assess whether using alternate classification systems affects condition scores. Weighted Effect Coding was used to test the difference among factor level means, weighted to account for differences in sample sizes among factor levels and to set a specific reference value for the model. Model diagnostics were run using the DHARMA package (Hartig & Lohse, 2022), and data visualisation used ggplot2 (Wickham, 2016). Akaike Information Criterion (AIC) values were used to compare between GLMMs for each habitat type (Bolker, 2008) to understand whether the model outputs varied between the two different habitat classification systems. Given that the models differ in fixed effects while using the same response variable, the difference in AIC is due to the different explanatory power of the fixed effects in our models.

3. Results

3.1. Indicator selection

Thirty-two indicators were selected for inclusion in the ecosystem accounts (Appendix C). Of these, seven were field-based, 13 were remote, and the remainder (12) combined field-based and remote elements. The indicators selected were not evenly distributed across either the SEEA-EA Ecosystem Condition Typology (Fig. 3a) or habitat type (Fig. 3b).

3.2. Extent accounts

The seven exemplar windfarm sites were categorised into broad land use types that included commercial forestry, upland blanket bog and heath, and agriculture (predominantly pasture with some tillage). Across the seven sites there were 27 habitats identified using the Fossitt level 3 classification (Fossitt, 2000). Improved agricultural grassland (GA1), and conifer plantation (WD4) were the two most frequently occurring habitats. Using the IUCN Global Ecosystem Typology 2.0 (Keith et al., 2022), 12 habitat types were identified at the Ecosystem Functional Group level. Sown pastures and fields (T7.3), urban and industrial ecosystems (T7.4), and boreal, temperate, and montane peat bogs (TF1.6) were the most frequently occurring habitats identified using the IUCN typology.

3.3. Condition accounts

The final dataset included 592 condition scores for individual habitat polygons across the seven sites, incorporating 24 Fossitt Level 3 habitat types and 11 IUCN Ecosystem Functional Group habitat types. Condition scores ranged from a minimum 0.17 to a maximum score of 0.89, with a mean score of 0.47 (from a possible range of 0–1, where zero represents poor habitat condition for biodiversity and one represents good habitat condition for biodiversity). Across the land use types (that is, agriculture, commercial forestry, and peatland), sites with commercial forestry as their land use had the highest average condition score (Fig. 4a, though see Discussion).

3.4. Differences among habitats

Using the IUCN Global Ecosystem Typology 2.0 (Keith et al., 2022)

