People, nature, and sustainability: A critical analysis of bioeconomy and natural capital

By

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B.A. (Mod.) Plant Science, 2017
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A thesis submitted in partial fulfilment of
the requirements for the degree of

DOCTOR OF PHILOSOPHY

BOTANY DEPARTMENT

SCHOOL OF NATURAL SCIENCES

TRINITY COLLEGE DUBLIN

2023

DECLARATION

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SUMMARY

The last century has been characterised by rising socio-economic measures of wellbeing against a backdrop of biodiversity loss and environmental degradation. This trend threatens the positive contributions nature makes to people and jeopardises the environmental conditions that have nurtured human civilisation for millennia. Two emergent concepts have been popularised to articulate the impacts and dependencies between people and nature and attached to contemporary environmental sustainability discourse. These concepts are bioeconomy and natural capital. In this thesis, I consider these concepts from a multidimensional perspective spanning conceptual integration, science-policy transitions, spatial modelling of people-nature interactions, and societal representation and use. I argue that bioeconomy and natural capital share a similar disciplinary background and timeline but have yet to realise potential synergies for positive environmental outcomes (Chapter 2). The thesis goes on to show the science-policy transition of natural capital and ecosystem services in Ireland (Chapter 3), and the application of spatial modelling using data from social media to map cultural ecosystem service flows that can aid environmental decision-making (Chapter 4). Chapter 5 considers bioeconomy's ability to connect disparate groups by using social media as an informal public forum of discourse and information flow. Together this work shows that the concepts of bioeconomy and natural capital can contribute to progressing towards environmental sustainability to some extent. This is promising given their embeddedness within environmental research, policy, and practice. Finally, in Chapter 6 I summarise future directions for research and practice that consider enablers and barriers for achieving potential positive environmental change. These findings can inform future use of bioeconomy and natural capital to maximise their environmental contributions. Given the scale and urgency of environmental degradation, the results of this thesis are important to aid the preservation of nature's contributions to people, both today, and for future generations.

A Plea for Nature

"I think I shall never see,
A poem lovely as a tree"

These words were penned so long ago,
By someone else, not I,
As he observed the mighty bough,
Stretch out its fingers to the sky.

The sentiment still apt today,
Let's show determination,
Make a stand and so curtail,
Out forests' decimation.

For if we let this challenge pass,
Mankind itself will suffer,
You may think we'll have it tough,
But our kids will have it tougher.

We all must do our utmost,
As far as we are able,
Tell the world to spare the tree,
The Ash, the Oak, the Maple.

Michael McKenna

ACKNOWLEDGEMENTS

This thesis was possible because of the support of many people to whom I am incredibly grateful. Firstly, thank you to Jane Stout, the most wonderful supervisor and talented scientist, whose generosity, passion, and curiosity are an inspiration. I also want to thank my co-supervisor Cathal O'Donoghue whose knowledge and expertise were invaluable to honing my writing and exploring new ideas.

I am grateful to have completed my studies in such welcoming and supportive places with amazing people. Thank you to all my colleagues and mentors in the School of Natural Sciences, especially those within Botany. I always enjoyed our shared conversations and have many wonderful memories at Trinity. I would also like to thank Stanford University, Gretchen Daily, and the Natural Capital Project team for allowing me the chance to spend seven months in their company. I learnt so much and will forever remember that time fondly.

This PhD was possible thanks to the funding provided by Science Foundation Ireland, the BiOrbic bioeconomy research centre, a Trinity non-foundational scholarship, and an EPA-Fulbright award. I appreciate how very fortunate I have been and earnestly hope that such opportunities and freedoms are accessible to all who wish to pursue research.

I am blessed to have amazing friends, nearby and in faraway places, whose company and companionship were a much-needed source of joy and connection, especially during the challenges of COVID-19 and moments of doubt. Thank you for being a part of my life and I look forward to many more celebrations together in the future.

Thank you to my family whose unconditional love, support, and encouragement have gotten me to where I am today. Thank you to my parents, Marie and Ken, to my siblings, Thomas and Lucy, and to my godmother, Clare. The past four years were challenging for many reasons, but especially because of difficult goodbyes and periods of separation and grief. I want to finish by expressing my love and gratitude for people I miss dearly, and who I wish were here to celebrate the triumph of this PhD. Thank you to my grandmother, Alison, to my nanny, Betty, to my Auntie Marie, and lastly to my grandfather, Michael, whose name I carry and whose poem serves as the dedication of this thesis. Thank you for everything you did for me. I know you would be so proud.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 | Introduction

1.1 People, nature, and sustainable development

The last century has heralded an era of improved standards of living as defined by rises in conventional indicators of wellbeing (Raudsepp-Hearne et al., 2010; UNDP, 2022). Simultaneously, increasing anthropogenic environmental destruction and degradation has occurred at an unprecedented speed and scale. This is exemplified by the dual crises of climate change and biodiversity loss, marked by rising temperatures (IPCC, 2023), and the erosion of biodiversity at all levels from genetics to species, habitats, and ecosystems (Ceballos and Ehrlich, 2018; IPBES, 2019). These trends threaten the essential, life-sustaining contributions nature—broadly referring to the natural world including all its living and non-living components—makes to people's lives (IPBES, 2019). These contributions are diverse and far-reaching, spanning the regulation of clean and safe air, water, and soil; the provision of food and materials; physical and mental health supports; cultural connections and heritage; facilitation of recreational spaces; spiritual enrichment; inspiration for art and creativity; and a stable and predictable climate (Sandifer et al., 2015; Díaz et al., 2018a; Haines-Young and Potschin, 2018b; IPBES, 2019; Dasgupta, 2021).

Humanity is dependent on nature's contributions; from the benefits that support the wellbeing and quality of life of individuals, to the creation and maintenance of a hospitable safe operating space that has allowed human society and economy to flourish (Rockström et al., 2013). This represents the utilitarian case for why the continued degradation of environmental systems is unjustifiable—the wellbeing of people depends on nature (Díaz et al., 2018a). Estimates suggest that even under a narrow, instrumental, economic lens, investing in nature represents greater long-term returns than short-term, destructive exploitation (Dasgupta, 2021; Johnson et al., 2023). Furthermore, there is an ethical perspective that nature has an intrinsic or existence value that is violated by anthropogenic environmental degradation (Davidson, 2013; Chan et al., 2016). Finally, a third argument as to why continued environmental decline is indefensible is that the erosion of nature represents a disenfranchisement of future people who will inherit an impoverished environment and as a result possess diminished capabilities and agency (Pelenc and Ballet, 2015; Bateman and Mace, 2020). In turn, this reduced operating space risks locking in a trajectory of continued environmental exploitation and degradation due to a lack of alternatives. From these perspectives, the coupling of socio-economic progress to environmental degradation is out of step and ultimately incongruous with securing improvements to human wellbeing, given that it threatens to disrupt the hospitable conditions that have nurtured life on this planet for millennia, within which all of society and economy are embedded (Rockström et al., 2009; Steffen et al., 2015).

A contributing driver to environmental declines is the failure of dominant economic systems to recognise contributions nature makes to people (Dasgupta, 2021). Only a subset of those contributions, typically the physical commodities that can easily be attributed with direct benefits to people, are easily measured, valued, and routinely included within the economic engines of decision-making such as markets or cost-benefit analyses (Millennium Ecosystem Assessment, 2005; Gómez-Baggethun et al., 2010). This renders the remainder of contributions—including those that indirectly benefit people of which many are irreplaceable and invaluable—invisible and silent (Dasgupta, 2021). This incomplete picture of the linkages between people and nature (Fig. 1.1) is compounded further by perverse incentives that discount or ignore negative environmental outcomes; a lack of knowledge, data, or valuation for the positive contributions nature provides; challenges of environmental governance and enforcement across jurisdictions; and the wicked problem of ecosystem management characterised by uncertainty and unpredictable outcomes (Guerry et al., 2015; DeFries and Nagendra, 2017; Helm, 2019; Dasgupta, 2021). Breaking down these barriers and more appropriately including nature's contributions within decision-making processes is one mechanism to guide improved environmental outcomes (Fisher et al., 2008; Guerry et al., 2015).

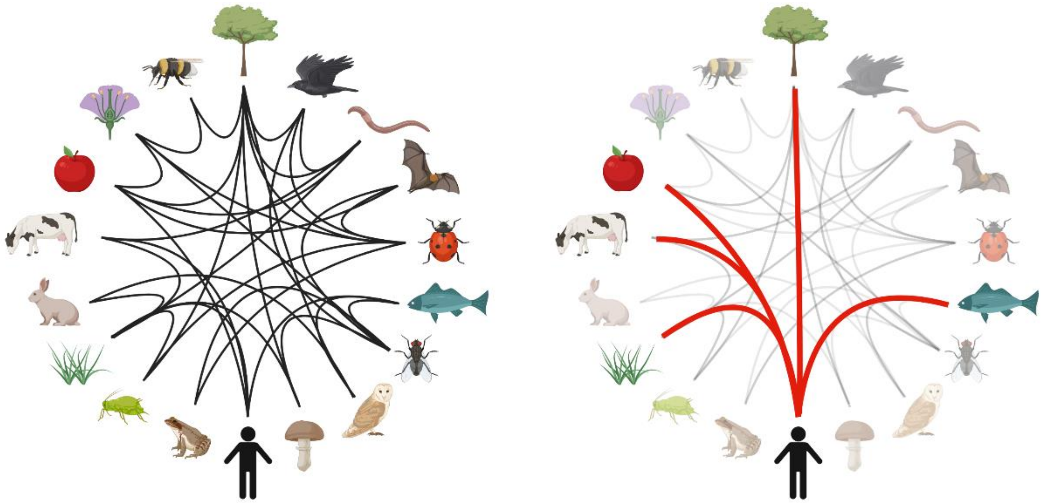

Figure 1.1: Conceptual graphic showing (**left**) the representation of all connections within ecosystems that may contribute to people's wellbeing (both directly and indirectly), and (**right**) the reductive extreme that only views a subset of direct benefits (red) and rendering other interconnections invisible and vulnerable to being ignored entirely.

A recognition of these issues and the antagonism between socio-economic development and environmental degradation has occurred over the past several decades. This is demonstrated by a push towards "sustainable development", a model that emphasises that all three pillars of development—economic, social, and environmental—are equal rather than interchangeable (Sachs, 2012; UN, 2015). Sparked by the high-profile United Nations (UN) Brundtland Report (1987) that described the existential threat environmental decay posed to a prosperous future for all, the environmental pillar has become a prolific theme within multilateral cooperation and international policy. Examples include the 1992 UN Earth Summit and Rio Declaration (UN, 1992), the Millennium Ecosystem Assessment (2005), the Sustainable Development Goals (UN, 2015), the European Union's (EU) Green Deal that re-emphasises the threat of environmental degradation (EC, 2019), and the development of indices that incorporate environmental trends such as genuine savings (Hamilton and Clemens, 1999), inclusive wealth (Polasky et al., 2015; Dasgupta et al., 2022), and gross ecosystem product (Ouyang et al., 2020). However, despite these promising developments that recognise nature's contributions, measurements of environmental conditions continue to show worrying declines including the continued rise in greenhouse gas concentrations in the atmosphere (IPCC, 2023) and plummeting wildlife populations (WWF, 2022), eliciting stark warnings from the global scientific community (Ripple et al., 2017).

1.2 Emergent concepts for environmental sustainability

Environmental sustainability is challenging to define and has a range of interpretations (Dietz and Neumayer, 2007; Pelenc and Ballet, 2015). Broadly, it requires ensuring biodiversity is not diminished and ensuring ecosystems (considering biotic and abiotic aspects) have the capacity to regenerate at a rate that meets the needs of people today and in the future (Ekins et al., 2003; Morelli, 2011; Helm, 2019). One pathway to progress towards environmental sustainability is to address the consistent undervaluing and omission of nature's contributions to people, and the underlying ecosystems that support those contributions, from decision-making (Helm, 2019; Dasgupta, 2021). This systematic shortcoming has become a research theme across disciplines spanning health and biological sciences, economics, politics, and social sciences due to the recognition that environmental issues have repercussions for all aspects of human civilisation (Braat and de Groot, 2012).

Emergent concepts that reframe the linkages between environmental and socio-economic systems have garnered support from political and research spheres because they propose an attractive pathway to maintain rising economic and social trends, while resolving environmental declines. Two of those concepts—born from the confluence of economics and natural sciences—are the topic of this thesis with respect to environmental sustainability: 1) bioeconomy and 2) natural capital.

The bioeconomy concept refers to an economic system centred around goods, processes, and technologies derived from biological carbon and organisms as opposed to fossil resources (EC, 2018; Patermann and Aguilar, 2018). Bioeconomy emphasises the pre-existing dependencies people have on natural systems (such as biomass production systems) and expands to include new interconnections (such as novel biotechnologies or bioresources). Traditionally, the bioeconomy broadly posits that negative environmental outcomes such as greenhouse gas emissions, pollution, and waste can be resolved through resource substitution, biotechnologies, and cascading resource use (Pfau et al., 2014; Aguilar et al., 2019). The reality of this outcome is contested amongst experts with unresolved issues including time-lags, land use change, and biomass supply (Pfau et al., 2014; Lewandowski, 2015; Székács, 2017; Holden et al., 2022).

Natural capital is a concept that describes the natural resources that make up the natural world including geology, soils, air, water, and biodiversity (Barbier, 2019; Bateman and Mace, 2020). The interactions of these capital stocks along with other forms of capital (such as produced and human capital) create a flow of benefits to people and the economy termed ecosystem services (Braat and de Groot, 2012; Costanza et al., 2017; Maseyk et al., 2017). The natural capital approach considers the underpinning stocks that support human wellbeing and their interactions, not just benefit flows, in a systems-approach (Helm, 2019; Bateman and Mace, 2020). Natural capital harnesses an economic vocabulary aligned with conventional decision-making processes to describe the interconnectedness of people and nature and how benefits for society emerge from natural systems. This framework has spurred valuation estimates of service flows (Costanza et al., 1997; Costanza et al., 2014; Remme et al., 2014), development of spatial models (Schröter et al., 2015; Sharp et al., 2018), and natural capital accounting (UNSD, 2018; Hein et al., 2020). Advocates of natural capital believe that improved environmental sustainability outcomes can be achieved through using such tools as vehicles to articulate a more complete set of information regarding how people and nature are interlinked and delivering this information to decision-making processes (Daily et al., 2009; Kareiva et al., 2011; Guerry et al., 2015; Jones et al., 2016). This has been controversial and opposing views include that this perspective oversimplifies the plurality of nature's values (Schröter et al., 2014), attempts to compare the incomparable (Robertson, 2012; Baveye et al., 2013), and is vulnerable to being misapplied (Wegner and Pascual, 2011; Bekessy et al., 2018).

Bioeconomy and natural capital have been subject to mirrored academic debates between two opposing views. There are those that argue that such concepts possess the potential to drive positive environmental change through acting as levers of change within the dominant, western, socio-economic system that can address the undervaluing or omission of nature's contributions (Daily and Matson, 2008; EC, 2018; Aguilar et al., 2021). Conversely, oppositional voices claim that these concepts bolster, and are constrained by, an extractive, capitalistic, neo-liberal status quo that reduces nature to a set of utilitarian values that obscures all others, and therefore, are doomed to perpetuate environmental declines (Birch et al., 2010; Baveye et al., 2013; Ramcilovic-Suominen et al., 2022).

The ability of bioeconomy and natural capital to contribute towards improved environmental outcomes is somewhere between these extremes. There is unlikely to be a single silver bullet that can be applied universally to resolve all the complexities of environmental sustainability across temporal and spatial scales. At the same time, these concepts have become increasingly embedded within research, policy, and financial systems, and have a growing momentum for positive environmental outcomes. For example, the €3.7 billion public-private bioeconomy initiative titled Bio-Based Industries Joint Undertaking has steered investment for environmental projects and policy outcomes catalysed by the EU Green Deal (Johnson et al., 2021). Natural capital has served as the core framework for ecosystem accounting exercises that represent an unprecedented ambition for environmental data collection at scale (Hein et al., 2020; UN, 2021). Given how these concepts have become associated with environmental initiatives, it is important that they are critically examined from a sustainability perspective. Such exercises should identify strengths and weaknesses in how they frame environmental problems, consider how they contribute to environmental decision-making, and their use as sustainability paradigms.

Providing an exhaustive analysis of these wide-reaching concepts is beyond the scope of any single project and compounded by their range of applications. However, the following chapters tackle specific knowledge gaps regarding these concepts within the context of the environmental sustainability. Given the urgency of the environmental crisis and how these concepts have become central to sustainability initiatives within policy and research, such holistic approaches are increasingly required to inform future sustainability research, while also providing practical outputs for decision-makers and environmental managers.

1.3 Thesis structure

This thesis explores environmental sustainability concepts from a multidimensional perspective spanning conceptual frameworks (Chapter 2), science-policy transitions and governance (Chapter 3), spatial modelling to assess people-nature interactions (Chapter 4), and societal acceptance, use, and representations (Chapter 5). Where applicable, case-studies are drawn from the EU and Irish contexts. The summary, introduction (Chapter 1), and discussion (Chapter 6) are written in the first-person singular given the independent nature of this thesis, while Chapters 2-5 are written from the first-person plural to reflect the collaborative nature of science.

Chapter 2 examines the conceptual underpinnings behind bioeconomy and natural capital. This work was inspired by the similar origins of the two concepts: emerging from interdisciplinary overlap between economics and biological sciences and subsequently incorporated within environmental policy discourse. The chapter outlines the case for how a natural capital approach can complement existing pillars of bioeconomy development and contribute to shaping a sustainable, future bioeconomy that considers all its intersections with nature. This chapter concludes by applying this dual lens to the EU bioeconomy strategies to articulate progress regarding environmental dimensions and demonstrate where gaps persist.

The focus of Chapter 3 is the science-policy transition of natural capital and ecosystem services in Ireland over a 25-year span. National policy is one of the most influential levers of environmental management and therefore integration within this form of governance possesses high potential for natural capital and ecosystem services to impact decision-making. I deploy a mixed-methods content analysis to policy documents spanning primary producing sectors, biodiversity policy, and environmental reporting. The results suggest that this science-policy transition is underway but incomplete, having occurred unequally across different policy areas and creating a fragmented policy landscape with regards to ecosystem services.

Moving from the conceptual and governance contexts, Chapter 4 applies spatial modelling to assess cultural ecosystem services (non-material benefits) in County Galway, Ireland, by using data derived from social media as a digital footprint. I use four spatial modelling approaches to provide information on the characteristics of places that facilitate people-environment interactions in terms of natural, human, and built capital characteristics. This analysis revealed biophysical attributes, accessibility, and local context are relevant for people-nature interactions and these results can inform policy spanning tourism and environmental management. In this chapter, I also present a guide for deploying such modelling exercises elsewhere to support researchers and practitioners carrying out similar assessments.

In Chapter 5, I examine the representation and use of the bioeconomy concept in a wider societal context as captured on a popular social media platform. Bioeconomy represents an interdisciplinary, but highly technical, concept in the academic literature and its ability to reach beyond core experts is uncertain. I examine both the message and messenger of bioeconomy-related terms on social media as a public forum of connection, discourse, and knowledge exchange to understand potential information flow and the key actors involved. The results suggest bioeconomy has transitioned into the informal space of social media and successfully bridged between stakeholders separated by geography and discipline, but key actors shaping the narrative are disproportionately highly-educated experts from the Global North.

I conclude in Chapter 6 by reflecting on the key findings presented in the previous four chapters and what this means for bioeconomy, natural capital, and environmental sustainability. I comment on broader themes for future research including the proliferation of environmental research and knowledge, novel data and analysis techniques, and fragmentation.

1.4 Additional work

Beyond this thesis, I have been involved in the following research.

Holden, N. M., **Neill, A. M**., Stout, J. C., O'Brien, D. & Morris, M. A. (2022). Biocircularity: a framework to define sustainable, circular bioeconomy. *Circular Economy and Sustainability*, **3**(1), 77-91, 10.1007/s43615-022-00180-y.

I was involved in the project conceptualisation and provided expertise related to natural capital, ecosystem services, and bioeconomy. I provided text to the first draft and editing to the final manuscript.

CHAPTER 2 | A natural capital lens for a sustainable bioeconomy: Determining the unrealised and unrecognised services from nature

Authors:

Andrew M. Neill, Cathal O'Donoghue, Jane C. Stout

Author contributions:

I developed the theoretical framework, conducted the analysis, produced the figures, and wrote the first draft of the manuscript as well as led revisions. Jane C. Stout and Cathal O'Donoghue provided guidance throughout and supervised the writing and revision process. All authors provided intellectual input and edited the manuscript.

Status:

This manuscript has been published in *Sustainability* (2020), **12**(9), 10.3390/su12198033 (Neill et al., 2020).

2.1 Abstract

Human activity has led to degradation of the natural environment with far-reaching impacts for society and the economy, sparking new conceptual framings for how people interact with, and depend upon, the environment. The bioeconomy and natural capital concepts both blend economics and natural sciences and propose new interdisciplinary, environmental sustainability framings. Despite this similarity, the two concepts are rarely applied together. This paper applies a natural capital lens to the bioeconomy at three different levels: environmental sustainability framings; experts' principles for a sustainable bioeconomy; and a case study of EU policy. We first construct an integrated cascade model that combines the unrealised potential of bioresources alongside unrecognised environmental services that tend to be systematically undervalued or ignored. Subsequently, we present five cornerstones identified from the sustainable bioeconomy-related literature from a natural capital perspective and highlight avenues of complementarity. The paper concludes with a policy case study of the EU Bioeconomy Strategy through a natural capital lens. There is evidence that the EU strategy has become increasingly aligned with the natural capital concept, but there is scope for further integration. The natural capital concept and related toolbox is an asset for the future bioeconomy to ensure it meets its environmentally sound and ecologically conscious objectives (Fig. 2.1).

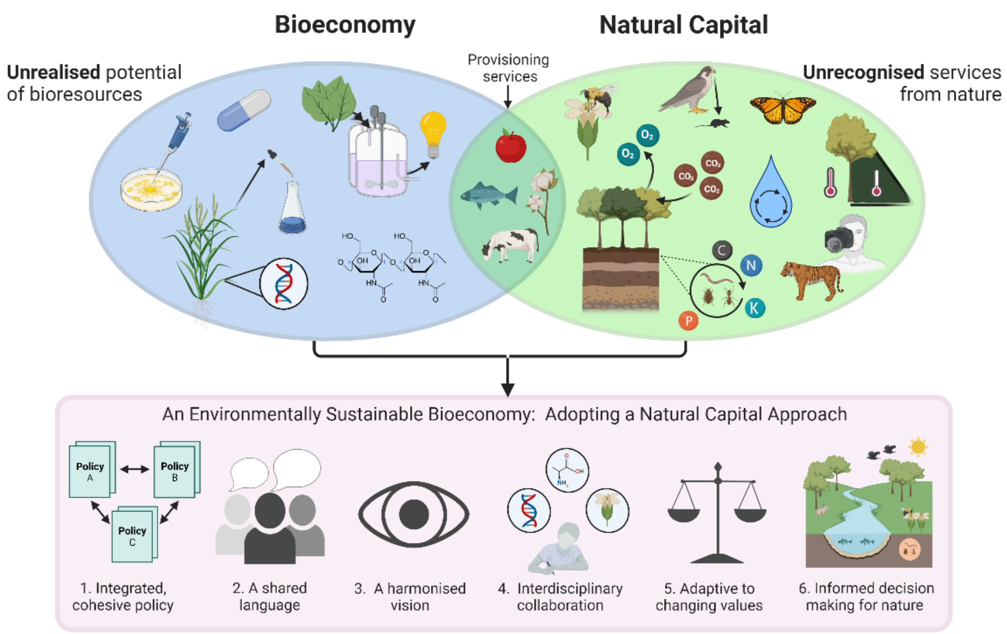

Figure 2.1: Graphical abstract showing limited overlap between natural capital and bioeconomy concepts and the potential opportunities for greater integration for environmental sustainability.

2.2 Introduction

2.2.1 *Environmental sustainability challenges and concepts*

The last century of human development has brought remarkable improvements to health, wellbeing, and economic growth but has come coupled with environmental degradation that threatens to deplete natural systems beyond recovery (Rockström et al., 2009; Raudsepp-Hearne et al., 2010). Pressures on the environment are further exacerbated by an increasing population, growing resource demands, shifting lifestyle patterns, dependencies on non-renewables, and land use change (Khanna et al., 2018; O'Neill et al., 2018; IPBES, 2019). Growing recognition of environmental challenges, particularly climate change and biodiversity loss, has generated new ways to conceptualise how people interact with, and depend upon, the environment. Approaches to reconcile socio-economic aspirations with environmental limits—addressing negative "externalities" that threaten the health and wellbeing of both people and the planet—are gaining traction (Zilberman et al., 2018). Two influential concepts at the forefront of policy and research that strive towards environmental sustainability are the bioeconomy and natural capital concepts.

The bioeconomy concept has been popularised across policy and governance as a pathway to resolve unsustainable resource use and resulting environmental degradation (McCormick and Kautto, 2013). It is premised on the replacement of fossil-based, non-renewable resources with biological alternatives. High-level representations of the bioeconomy concept in policy and academia associate it with economic growth, job creation, and value addition; move away from the linear, throughput economic model; and promote principles of renewable energy, circularity, and the cascading use of resources (Bugge et al., 2016; Hausknost et al., 2017; Gawel et al., 2019). Environmental sustainability aspirations also drive the bioeconomy concept through the reduction of greenhouse gas emissions, the prevention of pollution that threatens ecosystems and biodiversity, and the efficient use of resources that limits exploitation and land use change (McCormick and Kautto, 2013; Kleinschmit et al., 2017). The bioeconomy concept represents a restructuring of the relationships between socio-economic systems and the environment, centred around bioresources and bioprocesses sourced from nature (de Schutter et al., 2019).

Despite striving for a “win-win” for both the economy and the environment (Loiseau et al., 2016), it should not be assumed that all interactions between the bioeconomy and the environment are positive (Pfau et al., 2014; Székács, 2017). Rather, bioeconomy’s contributions towards achieving environmental sustainability are recognised as conditional on the surrounding system and context-dependent (Pfau et al., 2014; Gawel et al., 2019). Bioeconomic activities may have negative impacts upon the environment if implemented incorrectly (Graham-Rowe, 2011; Sheppard et al., 2011; Eyvindson et al., 2018; Heimann, 2019). Developing new ways to define, measure, and communicate bioeconomy’s environmental sustainability contributions are prerequisites to achieving the systemic change it aspires towards.