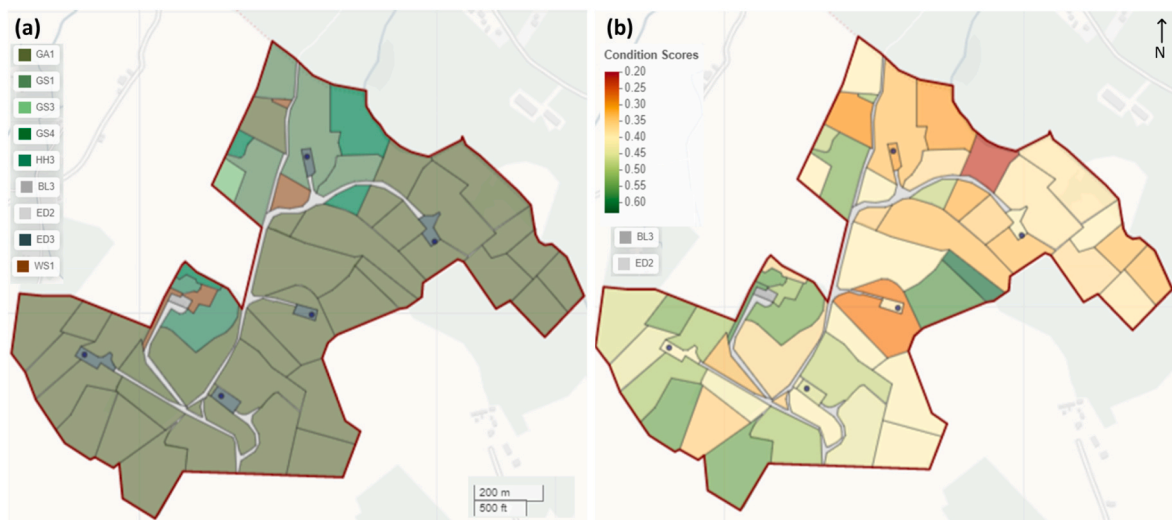


Fig. 2. (a) Extent map of habitats at an onshore windfarm, mapped using the 'Guide to Habitats in Ireland' (Fossitt, 2000). The land-use for this site was agriculture, as the site is dominated by improved agricultural grassland (GA1). (b) Condition scores mapped across individual polygons for the same onshore windfarm. Areas to the south-west of the site tended to have greater condition scores than those in the north-east. Blue points represent the turbine locations on both maps.