The natural capital concept uses the economic notions of “capital”, “stocks”, and “flows” to describe the environment, its functions, outputs, and benefits to humanity (Costanza et al., 1997). This economic lens connects socio-economic systems to the surrounding environment that they are embedded within, emphasising the services and resulting benefits provided—for free—from nature to people (Costanza et al., 1997; Barbier, 2019). These ecosystem services, classified as provisioning, regulating, or cultural, are derived from the interactions between the living and non-living components of the environment; valuable to people and the economy because of the benefits they provide, from clean air and carbon storage to waste breakdown and food provision (Millennium Ecosystem Assessment, 2005; Braat and de Groot, 2012; Costanza et al., 2017). The concept has gained momentum through highly cited global assessments that estimate the value of nature’s services as 2–3 times greater than global GDP—a clear argument that nature is vital to a healthy and functioning economy (Costanza et al., 1997; Costanza et al., 2014; IPBES, 2019; OECD, 2019). Natural capital has since branched into environmental sustainability practices such as its integration within national accounting standards (Hein et al., 2020), adoption within policy and decision-making spheres (Daily et al., 2009; Guerry et al., 2015), and application as a tool to explore biodiversity’s role in sustainable development and achieving the United Nations (UN) Sustainable Development Goals (SDGs) (Reyers and Selig, 2020).

The natural capital and bioeconomy concepts both blend economics with natural sciences to illustrate the relationships and dependencies between human society and the environment. By re-establishing and reframing this fundamental linkage via a systems approach to environmental management, policy, and decision-making, they seek to alleviate unsustainable environmental pressures that have resulted in the loss of nature across scales at an unprecedented rate (IPBES, 2019). Despite this similarity, the two concepts have different origins and spheres of influence: the natural capital concept emerged from environmental sciences and academia in the late 20th century and subsequently evolved into a decision-support tool (Ehrlich and Mooney, 1983; Costanza et al., 1997; Guerry et al., 2015), whereas the modern bioeconomy concept emerged through high-level policy adoption and promotion through the early 21st century (Fig. 2.2) (McCormick and Kautto, 2013; Bugge et al., 2016; Patermann and Aguilar, 2018). As a result, the two concepts are embedded within institutions, and leveraged by actors, in different ways, impacting their application and contributions towards environmental sustainability objectives.

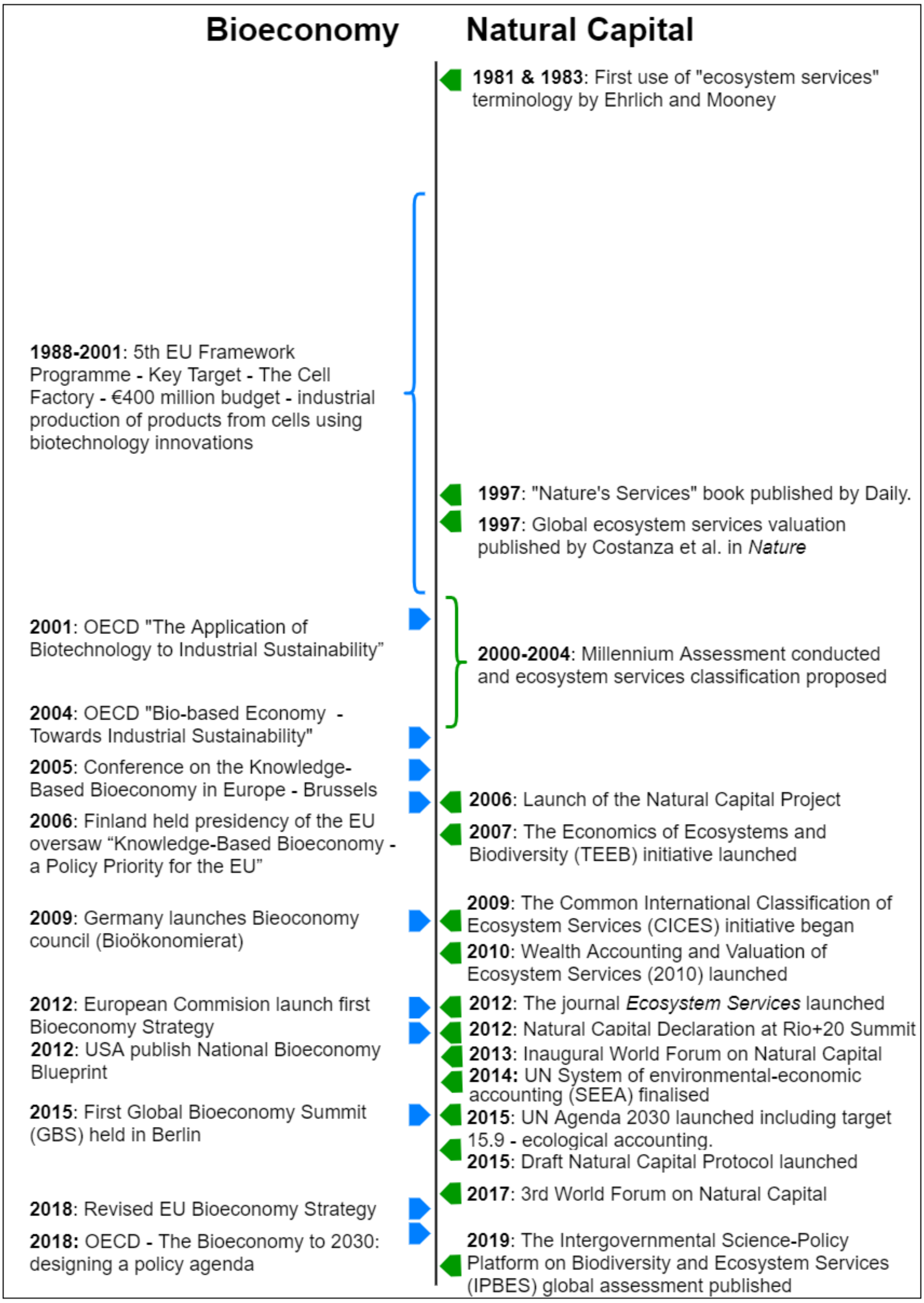

Figure 2.2: A timeline showing the emergence of the bioeconomy and natural capital concepts through key events since 1980 (Costanza et al., 2017; Patermann and Aguilar, 2018).

2.2.2 *The knowledge gap*

The sustainability of a realised bioeconomy system cannot be assumed as an inherent characteristic but is instead conditional on the context and surrounding system (Pfau et al., 2014; El-Chichakli et al., 2016; Priefer et al., 2017). Environmental sustainability research aims to inform these preconditions and steer bioeconomy development towards its sustainable ambitions and realisation of the SDGs (Kleinschmit et al., 2017; Gawel et al., 2019; Vainio et al., 2019; Ronzon and Sanjuán, 2020). The intersection of economics with natural sciences is common to both natural capital and the bioeconomy, yet they have seen little collaboration or interaction, remaining clustered within their respective areas of expertise. How the natural capital approach can contribute to shaping the environmental sustainability principles of bioeconomy has not been explored in detail.

There are few instances in the academic literature that bring together both concepts. For example, the only reference that directly connects the two in its title presents the importance of natural capital management to the success of a future wood-based bioeconomy and the forestry sector (Marchetti et al., 2015). The language of "ecosystem services" is more commonly linked to bioeconomy, but limited to a few examples such as the importance of soil ecosystem services for a future bioeconomy (Helming et al., 2018), the biosecurity dangers of an expanding bioeconomy (Sheppard et al., 2011), and the bioeconomy's emphasis on a subset of provisioning ecosystem services (D'Amato et al., 2019). These examples use the language of natural capital, or adjacent themes, to illustrate arguments that environmental sustainability is a necessity for the bioeconomy's success, but do not connect the two on a conceptual level. Conversely, one paper does present a social-ecological systems framework for the bioeconomy that includes the variety of impacts and dependencies between the bioeconomy and the environment, but does not include any reference to natural capital or ecosystem services (de Schutter et al., 2019).

There is a knowledge gap related to linking the natural capital and bioeconomy concepts on a theoretical level that explores how these two similar concepts differ and how natural capital can serve as a guiding principle for the realisation of a sustainable bioeconomy. We address this gap by applying a natural capital lens to the bioeconomy concept, creating a framework that recognises the value of ecosystems, biodiversity, and nature; informs integrated and coherent policy, research, and practice; and guides the realisation of an environmentally conscious, future bioeconomy. Creating this foundational linkage between the two concepts can serve as a launching pad for future studies and guide research questions towards practical, primary studies that advance knowledge of environmental sustainability.

2.2.3 *Objective and structure*

In this paper, we bring together the bioeconomy and natural capital concepts to demonstrate how they can be related and the unrealised complementarities for policy, research, and practice. We first provide an overview of the natural capital and bioeconomy concepts as represented in the literature and explore their environmental framings. We then build on this overview and construct an integrated cascade model that combines the spectrum of different bioeconomy narratives within one shared framework. Secondly, we consider five cornerstones for a sustainable, future, global bioeconomy as presented in the literature (El-Chichakli et al., 2016) and use these cornerstones as a scaffold around which to compare the natural capital and bioeconomy concepts and identify areas of opportunity. We conclude with a case-study analysis of the bioeconomy strategy of the EU as seen through a natural capital lens, and end with a series of recommendations and opportunities for future integration of the natural capital approach to the bioeconomy for coherent and synergistic policy design.

2.3 Conceptual framework and environmental framings

2.3.1 *The bioeconomy concept*

The bioeconomy concept refers to the replacement of non-renewable resources with biological, renewable alternatives—spanning biopharmaceuticals, primary producing industries, bioenergy, biomaterials, biochemicals, and more—and the accompanying changes to the economic system (EC, 2012; McCormick and Kautto, 2013). Nature provides these bioresources as products of ecosystem functioning, including biomass production, biological processes, and genetic resources (Lewandowski, 2015). Human civilisation has always depended upon biological resources and processes (such as agriculture and fermentation) and so it could be argued that bioeconomy is not a new idea (Zilberman et al., 2018). The modern conceptualisation of bioeconomy has evolved alongside advances in scientific knowledge and emphasises bioresources and novel uses, technological breakthroughs and their applications, and the replacement of non-renewables (Bugge et al., 2016). Therefore, bioeconomy's success depends upon both primary production—the supply of bioresources—and advances in biotechnology and its applications—the efficient use of those resources that creates demand.

Today, the bioeconomy concept has successfully garnered political momentum and policy support such as the EU Bioeconomy Strategy and the publication of over 45 national bioeconomy policy documents (OECD, 2009; EC, 2012; Bugge et al., 2016). This momentum was generated by the perceived economic opportunities associated with novel bioresources and emergent biotechnological capabilities in high-income nations and further catalysed through supporting publications such as "Biotechnology for Sustainable Growth and Development" by the Organisation for Economic Co-operation and Development (OECD) in 2004 (Fig. 2.2) (OECD, 2004; Bugge et al., 2016; Patermann and Aguilar, 2018). The permeance of bioeconomy is further enhanced by frequently cited economic statistics that estimate its value. For example, the EU's bioeconomy has a turnover estimated at €2.3 trillion and supports 8.2% of the EU workforce (EC, 2018). While a promising concept that has permeated policy across scales, questions remain over its scale, scope, and implementation.

There is no harmonised definition of bioeconomy (Hausknost et al., 2017), and so its use spans a suite of competing narratives and visions for the future. These narratives range from a narrow focus on biotechnology, bioresources, and high-tech solutions—the "dominant" narrative—to a broad, systems approach of ecosystem functioning and public goods—the "rival" narrative (Levidow et al., 2012; Bugge et al., 2016). As a result, the term encompasses many different meanings that are not applied consistently, creating a "master narrative" that lacks clarity (Levidow et al., 2012; Hausknost et al., 2017; Korhonen et al., 2020). This has been described as the "shades of green" of the bioeconomy as different applications have different environmental sustainability contributions and thus should not be assumed as equal (Kleinschmit et al., 2014). Paradoxically, the blurred definition of the bioeconomy concept has allowed it to act as a bridge between a wide range of sectors and stakeholders (Hodge et al., 2017; Korhonen et al., 2020). As this study is limited to exploring the environmental pillar of sustainability, we focus on those narratives that are most relevant to the environment rather than those of systemic economic change, political discourses, or specific synthetic biology case studies—either directly through the use of bioresources, or indirectly through developing new markets, value chains, and demand—while acknowledging that the concept has also been used in broader settings (Bueso and Tangney, 2017).

2.3.2 *The natural capital concept*

The natural capital concept represents the environment as a series of stocks or assets that can be thought of as the building blocks of the environment—both the living and the non-living components (Mace, 2019). The complex interactions between these building blocks produce ecosystem functions, giving rise to ecosystems. Some of those functions have a direct benefit to people, termed ecosystem services, and thus can be attributed value (Barbier, 2019). By recognising that all ecosystem services have value, but that not all are—or should be—monetised, the concept addresses the failure of traditional economics to capture only a subset of these services (Costanza et al., 2017). Natural capital accounting is an approach to measuring these stocks in terms of their quantity, quality, and attributes; the service flows they give rise to; and the changes to those stocks over spatial and temporal scales (Obst, 2015).

The core language of natural capital and ecosystem services is attributed to academic publications in the early 1980s (Ehrlich and Mooney, 1983; Costanza et al., 2017). In 1997, the journal *Nature* published a breakthrough paper by Costanza and colleagues that estimated the monetary value of all global ecosystem services, catapulting the concept into the spotlight (Costanza et al., 1997). Since then, research surrounding natural capital has continued to evolve, giving rise to a new vocabulary, shaping the discipline of ecological economics, and inspiring the journal *Ecosystem Services* (Braat and de Groot, 2012). What was originally a concept limited to academic study has expanded into a dynamic and diverse policy and decision-support tool for environmental management (Daily et al., 2009; Guerry et al., 2015; Bateman and Mace, 2020), and a shared language used by economists, policymakers, scientists, statisticians, and civil society (Costanza et al., 2017).

Adopting a natural capital lens reveals how the environment is connected to socio-economic systems through the valuable services it provides to people. This is conventionally depicted as the cascade model (Fig. 2.3 (Potschin and Haines-Young, 2011)) that was devised to show how biodiversity, ecosystem services, and human wellbeing were linked. By adapting the cascade model to encompass natural capital stocks—including biodiversity—the model can be used to link stocks, interactions, and processes in the natural world (ecosystem functions), flows, benefits, and values. This is a simplified model and does not include the feedbacks within the system, but it can provide useful knowledge from the abstract complexity of socio-economic interactions and dependencies on the environment (Potschin and Haines-Young, 2011).

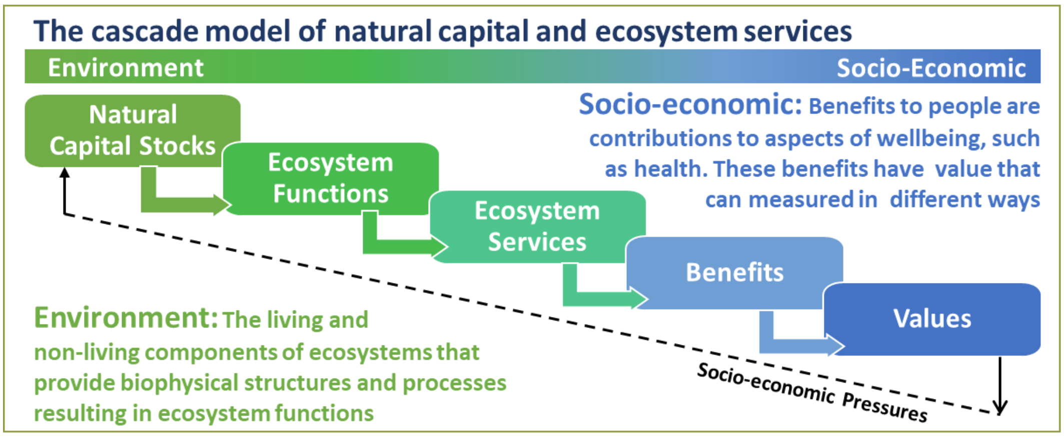

Figure 2.3: A simplified cascade model of natural capital that depicts how natural capital gives rise to ecosystem services that provide benefits to people and can be attributed value. Those values create socio-economic pressures and inform management decisions, connecting people back to the environment in a bidirectional relationship. Model adapted from (Potschin and Haines-Young, 2011).

Numerous organisations and initiatives are dedicated to promoting the natural capital concept including the Capitals Coalition (formerly Natural Capital Coalition (NCC)) (Natural Capital Coalition, 2016), The Economics of Ecosystems and Biodiversity initiative (TEEB) (TEEB, 2010), and the UN System for Economic and Environmental Accounting (SEEA) (UNSD, 2018). The concept has achieved a broad reach with members of the Capitals Coalition spanning high-level policy groups, NGOs, and private sector actors (including multinational industries). Within these initiatives are more specialised areas of activity. One TEEB sub-initiative explores agriculture and food systems (TEEB Agrifood), spanning the complexity of "eco-agri-food systems." This systems approach connects the economy to biodiversity, ecosystems, and livelihoods, using a framework of stocks, flows, outcomes, and impacts to describe biological production systems and the multiple services they provide. It includes brief mentions to competing biomass production for bioenergy and bio-plastics—bioeconomy-related demands—but does not yet draw the connection to bioeconomy as a sustainability concept, or to related themes (TEEB, 2018).

2.3.3 *Environmental framings of bioeconomy and natural capital*

The bioeconomy and natural capital concepts are anthropocentric; they represent how people benefit from, use, and depend on biological systems, crafting new metaphors for the interactions and dependencies between people and the environment (Ramcilovic-Suominen and Pülzl, 2018; Bateman and Mace, 2020). These metaphors shape how the environment is viewed from their respective vantage points, informing their underlying philosophy of environmental degradation and unsustainable practice, and how these problems can be resolved. Here we consider the environmental framings within each concept in turn.

The bioeconomy concept encompasses several different narratives concerning the environment that exist along a spectrum from the sole provision of private commodities to the simultaneous basket of public goods derived from nature (Levidow et al., 2012; Bugge et al., 2016). A dominant narrative, aligned with the "bioresource" vision described by Bugge et al. (2016), adopts a utilitarian and resource economics stance that states that the environment provides renewable, biological resources that should be used in an efficient way to maximise human welfare (Priefer et al., 2017). These resources include biomass, biologically-mediated processes, and innovative bioproducts—that may or may not rely on high-tech bioscience applications—but ultimately depend upon ecosystem functioning, such as agroecosystems, to be fully realised (Levidow et al., 2012; Lewandowski, 2015). An opposing "rival" narrative, or sometimes termed "agroecology" or "bioecology" vision, frames the environment as biological systems that produce numerous, simultaneous benefits that act as economic public goods and so management decisions should reflect this overall basket of services, rather than single-service outputs (Bugge et al., 2016). A separate study identified three main themes in the bioeconomy literature: (1) environmental sustainability as a challenge to rise to, (2) as a required standard that must be met, and (3) as a co-benefit that accompanies economic growth (Kleinschmit et al., 2017). The range of competing environmental framings exemplifies the "shades of green" of bioeconomy and its environmental sustainability contributions (Kleinschmit et al., 2014; Pfau et al., 2014; Hausknost et al., 2017).

Bioeconomy emphasises the socio-economic improvements made possible by using bioresources and associated biotechnology and how this can address environmental sustainability shortcomings under the economic status quo. Environmental degradation is framed as the reliance on non-renewables, especially fossil fuels, and the inefficient use of resources that create negative externalities such as waste and pollution. Bioeconomy argues this degradation may be addressed through more efficient use of biological resources, enabled through biotechnological capabilities (Zilberman et al., 2018). However, the interactions between the bioeconomy and nature are bidirectional; a growing bioeconomy will also apply pressure upon the environment (de Schutter et al., 2019). These pressures manifest as the conflicts of competing resource demands to achieve food security, energy security (the food versus fuel debate), and a supply of homogeneous, high-quality bioresources (Graham-Rowe, 2011; Lewandowski, 2015; Piotrowski et al., 2015). A realised bioeconomy will emerge as part of a globalised system of value chains that connect spatially isolated ecosystems as consumers in one area create demand for bioresources produced elsewhere (Dietz et al., 2018). The combination of growing demand and the spatial decoupling of production and consumption of bioresources reconfigures the pressures socio-economic systems place upon the environment. A sustainable bioeconomy pursues a balancing arrangement between bioresource production and consumption on one hand, and the resulting environmental pressures and ecological limitations on the other.

The natural capital approach argues that all socio-economic systems are embedded within the environment and so a healthy and functioning environment is essential for the service flows that contribute to the welfare improvements, capabilities, and freedoms that people enjoy (Pelenc and Ballet, 2015; Costanza et al., 2017; Reyers and Selig, 2020). A healthy, resilient, and functioning environment is ultimately dependent on its natural capital asset base. A subset of these environmental building blocks is considered "renewable" natural capital—those which can self-maintain or replenish over relatively short timescales—the consumption of which is permissible so long as it does not exceed the natural rate of replenishment (Costanza et al., 2017).

So long as socio-economic systems do not exploit ecosystems at a rate greater than they are able to self-maintain, environmental degradation, and the loss of ecosystem functions, can be prevented. Environmental degradation and biodiversity loss are thus the product of the systematic failure to account for only a subset of services—typically provisioning services at the expense of regulating and cultural services—and management decisions targeting single-service outcomes rather than maintaining a healthy natural capital asset base from which those services flow (Guerry et al., 2015; Maseyk et al., 2017).

The distinction between the terms ecosystem services (flows) and natural capital (stocks) is an important point of clarification that is sometimes lost in application (Pan and Vira, 2019). Ecosystem services contribute to human wellbeing and the economy—they are explicitly anthropocentric and dependent on human demand (Bateman and Mace, 2020)—but are a downstream product of ecosystem functions produced from natural capital stocks (Fig. 2.3), and realised through interactions with human and manufactured capital (Jones et al., 2016; Costanza et al., 2017). Management decisions and environmental pressures operate upon natural capital stocks, rather than the flow of ecosystem services, and it is important that this distinction is not lost when objectives focus on ecosystem service outputs (Hein et al., 2016; Maseyk et al., 2017).

Natural capital theorists have built upon and expanded this environmental framing. The term “critical natural capital” refers to natural capital stocks that are poorly substitutable by technology or other forms of capital meaning that they should be considered irreplaceable and their consumption cannot be justified (Ekins et al., 2003; Pelenc and Ballet, 2015; Cohen et al., 2019; Bateman and Mace, 2020). This is aligned with the strong sustainability paradigm that not all forms of capital can be assumed as substitutable (as opposed to weak sustainability that states all capitals are fully substitutable) (Pelenc and Ballet, 2015). A second principle, the aggregate natural capital rule, argues that so long as the aggregate of natural capital assets is non-decreasing, losses in some stocks can be compensated by gains elsewhere (Helm, 2019). So long as the critical natural capital base is maintained, and aggregate natural capital stocks are non-decreasing, environmental degradation can be prevented.

These guiding principles of environmental sustainability appear straightforward at first glance but are complex to implement effectively. For any context, we do not know which natural capital assets are "critical" to the functioning of an ecosystem, which necessitates caution. How to aggregate natural capital stocks that differ in measurement, quality, function, and perceived value, and how to make valid comparisons across scales, are ongoing challenges to applying the natural capital approach (Helm, 2019; Bateman and Mace, 2020). Due to these challenges, while the overarching framing of the environment is consistent, there is no singular "natural capital approach" that is appropriate for every situation and context. Instead, flexible frameworks that adopt steering principles of efficiency, equity, and sustainability are promoted as best-practice when using the natural capital concept for informed decision-making (Bateman and Mace, 2020; Reyers and Selig, 2020). The natural capital approach is a powerful tool to interrogate the relationships between people and nature, but the complexity of its application can be a barrier to its implementation.

2.3.4 *Uniting bioeconomy and natural capital – An integrated cascade model*

The bioeconomy and natural capital concepts share the principle that environmental resources are key to a stable economy and a fulfilled, healthy society. The dominant narratives of the bioeconomy seek novel bioresources and more efficient use of traditional bioresources that are provided from the environment as feedstocks that power the bioeconomy machine (McCormick and Kautto, 2013; Lewandowski, 2015; Bugge et al., 2016). This is aligned with the set of ecosystem services termed "provisioning ecosystem services" and have been labelled as such (D'Amato et al., 2017; D'amato et al., 2020). The rival narrative or "bioecology" vision argues that the basket of public goods sourced from biological productive systems should be considered as part of the bioeconomy, in conjunction with provisioning services (Levidow et al., 2012; Bugge et al., 2016). These public goods, such as carbon storage, nutrient recycling, and cultural landscapes, fall under the classifications of regulating and cultural ecosystem services (Costanza et al., 2017). The natural capital concept is grounded on the benefits sourced from the full range of services—provisioning, cultural, and regulating—that have value to people but may be lost due to socio-economic pressures operating upon their underpinning natural capital (Maseyk et al., 2017). As only a subset of those services is routinely valued or monetised, cost-benefit analyses fail to account for all benefits derived from nature, leading to sub-optimal management decisions. There is a danger that the predominant bioeconomy vision falls into the same trap, adopting a narrow focus on maximising provisioning service flows without considering other co-benefits, or the dependent natural capital asset base.

Broadly, bioeconomy considers the environment as an opportunity of unrealised benefits whereas the natural capital approach presents the environment as the necessity of unrecognised benefits. Both groups of services, the unrealised and the unrecognised, are valuable and should be accounted for in sustainable development pathways. The "agroecology" or "bioecology" narrative has some resemblance to the natural capital approach in this respect but retains the language of public goods leaning towards the traditional economic lens and retaining a focus on service flows, rather than the asset base (Levidow et al., 2012; Bugge et al., 2016). A social-ecological systems framework proposed by de Scutter touches upon the combination of private commodities (provisioning services) and public goods (regulating and cultural services) that contribute to the bioeconomy, but their framework does not draw the connection to ecosystem service classifications or the natural capital approach (de Schutter et al., 2019). As such, this natural capital approach serves as a complementary tool that considers the broad spectrum of bioeconomy narratives to better understand the ecosystem services they emphasise, the implications for natural capital stocks, and the application of related methods to bioeconomic activities.

The natural capital approach shows that these narratives exist along a spectrum, from a narrow focus on only a single provisioning service (for example monoculture biomass production) to the broad recognition of the full basket of environmental services—including regulating and provisioning services—derived from biologically productive systems. The bioeconomy literature emphasises new economic opportunities, business models, value chains, and the efficient use of bioresources, focusing on the socio-economic end of the cascade model: the "downstream" benefits, values and monetisation yielded from ecosystem services. A revised cascade model is shown in Fig. 2.4 that integrates these bioeconomic themes into the natural capital framework, expanding the view to include the "upstream" dependencies upon ecosystem functioning. It also incorporates the bidirectional relationship between ecosystems and bioeconomy—the impacts that a realised bioeconomy will have upon the environment, shifting pressures upon natural capital stocks in pursuit of increased, high-value, bioresource flows.