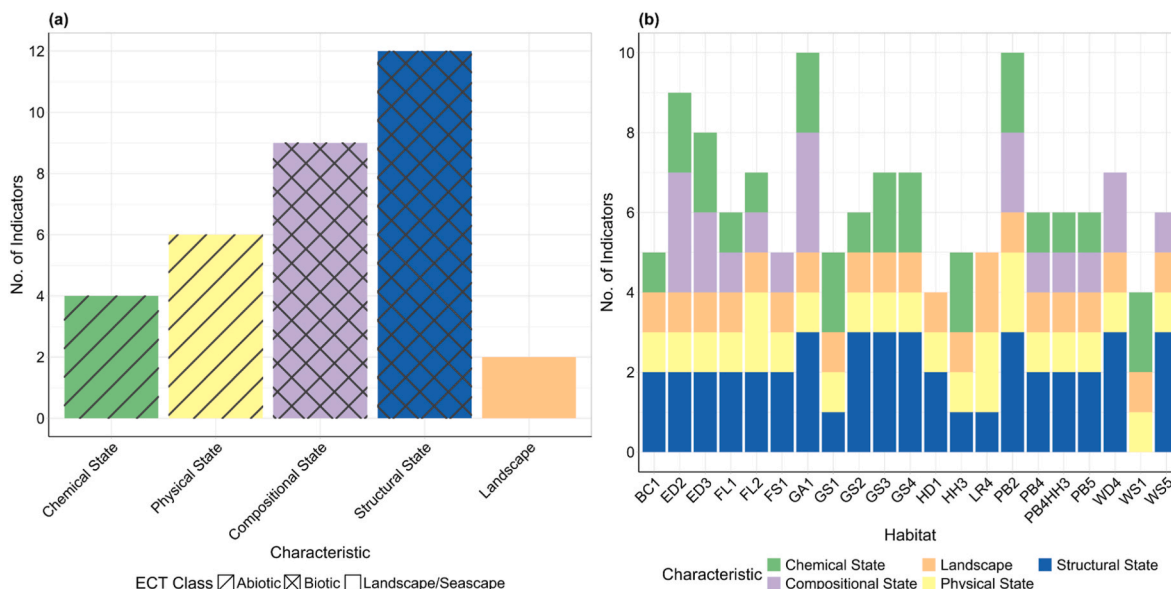


Fig. 3. Distribution of indicators across the (a) SEEA-EA's Ecosystem Condition Typology characteristics and (b) Fossitt (2000) habitat types identified on Irish windfarm sites (codes on x-axis), and their ECT characteristics. Structural indicators (dark blue) occurred most frequently across habitats, excluding WS1 (Scrub). GA1 (Improved agricultural grassland) and PB2 (Cutover bog) had the highest number of indicators used to assess condition. Full definitions of each Fossitt (2000) habitat code can be found in Appendix B, where BC1 – Arable crops; ED2 – Spoil and bare ground; ED3 – Recolonising bare ground; FL1 – Dystrophic lakes; FL2 – Acid oligotrophic lakes; FS1 – Reed and large sedge swamps; GA1 – Improved agricultural grassland; GS1 – Dry calcareous and neutral grassland; GS3 – Dry-humid acid grassland; GS4 – Wet grassland; HD1 – Dense bracken; HH3 – Wet heath; LR4 – Mixed substrata shores; PB2 – Upland blanket bog; PB4 – Cutover bog; PB4HH3 – Cutover bog & wet heath mosaic; PB5 – Eroding blanket bog; WD4 – Conifer plantation; WS1 – Scrub, WS5 – Recently-felled woodland.