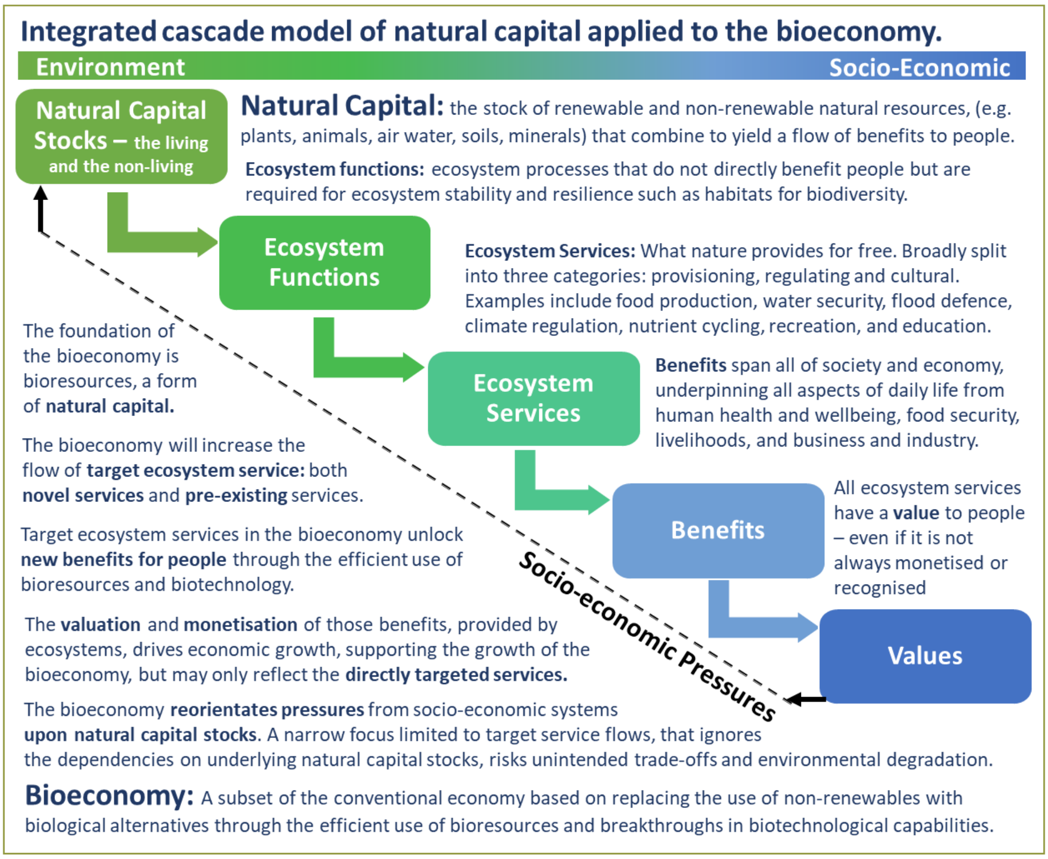

Figure 2.4: An integrated cascade model of the bioeconomy concept (lower left) and natural capital (upper right) based on the original by Potschin and Haines-Young (2011). The natural capital cascade provides a framework to understand how the bioeconomy is fuelled by benefits provided from natural systems while also reorientating pressures upon those systems. Management decisions targeting the maximisation of a narrow subset of ecosystem service flows in the quest for a fully realised bioeconomy are in danger of overlooking essential underpinning natural capital stocks and ecosystem functions.

This reasserts that bioeconomy-mediated pressures are motivated by desirable ecosystem service flows, but act upon natural capital stocks, creating a mismatch between management decisions and impact pathways that could have unintended and far-reaching negative impacts upon ecosystem function. This necessitates a systems approach to environmental sustainability in the bioeconomy that accounts for the wider range of services provided from nature—all of which have value—and can ensure that broader environmental benefits are represented in bioeconomy discussions. The natural capital approach creates this link, providing the terminology, classification system, and flexibility to bring together competing bioeconomy narratives in a systems approach, recognising all services but allowing for weightings based on perceived value. Opportunities to support this linkage already exist, including the TEEB Agrifood framework of stocks, flows, outcomes, and impacts of eco-agri-food systems, which recognises both the economically visible and invisible services (TEEB, 2018). The emergent bioeconomy will create new resource demands upon such eco-agri-food systems that must be accounted for in this framework, but currently the two ideas remain disconnected.

2.4 Natural capital and the cornerstones of a sustainable, future bioeconomy

The previous section explored the theoretical integration of the natural capital and bioeconomy concepts. We now examine how the natural capital concept can aid the development of a future, sustainable bioeconomy. In 2016, 37 experts from the International Advisory Committee for the Bioeconomy published a commentary piece in the journal *Nature* proposing five principles to advance the bioeconomy and contribute towards the SDGs (El-Chichakli et al., 2016). The article has since been well cited by other literature exploring the sustainability of the bioeconomy suggesting these principles have been influential within the field (Wesseler and von Braun, 2017; Dietz et al., 2018; Philp, 2018; Schütte, 2018; Ronzon and Sanjuán, 2020). The five cornerstones can be summarised as: research collaborations; measurement; multilateral policy linkages; education, knowledge, and skills; and research and development support programmes. The commentary article is brief but does include a reference to natural capital: “A global bioeconomy must rebuild natural capital and improve the quality of life for a growing world population”. This outlines that stewardship and appropriate management of natural capital are desirable outcomes of a sustainable bioeconomy. We explore these five cornerstones from a natural capital perspective by using them as a scaffold around which to question the complementarities and divergences between the two concepts.

2.4.1 *Cornerstone 1: International collaborations between governments and public and private researchers*

Bioeconomy is relevant for multiple disciplines, sectors, and industries, connecting international regions and value-chain actors. Research within the bioeconomy must reflect its interdisciplinary and interregional characteristics to achieve its environmental and economic sustainability aspirations. The dominant motivations and resulting narratives of the bioeconomy lean towards an economic lens of growth, value addition, and job creation, while emphasising STEM research, biotechnological innovations, and their applications (Bueso and Tangney, 2017; Ramcilovic-Suominen and Pülzl, 2018; Sanz-Hernández et al., 2019). Social sciences have an important role exploring public acceptance, policy design, and social sustainability but are less represented in the literature (Sanz-Hernández et al., 2019). Network analyses show that collaborations between disciplines and international research networks are already present, albeit dominated by wealthier regions with strengths in high-tech industry such as the USA, EU, and China (Bugge et al., 2016; D'Amato et al., 2017).

The natural capital concept is inherently multidisciplinary having emerged from ecology and environmental science through the incorporation of economic tools and language to better understand and communicate the relationships between people and nature (Costanza et al., 2017). Social sciences are also acknowledged for their role in identifying the values and preferences that people have regarding the environment and ecosystem services (Braat and de Groot, 2012). Research initiatives by organisations such as the Capitals Coalition, The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), and TEEB have adopted an international and collaborative approach that reflects how ecosystems transcend national boundaries and are relevant to all disciplines. However, there is evidence to suggest the natural capital concept remains clustered within highly specialised groups, dominated by wealthy, English speaking nations that may limit collaboration and bridging between clusters (Abson et al., 2014; Pan and Vira, 2019).

Both natural capital and the bioeconomy draw upon natural sciences and economics while striving towards a systems approach to untangling the socio-economic relationships with the environment. The natural capital approach has developed tools and language to consider these interdisciplinary and interregional relationships (Schröter et al., 2014; Hein et al., 2016), while also establishing international organisations that connect different actors together in a collaborative way to share knowledge, e.g., IPBES, Capitals Coalition. This cornerstone emphasises that the bioeconomy must create a similar research dialogue to optimise resource use and knowledge sharing. Organisations such as the Global Bioeconomy Summit and the Bioeconomy Strategic Working Group—under the EU Standing Committee for Agricultural Research (SCAR)—represent one pathway to achieve this (SCAR, 2017; GBS, 2018). In parallel to these initiatives, integrating a natural capital approach could unlock pre-existing, collaborative networks and their expertise regarding interdisciplinary environmental sustainability

2.4.2 *Cornerstone 2: Measurement of bioeconomy development and sustainability contributions*

Currently, measuring the bioeconomy resembles familiar economic metrics such as gross domestic product (GDP) share and value creation. These metrics often rely on proxies because of limited data resolution; what is sufficiently "bio-based" to be counted under the bioeconomy and what is not (Ronzon et al., 2017; Wesseler and von Braun, 2017)? Environmental metrics have been used to monitor bioeconomy initiatives such as life-cycle assessment (LCA) and environmental foot-printing (Cristóbal et al., 2016; O'Brien et al., 2017; D'amato et al., 2020). A review of wood-based bioproduct LCA studies concluded that only 20% of ecosystem services were represented in those analyses (D'amato et al., 2020). While standardised protocols for LCA are published, identification of system boundaries for bio-based products, data availability, and the selection of appropriate impact factors are all challenges when considering how to measure environmental sustainability impacts of the bioeconomy (Cristóbal et al., 2016; Karvonen et al., 2017; Crenna et al., 2018; D'amato et al., 2020).

The natural capital toolbox contains a diverse range of methods including field data collection and analysis, GIS mapping, and statistical modelling (Norton et al., 2018). Natural capital accounting can incorporate a range of accounts such as quantifying natural capital stocks; assessing the quality, attributes, and spatial arrangement of those stocks; identification of service flows; beneficiary mapping; valuation; and monetisation (where appropriate) (Obst, 2015). The UN SEEA has published a standardised approach to national natural capital accounting that has been adopted by some national accounting programmes (UNSD, 2018; Hein et al., 2020). This can make use of historical data while also responding to new methodological advances such as remote sensing (Norton et al., 2018). Despite this range of tools, natural capital approaches still wrestle with the wicked problems of complexity and uncertainty of ecosystem function (DeFries and Nagendra, 2017; Bateman and Mace, 2020). Overarching questions remain as to how natural capital stocks give rise to service flows, how the quality and attributes of stocks influence those service flows, and how different service flows interact (Jones et al., 2016). This can make the approach appear daunting to implement but this challenge has not gone unrecognised, with guidance documents and case-studies freely available from organisations such as The Natural Capital Project (2020).

The natural capital approach can formalise a system of measurement to understand the impacts and dependencies between the bioeconomy and the environment that complements other metrics as they emerge. Its foundation in natural sciences is a methodological strength that makes use of interdisciplinary methods, whereas the bioeconomy currently has a less established toolkit of its own but can leverage the legitimacy of well-regarded economic proxies. Emergent high-tech solutions can also be incorporated into both concepts such as remote sensing and statistical modelling, although harmonised data collection remains a limiting factor (El-Chichakli et al., 2016; O'Brien et al., 2017). To achieve a systems approach, environmental metrics must complement and build upon specialised but narrow metrics such as water use or carbon footprint (O'Brien et al., 2017). The natural capital concept provides such a systems approach by providing the scope to incorporate the full range of natural capital stocks and how they interact, the bidirectional pressures between socio-economic systems and the environment (Potschin and Haines-Young, 2011), the international dimensions of bio-based value chains and interregional ecosystem service flows, and the network of beneficiaries and suppliers of those services (Schröter et al., 2014; Pascual et al., 2017; Ouyang et al., 2020). Complexity and uncertainty remain a challenge in realising this systems approach, for example in assigning boundaries to the bioeconomy and understanding which ecosystem functions should be prioritised in future research.

2.4.3 *Cornerstone 3: Linkages with multilateral policy*

The modern conceptualisation of bioeconomy emerged in part due to economic policy documents in the early 2000s that generated widespread momentum and subsequent adoption (OECD, 2004, 2009; Patermann and Aguilar, 2018). Over 45 countries have a dedicated national policy or bioeconomy plan (Bugge et al., 2016; Priefer et al., 2017), some of which have been updated and revised, such as the EU strategy 2018 update (EC, 2018), suggesting the concept has retained relevance and interest. These policies skew towards countries with domestic strengths for high-tech biotechnological applications, and so may not yet incorporate traditional bioresource production systems (Dietz et al., 2018). The intersection of the bioeconomy with numerous traditionally siloed sectors and departments including primary production, such as agriculture, fisheries, and forestry, and other environmental departments, such as climate, culture, and heritage, make achieving policy coherence a challenge (Kelleher et al., 2021).

Policymakers and governance actors have adopted the natural capital approach, including some binding commitments. Its key themes are included in several international, high-level policy and governance documents such as the inclusion of ecological accounting in SDG 15 (UN, 2015), the commitment to the restoration and accounting of natural capital in the EU Biodiversity Strategy 2030 and the EU Green Deal (EC, 2019, 2020), and Aichi Target 2 for the inclusion of biodiversity value to national accounts (Millennium Ecosystem Assessment, 2005). Many high-level policy bodies are members of the Capitals Coalition, such as the European Commission and UN Environment Program, which suggests such organisations have had a role in promoting policy adoption (Natural Capital Coalition, 2016).

Bioeconomy has achieved broad policy inclusion over the past decade, but often taking the form of standalone national strategies, lacking established linkages to environmental, multilateral policy processes, such as the SDGs, the Paris Agreement, and Aichi biodiversity agreements (El-Chichakli et al., 2016). The natural capital approach is a potential bridge that could connect bioeconomy to environmental, multilateral policy as more formal, standardised accounting protocols for natural capital are mainstreamed across national reporting and the private sector (Obst, 2015; UNSD, 2018; Vardon et al., 2018). The support for natural capital has been catalysed by a push from academia to promote it as a tool for policymaking alongside support from dedicated international organisations (Daily et al., 2009; Guerry et al., 2015). The bioeconomy does not yet have the same level of organisational or institutional support although this may be emerging through initiatives such as the Global Bioeconomy Summit (GBS, 2018). Potential vehicles to solidify this natural capital-mediated bridge already exist such as the TEEB Agrifood initiative, which presents a systems-based policy support framework that emphasises the multiple services derived from eco-agri-food systems and promotes a holistic evaluation beyond economic production (TEEB, 2018).

2.4.4 *Cornerstone 4: Education, skills, and knowledge*

This cornerstone refers to "an interdisciplinary approach that emphasises systems thinking, strategic planning and evaluating environmental, social and economic performance" when considering the education, skills, and competencies needed for the developing bioeconomy. As discussed under cornerstone 1, bioeconomy has created collaborations between disciplines but how these disciplines communicate and disseminate their research is important for achieving systemic change. The lack of a universal definition for bioeconomy makes this challenging by allowing the concept to be moulded around the user's self-interest, creating different understandings of bioeconomy (Bugge et al., 2016; Gawel et al., 2019), and thus the required knowledge and skills. The language of bioeconomy is evolving but often reflects underpinning motivations for economic growth, such as economic metrics, coupled with perceived associations of sustainability contributions that are not necessarily justified (Bugge et al., 2016; Priefer et al., 2017). Associations with terms such as "green", "renewable", and "natural"—that may be linked to the "bio" prefix—demonstrate this, but are not always questioned, contributing to the "master narrative" criticism; a concept that has lost precise meaning (Levidow et al., 2012; Hausknost et al., 2017; Székács, 2017). These barriers for effective education and communication must be overcome to create the skilled workforce and informed society required to realise a sustainable bioeconomy.

In contrast to bioeconomy, the natural capital concept has created a precise vocabulary that has become commonplace across ecological economics and related disciplines (Costanza et al., 2017). This terminology is continually being expanded and refined as the understanding of ecosystem functioning changes (Hein et al., 2016). This has proved to be a useful asset in bringing together different actors with the same set of terminology to apply alongside their expertise that can aid communication and knowledge sharing (Braat and de Groot, 2012). Natural capital has created a bridge between policymakers, researchers, civil society, and the private sector that facilitates knowledge sharing and will continue to do so as natural capital is further mainstreamed into environmental decision-making (Bateman et al., 2013). The suite of tools outlined under cornerstone 3 are designed to be applicable to different contexts and scenarios, and to equip decision-makers with the necessary information to evaluate environmental management decisions (Daily et al., 2009; Kareiva et al., 2011).

Education, communication, and training are required for bioeconomy to achieve its sustainability ambitions that place the environment and the economy on an equal footing. The barriers to knowledge sharing can be partially addressed by leveraging the influence and resources of the natural capital approach. The established terminology of natural capital can address some of the challenges of the bioeconomy as a "master narrative". Furthermore, equipping bioeconomy decision-makers and practitioners with the natural capital toolbox to untangle the intersections between the bioeconomy and the environment is an additional asset for securing a sustainable, future bioeconomy. Providing the tools to effectively validate and communicate environmental sustainability contributions of bioeconomic activities is one of the capabilities needed to secure this cornerstone. Social media networks involving natural capital have already been observed as a communication tool (Pan and Vira, 2019), and the rise in online learning opportunities such as the Stanford-based Natural Capital Project provide additional resources and lessons learned for the bioeconomy as it develops.

2.4.5 *Cornerstone 5: Support for research and development programmes*

Bioeconomy requires investment in terms of finance, labour, and resources to develop and deploy new technologies and solutions for environmental sustainability challenges. Pilot projects and a subsequent scale-up of new biotechnology are needed to demonstrate the potential of new innovations and their contributions toward bioeconomy objectives (Vandermeulen et al., 2012; Dupont-Inglis and Borg, 2018). Allocating finite investment efficiently to areas of special interest or potential for the greatest impact should be a priority. Identifying those opportunities requires aspects of all four prior cornerstones through interdisciplinary expertise and perspectives, appropriate measures of change, supporting and enabling policy, and knowledge sharing and education.

The natural capital perspective can enable new investment opportunities and strengthen the allocation of already existing investment streams. Firstly, it provides environmental metrics and measures of change that demonstrate sustainability contributions from bioeconomy projects that can feed into evaluating and allocating support programme resources (Guerry et al., 2015). Natural capital's increasing adoption within other environmental policy, such as the SDGs and the EU Green Deal, lends a legitimacy to the integration of natural capital alongside the bioeconomy (UN, 2015; EC, 2019). Natural capital demonstrates additional value of bioeconomy projects, both in monetary terms and other forms of value, that are not represented in conventional analysis, creating a holistic, multidimensional lens for assessment (Pelenc and Ballet, 2015). This value of natural capital has already been adopted by private and financial sectors as demonstrated by the European Investment Bank's Natural Capital Financing Facility (EIB, 2017), the World Bank's genuine savings metric (Lange et al., 2018), and the growing push for "The business case for biodiversity", with numerous global assessments suggesting that services derived from nature provide 2–3 times the global GDP (Costanza et al., 2014; OECD, 2019). Bioeconomic projects that can demonstrate how they contribute to enhancing and conserving natural capital—in parallel to social and economic benefits—can unlock otherwise unavailable investment streams for research, development, and deployment.

2.5 A policy case study: Applying a natural capital lens to the EU Bioeconomy Strategy

We now present a case-study examination of the EU Bioeconomy Strategy first published in 2012 and updated in 2018 as viewed through a natural capital lens. For a broader review of the strategy and its formation, see (McCormick and Kautto, 2013; Bell et al., 2018; Patermann and Aguilar, 2018). We examine the elements of the natural capital concept represented in the strategy and then present opportunities and recommendations for further integration that could unlock policy synergies and progress for sustainability objectives.

2.5.1 *The EU Bioeconomy Strategy 2012*

The original bioeconomy strategy contained three key themes: investment in research, innovation and skills; reinforced stakeholder engagement and policy interaction; and the enhancement of markets and EU competitiveness (EC, 2012). Previous analysis has argued that economic aspirations of the strategy dominated over environmental or social considerations (Ramcilovic-Suominen and Pülzl, 2018). The strategy included an acknowledgement of environmental challenges, both climate change and biodiversity loss, and aspirations to address them via bioeconomy development, but also states that "the bioeconomy is not a niche area—it is about jobs and growth" (p. 4), centring the economic motivations underpinning the strategy.

When viewed through a natural capital lens, the strategy focused on marketable (economically visible), provisioning ecosystem services (although they are not labelled as such), the benefits they can provide (through replacing non-renewables in industry and creating new jobs), and emphasises their perceived, potential value (creating new markets, economic growth, and competitiveness). For example, when referring to biotechnology, fisheries, and the marine sector, the strategy states that 90% of marine biodiversity is "unexplored" and the "unexploited potential of the sea" (p. 36) could result in 10% annual growth for the sector (EC, 2012).

The strategy focused on producing sufficient food, biomass, and biomaterials—provisioning ecosystem services—to meet the demands of food security and the growth of bio-based industry, such as bioenergy and biorefineries (D'Amato et al., 2017); typified as the "bioresource vision" of the bioeconomy (Bugge et al., 2016). Climate mitigation was also present as an underlying driver and carbon storage was one of the few regulating services included in the strategy, although ecosystem service classification was absent. What could be labelled as regulating and cultural ecosystem services were acknowledged as "public goods" from multifunctional agricultural and forestry systems, but the strategy's goal was to maintain these "public goods" while maximising the flow of target, desirable biomass. A passage from the strategy's working document related to forestry demonstrates this: "An important goal is to mobilise more wood in appropriate areas while safeguarding biodiversity and other public goods delivered by forests" (p. 31). The document listed these public goods to include soil fertility, water retention, biodiversity habitats, and vibrant landscapes that are perhaps more visible in the forestry systems as they are not typically competing with the demands of food production (Eyvindson et al., 2018). Overall, the strategy leant towards a predominantly single-service lens, aligned with the conventional economic system, with the co-benefit of climate mitigation and other environmental "public goods."

The term "natural capital" was absent from the original EU strategy and its action plan, while the term "ecosystem service" was sparingly mentioned, without classification or specificity, and used when referring to non-target services provided simultaneously by primary production ecosystems. The desire to increase the provision of bio-based raw materials "without compromising ecosystem services" (p. 29) was included under the heading of enhancing bioeconomy-related markets. This implies that biomass provision was not considered an ecosystem service itself, and that these other referenced ecosystem services were viewed as outside the remit of the bioeconomy. While this hinted towards an appreciation of ecosystem trade-offs, it failed to expand on what is a "compromised ecosystem service", which could refer to decreases in the flow of a single service, decreases in the aggregate of multiple services, changes to the distribution of benefits, or losses of underpinning ecosystem functions. Furthermore, the statement did not explore the impact pathways for how management decisions to enhance target provisioning services could create these trade-offs, compromising secondary services. Soils were one of the few natural capital stocks articulated as being directly manipulated by management decisions through changes to nutrient status, salinity, and fertility, with consequences for service flows such as carbon storage and crop production, highlighting the pressures the emergent bioeconomy would place on the environment (Székács, 2017; Helming et al., 2018). Despite appreciating that growing demands for ecosystem services may act antagonistically, for example, food provision and biomass production for fuels (Graham-Rowe, 2011; Lewandowski, 2015), this was not expanded upon to capture the range of underlying natural capital stocks impacted by the shifting socio-economic pressures of bioeconomy. Instead, this framing "short-circuits" the cascade model by connecting human demand, values, and pressures straight to ecosystem service flows, bypassing the underpinning natural capital foundation.

Other environmental considerations regarding EU bioeconomy markets and competitiveness included the creation of LCA approaches for bio-based products, voluntary standards, certification and eco-labelling schemes, and environmental foot printing methods. The intention to design tools that examined and qualified the environmental sustainability of bio-based products and industries was notable, but they were regarded as aspirational rather than a reality, requiring further research and development before they could be deployed. This is consistent with ongoing challenges for creating these metrics such as assigning life cycle boundaries

(Cristóbal et al., 2016), selecting appropriate impact factors for ecological impacts (Seghetta et al., 2016; Crenna et al., 2018), and considering the broad range of environmental impacts rather than one-dimensional evaluations (O'Brien et al., 2017; D'amato et al., 2020).

2.5.2 *The EU Bioeconomy Strategy Update 2018*

The updated EU Bioeconomy Strategy, published in 2018, features more environmental aspects following criticism of the original's dominant economic focus (Ramcilovic-Suominen and Pülzl, 2018; Aguilar et al., 2019). The opening section emphasises the challenges of "ecological degradation" and "ecological boundaries" with a "respect for the ecological limitations of the planet" (p. 1). The commitment to environmental sustainability is echoed by the depiction of the EU's bioeconomy pathway as "economically viable with sustainability and circularity in the driver's seat" (p. 3), while simultaneously harkening back to economic motivations (McCormick and Kautto, 2013).

One of the most noticeable changes in the 2018 update from a natural capital perspective is a new definition of the bioeconomy that includes "all sectors and systems that rely on biological resources, their functions, and principles. It includes and interlinks land and marine **ecosystems and the services they provide**" (p. 1) (emphasis added). Therefore, it can be argued that under this definition, any ecosystem service that contributes to an economic sector—including regulating and cultural services—is included within the bioeconomy, rather than as a disparate co-benefit to be secured or trade-off to be mitigated. This extends the bioeconomy umbrella to all ecosystem services that support an economic sector, yet the strategy does not build on this extended flexibility and scope, retaining a familiar three-way focus on food security, the provision of biomass, and climate mitigation.

The 2018 update does not reference "natural capital" despite its inclusion within other predating EU environmental documents, such as the commitment to "protect, conserve and enhance" natural capital in the EU's 7th Environmental Action Plan, and the adoption of natural capital terminology within the European Environment State and Outlook Report (EC, 2014; EEA, 2015). The update does revise some terminology and language compared to the original. It states that natural resource management should "avoid ecosystem degradation, restore and enhance ecosystem functions" (p. 5). It is notable that "ecosystem function" is used rather than ecosystem service, indicating that direct human benefit or utility is not a requirement for implementing measures that prevent ecological degradation. This may represent an appreciation for the underlying ecosystem functions that support and give rise to target ecosystem service flows for the bioeconomy and, thus, are essential for ensuring long-term, sustainable service provision (Hein et al., 2016). However, the language remains unrefined and vague, without measurable indicators or targets. "Degradation" may refer to several different things, including the loss of species, service flows, or functions; or changes to the quantity, quality, or spatial arrangement of capital stocks. "Restore and enhance functions" suffers from a similar problem as it does not expand on what the reference condition for comparison should be, or what the target goal should look like. While this is context-specific, guidelines or principles to inform these goals of ecological restoration are missing.