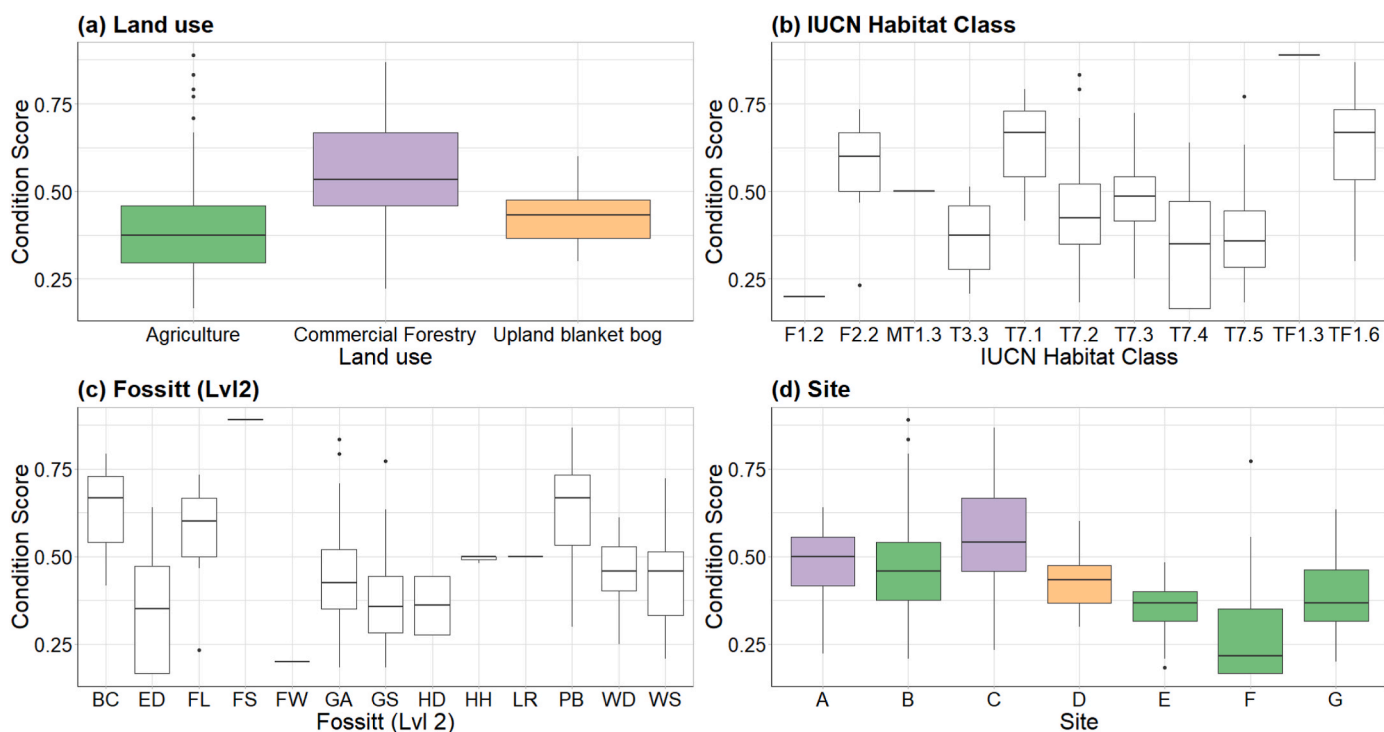


Fig. 4. Condition scores for (a) wind farm land use type, (b) IUCN habitat type (where F1.2: Permanent lowland rivers; F2.2: Small permanent freshwater lakes; MT1.3: Sandy shorelines; T3.3: Cool temperate heathlands; T7.1: Annual croplands; T7.2 Sown pastures and fields; T7.3: Plantations; T7.4: Urban and industrial ecosystems; T7.5: Derived semi-natural pastures and oldfields; TF1.3: Permanent marshes; TF1.6: Boreal, temperate and montane peat bogs), (c) Fossitt Level 2 (BC: Cultivated and build land; ED: Disturbed ground; FL: Lakes and ponds; FS: Swamps; FW: Watercourses; GA: Improved grassland; GS: Semi-natural grassland; HD: Dense bracken; HH: Heath; LR: Littoral rock; PB: Bogs; WD: Highly modified/non-native woodland; WS: Scrub/transitional woodland, and (d) windfarm sites (anonymised; AG: Agriculture; CF: Commercial forestry; BB: Upland blanket bog).

classification, condition scores varied at the Ecosystem Functioning Group level (Table 1 in Appendix D). In general, small permanent freshwater lakes (F2.2), annual croplands (T7.1), permanent marshes (TF1.3), and boreal, temperate, and montane peat bogs (TF1.6) had higher than average condition scores (Fig. 4b). In contrast, derived semi-natural pastures and oldfields (T7.5), cool temperate heathlands (T3.3), urban and industrial ecosystems (T7.4) and sown pastures and fields (T7.2) had lower than average condition scores.

Condition scores also varied by habitat type across Fossitt habitat classifications (Table 2 in Appendix D). In general, arable crops (BC1), dystrophic lakes (FL1), reed and large sedge swamps (FS1), upland blanket bog (PB2), cutover bog (PB4), cutover bog/wet heath (PB4HH3), and recently-felled woodland (WS5) had higher than average condition scores. In contrast, recolonising bare ground (ED3), acid oligotrophic lakes (FL2), depositing lowland rivers (FW2), improved agricultural grassland (GA1), dry calcareous and neutral grassland (GS1), dry meadows and grassy verges (GS2), dense bracken (HD1), and scrub (WS1) had lower than average condition scores (Fig. 4c).

Condition scores did not significantly vary with land use type (Fig. 4a). Moreover, the explanatory power of both the IUCN Ecosystem Typology (Fig. 4b) and the national Fossitt system (Fig. 4c) in describing condition scores was similar (AIC for models based on the IUCN Ecosystem Typology: df 15, AIC -871.4; AIC for Fossitt Habitat Classification: df 27, AIC -873.4). The difference in AIC values of the model (ΔAIC) was <2, indicating that the two models have similar support from the data, and were similar in their output (Bolker, 2008).

4. Discussion

We developed thematic ecosystem accounts for seven windfarm sites across Ireland, introducing an additional step into the SEEA-EA framework to incorporate information on data uncertainty, non-linearity, and directionality. Our accounts provide an example application of the SEEA-EA framework as a tool for local-scale biodiversity monitoring and highlight the adaptability of the method. We also demonstrate the flexibility of the SEEA-EA, as our results show the interchangeability of using national classification systems [i.e., Fossitt Guide to Habitats in Ireland (Fossitt, 2000)], with the recommended IUCN Global Typology (Keith et al., 2022), with both systems having similar explanatory power for condition scores. Previous work in ecosystem accounting focused primarily on the regional (e.g. Farrell et al., 2021) and national (e.g. Hein et al., 2020b) scales. Here, we provide a case-study for accounting at the site scale for the purpose of management decision-making, building on the framework for site-scale accounting developed by Gorman et al. (2024). The biodiversity-themed accounts identify the capacity of the ecosystem type to provide habitat or resources for biodiversity. Outputs of the accounts were used to identify preferable habitat for biodiversity, or areas requiring greater management input.

Under the IUCN Global Ecosystem Typology (Keith et al., 2022), small permanent freshwater lakes (F2.2), permanent marshes (TF.3), annual croplands (T7.1), and peat bogs (TF.1) had higher than average condition scores. Similar habitat types under Fossitt (2000), a common national-scale typology used in biodiversity surveying in Ireland, also had higher than average condition scores, such as upland blanket bog (PB2), arable crops (BC1), reed and large sedge swamps (FS1). Many of these align with research on biotic assemblages as, for example, peatlands such as upland blanket bog can support unique assemblages of flora in Ireland (Sottocornola et al., 2009), birds (Bracken et al., 2008) and invertebrates (Hannigan and Kelly-Quinn, 2014). The further division of peatlands in the Fossitt (2000) classification system demonstrated the ability of cutover peatlands (PB4) to provide habitat for biodiversity (Crowley et al., 2021; D'Astous et al., 2013), albeit slightly lower on average than upland blanket bog (PB2). This highlights an advantage of the national classification system, which includes breakdown of habitats that are more specific, with different reference levels and localised to Ireland, compared to the generalised peat bogs (TF1.6)

category in the IUCN typology.

Similar habitat types in the two different classification schemes show a significantly lower than average condition score. Under the IUCN typology these were derived semi-natural pastures and oldfields (T7.5), cool temperate heathlands (T3.3), urban and industrial ecosystems (T7.4) and sown pastures and fields (T7.2) and, under Fossitt (2000), dry meadows and grassy verges (GS2), recolonising bare ground (ED3), improved agricultural grassland, scrub (WS1) and dense bracken (HD1). For pastures and agricultural grasslands (e.g., T7.5, GA1, GS2) and highly modified habitats (T7.4, ED3), this would be expected, as these areas are often highly altered and can be difficult for species to utilise (Plantureux et al., 2005; Urziceanu et al., 2021, 2024). Comparing the model fit for condition scores showed interoperability between the two classification systems, with similar explanatory power on condition scores. This allows for flexibility in terms of use as a management tool, as the Irish standard classification system is more practical for practitioners, whereas the IUCN classification system would allow greater capacity for international windfarm operators to compare sites across regions. Additionally, as classification systems are updated, for example the Irish Vegetation Classification (IVC) (National Parks and Wildlife Services et al., 2021) is becoming increasingly used in place of the older Fossitt classification, flexibility in accounting will be useful to ensure that accounts can continue to be updated also as long as the two classification systems can be aligned.

At the broadest level of habitat grouping (land-use), commercial forestry had the highest average condition score, compared to agriculture or commercial bog. The biodiversity potential of commercial forestry plantations has long been debated (Brockerhoff et al., 2008) and, despite the overall land-use resulting in the highest average condition score, with the finer grained habitat classifications [Fossitt (2000) Level 3 and IUCN Global Ecosystem Typology EFG], land use did not have a statistically significant effect on the condition scores. Each land-use, that is, commercial forestry, agriculture, and peatlands, can be considered an economically productive land-use in Ireland (Bullock et al., 2012; DAFM, 2021; Ní Dhubháin et al., 2009), and previous research has highlighted that plantation forests can have a higher biodiversity benefit than other productive land-uses, in particular agriculture (Brockerhoff et al., 2008). In addition, commercial forestry in Ireland is often located on peat soils due to historic afforestation grants (Bullock et al., 2012), and therefore the commercial forestry sites included here also had peatland and lake habitats within them, which were some of the habitats that had higher than average condition scores [peat bogs TF1.1 in IUCN, and PB2 in Fossitt (2000), and freshwater lakes F2.2 in IUCN GET]. Assessment of the biodiversity value of commercial forestry plantations themselves rather than sites classed as commercial forestry due to the dominance of this land use therefore requires a more fine-grained approach than we have taken here.