One of the three key action areas of the 2018 update is titled "Understand the ecological boundaries of the bioeconomy" that clearly recognises that there are ecological limitations for the bioeconomy—and perhaps borrows language from the popularised planetary boundaries concept of sustainability (Rockström et al., 2009). These ecological boundaries are not defined but involve the sustainable maximisation of biomass extraction that can also "enhance the full-range of ecosystem services" (p. 10) and "reinforce resilience and enhance biodiversity" (p. 10). Again, it is not clear what is meant by "enhance" or "reinforce" but it echoes a familiar desire to maximise the efficiency of what people receive from nature—finding out how target provisioning services, and their downstream benefits and values, can be maximised without negative consequences for other ecosystem characteristics. The 2018 update references the benefits of "biodiversity-rich ecosystems" (p. 12) for primary production, with a specific reference to pollination. This may be inspired by high-profile research publications concerning agriculture's dependence upon (Klein et al., 2007), and monetary value attributed to (Gallai et al., 2009), pollination services, and an influential global assessment of pollinators, pollination, and food production (IPBES, 2016). The specific inclusion of this non-provisioning service and the recognition of biodiversity's importance is encouraging but remains a single example that emphasises the ecosystem service—pollination—

that is dependent upon numerous natural capital stocks, of which only one—the biodiversity of agroecosystems—is mentioned (Maseyk et al., 2017).

The ecological boundaries section of the updated strategy contains another element of complementarity between the natural capital and bioeconomy concepts. To better understand these boundaries, the strategy refers to acquiring data, information, and systematic analysis to reveal the "status and resilience . . . of ecosystems and biodiversity" (p. 10). There is an appreciation that these ecological data are not well known, and that addressing these knowledge gaps regarding biodiversity and nature is important for managing the biologically productive systems the bioeconomy depends upon. This call for better data collection and environmental knowledge is analogous to the exercise of natural capital accounting which takes stock of nature's assets to provide a foundation for informed decision-making (Obst, 2015; Vardon et al., 2018). It includes attributes regarding quality and spatial arrangement of those stocks and covers local to national to global scales (Daily et al., 2009; Kareiva et al., 2011). Despite ongoing work regarding natural capital accounting in the EU that predates the publication of this updated strategy, it is noticeably missing from this section of the strategy (EEA, 2019a).

2.5.3 *Future policy and recommendations*

The 2018 update to the initial 2012 EU Bioeconomy Strategy contains a patchwork of elements aligned with the natural capital concept but is missing some aspects that could be developed further. A bioeconomy that embraces the natural capital framework could benefit from the lessons learned within the natural capital approach and unlock policy synergies regarding the relationships between socio-economic systems and the environment. The following section outlines some recommendations and opportunities to incorporate the natural capital lens into the future bioeconomy strategy in the EU.

2.5.3.1 A shared language

Firstly, the language of natural capital can clarify the intent behind terms such as biological resources, bioresources, and natural resources. Distinguishing between natural capital, ecosystem functions, and ecosystem services can refine objectives and better describe the relationship between these ecological constructs and the development of the bioeconomy. For example, considering the growing market for wood-based bioproducts and the forestry sector, the stand of trees is a natural capital stock, the production of new wood biomass is an ecosystem function, and the provision of harvested timber—realised through combinations of human, manufactured, and natural capital—is an ecosystem service (Marchetti et al., 2015). This distinction resolves ambiguous meanings and aids the identification of appropriate management levers through a proposed impact pathway. As management changes manipulate natural capital stocks, either in quantity, quality, or spatial arrangement, rather than the flow of functions or services that are impacted indirectly, it is important that this clarity is present for informed decision-making (Maseyk et al., 2017). The presence of ecosystem service and ecosystem function terminology in the 2018 update is an encouraging sign. However, the vocabulary is incomplete and at times applied ambiguously, as in the case of the focus on biodiversity in relation to pollination in bio-based value chains. The value of pollination is implied but is not related to the ecosystem service framework or acknowledged as a direct contribution of value to the bioeconomy. While there is an appreciation that biodiversity can contribute to service flow, the action plan does not refer to management options that manipulate underlying natural capital stocks to support biodiversity, such as suitable habitat creation, landscape heterogeneity, or resource availability (Maseyk et al., 2017).

2.5.3.2 A harmonised bioeconomy

A second opportunity is the creation of a framework that brings together the fragmented mosaic of bioeconomy visions (Bugge et al., 2016). The revised strategy already expands the definition of bioeconomy to include ecosystem services from land and marine ecosystems and "biological functions" that contribute to bioeconomy sectors. This definition cements the view that regulating and cultural services are included under the bioeconomy umbrella. Whether the use of "biological function" refers to ecological functions as represented in the natural capital concept is unclear. While this new definition places regulating and cultural services within the bioeconomy, the linkage to the original strategy's depiction of "public goods" from multifunctional, agricultural, and forestry systems must be further elucidated. This updated definition provides the scope to embrace the natural capital lens, acting as a bridge between the "dominant" and "rival" imaginings of the bioeconomy (Levidow et al., 2012; Bugge et al., 2016). This framework could encompass the full basket of services provided from ecosystems—

as depicted by the rival or agroecology vision—and be weighted towards services attributed high value, such as target provisioning services—aligned with the bioresource vision. This approach could bring together advocates of different narratives such as civil society groups who promote the agroecology approach (Meyer, 2017) and private sector and policy actors who promote more biotechnological narratives (Bugge et al., 2016; Aguilar et al., 2019). By creating a shared understanding, precise vocabulary, and unifying foundation to explore the concept, the natural capital lens may also address some of the criticisms of bioeconomy as a master narrative with shades of green, moving towards a platform for collaboration and knowledge sharing (Levidow et al., 2012; Kleinschmit et al., 2014; Hausknost et al., 2017).

2.5.3.3 Improved indicators, metrics, and measures

Thirdly, the natural capital approach and natural capital accounting can provide useful metrics and indicators for bioeconomy. A significant portion of the 2018 update concerns respecting the "ecological boundaries" of a realised bioeconomy and the importance of knowledge sharing, data collection, and analysis to better understand these boundaries. Natural capital accounting has a proven record of applying approaches highlighted in the strategy such as remote sensing (Norton et al., 2018), assessment at the local or regional scale (Hein et al., 2016), creating national-level accounts (Ouyang et al., 2016), global valuations (Costanza et al., 1997), and assessing change over time (Ouyang et al., 2020). Natural capital accounts are increasingly valued for supporting policy decision-making (Daily et al., 2009; Vardon et al., 2018; Ruijs et al., 2019). Building upon a robust set of natural capital accounts can facilitate the creation of minimum standards, environmentally sound certification schemes, and demonstrable measures of change that ensure that commitments to "enhancing and protecting" natural capital are being adhered to. Mapping ecosystem services can also shine a light on environmental justice and the flow of valuable benefits within the bioeconomy between spatially separated people and regions (Schröter et al., 2014; Ouyang et al., 2020). The facilitation of local-level bioeconomy initiatives and "more proportionate sharing of the benefits" (p. 11) (EC, 2018) are key aspirations of the EU bioeconomy. Natural capital tools can value and map those benefits for more economically just and equitable outcomes (Bateman and Mace, 2020; Ouyang et al., 2020).

2.5.3.4 Policy synergy and coherence

The adoption of natural capital principles within the bioeconomy would align the strategy with other environmental EU policies to create a more integrated and united environmental policy approach (Jordan and Lenschow, 2010). Natural capital has been adopted in EU policy previously, for example in the 7th Environmental Action Plan (EEA, 2015), and more recently, in the EU Green Deal that states that all EU policy moving forward must "contribute to preserving and restoring Europe's natural capital" (p. 13) (EC, 2019). The EU Biodiversity Strategy for 2030 includes similar commitments regarding investment in natural capital and natural capital accounting (EC, 2020). This adoption of the natural capital concept will have implications for all future EU policy, including those sectors particularly central to the bioeconomy such as agriculture, forestry, and fisheries. The broad adoption of the natural capital lens in policy represents a shift in the conceptualisation of peoples' relationships with nature that bioeconomy should mirror to maintain policy coherence and create synergy. Bioeconomy-related policies often stipulate that sustainability is a priority but do not identify what this means practically. Natural capital could provide knowledge that identifies impacts and dependencies between the environment and bioeconomy development pathways, and policy support tools to facilitate this synergy already exist, such as the TEEB Agrifood framework (TEEB, 2018).

2.5.3.5 A flexible and adaptable tool for decision-making

Finally, adopting a natural capital lens on the bioeconomy ensures that the concept remains flexible, adaptable, and responsive to changes to environmental approaches to sustainability. The modern conceptualisation of the bioeconomy is still emerging with an uncertain trajectory towards new biotechnological capabilities, resource demands, and public acceptance (Gawel et al., 2019). The bioeconomy will realise new ecosystem services, such as by-products of conventional primary production or the use of waste streams (Lewandowski, 2015). The natural capital concept can incorporate these new services and their values both retroactively and for future analysis to be used as a decision-support tool (Kareiva et al., 2011). A bioeconomy strategy that adopts the natural capital framework is responsive to changes in ecosystem service demand, their respective values and valuation techniques, and shifting environmental impacts and dependencies of bio-based value chains. This allows for dynamic, responsive decision-making as the bioeconomy changes pressures on natural capital stocks that reorient the relationships between socio-economic systems and the environment (Daily et al., 2009; Kareiva et al., 2011).

2.6 Conclusions

We have successfully applied a natural capital lens to the bioeconomy concept across three levels: an integrated cascade model, expert's cornerstones for a sustainable bioeconomy, and a case-study of the EU bioeconomy strategy. The natural capital concept and its associated methodological toolbox have the potential to play an important role in securing the bioeconomy's environmentally sound and ecologically conscious objectives. Despite a similar multidisciplinary background and growing influence within research and policy spheres, the integration of the two concepts has not been examined in this way previously. This study has shown that there are areas of overlap between the bioeconomy and natural capital concepts, but there remains scope for further integration across policy, research, and practice.

The current patchwork of environmental framings within the bioeconomy has led to fragmented understandings of how the bioeconomy intersects with ecosystems and nature. There are opportunities to operationalise the natural capital approach within the bioeconomy to address this fragmented sustainability landscape. The integrated natural capital cascade model serves as a mechanism to unite the unrealised and unrecognised services provided from the environment by ensuring that all of nature's services—the economically visible and invisible—are included in decision-making. By ensuring that both the unrealised and unrecognised services from nature are included in a holistic, systems-based approach to decision-making and policy design, bioeconomy can avoid unintended trade-offs and environmental degradation. Furthermore, this can qualify the "shades of green" of bioeconomic activities and unlock policy-policy synergies relating to environmental decision-making and safeguarding nature.

The bioeconomy concept is amorphous; constantly shifting and evolving as new research emerges and is subsequently adopted by bioeconomy-related actors. We cannot predict how the concept will continue to change, or how the shifting values and preferences of societies will shape its development. Therefore, this analysis represents the current state of the art understanding of how the bioeconomy intersects with the environment while acknowledging that some other understandings of the term "bioeconomy" may not be captured e.g., bioeconomic modelling or narrow, specialised synthetic biology applications. Research that builds upon the themes presented here must remain responsive to changes to the bioeconomy concept as it evolves. The same is true for natural capital as there is no universal natural capital solution to a given environmental problem, but instead a set of guiding principles that can inform decision-making. Care must be taken to consider the given context for deploying natural capital to a bioeconomic activity such as data availability and suitability, the particular environmental problem to be solved, and social context it operates within.

Future research can build upon this analysis by identifying appropriate case studies that move from the theoretical integration of these concepts towards applied and demonstrable examples. A challenge and limitation to achieve this is the siloed nature of research; a constellation of relevant studies within agricultural science, environmental science, sustainability science, and bioeconomy are likely ongoing but do not cross the boundaries between their respective clusters of expertise. This is echoed in the variety of appropriate methodologies that can be used to examine natural capital and the bioeconomy which span biophysical studies of ecosystems, social sciences and perceived values, monetary evaluations, economic analysis, and scenario modelling. Facilitating the dissemination of research across disciplines must be a priority for natural capital researchers. Evidence of these linkages is emerging as demonstrated by the adoption of some natural capital elements within the EU bioeconomy strategy. The breakdown of fragmented and siloed pockets of environmental sustainability expertise that moves towards an interdisciplinary and holistic approach is required for sustainable development that safeguards nature.

CHAPTER 3 | Conceptual integration of ecosystem services and natural capital within Irish national policy: An analysis over time and between policy sectors

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Author contributions:

I conceived the research questions, designed the study, collected the data, conducted the analysis, produced the figures, wrote the draft of the manuscript, and led the revisions. Jane C. Stout and Cathal O'Donoghue provided guidance throughout and supervised the writing and revision process. All authors provided intellectual input and provided comments on the revised manuscript.

Status:

This manuscript has been published in *Ecosystem Services* (2022), **57,** 101468, doi.org/10.1016/j.ecoser.2022.101468 (Neill et al., 2022).

3.1 Abstract

Ecosystem service (ES) and natural capital (NC) concepts have been promoted as influential tools for environmental management within national public policy. To achieve this potential, these concepts must transition across the science-policy interface and become integrated within governance systems. This study examines 25 years of ES and NC concepts within national public policy at two levels: explicit use of terminology, and implicit description of services. Using the case-study of Ireland as a country with significant bio-based industry and dependence on its NC, we ask when, where, and what conceptual integration has occurred within the national policy landscape. Data were collected using mixed-methods content analysis applied to 50 Irish policy and reporting documents spanning 1996–2020. Results showed i) conceptual integration began in 2008; ii) explicit use of ES was more common than NC (442 compared to 92 uses); iii) explicit use disproportionately occurred within biodiversity policy and environmental reports; iv) use of explicit terminology contained interdisciplinary themes; v) implicit descriptions of ESs differed between policy types; vi) cultural service descriptions were identified throughout the sample whereas regulating services were more visible in more recent documents. Overall conceptual integration was found to be present but fragmented, which may create a barrier to achieving a policy landscape that is responsive to emerging ES science. Conceptual integration is dependent on the broader environmental and governance context and further research is required to understand how this impacts downstream implementation and operation. We conclude by commenting on the implications for future conceptual integration and environmental policy development.

3.2 Introduction

The ecosystem service and natural capital concepts (ES and NC respectively throughout this chapter) connect the environment to socio-economic systems (Braat and de Groot, 2012). These concepts have become increasingly popular and are now commonplace within both academic literature and global environmental discourse (Chaudhary et al., 2015; Costanza et al., 2017; Mace, 2019). These economic metaphors shape a vocabulary that connects society's benefits to the environment that underpins them, with the aspiration to enable improved environmental decision-making that accounts for a more complete set of information (Daily et al., 2009; Guerry et al., 2015). Driven by a realisation that the current trajectory of human development threatens to disrupt the essential life-supporting benefits ecosystems provide to people (Rockström et al., 2009), proponents of these concepts argue that they can address systematic shortcomings that render many of nature's benefits silent and invisible (Daily et al., 2009; Dasgupta, 2021). For this aspiration of avoiding unintended impacts and negative outcomes regarding environmental management to become reality, the ES and NC concepts must transition from the academic sphere and become familiar, accessible, and useful to those involved in ecosystem management (Guerry et al., 2015). The integration of ES and NC concepts within environmental governance is one mechanism to realise this vision (Fisher et al., 2008; Daily et al., 2009).

Integration into public policy is one such opportunity for NC and ES concepts to influence ecosystem management (Daily et al., 2009; Maes et al., 2013). For the purposes of this study, conceptual integration refers to the process of harmonisation as ES and NC concepts are taken up and used within policy to describe people-nature interactions and consider environmental problems (Fisher et al., 2008; Claret et al., 2018). At the higher level, the ES concept featured within the Sustainable Development Goals and Aichi Biodiversity Targets (Millennium Ecosystem Assessment, 2005; UN, 2015). Similarly, at European level, the NC and ES concepts are included within the current European Union (EU) Biodiversity Strategy 2030, its 2011 predecessor, and the EU Green Deal (EC, 2011, 2019, 2020). However, the slow, incremental pace of international policy reform and iteration has been suggested as a barrier to creating an ES-literate policy landscape that can readily respond to emerging ES science (Bouwma et al., 2018).

National-level public policy has been proposed as an influential lever for transitioning ES and NC from academic concepts into tools for decision-making because sovereign nation states hold the authority to drive change regarding environmental management within their jurisdictions (Maes et al., 2013; Bouwma et al., 2018). A limited number of studies have explored national-level integration of ES and NC (for example Scotland (Claret et al., 2018), Poland (Maczka et al., 2016)). Variation of environmental and governance contexts means that a singular, common pathway to policy integration cannot be assumed and greater effort is needed to understand how this process occurs in different places (Jordan and

Lenschow, 2010). One challenge is that integration can take different forms across the science-policy transition timeline (Kettunen et al., 2014; McKenzie et al., 2014). For example, integration can be described as explicit (the deliberate, specific use of precise terminology) or implicit (the description of specific concepts and related ideas without the associated terminology). The recognition of benefits provided by nature is not unique to ES theory and so what is now easily classified as an ES may be represented within policy despite an absence of ES terminology (Maes et al., 2013). There is a recognition that more research is needed to unravel how ES and NC become integrated within policy, and the implications for how these concepts can contribute to resolving environmental problems (Kettunen et al., 2014; Claret et al., 2018).

This paper contributes to this knowledge gap by examining ES and NC integration within national public policy across two dimensions: temporal and sectoral scales. Primary producing industries represent both a producer and beneficiary of ESs as they co-produce goods and services such as biomass and cultural heritage, while also benefitting from nature's functions that provide suitable and reliable conditions for production such as water quality and soil fertility (Swinton et al., 2007). Nations with economies centred around bio-based industries are among the most reliant on their NC assets and therefore the potential influence of ES and NC concepts within national policy is especially pronounced in such contexts. Biodiversity and environmental policies, plans, and reports also have a role in environmental management and its value (in its plurality including intrinsic, biophysical, socio-cultural, and utility values), and represent another area of national policy where ES and NC concepts may prove influential. To fully explore the phenomenon of ES and NC integration within national policy, the range of relevant policy sectors should be considered throughout the time period since ES and NC emerged as influential ecological ideas within academia.

Ireland was selected as a unique and timely case-study to explore the science-policy transition of ES and NC as a country with strong dependencies on its NC, established environmental policy and reporting structures, and available governance documents covering a 25-year time span. Firstly, Ireland's NC assets and favourable climate have enabled the growth of economically important agriculture, forestry, and marine sectors and created a global reputation for high-quality, green products. This advantage is reflected in agricultural land use with 68% of land dedicated to grasslands or cereals and 10.7% under forestry (Government of Ireland, 2018; CSO, 2020). The economic importance and land use footprint of these industries in Ireland means that ecosystem management—and therefore the potential impact of ES and NC concepts—holds substantial sway over societal wellbeing and economic growth. Secondly, Ireland has a track record of producing biodiversity plans and environmental reports spanning the past three decades and has more recently begun piloting ES science (such as pilot ES assessments and NC accounts (Parker et al., 2016; Farrell et al., 2021)). Simultaneously, the gravity of environmental degradation has been recognised by the Irish government through declarations of both a biodiversity and climate emergency (Dáil Éireann, 2019). Finally, as a relatively small EU nation that is subject to top-down policy influences that have already embedded ES and NC concepts such as EU environmental directives, a comprehensive analysis of the policy landscape spanning the past 25 years can be undertaken.

We adopt a holistic approach that considers integration over time and between sectors, both implicitly and explicitly. By doing so, we provide deeper insight into the past 25 years of policy development with respect to ES and NC theory that provides lessons learned for other contexts and considers what this means for future policy development and environmental governance more broadly.

The research questions addressed in this study are:

1. When (if at all) have ES and NC been explicitly integrated into Irish policy over time?
2. Where in the policy landscape has integration occurred?
3. What ESs are described implicitly within the policy landscape?

3.3 Methods

3.3.1 *Content analysis*

Mixed-methods content analysis was selected to investigate the conceptual integration of ES and NC at two levels: explicit use of terminology and implicit descriptions of ES within the text (Bouwma et al., 2018). Content analysis refers to making “replicable and valid inferences from texts to the contexts of their use” and is useful for exploring phenomena of interest that “lack direct, observational evidence" (Krippendorff, 1980), and is a standard method of investigation for similar ES studies (Kettunen et al., 2014; Kabisch, 2015; Rall et al., 2015; Claret et al., 2018). For further detail on content analysis methods, see White and Marsh (2006) or Elo and Kyngäs (2008). A deductive, mixed-methods approach was selected due to the dual level of investigation, and the phenomenon of interest being a well-established academic framework and ES classification scheme.

3.3.2 *Data sources*

A purposeful sample of 50 policy and reporting documents published between 1996–2020 was compiled (appendix A). Purposeful sampling was used to maximise data collection given the constrained number of potential data sources reflecting the gradual, multiyear cycle of policy emergence and reporting. Data sources were assigned to six different categories: four agenda-setting national policy categories (agri-food, forestry, marine, biodiversity) and two reporting categories (Department of Agriculture, Food, and the Marine (DAFM) annual reports, and Ireland's State of the Environment Reports published every four years). It is inevitable that there is some degree of overlapping content between these documents due to evolving responsibilities and scope of government departments over 25 years. Documents were assigned to agenda-setting strategy categories based on their primary intended purpose although there may be secondary areas also included. For example, steering agri-food sector development (agri-food referring to the agricultural sector and food manufacturing industry) documents may include some discussion of tree planting on farms. The environment category refers to a time-series of reports conducted by the Environmental Protection Agency outlining the state of Ireland's environment. Similarly, Department of Agriculture, Food and the Marine annual reports are a time-series reporting on the performance of the entire department (often containing chapters on agriculture, forestry, and marine sector economic performance) rather than stating new policy or strategy directions. All documents were freely available and accessible online except for three reports that were requested from the corresponding agency. The time frame (1996–2020) was selected to capture important breakthroughs for the ES framework such as the first global ES valuation study published in 1997 (Costanza et al., 1997), the emergence of ES within global international policy discourse e.g., Millennium Ecosystem Assessment (Chaudhary et al., 2015), and to reflect shifting environmental perspectives of rural development more broadly such as the Cork Declaration in 1996 (EC, 1996).

3.3.3 *Data collection and analysis*

Mixed-methods content analysis was conducted using NVivo software v 1.4. All documents were read in their entirety and coded in a systematic way. The coding unit was determined as the minimum length of text that preserved independent meaning, typically a full sentence although occasionally longer if required.

3.3.3.1 Explicit integration

All explicit use of the terms "ecosystem service" and "natural capital" within the core texts (excluding appendices, forewords, contents pages, and bibliographies) were recorded and summarised to examine use over time and between document types. Thematic analysis was then conducted based on the interdisciplinary foundation of ES and NC concepts to examine how this was reflected in policy use. The three themes were based on the premise of ES theory: connecting the environment to socioeconomic systems for positive environmental action. A coding scheme was created to define themes in a consistent, replicable way (Table 3.1), discussed amongst the authors and subject experts, trialled on a set of unrelated policy documents, and revised accordingly. The three themes were designed to not be mutually exclusive because multiple themes can be contained in the same passage of text. Instances of identical coded units (text) repeated within the same document were coded as "duplicate" and omitted from thematic analysis to prevent inflation of themes due to repetition without contributing additional information or meaning. After an initial round of thematic coding the process was repeated with a blind set of data and cross-checked to ensure consistency and reliability. Inconsistencies were identified and discussed amongst authors and reviewed against the coding scheme. A third and final blind round of coding was then conducted after which no discrepancies remained.

Table 3.1: Coding scheme used for thematic analysis of explicit references.

Code	Description
Duplicate	Coded unit appears elsewhere in the same document in an identical or almost identical form that contributes no additional meaning.
Ecological	Contains some environmental or ecological ideas such as (but not limited to): conservation, biodiversity, habitats, fragmentation, specific ecosystems (e.g., peatlands), species, genetic resources, native, nature, ecological function, connectivity, degradation, protection.
Socio-economic	Contains ideas relating to people or the economy. Examples include but are not limited to value, monetary valuation, payments, social benefits, health, wellbeing, appreciation, community, industry, forestry, business, private sector, agriculture, cultural values, heritage, spiritual connection, sense of place, opportunity, livelihoods, income, price premiums, agri-environmental schemes, development.
Action or Implementation	Contains some idea of promoting, developing, or applying ES or NC approaches including education, awareness, mainstreaming, decision-making, scenarios, modelling, mapping, identifying appropriate areas for action or intervention, knowledge generation, indicators, targets, objectives, opportunity costs, options, planning, accounting.

3.3.3.2 Implicit integration

The Common International Classification of Ecosystem Services (CICES) version 5.1 was used to construct a coding scheme for implicit ES descriptions (appendix A) (Haines-Young and Potschin, 2018b). Modifications to CICES were required because the level of complexity and resolution was not always suitable for less specialised text. Changes involved combining categories that were too high resolution for differentiation based on the data available (such as biomass produced by wild versus cultivated populations), or sub-dividing categories that are considered one service in CICES v5.1, but previously were separated or showed differentiation based on the data (for example, habitat regulation versus maintenance of nursery populations). Basic statistical analyses were conducted in Rstudio v.1.4.17 (R Core Team, 2021). This included Welch's t-tests for unequal sample size to compare the incidence of implicit service inclusion across two time periods (before and after the introduction of explicit ES terminology), and chi-squared tests to compare the incidence of implicit service inclusion between document types based on classification type.

3.4 Results

3.4.1 *Explicit use of ES and NC terminology*

The term ES was identified in 462 coded units compared to 104 containing NC (Fig. 3.1a). The first use of ES occurred in 2008 in an environmental report and subsequently increased in use, whereas brief references to NC occurred in both 1996 and 2000 environmental reports, but then disappeared from the sample documents until 2011. The difference in inclusion suggests that the ES term has been more readily incorporated into the policy sphere compared to NC. All categories of policy and reporting documents were found to contain at least one reference to NC and ES, but usage was distributed unequally across different document categories (Fig. 3.1b). For all categories, the frequency of ES use was greater than NC. Biodiversity policy and environmental reports contained most ES coded units with 47% and 26% of total units respectively. For NC, this ranking was reversed with 51% contained within environmental reports and 38% within biodiversity policy. Of primary producing sector policy, forestry documents showed a moderate use of ES terminology, while Department of Agriculture, Food, and the Marine annual reports and agri-food policy contained low use and NC was very rarely included. Due to the limited sample size and differing lengths, mandates, objectives, and lifespans of documents, further disaggregation was not appropriate.