The SEEA-EA was developed to fit alongside the System of National Accounts (SNA), and facilitate countries accounting for non-economic capital in their national reports (United Nations, 2021). The SEEA-EA framework can also be used for smaller-scale accounting but, due to their design for national level purposes, some approaches are not feasible at smaller site scales (Faccioli et al., 2023). Non-financial reporting is becoming an increasingly popular exercise at corporate level and, as a UN Statistical Standard, the SEEA-EA is well-placed to facilitate such accounting. However, adaptation is required to tailor accounts to smaller scales. Our results highlight that corporate ecosystem accounts can be compiled at the site-level and can identify within-site variation that could be used to inform management decisions, similar to findings of other habitat-based accounts (e.g. Mokany et al., 2022; Parkhurst et al., 2024).

Ecosystem accounting is a data-driven process, and data availability is a limitation of the SEEA-EA at all scales (Hein et al., 2020a; Vári et al., 2024). This issue is, however, particularly acute at local scales (Faccioli et al., 2023). In developing ecosystem accounts for onshore windfarm sites, many available spatial datasets could not be included, as they were

at a resolution too large to cover the range in the site's boundary areas and provide sufficient detail. Thus, 59 % of indicators selected required an element of field-based data collection. This was possible in that the sites were accessible, and the indicators used could be gathered by observing the focal ecosystem asset. Scorecards, used to reduce field-based subjectivity, were particularly useful for biodiversity-related indicators, as they allowed for a range of values to be represented by a single value in a 0–3 index. This meant that indicators of biodiversity, such as vegetation structure, were quantifiable and could be included in the accounts. The introduction of a standardisation step was an important addition that increased the feasibility of creating biodiversity-themed accounts. Using a standard 0–3 index also allowed for clarity surrounding directionality of variables, especially more complex variables, where both a high value and low value could be negative for biodiversity.

In the SEEA-EA framework, directionality in the condition accounts is poorly addressed, as there cannot be more than one value for each of the high and low reference values. For example, both low and high values of tree cover density can be negative for biodiversity (Smith et al., 2009). Following the traditional SEEA-EA framework, it would have been difficult to include two values as a lower reference value. By placing both values lower in the standardised index, however, this issue can be overcome, and the variable can still contribute towards the accounts. Ryan et al. (2023) also transformed their data prior to the reference stage of the condition accounts, using a dimensionless scale. Similarly, Parkhurst et al. (2024) also transformed their condition variables into a dimensionless scale (0–100 %) to deal with the issue of directionality. The addition of a 'standardisation step' into the condition accounts allows more flexibility in cases where data may be limited or more complex, which is common for biodiversity indicators.

Biodiversity-themed accounts are the least developed accounts of the SEEA-EA (Remme et al., 2016), as the pace slowed due to debate surrounding biodiversity's place within the ecosystem services concept (Grover et al., 2023; Mace et al., 2011; Reyers et al., 2012). The accounts developed here use habitat-based metrics to infer change in biodiversity (Larsen et al., 2021), through identifying the habitat's capability to support and provide resources. Spatial scale has been described as one of the main barriers to accounting for biodiversity, which led to the development of a guidance paper on the topic (Larsen et al., 2021). Here, the scale of accounting was determined by the windfarm operator's site boundaries. This limited the availability of data, as much remote data is found at a scale of 10 km² [e.g., Biodiversity Maps from the National Biodiversity Data Centre (NBDC, 2024)]. Acknowledging that there is ongoing work to continue to progress accounting for biodiversity (United Nations, 2021), it is evident there is more research needed to allow biodiversity-themed accounts to progress to the extent of other themes, such as carbon and water (Lange et al., 2022). A lack of suitable ecological data or indicators of the status or trends in biodiversity is one of the major limitations encountered when developing accounts for onshore windfarms, and in other accounting exercises (Faccioli et al., 2023; Feld et al., 2009). This can also lead the use of condition indicators that may not have the strongest biophysical link to the goal of the accounts. Further, in instances where biodiversity data is available, time-series data to document change may not align with the accounting period. Selecting biodiversity indicators to inform the status of biodiversity was a challenging process (Hein et al., 2020a), requiring many iterations and expert consultation.