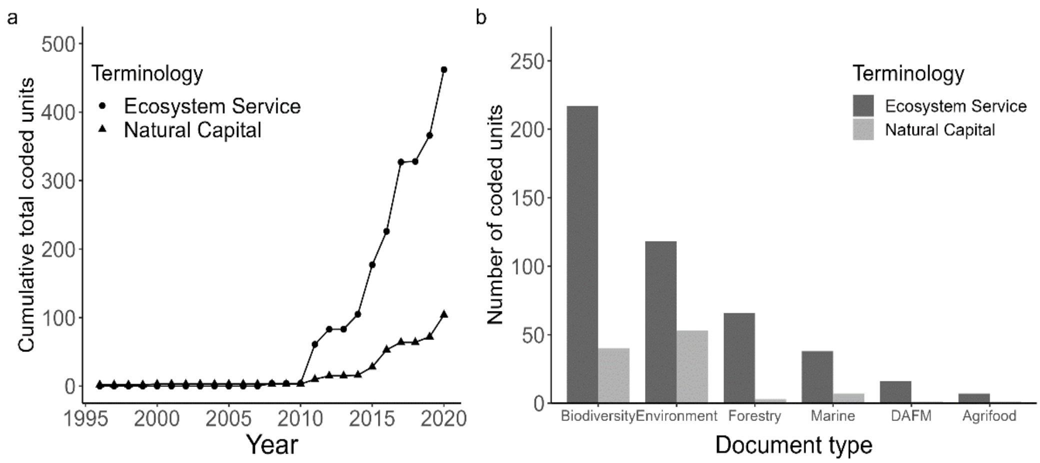

Figure 3.1: Use of the terms "natural capital" and "ecosystem services" within Irish policy and reporting documents. **a**) Cumulative sum of use 1996-2020, **b**) distribution of occurrence between document types.

3.4.2 *Thematic analysis*

Thematic analysis successfully differentiated between ideas represented alongside ES and NC terminology. Removing duplicate coded units within the same document reduced the number of unique coded units to 392 ES and 88 NC. Instances of coded units referring to ES and NC only as part of a proper noun such as the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) or Natural Capital Ireland, were omitted as such titles are separated from the core conceptual meaning. A blend of interdisciplinary themes was recorded for both NC and ES (Fig. 3.2). For both ES and NC, the most common combination of themes was the overlap of all three—ecological, socio-economic, and action. The most common theme for ES was ecological (84%) while action was most common for NC (78%). Ecological themes were associated with ideas of biodiversity, conservation, or the degradation of nature. Socio-economic themes contained a variety of underlying ideas including specific industries (agriculture especially), agri-environmental schemes, societal benefit, and monetary evaluation. Neither term showed a predisposition towards the association with socio-economic ideas with 62% and 61% units for ES and NC respectively. The action and implementation theme was associated with the setting of targets and objectives, decision-making support tools (maps, scenarios, models), awareness raising and mainstreaming, and the development of natural capital accounts.

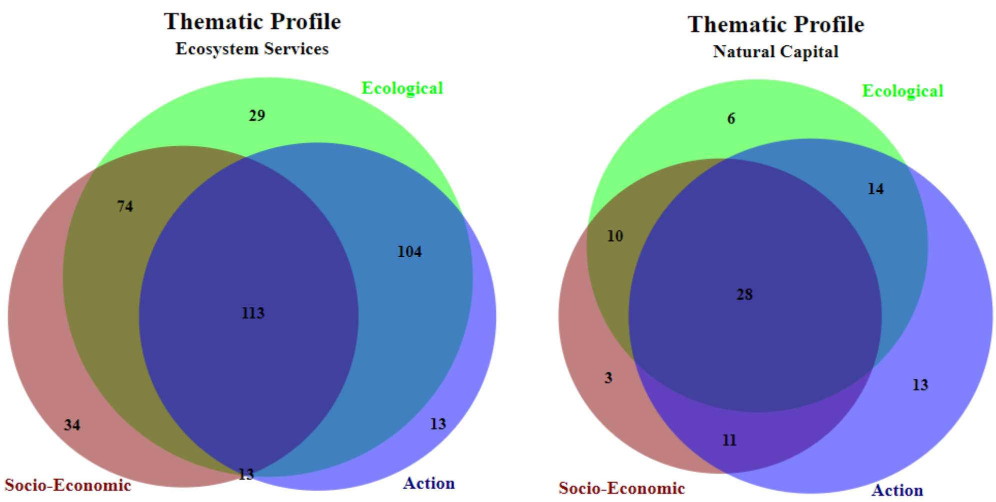

Figure 3.2: Thematic analysis of unique coded units using the term "ecosystem service" (n = 392) and "natural capital" (n = 85) within sample of Irish policy and reporting documents 1996-2020. Area of circles proportional to frequency. Venn diagrams created using BioVenn (Hulsen et al., 2008).

3.4.3 *Implicit ES integration*

Descriptions of ESs were present throughout the entire sample, including those that predate the introduction of ES terminology. A total of 35 services were found at least once throughout the sample however their relative occurrence differed (Fig. 3.3). The presence or absence of each service within each document was used in this analysis due to the challenge of interpreting inconsistent language. Services such as pollination describe a well-defined, widely understood, biological process and are thus unmistakable and can be coded exhaustively. Other services such as amenity or landscape, were not described consistently and instead relied on more general language that sometimes lacked a clear attribution of benefit to ecosystems, making exhaustive coding ambiguous and uncertain. This was expected given that sampled documents were not intended to reflect precise ecological concepts and ES classification has undergone frequent revisions (Haines-Young and Potschin, 2018b). The presence and absence of services remains useful to capture the portfolio of services contained in policy documents and identify the most consistently embedded and underrepresented within the policy landscape.

Provisioning services such as biomass, timber, and energy were common across the sample which is consistent with their economic visibility and focus of public policy. Biodiversity was mentioned in some form in almost every document and associated with varied ideas including intrinsic and irreplaceable value, endangered or threatened species of interest, agri-environmental scheme design, and the role of protected areas. Other cultural services mentioned in at least 50% of documents included recreation, landscape, tourism, and heritage and culture. Regulating services showed a wide range in occurrence with only 4 of a possible 20 featured in at least 50% of documents (habitats 96%, terrestrial carbon sequestration 80%, water quality 60%, and soil quality 52%). The remaining 16 regulating services identified occurred less frequently (< 50% of documents).

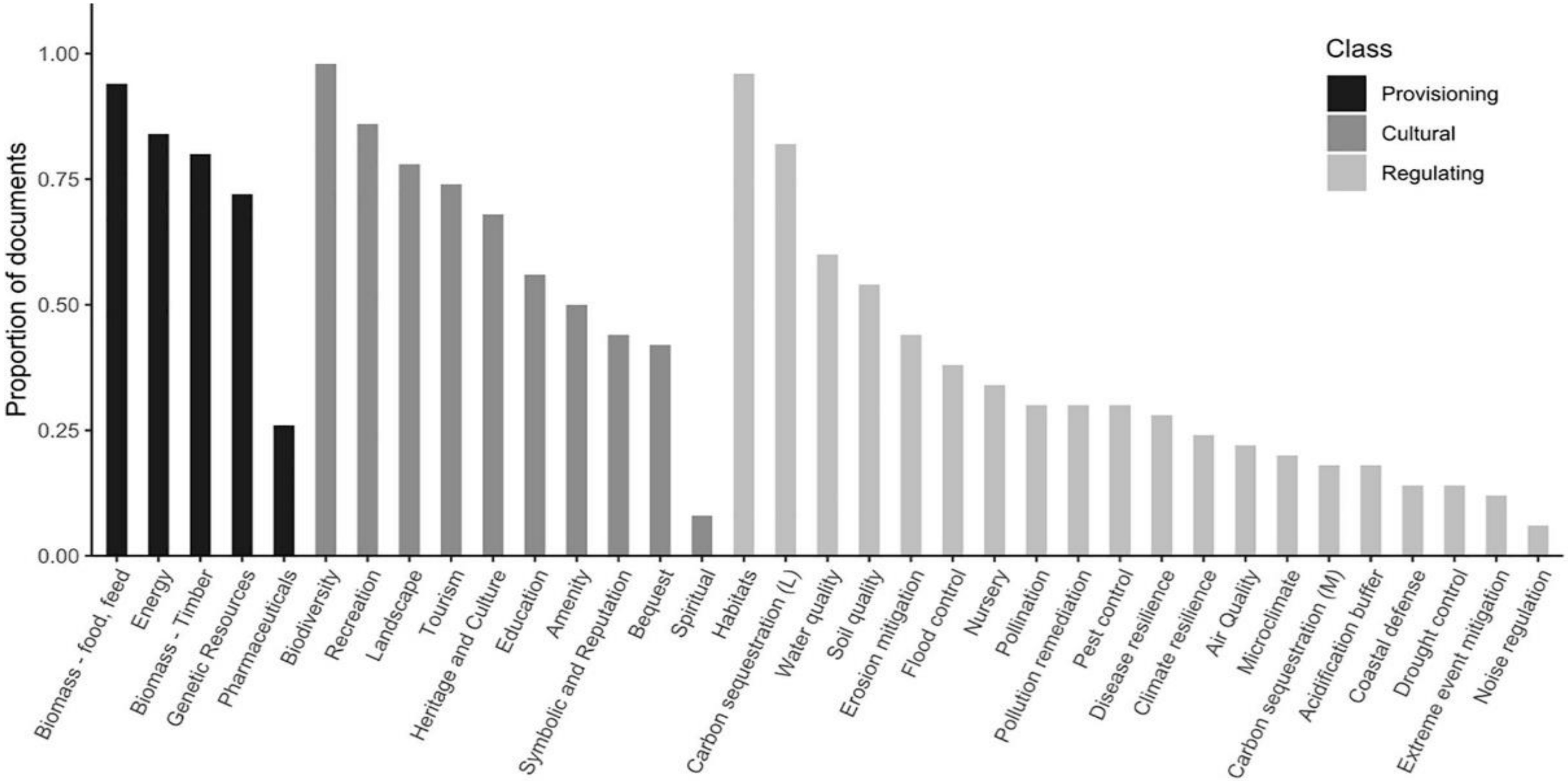

Figure 3.3: Implicit descriptions of ecosystem services included within sample of 50 Irish policy and reporting documents and presented by classification type under CICES 5.1. Carbon sequestration services are split into land (L) and marine (M) based ecosystems.

The coding scheme included 5 provisioning, 10 cultural, and 20 regulating services. As a result, regulating services showed the highest average total of services per document (6.6) but this represents only 33% of the total variety of regulating services present across the entire sample (Fig. 3.4a). Provisioning and cultural services showed a greater visibility with 71% and 60% of possible services included per document respectively. Chi-squared tests were conducted to compare the inclusion of the three service classes between document categories (i.e., the total number of inclusions compared to the theoretical maximum if all documents included every possible service). For all three service classifications there was a significant difference in occurrence between document types with the greatest difference for regulating ($\chi2 = 98.8$, $p < 0.001$), followed by cultural ($\chi2 = 19.4$, $p < 0.01$), and then provisioning ($\chi2 = 15.4$, $p < 0.05$). This result suggests policy categories displayed differing levels of ES representation across all three classification types. To examine how the inclusion of service classes has changed over time, the sample was split into two groups for comparison: those published before the emergence of ES terminology in Irish policy (1996–2008, n = 18) and those published after (2009–2020, n = 32) (Fig. 3.4b). Welch's t-test was used to compare the average number of services per classification present in each document between the two time periods and to account for the unequal sample size and variance between the two time periods. The results showed a statistically significant increase only for regulating services (7.75 compared to 4.56, $p < 0.01$, $df = 36$). Mean

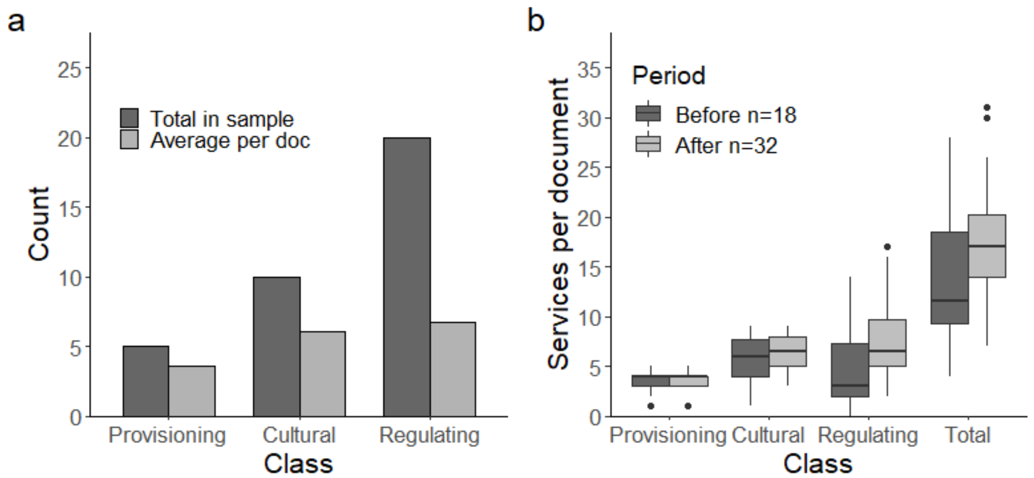

Figure 3.4: a) Total number of services per classification type across sample and mean number of services per document. **b)** Boxplot showing number of services per classification per document between 1996 - 2008 (before introduction of ES terminology) and 2009 - 2020 (after introduction of ES terminology).

provisioning and cultural services also increased, but not significantly (mean provisioning, 3.75 compared to 3.17, $p = 0.08$, $df = 25$; mean cultural, 6.25 compared to 5.56, $p = 0.28$, $df = 30$). This analysis shows a shifting ES profile within the policy landscape between the two time periods, coinciding with the rise of ES conceptual integration, but is not intended to attribute this change to one specific driver.

There were differences in the average portfolio of services included within different policy categories (Fig. 3.5 and appendix A). Results suggested cultural and regulating services were well represented within environmental reports compared to any other category whereas sectoral policy areas showed frequent inclusion of a specific subset of services while others were mostly excluded. This is shown by the jagged pattern of the radar plots in Fig. 3.5 for sectoral policy (agri-food and marine) compared to the broader, rounder shape of environmental reports. There was evidence that policy documents were specialised to reflect specific services of interest. For example, marine policy contained high average inclusion of nursery habitats, forestry policy contained high average inclusion of tourism, biodiversity policy contained high average inclusion of pollination. Overall, biodiversity policy and environmental reports showed a broader basket of services overall (less specialisation) compared to primary producing policy documents and Department of Agriculture, Food and the Marine annual reports.

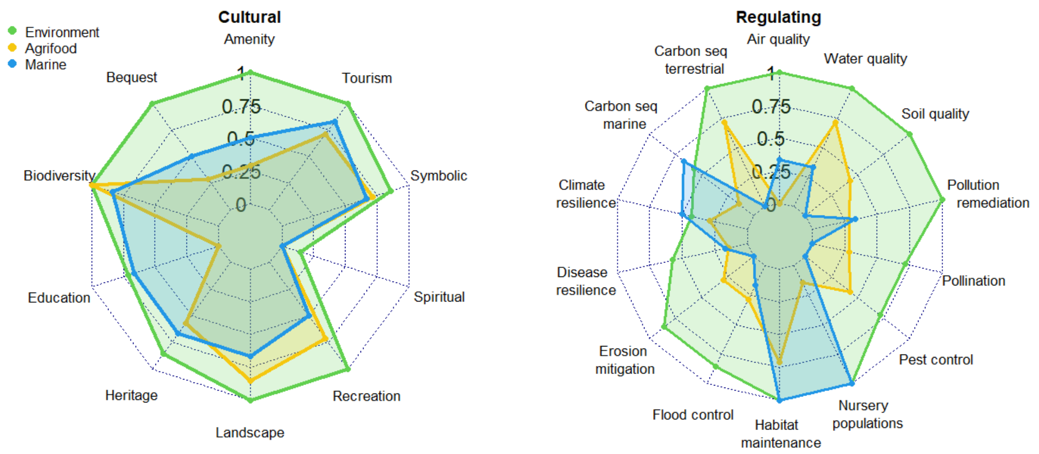

Figure 3.5: Example of average service portfolios represented within different policy document categories. Axes show proportion of documents within category with presence of corresponding service. Environment reports (green) showed broad inclusion of services compared to sectoral policy that showed greater specialisation towards specific services. Overall cultural services showed greater inclusion compared to regulating. For full data and regulating service definitions see appendix A.

3.5 Discussion

The explicit conceptual integration of ES and NC ideas within the Irish policy and reporting landscape began in 2008. However, the overall science-policy transition and integration of ES and NC is fragmented and incomplete between policy areas. Similarly, implicit descriptions of some ESs are commonplace throughout the sample but show variation in inclusion within different policy categories, while others have become more frequently included in more recent governance outputs. These differences show that conceptual integration of ES and NC in Ireland has some similarities to other contexts, but also some important differences that provide useful insight for conceptual integration in broader settings.

3.5.1 *Use of explicit terminology – an unequal rise*

The consistent use of ES and NC explicit terminology within Irish policy began in 2008 and has increased since, mirroring the rise in popularity observed in academia (Schleyer et al., 2015; Costanza et al., 2017), and global policy discourse (Chaudhary et al., 2015), albeit with a time-lag. The use of ES as a term was found to be four times as common as NC across the sample despite a potential "head start" for NC that was briefly included in environmental reports published in 1996 and 2000 but then disappeared entirely until 2011, after the introduction of ES. Those very first references were linked to contemporary sustainable development debates of the time such as the Brundtland Report (Brundtland, 1987), and were not retained or transferred into more specific land use or environmental texts despite similar meaning to how it is understood and used today. The popularity of ES compared to NC may be linked to familiar lexical parallels embedded within environmental texts such as "public goods" or "environmental benefits" that allow ES to serve as a new term for established ideas (Matzdorf and Meyer, 2014; Claret et al., 2018). This difference (ES arriving first, followed by NC) mirrors the origins of the ES framework and the more recent development and emergence of the NC approach—a shift from a foundation in utilitarian themes focused on mapping, assessment and valuation of human benefits (Costanza et al., 1997; Daily and Matson, 2008; Fisher et al., 2008), and towards a systems approach that captures all impacts and dependencies on ecosystems (Maseyk et al., 2017; Bateman and Mace, 2020). There is some evidence that this shift has become manifest within public policy as 32% of all NC uses were published in 2020 and associated with two themes: 1) NC accounting as a methodological approach and decision-support tool, and 2) the role of Natural Capital Ireland as a non-profit organisation promoting the NC approach. It is also interesting that despite first appearing in policy in 2008, ES mapping by a government body was not completed until 2016 (Parker et al., 2016), and pilot NC accounts initiated in 2018 (Farrell et al., 2021). This is consistent with previous work that shows conceptual integration occurs earlier in a science-policy transition timeline compared to operational integration (Kettunen et al., 2014; McKenzie et al., 2014). This time-lag may reflect time needed to gain stakeholder buy-in, build capacity, or assemble relevant information into the necessary format (Turnpenny et al., 2014).

Variation in the degree of conceptual integration between policy categories (horizontal integration) is consistent with previous research (Kettunen et al., 2014; Bouwma et al., 2018). In the case of Ireland, biodiversity policy and environmental reports contained the majority of ES and NC explicit use compared to primary producing sectoral policy and reporting. The former areas are directly involved in ecosystem management and actors involved are more likely to be exposed to ongoing ES and NC knowledge creation as their objectives are aligned and complementary to the crux of ES theory—preserving nature for the benefit of people. Other studies showed greater conceptual integration within agriculture and forestry policy areas explained due to close associations with environmental management as sectors deemed “close to nature” (Maczka et al., 2016; Bouwma et al., 2018; Claret et al., 2018), yet in Ireland’s case, agri-food, forestry, and marine documents contained limited explicit integration. Of these, forestry showed the greatest use of ES terminology which may build upon historical terms such as “multifunctional”, “non-timber benefits”, and “public goods” present throughout those documents, especially linked to carbon storage contributions (Maczka et al., 2016).

Agri-food policy and Department of Agriculture, Food and the Marine annual reports contained limited use of ES and NC terminology, usually occurring in case-study examples rather than embedded within the core text. National level agricultural policy is subject and accountable to multiple competing political priorities (Taylor et al., 2012). This may be especially pronounced in the Irish context as the agri-food sector contributes significant economic value and employment (8.8% export value, 7.1% total employment in 2020 (DAFM, 2020)). It is primarily an economic realm of policy that may create barriers to the adoption of perceived ecological ideas, especially if historic and embedded rules, norms, and perceived responsibilities perpetuate a sense that environment and economy are antagonistic, separated silos of governance (Taylor et al., 2012; Turnpenny et al., 2014; Saarikoski et al., 2018). It also takes time to build sufficient capacity and intellectual capital to transition new concepts into unfamiliar policy areas to demonstrate relevance and applicability to its objectives that may further lengthen the time to integration (Posner et al., 2016). The difference compared to results found in Scottish agricultural policy, deemed as "striving to become an exemplar", is notable given the similar geographic and cultural context (Claret et al., 2018). While agriculture and land use is a devolved area of governance, the UK is a pioneer in the field of ES and NC knowledge and implementation (for example, the establishment of the Natural Capital Committee in 2012) (Turnpenny et al., 2014). This early adoption and investment in ES knowledge, coupled with the political legitimacy granted by government led initiatives, serves as significant intellectual capital and accelerant available to Scottish policymakers that is not yet the case for Ireland (and most nations) (Saarikoski et al., 2018).

The language used surrounding ES and NC terms retained an interdisciplinary blend, reflecting the original disciplinary background of the concepts. Thematic analysis revealed ES terminology was most closely associated with ecological themes, and NC terminology with action orientated themes, although no one theme dominated for either. The use of economic metaphors such as ES and NC has been criticised as vulnerable to assigning monetary prices to nature at the expense of other values (such as biophysical, relational, and existence values) (Baveye et al., 2013; Schröter et al., 2014). References to monetary values and valuation studies were present in this sample, such as Bullock et al. (2008), but were not found at the expense of other related ideas. This may partially be a legacy of where ES and NC occurred: biodiversity and environment focused documents have objectives orientated towards conservation and biodiversity and so such adjacent themes can be easily added to the text without disrupting the overall narrative (Blicharska and Hilding-Rydevik, 2018). It remains notable that ecological themes are represented across the entire sample, not just those documents. Caution is required however, as thematic analysis reflects the language used surrounding ES and NC terms in an objective way and does not assume the intent of the authors, or interpretation by future stakeholders and practitioners, which may place greater emphasis on monetary pricing.

3.5.2 *Implicit descriptions of ESs – variation in visibility*

Descriptions of ESs were identified across all documents in the sample regardless of explicit ES terminology. Provisioning services with established markets (food, energy, timber), services related to conservation and nature (biodiversity, habitats), and carbon sequestration were common. Some policy documents showed specialisation towards a specific set of services such as nursery populations for marine policy and pollination for biodiversity policy. This specialisation means that different policy areas grant visibility to different baskets of ESs. If downstream action and decision-making is also skewed towards this specific portfolio of services, different silos of governance will come to different decisions regarding environmental management, even when considering the same ecosystem. Results also showed that regulating and cultural services are not universally silent or invisible within policy and reporting documents but instead show a spectrum of inclusion from almost universally present to very rarely included.

Five cultural services were found in over half of sampled documents with an average of six cultural services identified per document. This did not differ between documents published before and after the introduction of explicit ES language (2008). This suggests that an awareness and appreciation for cultural services and associated socio-cultural values were present across the entire sample range 1996–2020. Knowledge of non-material benefits from nature are not unique to ES theory (Schröter et al., 2014). However, the description of ESs within documents does not necessarily equate to downstream action or weight within decision-making as assigning value to cultural services is difficult, intangible, or sometimes inappropriate within conventional analyses (Fish et al., 2016; Chan and Satterfield, 2020). Perhaps most obviously, while biodiversity was mentioned in 98% of documents since 1996 and therefore visible within governance in some form, biodiversity has declined over this period as exemplified by the current national biodiversity emergency (Dáil Éireann, 2019; NPWS, 2019). This research shows that cultural services are historically visible within policy and reporting documents in Ireland and calls into question the role of ES integration to generate change if such benefits are already captured within the text. Harmonisation of language through further conceptual integration will be of limited impact unless it leads to greater voice for such services within downstream environmental management i.e. operational integration and implementation.

Documents sampled included an average of 6.6 regulating services of a possible 20. Two overall trends were observed: most regulating services showed low inclusion except for habitat regulation and carbon sequestration (two services with significant environmental directives and associated obligations), and documents published after the first evidence of explicit ES integration (2008) contained a greater number of regulating services. While this study is insufficient to attribute this increase to the integration of ES terminology, the mainstreaming of ES and NC ideas, coupled with a growing awareness of environmental sustainability and the utilitarian arguments for environmental sustainability (Goulden and Kerret, 2021), are likely to have played a role in the increasing diversity of regulating services recognised. Regulation of soil and water quality were two moderately well-represented regulating services (52% and 60% documents respectively). These services have a bi-directional relationship with the management practices of primary producing sectors, and have been shown to be vulnerable to decline in recent environmental reports (EPA, 2020). The contribution to economic and societal wellbeing is apparent to policymakers which may lend itself to greater visibility within policy and reporting. Conversely, services that do not have a straightforward contribution to human wellbeing under normal conditions are less commonly mentioned such as noise buffering (6%), mitigating natural disasters (fires, storms, landslides) (12%), and drought control (14%). While Irish ecosystems have the potential to deliver these services, service flows are not realised except under extreme events, resulting in limited awareness and appreciation and therefore visibility (Hein et al., 2016). The comparatively higher inclusion of flood mitigation services (38%) supports this finding as flooding, while still rare, is a more common phenomenon in Ireland that has significant negative impacts on people.

3.5.3 *Implications for broader environmental policy development*

The findings of this research provide insight into the conceptual integration of ES and NC relevant to environmental governance internationally and across scales. The results support that there is no singular trajectory for the science-policy transition of emerging environmental concepts (Jordan and Lenschow, 2010). Different policy areas may more readily incorporate new ideas, while others may require more targeted, deliberate efforts. The causes of these differences depend on the environmental and governance context such as historical responsibilities, intellectual capital, linguistic legacies, and competing interests, and therefore should not be assumed to follow patterns observed in other countries or levels of governance. Similarly, conceptual integration is not a foregone conclusion as introduced terms may disappear from the policy landscape rather than become systematically embedded over time. Case-study projects or organisations that serve as "flagships" that champion and normalise ES and NC concepts were identified as features that may aid the incorporation of these concepts in policy areas that otherwise show limited integration, for example, Natural Capital Ireland.