The ecosystem accounts built here provide a case study of accounts developed for a management purpose. The aim was to develop accounts that could inform biodiversity capital or potential capital of windfarms, which could be integrated into management tools such as a risk register (Mace et al., 2015) and biodiversity action plans. One limitation was that all windfarms in our study were operational and, due to the field-based data collection, we were unable to develop accounts for each site prior to the installation of the windfarm. This would have been useful to inform on change in habitats over time due to the windfarm

infrastructure. To maximise the use of such ecosystem accounts for this specific industry, developing ecosystem accounts from the earliest opportunity (planning stage) would allow for significant knowledge gain and support decision-making throughout the windfarm's lifetime. It would also further enable the industry to avoid negative impacts by avoiding areas of high biodiversity condition and empower them to incorporate positive biodiversity actions into their development plans using the indicators and condition scores to implement tailored and targeted actions.

There are several decisions that are required when tailoring accounts for industry or specific use cases (Gorman et al., 2024). One overarching concern in developing accounts for industry is ensuring the process, from development through to delivery of the accounts, was accessible to non-experts in the onshore wind energy industry, as complexity of accounting can be seen as a barrier to implementation (Fleming et al., 2022). This included selecting indicators that were open-access, or relatively straightforward to collect in the field. Striking a balance between this accessibility and the need for meaningful scientific biodiversity indicators was challenging. Additionally, we used one reference condition (best attainable condition) across all habitats. Varying the reference condition used, such as best attainable for highly modified habitats (e.g., road verges), and least disturbed for natural habitats (e.g., peatlands), may have increased the accuracy of our condition scores. However, we chose to use only one reference condition to reduce complexity in finding alternate conditions for each of our indicators and because this would have limited our already small set of available condition variables. Moreover, finding additional data at a fine resolution would have been difficult. Future work exploring methods of varying the baseline capacity via the reference condition at fine scale could be useful to improve the accuracy of the condition scores.

Developing ecosystem accounts is a time-consuming process and accounts built for industry will need to embrace this complexity (Fleming et al., 2022) and include time in their framework to facilitate educating those in industry about the process, through workshops or training. Companies' capabilities vary, and some may not have the resources required to continue ecosystem accounting themselves (van Putten et al., 2021). Consultants may, therefore, be required to build accounts on behalf of the industry. Development of accounts for industry can be collaborative, incorporating GIS specialists, environmental experts, ecologists, and asset managers (Bagstad et al., 2021). Multiple people may, therefore, need to be trained on the topic. When developing accounts for industry, the purpose of the accounts must be explicit from the beginning of the process, whether it be for biodiversity capacity, to measure service-flows of natural capital, or to monitor change in natural capital over time (e.g. Keith et al., 2020). Selection of indicators can be the most time-consuming and challenging part of the SEEA-EA process (Czúcz et al., 2021). In this case study, development of a scorecard of indicator variables hastened the process of collecting data in the field, especially data that was already rescaled in the additional standardisation step to incorporate biodiversity data. Martini et al. (2024) provide an example of the additional rescaling standardisation step using just remote data for the forestry industry. While the SEEA-EA framework provides comprehensive instructions and amendable spreadsheets that can be used to develop extent and condition accounts, further standardised guidelines, specifically focused on accounting for biodiversity, must be developed to facilitate industry's ecosystem accounting needs (Czúcz et al., 2021; Edens et al., 2022). Additionally, another option to improve the feasibility of industries developing ecosystem accounts is to build tools that can automate the accounting process [e.g., ExactR (Gibbons et al., 2024) ARIES (Villa et al., 2009)] or digitise the data collection process (Fleming et al., 2022).