The inclusion of specific benefits from nature within policy documents is also nuanced. Unsurprisingly we found that services with significant legislative backing and visibility (carbon storage, habitats, and biodiversity) and economically relevant services (provisioning services) were well represented. The inclusion of other services reflected the specialisation within traditional policy silos that lends voice to services of greater perceived relevance and benefit. Regardless of terminology, environmental management premised on this unequal representation of ESs will fail to account for the full suite of benefits provided by ecosystems, and efforts to address these gaps will require breaking down barriers between historically separated areas of governance. Interestingly, this study suggests that non-material services (cultural services) should not be assumed to be absent from the governance landscape as their benefits may be well recognised regardless of ES integration, although the important caveat remains that visibility does not mean weight or voice within downstream environmental management and decision-making. The role of conceptual integration of the ES concept as a lever for resolving environmental trade-offs should also be interrogated if the challenge lies downstream rather than with foundational recognition and inclusion.

Looking forwards, there are reasons to suggest that the growing conceptual integration of NC and ES ideas will continue within the national and international policy sphere. Ongoing environmental discourse continues to advance our understanding of how the environment supports our society and economy. Influential multilateral agreements and projects showcasing NC and ES concepts are growing in number such as the adoption of NC accounting by the UN Statistical

Division, the publication of the Dasgupta review of The Economics of Biodiversity, and the IPBES global assessments (IPBES, 2019; Dasgupta, 2021; UN, 2021). These developments have the potential to mirror previous drivers of national-level integration such as the Aichi targets and EU Biodiversity strategies. Coupled with national or regional level flagships, the ES and NC concepts can continue to penetrate unfamiliar or distant areas of policy and governance that hold power over ecosystem management and the preservation of irreplaceable benefits for society and the economy

The conceptual integration of ES and NC within the national policy landscape of Ireland could be considered a partial success in terms of changing how environmental management is considered within governance documents and penetrating all policy areas in this study to some degree. However, we would caution that if integration is largely limited to only policy areas already aligned with environmental protection and stewardship (such as biodiversity policy), there is constrained potential for impact beyond an expanded terminology. Rather, integration in those areas must serve as an amplifier and accelerant throughout the broader national policy landscape that necessitates a joined-up, transdisciplinary approach. There is evidence to suggest this is already occurring as these concepts appeared within all types of documents included within this study—including broader economic realms of governance. Other areas of integration were also identified such as the Central Statistics Office initiating a system of ecosystem accounts at national scale, case-study projects led by the research sector (e.g., natural capital accounting), and the establishment of civil society organisations such as Natural Capital Ireland. The linkages between these adjacent initiatives and national policy development have not been formally assessed but it is likely they have a feedback effect on the process of conceptual integration within policy by generating momentum and lending legitimacy to these concepts. Given the urgency of environmental degradation and the inevitable time-lags of policy formation and implementation, greater investment in developing case-study projects and policy-ready tools is required to deepen integration and address remaining gaps. Local-level integration and bottom-up influences for conceptual integration are one aspect that remain underreported and warrant investigation as a potential complementary influence to top-down, multilateral policy processes.

3.5.4 *Lessons learned and next steps*

The sample size of this study is limited to 50 by the number of available environmental governance documents for analysis and the scope of the research question. This in unavoidable due to the incremental, multi-year process of policy formation and review coupled with the governance context of Ireland. A purposeful sampling approach was used to maximise the data collected to capture as much information as possible given this constraint. We acknowledge that these documents were formed through complex processes of review, iteration, and compromise and so may not reflect the diversity of thought within the broader governance landscape. However, they do represent a form of replicable, accountable, and accessible evidence to explore the science-policy transition of ES and NC concepts. While this is only one lever of environmental governance, national public policy has significant power over environmental management and therefore possesses the opportunity for ES and NC science to contribute to resolving environmental problems.

This research is an empirical analysis of the conceptual integration of ES and NC through explicit use of terminology and descriptions of ESs and adopts a deductive, objective lens. It is not appropriate to assume intent or motivation behind the formation of the text, or what this may mean for downstream operational integration. Instead, we hope that this research serves as a window into the 25-year science-policy transition of ES and NC into environmental governance and reporting. This process is important as the first step towards realising the problem-solving potential of ES science (Daily et al., 2009; McKenzie et al., 2014). There is scope to build on this work in a number of directions. Environmental governance is polycentric, and national public policy is only one level where integration can occur. Research examining the role of ES and NC within other levels of environmental governance e.g., community level, can contribute to building a complete picture of the governance landscape. This study provides a baseline of conceptual integration over a 25-year period and can serve as a foundation to explore downstream impact and operationalisation. Thematic analysis suggests that action and implementation themes are present in language but does not explore what this means in practice. Finally, this work can be enhanced further by considering other forms of evidence beyond document analysis such as interviews or surveys with stakeholders and policymakers to explore awareness and intent of those who shape policy formation.

3.6 Conclusion

Conceptual integration of the ES framework is not a silver bullet to resolving the challenges of environmental sustainability (Schleyer et al., 2015), but within public policy it serves as a first step to create a level-playing field for all the benefits nature provides to people. As knowledge relating to ESs and NC emerges, "ES-literate" public policy is primed and ready to apply and operationalise that knowledge as opposed to starting from a blank canvas (McKenzie et al., 2014). It is not unexpected that Ireland as an EU-member state and Convention on Biological Diversity signatory is responsive (with some time lags) to environmental discourse at high level. What is perhaps less expected is the variation in inclusion and uptake under the surface. This should be a top-priority for those involved in environmental management and decision-making as the ES framework is included within fast-approaching binding commitments: SDG 15 target 15.9 calls for ecosystem accounting at national and local scales (UN, 2015), the EU Green Deal states that all EU policies should aim to "protect, conserve and enhance the EU's natural capital" (EC, 2019), and in Ireland's case, the current biodiversity strategy includes targets to conserve ESs (Government of Ireland, 2017). This conceptual framing of people-nature interactions is embedded in environmental policy across scales, and this is unlikely to change in the short-term. Ireland has begun creating an ES-literate policy landscape, but it is fragmented, with gaps and laggards that need to be addressed for a cohesive and integrated approach to environmental governance. Addressing these shortcomings will enable a transition towards using ES and NC science to meet fast-approaching environmental targets and contribute to safe-guarding nature for future generations.

CHAPTER 4 | Spatial analysis of cultural ecosystem services using data from social media: A guide to model selection for research and practice

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Author contributions:

I conceived the research questions, designed the study, collected the data, conducted the analysis, produced the figures, wrote the draft of the manuscript, and led the revisions. Jane C. Stout and Cathal O'Donoghue provided guidance throughout and supervised the writing and revision process. All authors provided intellectual input and provided comments on the revised manuscript.

Status:

This manuscript has been published in *One Ecosystem* (2023), **8**: e95685, 10.3897/oneeco.8.e95685 (Neill et al., 2023b).

4.1 Abstract

Experiences gained through in person (in-situ) interactions with ecosystems provide cultural ecosystem services. These services are difficult to assess because they are non-material, vary spatially, and have strong perceptual characteristics. Data obtained from social media can provide spatially explicit information regarding some in-situ cultural ecosystem services by serving as a proxy for visitation. These data can identify environmental characteristics (natural, human, and built capital) correlated with visitation and, therefore, the types of places used for in-situ environmental interactions. A range of spatial models can be applied in this way that vary in complexity and can provide information for ecosystem service assessments. We deployed four models (global regression, local regression, maximum entropy, and the InVEST recreation model) to the same case-study area, County Galway, Ireland, to compare spatial models. A total of 6,752 photo-user-days (PUD) (a visitation metric) were obtained from Flickr. Data describing natural, human, and built capital were collected from relevant databases. Results showed a blend of capital types correlated with PUD suggesting that local context, including biophysical traits and accessibility, are relevant for in-situ cultural ecosystem service flows. Average trends included distance to the coast and elevation as negatively correlated with PUD, while the presence of major roads and recreational sites, population density, and habitat diversity were positively correlated. Evidence of local relationships, especially town distance, were detected using geographic weighted regression. Predicted hotspots for visitation included urban areas in the east of the region and rural, coastal areas with major roads in the west. We conclude by presenting a guide for researchers and practitioners developing cultural ecosystem service spatial models using data from social media that considers data coverage, landscape heterogeneity, computational resources, statistical expertise, and environmental context.

4.2 Introduction

Cultural ecosystem services are defined as “the non-material outputs of ecosystems that affect physical and mental states of people”, some of which require physical (in-situ) interactions between people and ecosystems (Haines-Young and Potschin, 2018b). These outputs include benefits, such as improved physical and mental health, opportunities for recreation and social interaction, connections to socio-cultural heritage, spiritual enrichment, and biodiversity appreciation (Scholte et al., 2015; Haines-Young and Potschin, 2018a). The flow of cultural ecosystem services at a given place is the result of the underpinning stock, condition, and configuration of natural capital (natural assets including geology, hydrology, soil, air, and biodiversity), human capital (knowledge, skills, and social networks within a population), and built capital (human-made infrastructure and assets, such as roads and buildings) (Chan et al., 2012b; Fish et al., 2016; Costanza et al., 2017; Díaz et al., 2018a; Langemeyer et al., 2018). The values associated with these benefits encompass instrumental, relational, intrinsic, economic, and community-based values that contribute to peoples' health, happiness, and wellbeing (Chan et al., 2016). Assessments of cultural ecosystem services are required to incorporate these benefits and values within environmental decision-making and secure their long-term provision (Daily et al., 2009; Costanza et al., 2017; Dasgupta, 2021).

Assessing cultural ecosystem services is challenging for several reasons, one of which is that they vary spatially. As the mosaic of capital stocks varies across the landscape, so too does the basket of services those ecosystems provide to people (Carpenter et al., 2009; Andrew et al., 2015; Costanza et al., 2017). This is complicated further because different individuals receive different cultural ecosystem services flows, based on their own values and preferences (Chan et al., 2012a; Díaz et al., 2018a; Chan and Satterfield, 2020). This variation across spatial scales and between people means that cultural ecosystem services have strong perceptual characteristics and have been described as simultaneously "everywhere and nowhere" (Chan et al., 2012b; Chan et al., 2016). Investigating where people choose to visit across a landscape can lend insight into places that facilitate in-situ cultural ecosystem service flows and, therefore, provide benefits to people. This is relevant for decision-making and environmental management because, without spatially explicit assessment, these services are vulnerable to being excluded from consideration (Daily et al., 2009; Andrew et al., 2015; Plieninger et al., 2015).

Social media platforms contain information related to in-situ environmental experiences through uploaded content and associated metadata, such as GPS coordinates, descriptive text, titles, and date of content creation (Oteros-Rozas et al., 2018; Zhang et al., 2022). Accessing these data represents a passive form of data collection at a scale that is rarely possible with alternative methods (interviews, visitor surveys) and has proven especially useful in otherwise data-scarce or inaccessible regions (Wood et al., 2013; Ghermandi and Sinclair, 2019; Wood et al., 2020; Zhang et al., 2022). The popularity of social media platforms, the potential for large volumes of data collection, and lower resource costs have made social media studies on the topic of people-environment interactions increasingly common (Zhang et al., 2022).

GPS-tagged content uploaded to social media is an emergent source of spatial data used as a proxy for visitation occurrence and intensity because it records a "digital footprint" of places where people have visited (Wood et al., 2013; Levin et al., 2015; Tenkanen et al., 2017; Mancini et al., 2018; Zhang et al., 2022). Researchers and practitioners can then apply spatial statistics to create models of visitation as a proxy for some form of in-situ cultural ecosystem service flow. This is an expanding field of research as cultural services are amongst the services most commonly studied (Czúcz et al., 2018), and in-situ cultural ecosystem service studies, recreation in particular, are a leading application of data from social media (Cheng et al., 2019). While not every study uses the same cultural ecosystem service framework to define their research question, the applications of GPS-tagged content to explore people-environment interactions are numerous. Examples include mapping visitor behaviour within national parks (Levin et al., 2015; Tenkanen et al., 2017; Sinclair et al., 2020) and at tourism hotspots (Fisher et al., 2019; Kim et al., 2019; Pickering et al., 2020); evaluating aesthetic preferences using photographic content and location (Figueroa-Alfaro and Tang, 2017; Yoshimura and Hiura, 2017); evaluating the success of restoration projects (Kaiser et al., 2021); and identifying cultural ecosystem service flow hotspots across landscapes (Richards and Friess, 2015; Oteros-Rozas et al., 2018; Arslan and Örücü, 2021).

Modelling the relationships between visitor occurrence and environmental characteristics (both biophysical, and human and social attributes) is a common analysis applied to spatial data from social media (Zhang et al., 2022). Examples of spatial model structures include the calculation of regional-level average relationships, local-level spatially varying relationships, and predictive models of visitation suitability and occurrence. Expertise in the most up-to-date spatial statistics and modelling approaches is a potential barrier to creating such assessments given the growing volume and availability of "big data" from social media databases, and machine-learning and remote sensing applications (Richards and Friess, 2015; Pettorelli et al., 2018). The need for such spatially explicit assessments of cultural ecosystem services is growing as momentum behind natural capital accounting and ecosystem service assessment continues to build (Hein et al., 2020; UN, 2021).

We selected four different modelling approaches to spatial data from social media based on their use within literature: 1) global regression, 2) local regression, 3) maximum entropy (MaxEnt), and 4) InVEST recreation model. Throughout this chapter, the term global refers to the study area in its entirety (not in the planetary sense) and corresponding models that summarise one average relationship (Tenerelli et al., 2016). While presented as four parallel workflows for clarity and comprehension, they are really a nested set of regression analyses that share the same foundational underpinnings, but vary in their depth, complexity, and method of computation. The assessment is focused on the spatial modelling of biotic, in-situ, cultural ecosystem services using visitation as a measure of potential people-ecosystem interactions (label 3.1 using the classification scheme from CICES v.5.1, (Haines-Young and Potschin, 2018b)). Further disaggregation within this category was not attempted given the strong perceptual nature of these services and the passive nature of data collection that does not include users' perceived benefits

Regression models applied at the global scale of a study area, such as generalised linear models (GLMs), summarise the average relationship between variables of interest and social media metrics. Examples include travel-cost estimations for tourism (Sinclair et al., 2018) and analysis of USA national park visitation (Sessions et al., 2016). Local regression uses geographic weighted regression (GWR) that allows relationships to vary over space rather than calculating one single average relationship for the entire study area (Fotheringham, 2020). This method has been used to consider varying visitor preferences across Europe (Tenerelli et al., 2016) and tourism patterns in South-East Asia (Kim et al., 2019). MaxEnt modelling uses machine-learning and presence records to predict areas of high suitability for a phenomenon of interest (Phillips, 2017). MaxEnt has been used to predict potential cultural ecosystem service hotspots in several case-studies, for example, in Japan (Yoshimura and Hiura, 2017), Portugal (Clemente et al., 2019), and Turkey (Arslan and Örücü, 2021). Finally, the InVEST recreation model from the Natural Capital Project provides a self-contained tool to model recreation and tourism services using ordinary least squares (OLS) regression (Sharp et al., 2018) and has been used in a number of studies, such as a restoration project in China (Zhao et al., 2021), and spatial planning in Chile (Outeiro et al., 2015).

Few published studies consider more than one of the modelling approaches outlined above (exceptions include Byczek et al. (2018) who used the InVEST model to triangulate their custom model and Tenerelli et al. (2016) who first discounted a non-spatial, global GLM in favour of a GWR). To our knowledge, no study has compared the application of different social media-derived spatial models for the same case-study area. Similarly, no such model of in-situ cultural ecosystem services, based on data from social media, has been used in Ireland. We addressed this dual knowledge gap by deploying four modelling approaches using data collected from social media in a previously untested case study, County Galway, Ireland. The research questions were as follows:

1. What environmental characteristics are correlated with social media-derived visitation as a proxy for in-situ cultural ecosystem service flows in Galway, Ireland?
2. What are the main differences in output and useability between spatial models and how can this provide information for future cultural ecosystem service assessment?

Model selection for ecosystem service assessment should be co-informed by data availability, data-processing expertise, research questions, and spatial extent of the area of interest (Pettorelli et al., 2018; Meraj et al., 2022). We aim to provide a guide for future cultural ecosystem assessment that takes into account these dimensions and that is relevant for researchers and practitioners using spatial models coupled with social media-derived data.

4.3 Methods

4.3.1 *Study area*

County Galway, Ireland, was selected as the study area because of its heterogeneous landscape, socio-cultural heritage, and high visitor numbers. In 2018, visitor numbers were estimated at 1 million domestic and 1.8 million international, contributing a total of €800 million in revenue (Cunningham et al., 2015; Galway County Council, 2021). Located on the west coast of Ireland (53°19' N, -9°00' W) (Fig. 4.1), the county covers 6,150 km^2 with a population of 175,000 in 2011 (CSO, 2012). The scope of this study focused on spatial trends over a continuous, semi-natural landscape. Therefore, the area of interest was restricted to exclude Galway City as an urban hotspot, Lough Corrib as an inaccessible expanse of freshwater, and islands. The remaining area (5,850 km^2) contains a diverse landscape of natural features including mountainous areas, grasslands, wetlands, forested areas, and coastline. The region also contains areas of biological interest such as Connemara National Park, 19 Special Protection Areas (SPAs), and 77 Special Areas of Conservation (SACs) (NPWS, 2022).

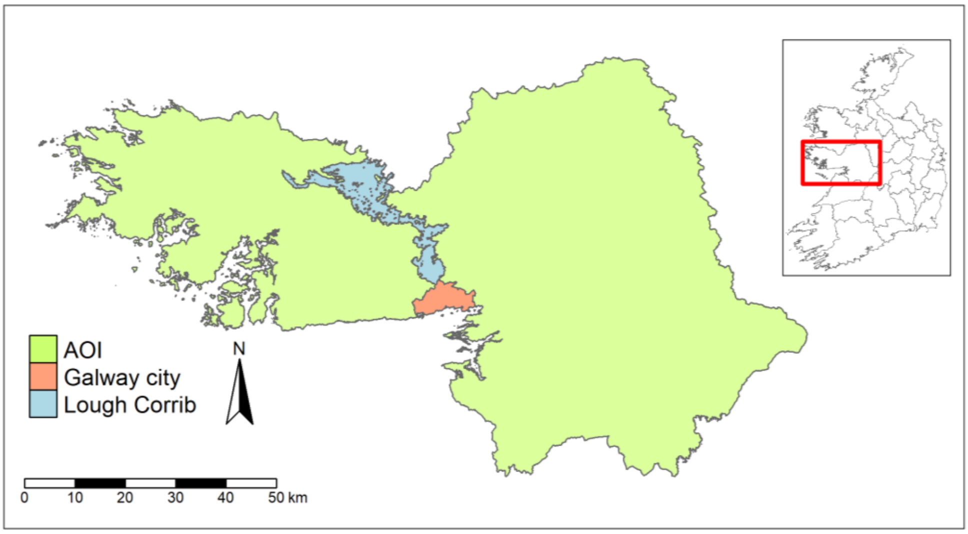

Figure 4.1: Case-study area of interest, County Galway, and its location on the west coast of Ireland. Areas excluded from analysis (Galway City and Lough Corrib) are highlighted.

4.3.2 *Social media data collection*

Data were collected from the Flickr social media platform using the statistical programming language R v.4.1.2 (R Core Team, 2021), the Flickr API, and the R package photosearcher v.1.0 (Fox et al., 2020). Flickr was selected because of its sizeable userbase estimated to have uploaded 5.67 billion photos between 2004 and 2016 (Ding and Fan, 2019), previous work that suggested the platform hosts a more diverse userbase compared with other platforms (Oteros-Rozas et al., 2018), and its use in similar studies on the topic (Wood et al., 2013; Tenerelli et al., 2016; Wood et al., 2020). Flickr has the benefit of complementary data access policies that permit the collection and use of data for academic research purposes (Fox et al., 2020). Photosearcher calls on the Flickr API to retrieve data based on user provided parameters. All searches were conducted in February 2022 and parameterised to retrieve photo records with GPS coordinates taken between 1 January 2010 and 31 December 2019. This time range was selected to ensure a sufficiently large dataset for modelling purposes, to reflect the widespread use and accuracy of GPS devices, and to exclude the disruption of travel restrictions imposed due to COVID-19 legislation in 2020. Two datasets were collected: a validation dataset and a modelling dataset. Firstly, popular locations, based on official national tourism statistics with recorded visitor numbers from Fáilte Ireland (2019a), were used to validate the relationship between social media records and visitation. Validation sites were selected, based on two criteria: 1) sites with visitor number estimates by the national tourism body for at least 4 years between 2010 and 2019 (Fáilte Ireland, 2019a) and 2) solely indoor sites (such as concert venues and indoor museums) identified using authors' expert knowledge were removed as they were suspected to provide limited potential for in-situ ecosystem service supply. This process produced 38 sites (appendix B). The second dataset was collected to model visitation across the area of interest. A vector file defining Galway was used to retrieve photo records and the output was cleaned to contain only photo ID, user ID, date taken, and GPS coordinates.

4.3.3 *Photo-user-days calculation*

The photo-user-days (PUD) metric developed by Wood et al. (2013) has been used as an indicator for visitation based on geo-tagged social media data in a number of studies (Sonter et al., 2016; Lee et al., 2019; Wood et al., 2020). The PUD metric is defined as the number of users who upload at least one photograph in a day, at a given area or location, and is designed to prevent the inflation of photo-counts based on extremely active users. For the validation dataset, PUD values were calculated at the site level to match official visitor statistics and provide an appropriate comparison to validate PUD as a proxy for visitor numbers (Fáilte Ireland, 2019a). The relationship between visitor numbers and PUD counts was checked using Pearson's correlation statistic and the suitability of this test checked using the Shapiro-Wilk test for normality (Crawley, 2005). In the modelling dataset, PUD values were calculated per 2 km grid square as users may choose to visit multiple places in a single day and it was desirable to capture these multiple visits. GPS points were assigned a 200 m buffer based on a conservative estimate of technological accuracy and previous work that found photos uploaded in Western Europe had a mean inaccuracy of 100 m (Zielstra and Hochmair, 2013). GPS points were overlayed with a 2 km^2 grid and assigned a grid ID based on spatial overlap. A variable representing the combination of user ID, grid ID, and date was constructed. The final PUD dataset was created by randomly slicing this variable to give one data point per unique user ID, grid ID, and date combination. This sampling technique prevents the inflation of data based on individuals contributing many photos from a single visit to one grid cell in one day but allows users to contribute to multiple cells per day.

4.3.4 *Environmental variable selection and data sources*

Environmental variables were selected based on natural, human, and built capital attributes identified as factors contributing to cultural service flows (particularly recreation) in the UN System of Environmental-Economic Accounting framework (UN, 2021) and previous studies using geo-tagged social media records (Tenerelli et al., 2016; Byczek et al., 2018; Tieskens et al., 2018; Chang and Olafsson, 2022). Natural capital attributes included biophysical variables describing ecosystems at a given location linked to potential ecosystem service supply, built capital attributes included infrastructure associated with the accessibility and attraction of a given place, and human capital was included using population density as a proxy for service demand (Table 4.1). While this does not capture the complexity of all factors linked to cultural service flows, this schema was designed to cover the variety of capital stocks identified in literature, given the available data for the study area. Spatial data related to these variables were collected from existing databases and clipped to the area of interest. The raw spatial data were saved, and a second set of maps were created by calculating an indicator value per 2 km^2 grid cell using zonal statistics tools in ArcMap v.10.7.

Table 4.1: List of variables and indicators capturing human, natural, and built capital for each 2 km^2 grid cell and their sources.

Predictor	Capital	Indicator	Data source and format
Elevation	Natural	Average elevation	Copernicus remote sensing DEM. 25 m raster data (EEA, 2017).
Slope	Natural	Average slope	Copernicus remote sensing DEM. 25 m raster data (EEA, 2017).
Rivers	Natural	Length of river	Environmental Protection Agency. Vector data of river bodies (EPA, 2016).
Freshwater cover	Natural	Area of freshwater (lakes, ponds, rivers)	Environmental Protection Agency. Vector data of lake segments (EPA, 2016).
Coastline	Natural	Distance to coastline	Land mask of Ireland 250 k vector file (OSi, 2020).
Habitat diversity	Natural	Number of CORINE classification types	CORINE land cover map 2012. Raster of land cover types at 100 m (EEA, 2019b).
Land cover	Natural	Area of land cover types (agriculture, wetlands, urban, forestry and natural area)	CORINE land cover map 2012. Raster of land cover types at 100 m (EEA, 2019b).
Land cover diversity	Natural	Shannon's diversity index	CORINE land cover map 2012. Raster of land cover types at 100 m (EEA, 2019b).
Geological heritage	Natural	Presence of designated geological heritage	Geological Survey Ireland. Vector data of recommended heritage sites (Meehan, 2019).
Protected status	Natural	Area covered under protected status	National Parks and Wildlife Service. Vector of protected areas. (NPWS, 2022).
Town distance	Built	Distance to nearest town	CSO Census 2011. Boundaries of designated towns and cities (vector) (CSO, 2013).
Population	Human	Population density	CSO Census 2011. Grid of population density at 1 km2 (CSO, 2013).
Major Roads	Built	Presence of a major road	Ordinance Survey Ireland. National road network vector file (OSi, 2020).
Path density	Built	Density of path length	Open street map roads database (vector) (OSM, 2021).
Amenity or recreation sites	Built	Presence of recreational site (e.g., bike rental, sports trails, boating, angling, golf courses)	Fáilte Ireland activity database (point data) (Fáilte Ireland, 2019b), Sport Ireland trail map (vector) (Sport Ireland, 2021).

4.3.5 *Statistical modelling*

Four modelling exercises were applied in this study: 1) global regression (using both presence and count data), 2) local GWR (presence data), 3) MaxEnt, and 4) InVEST (Table 4.2).

4.3.5.1 Global Regression

A logistic GLM (model a) was computed in R using a binary response variable describing the presence of PUD records per 2 km^2 grid cell according to the formula:

PUD presence ~ Environmental predictors, family = binomal (link = logit) **(a)**

The grid size was selected to ensure a sufficient proportion of cells contained presence records and to capture the variation of environmental attributes. Model optimisation was conducted using stepwise model selection to minimise the Akaike information criterion (AIC). This is a standard model optimiser that balances performance and complexity to identify the most parsimonious model (Crawley, 2005). Multicollinearity was checked using variance inflation factors (VIF). Dispersion, outliers, and the assumption of homoskedasticity were checked using the dHARMA package (Hartig, 2017). The receiver operator curve (ROC) was used to assess model fit to the dataset. The area under the curve statistic (AUC) quantifies this trait with values of 0.5 describing a model that performs as well as a random model and a value of 1 describing a model that perfectly fits the data (Swets, 1988; Yoshimura and Hiura, 2017).

The output of this global model summarised average trends for the entire region. We hypothesised that these relationships may vary across the landscape due to local socio-environmental context and accessibility. Model performance across spatial scales can be assessed by testing for spatial autocorrelation of the residuals (Fotheringham, 2020; Comber et al., 2023). We checked for evidence of spatial autocorrelation using Moran's I correlograms generated in the pgirmess package (Giraudoux et al., 2022). This test assesses if model performance (magnitude of residuals) is randomly dispersed across the area of interest (Comber et al., 2023). Evidence of spatial autocorrelation was detected and, therefore, the development of models that account for this spatial heterogeneity was recommended (appendix B). This was done in two ways: 1) a spatially autocorrelated mixed-model (SAM) that models global relationships, but incorporates a spatial random effect and 2) a GWR that permits locally varying relationships (see next section). The SAM model (model b) consisted of two components: environmental predictor fixed effects and a spatial random effect, based on latitude and longitude, computed using the spaMM package (Rousset and Ferdy, 2014), with the following formula.

PUD presence ~ Environmental predictors + Matern(1|Lat + Long), family = binomal (link = logit) **(b)**

This procedure is a recommended approach for modelling spatial data in ecology where spatial autocorrelation is detected (Comber et al., 2023). Model checks were computed as outlined in the previous section.

The PUD count per 2 km^2 grid cell was used as the response variable in a third model. Count data are typically modelled using a poisson GLM (O'Hara and Kotze, 2010). Upon inspection, the global poisson model was not appropriate due to overdispersion, homoskedasticity, and spatial autocorrelation of residuals. Instead, a SAM (model c) was deployed in the same procedure as above, according to the formula:

PUD Count ~ Environmental predictors + Matern(1|Lat + Long), family = poisson (link = log) **(c)**

Table 4.2: Outline of four models and description of their basic structure, data requirements, and output. PUD refers to photo-user-days metric.

Model family	**Model structure**	**Description**	**Response** (GPS-tagged content)	**Predictors** (natural, human and built capital)	**Output**
Global regression (1)	**(a)** Non-spatial global logistic regression	Generalised linear model (binomial family and logit link).	Binary. PUD presence	Environmental indicators at 2 km^2 resolution	Average relationships between environmental attributes and likelihood of PUD occurrence.
	(b) Global logistic spatially autocorrelated mixed-model (SAM)	Generalised linear mixed-model (binomial family and logit link). Environmental predictor fixed effects and spatial random effect (long + lat).	Binary. PUD presence	Environmental indicators at 2 km^2 resolution	Average relationships between environmental attributes and likelihood of PUD occurrence accounting for spatial heterogeneity.
	(c) Global poisson spatially autocorrelated mixed-model (SAM)	Generalised linear mixed-model (poisson family and log link). Environmental predictor fixed effects and spatial random effect (long + lat).	Count. PUD total	Environmental indicators at 2 km^2 resolution	Average relationship between environmental attributes and PUD counts accounting for spatial heterogeneity.
Local regression (2)	Logistic geographic weighted regression (GWR)	A series of logistic regressions (binomial family) computed across the landscape, weighting data based on proximity to regression point.	Binary. PUD presence	Environmental indicators at 2 km^2 resolution	Local relationship between environmental attributes and PUD occurrence that vary spatially in magnitude, direction and significance.
Maximum Entropy (3)	Maximum Entropy (MaxEnt)	Predictive model that uses machine-learning and a presence-only approach, based on observed occurrence to predict areas of high suitability.	Point coordinates. PUD occurrence	Environmental variables as 100 m rasters	100 m resolution model of predicted visitation occurrence and variable contributions to model performance.
InVEST (4)	InVEST recreation model	Self-contained model that queries an archived data set and calculates spatial statistics on user-supplied spatial data to compute an OLS regression.	Log Count. Annual PUD	Raw spatial data (vector or raster) analysed using pre-set options	Average relationship between environmental attributes and log annual PUD.

4.3.5.2 Local regression – Geographic weighted regression

A logistic GWR model was conducted to test for spatially varying relationships using the presence of PUD. GWR computes repeated regression analyses across the landscape and applies a distance-based weighting function so that data points closer to the regression point are weighted more compared to distant data points (see Fotheringham et al. (2003) for an in-depth methodological text). The maximum distance around each regression point to include a data point is referred to as the bandwidth and the shape of the weighting function is referred to as the kernel (Fotheringham et al., 2003). The model output supplies a regression coefficient and t-value for each predictor variable at each regression point. Changes in sign, magnitude, and significance for any relationships between environmental attributes and PUD occurrence can then be mapped and inspected. The GWR analysis was computed in MGWR v.4.3 software using the fixed kernel setting and optimised using the CV method (Oshan et al., 2019). Local-level independence was checked using local VIF values. As with the previous models, Moran's I correlogram and the ROC were plotted, and AUC value calculated. Coefficient surfaces for each environmental predictor were mapped using the tmap package (Tennekes, 2018).

A GWR model using the PUD count variable was trialled, but ultimately deemed inappropriate. As a global poisson GLM was not supported due to overdispersion and deviations from the error distribution assumptions, it was surmised that a GWR using a poisson distribution was not recommended as this simply runs a series of repeated poisson models with the same variables, just different weighting schemes. More sophisticated model structures to address this (e.g., negative binomial, quasipoisson) are not currently available in combination with GWR techniques and prototypes lack consensus in the academic community and so were not pursued further by us. As more sophisticated model structures become available in the future, these could be considered.

4.3.5.3 MaxEnt model

MaxEnt was the third model type tested. This model predicts areas of high probability for visitation, based on characteristics associated with sampled PUD occurrence. MaxEnt differs from the regression models outlined above because it adopts a "presence-only" approach. Sampling social media records cannot prove the absence of visitation and, therefore, a value of 0 PUD does not reflect a true and tested absence of visitation (Phillips, 2017). Instead, MaxEnt uses high-resolution environmental data to compare areas of observed presence records to a set of background pixels using machine-learning software to model the probability of PUD occurrence. All environmental predictors were converted into 100 m raster format using spatial statistics tools in ArcMap v.10.7 because MaxEnt only accepts data of identical resolution and extent. The objective of this exercise was to predict the suitability of visitation and so the PUD dataset was randomly partitioned into 75% training data and 25% test data. We ran the model 100 times using a bootstrap procedure to produce an average map of suitability and jackknife analysis was used to compare model performance (Phillips, 2017). Jackknife analysis runs two models for each environmental predictor: the first includes only that predictor in isolation and the second includes all variables, except that predictor. Differences in model performance compared to the maximal model can identify predictors of greater contribution and predictive influence.

4.3.5.4 InVEST model

The final model considered was the InVEST Visitation, Recreation, and Tourism v.3.10 ecosystem service model (Sharp et al., 2018). The InVEST model uses an archive of Flickr data from 2005-2017 to calculate annual PUD values and the user supplies spatial environmental predictor data. The model performs spatial analysis to create indicator values "in-house", based on a limited number of pre-set options. It can also compute an OLS regression using those generated indicators, user specified cell size, and retrieved PUD archives. We ran the InVEST model using the OLS regression option at a 2 km^2 grid size from 2010-2017 and supplied the shapefiles of environmental attributes (appendix B).

4.4 Results

4.4.1 *Validation of PUD and visitation*

All 38 validation sites returned PUD counts that were plotted against official visitor numbers reported by Fáilte Ireland (2019a) (Fig. 4.2). The Pearson correlation coefficient was 0.7 indicating a positive correlation and a significant relationship was observed using OLS regression ($p < 0.001$ at the 0.05 level, $R^2 = 0.3$). This result supports the use of social media-derived PUD as a visitation proxy in Ireland.

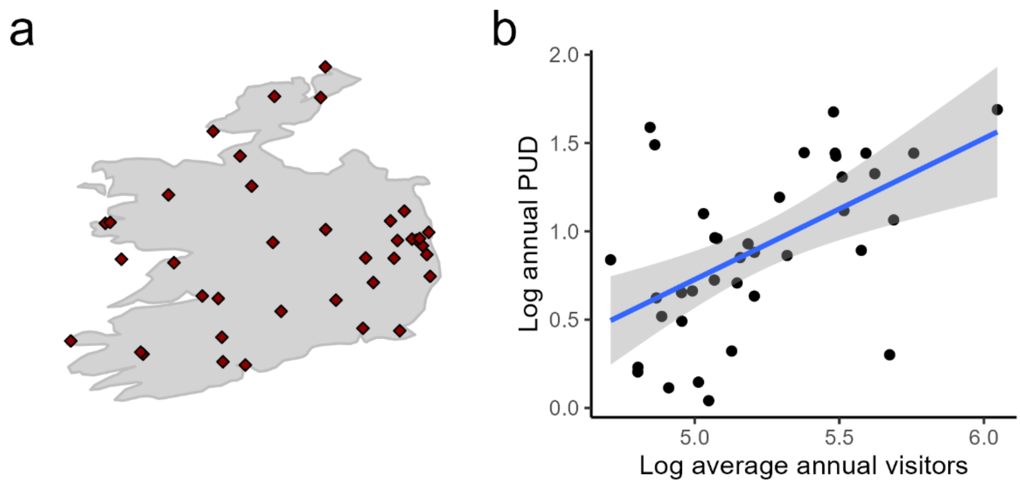

Figure 4.2: a) Location of 38 tourist sites, **b)** scatterplot showing significant positive correlation between official visitor counts and photo-user-days visitation metric (log scale).

4.4.2 *Social media data and PUD calculation*

A total of 25,170 geo-tagged photographic records were retrieved and converted into 6,762 PUD records (Fig. 4.3a-b). The number of PUD per grid cell ranged from 0 to 413 with a mean of 5.65 and standard deviation of 20.8 (Fig. 4.3c). Spatial analysis using the Getis-Ord Gi* tool in ArcMap v.10.7 showed significant clustering of PUD, and therefore, a non-random distribution (Fig. 4.3d). Hot spots were found in western, coastal areas and the area south-east of Galway City. Cold spots of low PUD count were concentrated in the east of the region.

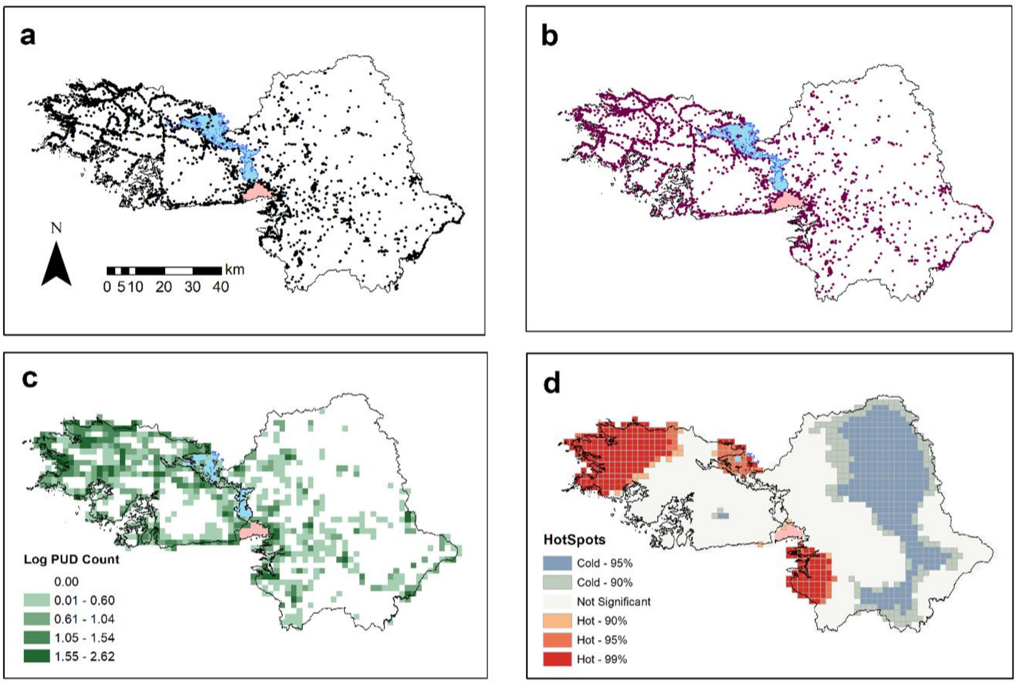

Figure 4.3: a) GPS points of 25,170 photographs retrieved, **b)** GPS points of 6,762 photo-user-days (PUD), **c)** aggregation of PUD points into 2 km grid resolution (log scale), **d)** Getis-Ord Gi* statistic hot and cold spots

4.4.3 *Global regression*

4.4.3.1 Logistic regression – PUD presence

The non-spatial, logistic GLM model of PUD presence contained 11 environmental variables (Table 4.3a). Land cover type variables produced collinearity concerns (VIF > 5), while protected status, town distance, and Shannon's diversity index of land cover were not significant. These variables were not included in the final model. VIF values for the 11 remaining predictors were < 5 and, therefore, satisfied the assumption of independence (Guisan and Zimmermann, 2000). Distance to the coast and elevation were found to significantly decrease the likelihood of PUD occurrence, while the remaining variables were found to increase the likelihood of PUD occurrence. The AUC value was 0.839 indicating a moderate fit to the dataset (Fig. 4.4). The Moran's I correlogram of the model residuals showed statistically significant values at distance classes < 25 km, supporting evidence of spatial autocorrelation (appendix B).

Table 4.3: Results of global regression models. PUD refers to the photo-user-days metric. SAM denotes a spatially-autocorrected mixed-model using a random spatial effect. Coef and SE refer to coefficient and standard error respectively. Significance levels (Sig) are denoted as *** p < 0.001, ** p < 0.01, * p < 0.05.

	Global logistic non-spatial (**a**) (PUD Presence)			Global logistic SAM (**b**) (PUD Presence)			Global poisson SAM (**c**) (PUD Count)		
Predictor	Coef	SE	Sig	Coef	SE	Sig	Coef	SE	Sig
(Intercept)	-1.303	-0.291	***	-1.767	0.582	***	-1.109	0.243	***
Elevation	-0.016	-0.002	***	-0.018	0.003	***	-0.009	0.002	***
Slope	0.278	-0.042	***	0.309	0.072	***	0.129	0.025	***
Coast distance	-0.029	0.005	***	-0.047	0.011	***	-0.037	0.006	***
River length	0.785	-0.18	***	0.943	0.353	***	0.373	0.159	***
Water cover	0.022	-0.004	***	0.031	0.007	***	0.012	0.002	***
Path length	0.082	-0.025	***	0.127	0.034	***	0.103	0.011	***
Major road	0.674	-0.138	***	1.131	0.189	***	0.767	0.08	***
Population	0.019	0.004	***	0.022	0.001	***	0	0	
Recreation site	0.608	-0.152	***	0.666	0.229	***	0.507	0.086	***
Geological heritage	0.555	-0.161	***	0.742	0.245	***	0.29	0.089	***
Habitat diversity	0.118	-0.053	**	0.19	0.079	**	0.152	0.031	***
N	1642			1642			1642		
Log likelihood	-803			-748			-3076		
AIC	1629			1518			6178		
Spatial auto-correlation of residuals detected:	Yes			No			No		

A logistic SAM was constructed given the spatial autocorrelation detected in the logistic GLM (Table 4.3b). This model identified the same variables as significantly correlated with PUD presence, although coefficients and standard errors varied marginally. The logistic SAM displayed a lower AIC value compared to the non-spatial global model (1518 compared to 1629) and so this was identified as the more parsimonious model for PUD occurrence at the global scale. Evidence of spatial autocorrelation was not detected (appendix B).

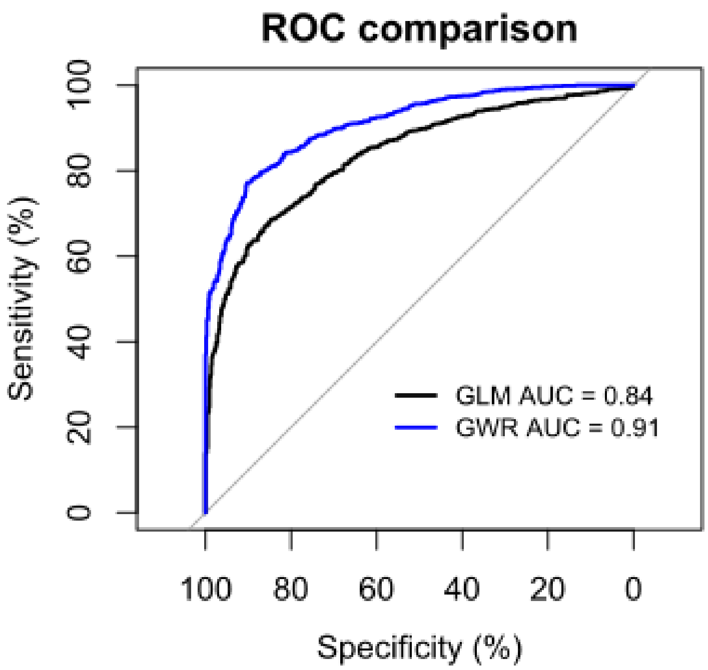

Figure 4.4: ROC plots for global logistic regression (black) and local GWR logistic regression (blue), based on presence of PUD at 2 km^2 pixel size.

4.4.4.2 Poission regression – PUD count

Visitor intensity was modelled using a SAM of PUD counts (Table 4.3c). Results showed that all coefficients retained the same direction (sign) as the presence model, although population was not significant at the 95% level. This suggests similar characteristics are associated with places most likely for Flickr contributors to visit and places with the highest visitation rates, with the exception that places with high population density are more likely to have a PUD > 0, but not necessarily high total PUD counts. Model performance was inspected by plotting observed PUD counts and model predicted PUD counts (Fig. 4.5). The results showed a significant positive correlation (slope = 0.84, $p < 0.001$) and a coefficient of determination (R^2) value of 0.5. The PUD variable is skewed with many zero values and fewer high values. This is reflected in the model fit with greater statistical noise at lower PUD values. Evidence of spatial autocorrelation was not detected (appendix B).

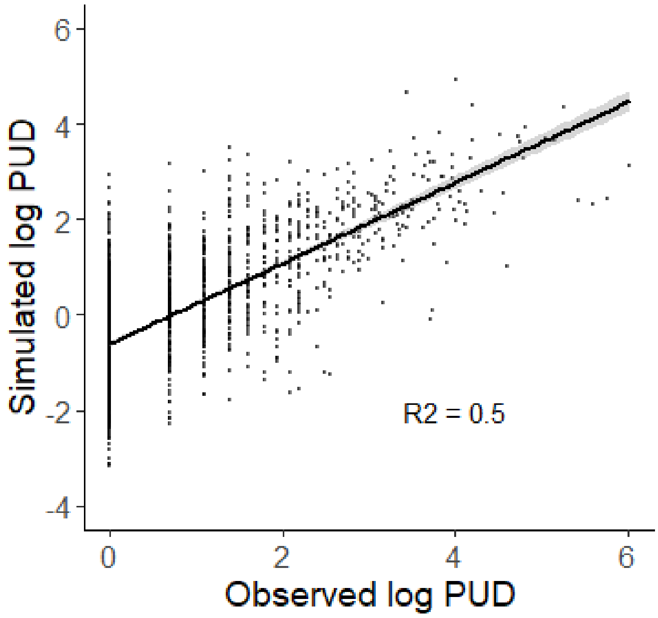

Figure 4.5: Observed photo-user-day (PUD) counts plotted against modelled PUD, based on SAM output (log scale), with an R^2 value of 0.5.

4.4.4 *Geographic weighted logistic regression – PUD presence*

The global logistic model displayed evidence of spatial autocorrelation that may mask local relationships. GWR was used to investigate this and the resulting coefficients were mapped to show variation in magnitude, direction, and significance (Fig. 4.6). Distance to the coast was found to produce collinearity problems and dropped from this model. Monte Carlo simulation produced a significant result ($p < 0.01$) for all predictors, further supporting the presence of spatially varying relationships. Several variables showed changes in significance levels across the area of interest, most notably town distance that showed a negative coefficient in eastern areas and a positive coefficient in the west. In other words, areas close to towns in the east of the region are more likely to have a PUD record, but remote areas far from towns are more likely to record a PUD in the west. The presence of recreational sites was found to be significant in three hotspot areas across the landscape. The ROC for the GWR local model was plotted with an AUC of 0.909 (Fig. 4.4). Compared to the non-spatial global logistic model, the GWR local model showed an improved model fit as indicated by its AUC value (0.909 compared to 0.839) and AIC value (1469 compared to 1629).

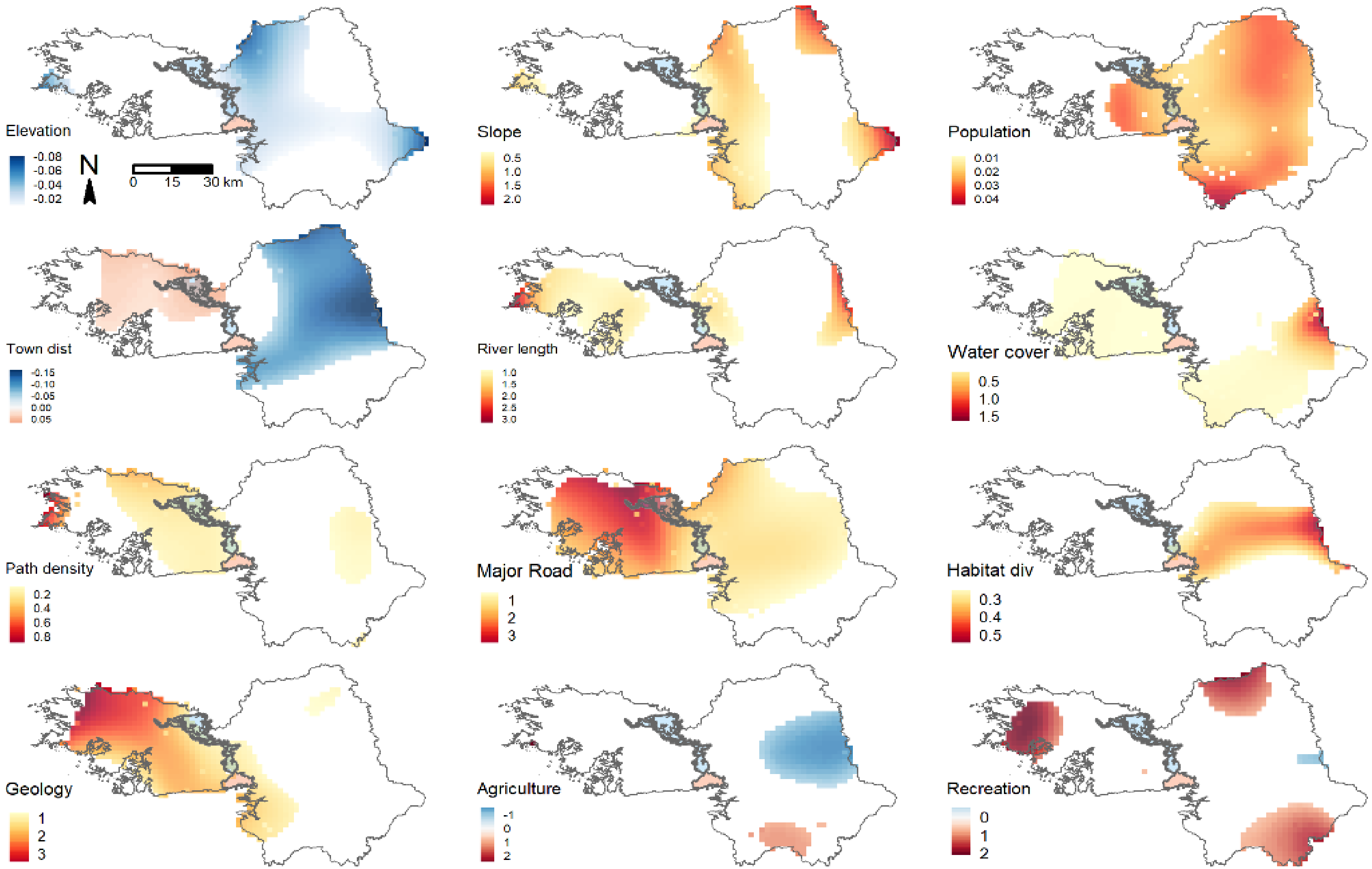

Figure 4.6: GWR coefficient surfaces for environmental predictor variables used to model photo-user-day occurrence. Only significant coefficients at the 95% level are shaded. Warm colours indicate a positive coefficient, while cold colours indicate a negative coefficient.

4.4.5 *MaxEnt model*

The MaxEnt model used 100 m rasters of environmental predictors and PUD occurrence coordinates to predict areas of visitation suitability (Fig. 4.7). The mean AUC value was 0.8 indicating an improved discrimination compared to a random prediction model. The results show hot spots of high suitability for PUD visits in clusters in the east of the county, along road networks and coastal areas, and surrounding Galway City. Dark blue areas indicate low likelihood of suitability for PUD occurrence and span the predominantly agricultural areas in the east, and wetlands with poor connectivity and low population. Variable response curves are included in appendix B.

MaxEnt's jackknife analysis, based on average AUC values, is shown in Fig. 4.8. Distance to the coast, elevation, presence of major roads and presence of recreational sites contributed the most information to the model in isolation (shown in dark blue bars). Similarly, the model performance showed the greatest decrease with the removal of elevation and major roads (shown by the light blue bars) suggesting that these variables contain information that is not captured by other variables. The variables with the lowest contribution to the model include geological heritage sites, river length, and slope that suggests they have limited predictive power in isolation.

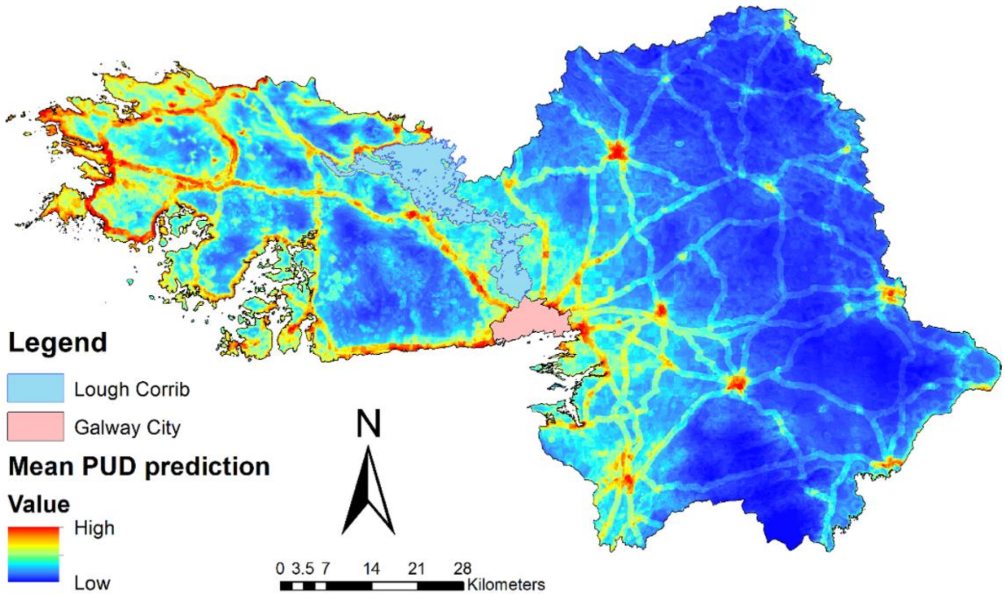

Figure 4.7: Average suitability for Flickr-derived photo-user-day occurrence (100 replicates) at 100 m resolution generated by the maximum entropy model.