The format of the accounting outputs is another important consideration when developing ecosystem accounts targeted for industry (van Putten et al., 2021). Displaying the ecosystem accounts as maps were a visual aid in identifying areas and specific habitats for management. In particular, windfarm sites operating under herringbone leases with

multiple landowners highlighted that mapping condition scores was useful for informing where on-site management decisions for biodiversity could be taken, and which landowners may need stronger encouragement or incentivisation to engage with biodiversity actions. Biodiversity-themed ecosystem accounts can be a useful visual tool to demonstrate how future management can be implemented or improved.

We demonstrate how thematic ecosystem accounts can be developed at the site scale for industry. Ecosystem accounting can facilitate biodiversity decision-making using terminology more familiar to those in industry while also incorporating ecological evidence. The methodology developed here highlights the flexibility of the SEEA-EA framework when compiling accounts, including the ability to select more appropriate ecosystem classification systems that can be mapped with the IUCN Global Typology. We recommend the inclusion of a 'standardisation' step within the SEEA-EA to facilitate the incorporation of complex indicators, especially for thematic accounts for biodiversity where indicators can be particularly limited. Delivering accounts as spatial maps highlighted the benefits of this method as a management tool, in addition to forming a baseline of other management tools. Ultimately, small-scale accounting using thematic accounts for biodiversity needs to be an iterative co-design process, with involvement and input from ecologists, SEEA-EA experts, stakeholders, and industry end-users. Our accounts were able to highlight the potential for habitat to support biodiversity, and identified areas where management may be required to support or enhance biodiversity capacity. While developed specifically for windfarms, this work demonstrates a use of the SEEA-EA for site-scale, industry-focused accounts. While elements of developing the accounts were challenging, they did not impede the development of the accounts and adaptations could be made to adjust to specific needs. With increased uptake and usage, barriers to accounting should become less frequent, and site-scale accounting more standardised and accessible.

CRedit authorship contribution statement

Emma King: Formal analysis, Writing – review & editing, Data curation, Writing – original draft, Conceptualization. **Jane C. Stout:** Conceptualization, Writing – review & editing, Funding acquisition. **Yvonne M. Buckley:** Conceptualization, Writing – review & editing, Funding acquisition. **Ian Donohue:** Funding acquisition, Writing – review & editing, Writing – original draft.

Funding sources

This paper comprises an output of the Nature + Energy Project, funded by Taighde Eireann - Research Ireland (12/RC/2302_P2), industry partners (NTR Foundation, ESB, SSE Renewables, Asper Investment Management, Ecopower, Energia, EnergyPro, Greencoat Renewables, Ørsted) and MaREI, the Research Ireland Research Centre for Energy, Climate and Marine Research and Innovation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Ian Donohue reports financial support was provided by Taighde Eireann Research Ireland. Ian Donohue reports financial support was provided by MaREI the SFI Research Centre for Energy Climate and Marine. Ian Donohue reports financial support was provided by NTR plc. Ian Donohue reports financial support was provided by Electricity Supply Board. Ian Donohue reports financial support was provided by SSE Renewables Ltd. Ian Donohue reports financial support was provided by Ørsted AS. Ian Donohue reports financial support was provided by Schrodgers Greencoat Ltd. Ian Donohue reports financial support was provided by Energia Group. Ian Donohue reports financial support was provided by EnergyPro. Ian Donohue reports financial support was

provided by Ecopower Limited. Ian Donohue reports financial support was provided by Asper Investment Management. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors thank Courtney Gorman for assistance in data collection, Caroline McKeon for advice on modelling, and windfarm site managers and contacts for permission to conduct data collection on their sites.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jenvman.2025.126618>.

Data availability

The data collected and code produced are available in the 'KingE_AccountingforBiodiversity' repository on GitHub and can be accessed at: https://github.com/elouiseking/KingE_AccountingforBiodiversity.

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