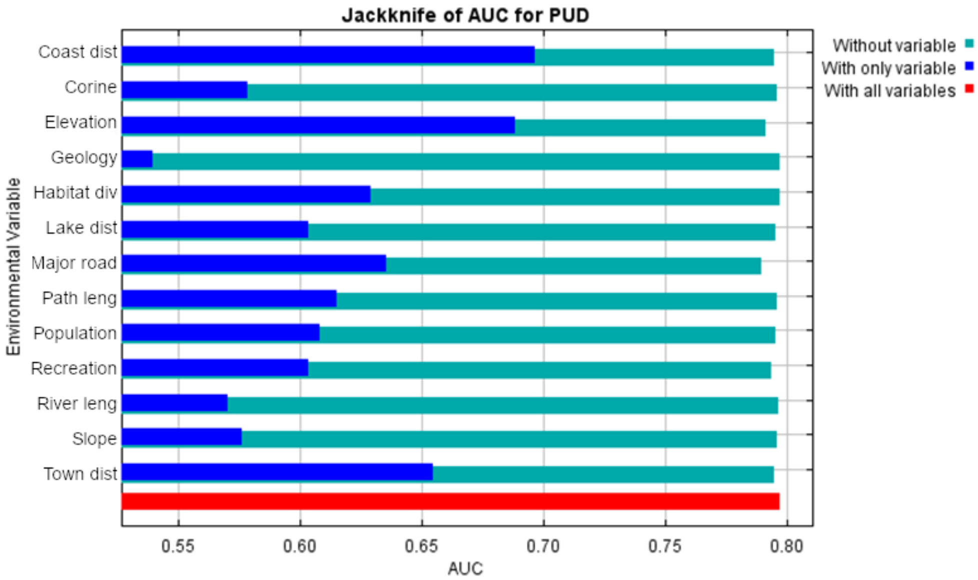

Figure 4.8: Jackknife tests for environmental predictor contributions to MaxEnt prediction models. Dark blue shows models with the variable in isolation, light blue shows the full model minus the variable, and red shows maximal model for comparison.

4.4.6 *InVEST recreation model*

The output of the InVEST recreation model reports an OLS regression of log transformed annual PUD values (retrieved from an archived dataset) on environmental predictors (Table 4.4). Direct statistical comparison to other models is not appropriate given differing input data. However, we provide some observations regarding outputs and computation. The InVEST model uses log annual PUD as the response variable that is characterised by low values and produces correspondingly small absolute coefficient values. This model output included land cover variables manually dropped from previous models due to collinearity concerns. The InVEST tool does not compute or report collinearity check. Other differences compared to previous analyses include river length and geological heritage being insignificant. All land cover variables are reported with a negative sign suggesting that any cell dominated by one land cover type has fewer PUD counts. This is consistent with a positive and significant coefficient for habitat diversity.

Table 4.4: InVEST regression model output (ordinary least squares regression and log annual PUD response). Significance levels (Sig) are denoted as *** p < 0.001, ** p < 0.01, * p < 0.05.

	Coefficient	Standard error	t value	Sig
Intercept	0.112	0.108	1.04	
Elevation	-0.00216	0.00034	-6.35	***
Slope	0.045	0.00599	7.51	***
Population	0.00115	0.00026	4.41	***
Habitat diversity	0.141	0.0337	4.17	***
Agriculture	-0.00462	0.000958	-4.83	***
Forest and Natural Area	-0.00538	0.00109	-4.92	***
Wetlands	-0.00331	0.000932	-3.55	***
Coast distance	-0.00000356	0.000001	-3.21	**
Town distance	0.00000871	0.000001	8.72	***
Path Length	0.0000516	0.000004	13.17	***
Recreation distance	-0.0000158	0.000004	-4.09	***
Degrees of freedom	1586			
Adjusted R2	0.487			

4.5 Discussion

This study investigated potential in-situ cultural ecosystem service flows across a previously untested context using data from social media as a visitation metric and a spectrum of spatial models. The following discussion is split into three major themes: (1) PUD as a proxy for potential in-situ cultural ecosystem service flows in County Galway, (2) spatial model selection and use, and (3) general comments about the use of social media data.

4.5.1 *Cultural ecosystem service assessment using PUD in County Galway*

This is the first study to use a social media-derived PUD indicator in the Irish context and the positive correlation between PUD and official visitor counts is consistent with other validation studies (Sonter et al., 2016; Fisher et al., 2019; Kim et al., 2019). Application of the PUD metric successfully revealed global trends, local relationships, and predictive suitability maps. These results demonstrate the applicability of social media-derived analysis for providing spatially explicit information for ecosystem service assessments. This information is useful for environmental management by providing a mechanism for decision-makers to account for these services and corresponding benefits in policy and planning. For example, this information could contribute to designing future tourism plans and local development strategies given the projected increase in visitor numbers to the area and understanding how and where those people interact with nature (Galway County Council, 2021). In the long-term, spatially explicit assessment of the contributions ecosystems make to peoples' lives can support the preservation of these contributions for future generations (Díaz et al., 2018a; Dasgupta, 2021).

A core set of environmental attributes representing a blend of natural, human, and built capital were identified as correlated with PUD across all models: coastal distance, presence of major roads, population density, habitat diversity, elevation, and presence of recreational sites. The finding that a blend of capital stocks was correlated with PUD mirrors results in other contexts (Tenerelli et al., 2016; Byczek et al., 2018; Tieskens et al., 2018), and demonstrates that natural and biophysical characteristics, socio-cultural context, and accessibility are all implicated in the potential flow of cultural ecosystem services (Byczek et al., 2018). This is aligned with the natural capital approach that considers the underpinning stocks that give rise to ecosystem services in terms of their unique combination, configuration, and condition at a given place (Chan et al., 2012b; Jones et al., 2016; Costanza et al., 2017; Mace, 2019). Another shared result between all models used was that protected status was not correlated with the PUD indicator, unlike in other studies, for example, USA (Figueroa-Alfaro and Tang, 2017) and Japan (Yoshimura and Hiura, 2017), which may suggest that protected areas serve a different role in people-environment relationships compared to other contexts. The majority of protected areas in Co. Galway fall under SAC and SPA designations that are targeted at nature conservation under EU wide nature directives (NPWS, 2022). This may be a reason why protected status does not appear to be correlated with in-person visitation in Co. Galway, as the primary purpose for their designation lies in biodiversity conservation rather than providing a societal utility. It may be that characteristics that allow for sites of high biodiversity value prevent high visitor numbers, for example, inaccessible places without built infrastructure, or sites unsuitable for such development.

The global, non-spatial logistic model was found to display spatial autocorrelation (violating the assumption of independence) and a higher AIC value compared to both spatial model alternatives (SAM and GWR). Therefore, models that account for the spatial nature of geo-tagged social media data should be used in such cases.

Spatially varying local relationships were found using GWR. This is consistent with studies that found evidence of local relationships when modelling cultural ecosystem service flows (Tenerelli et al., 2016; Schirpke et al., 2018; Kim et al., 2019). In the most extreme case of town distance, the relationship was reversed across the study area with remote areas correlated with visitation in the west and places close to towns correlated with visitation in the east. By definition, this phenomenon was obscured by models that produce one single relationship for the entire region: in both the global logistic regression and the SAM town, distance was not significant, while the InVEST model suggested a positive relationship overall. Previous European studies identified natural areas close to urban sites as potential hotspots for providing cultural ecosystem services (Ridding et al., 2018; Long et al., 2021) and, in Galway, this appears to be the case for some areas, but not everywhere. The rugged mountainous and wetland landscapes in western areas may be perceived as more attractive to visit because of their remoteness and attract visitors away from urban areas, whereas the predominantly agricultural landscapes surrounding towns in the east may not. In less pronounced examples of local-level relationships, some variables were found to be significant, but only in limited areas rather than across the entire region, for example, habitat diversity, recreational sites, and geological heritage. The identification of local relationships using GWR shows that caution should be applied when downscaling global average trends (non-spatial GLM, SAM, InVEST) to local areas (Fotheringham, 2020; Comber et al., 2023).

The MaxEnt model was the only method used for prediction due to its presence-only approach (as opposed to testing for correlations in GWR and SAM models). Jackknife analysis showed that elevation, coastal distance, recreational sites, and town distance were the variables of greatest predictive influence in the model. Other variables were found to have limited contributions to model prediction, such as river length, water cover, and geological diversity, despite showing significant correlations in regression analysis. This result can support the prioritisation of data collection when designing management interventions as some variables appear to be more informative. Results in this case-study suggest rural areas, close to the coast, of moderate elevation, and with a major road should be prioritised for targeted management interventions. These areas have the potential to experience high visitor volumes through in-situ cultural ecosystem service supply and the associated anthropogenic disturbance could contribute to negative ecological consequences and compromise long-term service flows.

The InVEST model presented some differences compared to the other models, such as the inclusion of land cover variables and different significance levels for water cover and geological diversity. This is not unexpected given that InVEST is premised on a different response variable dataset (archived Flickr database), but it does provide a comparator to triangulate with other methods. Overall, the variables of greatest significance in user-led regression techniques (coast distance, elevation, recreational sites, major roads) were also identified as significant using InVEST with less intensive processing of data required. Stepwise model optimisation and diagnostics are not provided by the default InVEST tool and so any changes must be led by the user manually inspecting model outputs, making desired changes, and re-running the model in its entirety, which can be time-consuming. These characteristics may be limitations to the InVEST model depending on the research context and similar remarks have been stated in literature (Byczek et al., 2018).

This is the first social media-based spatial modelling study in the Irish context and so comparison is limited. Previous research used a stated-preference methodology to elicit aesthetic preferences of rural landscapes in Ireland, based on a nationally-representative survey of 430 individuals (O'Donoghue et al., 2020). The results showed some overlap between highly valued aesthetic characteristics and characteristics correlated with the social media-derived PUD variable, for example, freshwater (lakes, ponds, rivers), marine areas and beaches, heritage monuments and geological features (mountains and cliffs). On the other hand, built attributes (roads, fences, buildings) were assigned a low value in the stated preference study, but urban areas and roads were found to be correlated with the PUD indicator. These differences may be due to the different phenomena investigated (visitation versus aesthetics), the different cohorts sampled, differences between revealed behaviour and stated preferences, and the reality that not all areas in the landscape may be equally accessible and, therefore, visitor occurrence may not reflect a true “choice” amongst all possible options. This emphasises the value of assembling a diverse suite of tools to investigate cultural ecosystem services and the contributions they make to peoples' lives (Zhang et al., 2022).

4.5.2 *Model selection and useability*

The results demonstrate the applicability of social media to developing spatial models of visitation. The differences in model outputs identified have the potential to create differing interpretations when a single approach is deployed in isolation. Therefore, we find merit in investigating multiple modelling tools—even if, ultimately, one is favoured for final reporting. While this study presented four workflows for clarity and comprehension, there is flexibility to customise these approaches to user needs beyond what is presented here. Some observations regarding data availability, data processing, expertise, research question, and spatial extent required are presented below to provide information for future cultural ecosystem service assessment using these methodologies.

4.5.2.1 Area of interest and scale

Data from social media are widely applicable, but their geographic coverage is unequal. The InVEST model is not suited for use in data-scarce regions as it recommends at least 50% of cells contain PUD records (Sharp et al., 2018). Data availability also has a role when designing global and local regression analysis. In areas of limited data coverage, the resolution of analysis (cell size) may be constrained to ensure sufficient coverage and variation in the response variable. Both global regression and GWR can adopt model families to account for non-normal response variables (count data, presence data); however, GWR lacks consensus regarding more complex model types and optimisation that limits its application, for example, the negative binomial GLM family, is currently unsupported and multiscale (varying bandwidth) GWR cannot be combined with GLM model families (Oshan et al., 2019). MaxEnt's presence-only approach lends itself most easily to data-scarce regions as it was intended for use on species distribution data that are often characterised by a low number of observations.

Model resolution should also consider the size, the heterogeneity of environmental attributes and the suspected behaviour of the sampled population of the area of interest. For large areas with suspected variation in local socio-environmental context, the presence of local relationships may be hypothesised from study initiation (Tenerelli et al., 2016), whereas, for more constrained areas with a shared socio-environmental context, for example, visitation within a self-contained national park (Tenkanen et al., 2017; Sinclair et al., 2020), this may not be the case.

The case-study of County Galway used a 2 km^2 resolution to create the PUD indicator and calculate environmental indicators to account for both data coverage and local knowledge that people engage in several visits to distinct locations within single daytrips. Spatial autocorrelation of model residuals should be inspected regardless of scale. In this case, Moran's I statistic was used to assess model performance by testing model residuals to see if they behave in a clustered, dispersed, or random pattern. If spatial autocorrelation is detected, alternative models that account for this should be considered, such as a mixed-model using spatial random effects (SAM) or a GWR analysis (Comber et al., 2023). This was the case for the non-spatial, global, logistic GLM reported in this study that was ultimately discounted due to evidence of spatial autocorrelation. The selection between the logistic SAM and GWR models can then be determined based on the research question, context, and statistical support for spatially varying relationships. Without these checks, there is a danger of landing on a model that performs differently in different places, but is poorly representative everywhere (Fotheringham, 2020).

4.5.2.2 Variable selection and indicator calculation

The available environmental data also determine grid size and mapping outputs for all four model workflows discussed. Variable selection should be grounded in the hypothesis for the phenomenon of interest and data may be gathered from available regional or national data sources, on-the-ground sampling, or remote sensing. Where appropriate data are available, indicator calculation is limited only by the users' expertise with data processing with a range of basic spatial statistics tools available in most GIS software, for example, proximity, presence, count, density, mean, min, max values. These indicators should be designed so that they vary across the landscape in a meaningful way, based on the cell resolution selected and this necessitates an interplay between indicator design and model resolution. For example, the use of "river presence" was not appropriate for modelling Co. Galway because the landscape contains many river features and, at the 2 km^2 scale, almost all cells contained an identical value that was not meaningful. Instead, river length was selected as the indicator. When using GWR, this should also hold true at the bandwidth scale to ensure sufficient variation around each regression point, in addition to local multicollinearity checks (Fotheringham et al., 2003). The use of GWR may also preclude the use of some proximity-based indicators that vary monotonically across the landscape and introduce collinearity problems, for example, coastal distance in the case of Co. Galway (Comber et al., 2023).

The balance between resolution and indicator selection was also apparent when creating raster files for use in MaxEnt. Input data to MaxEnt must be of identical extent and resolution in raster format that matches the desired output resolution. This required adjusting indicator file formats (indicator values themselves were not recalculated in this process). A second adjustment was made to change some indicators that were informative at the 2 km^2 resolution, but less informative at the 100 m resolution. For example, at the larger cell size, binary presence indicators (presence of geological heritage, presence of recreational sites) captured the effect of a feature throughout the surrounding area, whereas, when using smaller cell sizes, this landscape effect was lost. Instead, a proximity or density-based indicator may be more appropriate at fine resolution where the impact of a feature is hypothesised to extend beyond the cell size. Careful consideration is required to understand these relicts of model specification and may require a back-and-forth approach to identify the most appropriate indicators for a given resolution. These considerations are significantly constrained when using the InVEST model which only contains seven pre-set options to the user for calculating environmental indicators (two raster, five vector data types) that stymies customisation (Byczek et al., 2018).

4.5.2.3 Computational and resource costs and savings

Beyond statistical details, there are practical considerations that may determine the analysis of data from social media in ecosystem service assessments, such as the availability of computational resources, time, and expertise. The InVEST recreation model is designed to be accessible to any user who may be unfamiliar with advanced coding, statistics, or GIS by providing a self-contained, comprehensive interface and interpretable outputs (Sharp et al., 2018). Running the model requires an internet connection but is otherwise computationally light. It also benefits from available online tutorials and documentation provided by the Natural Capital Project to guide users (Sharp et al., 2018). These advantages must be balanced against some drawbacks, such as the use of an archived dataset of only Flickr-based records that may become outdated (2005-2017 currently) and limited user-customisation of model structure and variable calculation.

The MaxEnt model is supported through a self-contained programme (and compatible R package) with introductory online resources available (Phillips, 2017). The user must supply a suitable set of raster datafiles of identical extent and resolution that requires some experience working with spatial datasets to prepare. The model then computes a form of logistic regression using machine-learning to optimise model gain. Computing this potentially complex model structure from scratch would require advanced knowledge unavailable to many potential users and, therefore, the MaxEnt tool makes otherwise inaccessible statistical analyses possible. The default output includes a heatmap of predicted suitability that is intuitive; however, advanced options (jackknife analysis, scenario comparison, bootstrap replications) require a greater depth of interpretation and expertise. The model may also take a significant length of time to compute when including replication. The MaxEnt model was often deployed amongst studies that clearly defined cultural ecosystem services within the core research question(s) (examples included Richards and Friess (2015); Yoshimura and Hiura (2017); Clemente et al. (2019); Arslan and Örücü (2021); Long et al. (2021)), possibly due to the model's origin in biodiversity mapping and shared ecological disciplinary overlap.

The use of user-defined global regression techniques, for example, GLMs and SAMs, is the most customisable approach detailed in this study. The user should follow the usual statistical checks (outliers, dispersion, error distribution assumptions), as well as spatial autocorrelation checks. The user must prepare a data table containing the response variable and environmental indicator for each cell in the landscape, which often requires data wrangling, cleaning, and manipulation using spatial statistics. Highly advanced model structures may be theoretically possible, but inaccessible due to the expertise required to define, run, and interpret them. In some cases, the desired model may not yet be computationally possible. For example, multiscale GWR is currently limited to gaussian distributions, while GWR using poisson and binomial model families can only use fixed bandwidths. GWR can be computed in a number of ways including a number of R packages, Python, and the stand-alone MGWR tool, although their respective optimising algorithms vary, leading to different outputs. GWR model runs can be computationally intensive and take long periods of time depending on the size of the dataset, optimisation criteria, and use of Monte Carlo simulation (Oshan et al., 2019; Comber et al., 2023).

These considerations (summarised in Table 5.5) have implications for the time, resources, and expertise required to conduct analysis using geo-tagged social media data. In some cases, more than one model is required necessitating a to-and-fro procedure. This level of consideration is required from project inception to create the most informative model for a given phenomenon of interest. The alternative is the creation of knowledge premised on the shaky foundation of what is most familiar and accessible, rather than what is most appropriate.

Table 4.5: General findings from deploying four spatial model types to the same area of interest for providing information for model selection.

	Global regression (1)	Local regression (2)	Maximum entropy (3)	InVEST recreation (4)
Are of interest and resolution	· Determined by landscape heterogeneity and phenomenon of interest · Data coverage determines resolution	· Variation at local scale required · Deployed where spatially varying relationships hypothesised · Data coverage determines resolution	· Useful in data-scarce regions with low observations · Permits fine resolution	· Resolution should ensure 50% cells contain > 0 annual PUD · Limited use in data-scarce regions
Social media indicator	· User-determined (automated or manual collection)	· User-determined (automated or manual collection)	· User-determined (automated or manual collection)	· Flickr only 2005-2017 · Stable database
Response variable	· Pre-processing and filtering possible · GPS inaccuracy can be buffered · Response variable user defined such as occurrence, rate or count variables	· Pre-processing and filtering possible · GPS inaccuracy can be buffered · Response variable user defined, such as occurrence, rate or count variables	· Pre-processing and filtering possible · Point data required (GPS coordinates of occurrence)	· PUD variable fixed and calculated automatically · GPS assumed accurate · Pre-processing and filtering not possible
Environmental predictor variables	· User-driven indicator calculation · May require spatial statistics and GIS · Standard procedure for variable inspection (outliers, collinearity, skewness)	· User-driven indicator calculation · May require spatial statistics and GIS · Variable inspection at global and local scale (outliers, collinearity, skewness) · Proximity variables may be unsuitable	· User-driven indicator calculation as raster files of identical extent · May require GIS to prepare · Limited variable inspection and diagnostics	· User supplied spatial data files · Indicators calculated by pre-set spatial statistics within model run · Output returns variables calculated · Edits require re-running entire model
Computation	· Standard regression tools in any statistical software, for example, R	· Specialised tools available, for example, MGWR software · Emerging packages (R and Python)	· Standalone model software open-access and freely available	· Standalone model software, open-access and freely available

	· Model assumptions require manual checks (dispersion, outliers, normality, spatial autocorrelation) · If spatial autocorrelation detected, consider SAM or GWR models	· Bandwidth and kernel set by user · Prior to run, standard checks required (dispersion, outliers, normality) · Local model checks also required, for example, local VIF, Cook's distance	· Compatible R packages also available · Default output includes model gain, AUC and variable response curves · Optional jackknife analysis included · Optional replication and data partition	· Some additional tools in Python API · Automatically runs OLS regression · No available option for model inspection beyond default regression table output
Accessibility and transferability	· Basic knowledge of statistics and software of choice, for example, R · Flexible and customisable model structure that can be altered by the user with relative ease along a spectrum of complexity · Available to any user familiar with basic regression techniques	· Advanced spatial modelling approach with some customisation (bandwidth, optimiser criteria, GLM family) · Requires some specialist knowledge for preparation and interpretation · Advanced model runs may take time, especially Monte Carlo simulation · Evolving field of research with some limitations, for example, multiscale bandwidth models	· Available online supports · Software and machine learning permits complex modelling that otherwise may be unavailable · Advanced model runs may take time especially when replication is used · Interpretation requires expertise with statistics · Optional scenario modelling included	· No coding knowledge required · User-friendly, stand-alone interface and outputs · Dedicated online support tools and tutorials available · Optional scenario modelling · Uncertain future as archive becomes outdated
Summary	Widely applicable and customisable, but requires consideration when selecting resolution, scale, indicators and response variable calculation. May be limited depending by data availability and presence of local relationships	Useful for investigating spatially varying relationships at the landscape scale, but should only be used when justified. Requires knowledge of spatial statistics and mapping tools. Some limitations due to evolving research field and development of new statistical approaches	Applicable at high resolution and in data-scarce regions to predict areas of high suitability, but requires exact GPS coordinates and some degree of advanced statistical interpretation, computational resources and preparation of raster files	Useful for users to detect and visualise general trends with limited resources and expertise in regions that are sufficiently data-rich, where the use of 2005-2017 Flickr data is deemed sufficient

4.5.3 *Social media data use and limitations*

The focus of this study was the application of social media-derived data in different spatial models, not social media-derived data itself. The caveats of social media as a data source have been well described in literature, but its use continues to increase, especially in studies related to cultural ecosystem services (Cheng et al., 2019; Ghermandi and Sinclair, 2019; Zhang et al., 2022). We make some general comments here to contextualise the use of social media data and, despite these caveats, the results presented remain relevant as the first such application in Ireland and they provide transferable insight regarding spatial model selection for other contexts.

Potential inaccuracy in the geo-tagged coordinates was accounted for by using a 200 m buffer when calculating the PUD variable, given the suspected technological accuracy in northern Europe (Zielstra and Hochmair, 2013; Tieskens et al., 2018). MaxENT requires precise GPS points and InVEST assumes GPS-tags are accurate. If there are suspected errors in GPS accuracy, a user can choose to manually validate GPS tags by inspecting photographic content (although this is costly for large samples) (Walden-Schreiner et al., 2018), or select a resolution coarse enough to render the suspected error marginal.

Social media user-groups are a self-selecting, unrepresentative sample of the general population and so data collected carries with it the bias of the userbase (Ghermandi and Sinclair, 2019; Sinclair et al., 2020). Typically, this bias skews towards wealthier individuals, younger people, and contains a gender-bias depending on the platform (Zhang et al., 2022), although some studies suggest Flickr is more diverse than other leading platforms (Fox et al., 2020). We acknowledge that the results of this study represent a self-selecting group of Flickr contributors and do not intend to generalise the overall population interacting with the landscape of County Galway. While skewed towards a specific userbase, the results of this pilot study provide a first look into social media data applications in Ireland and future work can complement these findings by deploying a range of social media platforms and other data sources (visitor statistics, choice-based experiments, participatory data collection) (Wood et al., 2020).

The social media content used in this study was not screened or filtered beyond the removal of areas outside the area of interest. The volume of data collected (25,000 data points contributed by 1,866 users) and the widespread distribution of those points across the landscape suggest that the sampled data contain a diversity of information and were successfully applied as per other similar studies exploring visitation (Sonter et al., 2016; Sinclair et al., 2020). We emphasise that this study considered in-situ cultural ecosystem services broadly without disaggregating specific services or assuming user intentions and, therefore, analysis is based on the location of the photographer, not the content captured in the photograph itself (which would require inspection) (Tenerelli et al., 2016; Langemeyer et al., 2018). There is also an assumption that the physical presence of an individual in an ecosystem represents a potential cultural ecosystem service flow. Investigators may choose to filter content to varying degrees depending on their available resources, data needs, and research questions (e.g., based on sentiment, content, contributor, or machine-learning) (Langemeyer et al., 2018; Oteros-Rozas et al., 2018; Lee et al., 2019; Fox et al., 2021). Even with these efforts, it is not possible to know with certainty the intent and values behind the location content was created without the input of the individual contributor. We also do not suggest that the findings of this study reveal true “preferences” as this implies a degree of choice amongst all options that was not tested in this study and there is an inherent bias towards more “picturesque” places as an artefact of using a photo-sharing platform (Clemente et al., 2019). All social media-based studies must grapple with these problems and, despite these caveats, the popularity and breadth of social media applications continues to grow (Ghermandi and Sinclair, 2019; Zhang et al., 2022).

4.6 Conclusions

Spatial models applied to data from social media revealed a blend of environmental characteristics related to visitation and potential in-situ cultural ecosystem service flows across County Galway, Ireland. These characteristics included coastal distance, elevation, major roads, recreational sites, urban distance, and habitat diversity. Famously, all models are imperfect; but by discussing the workflow for each approach, we have articulated where and why different models may be useful. We hope that this exercise, zooming in on the application of spatial models using social media data to investigate cultural ecosystem services, can serve as a useful signpost for researchers and practitioners involved in ecosystem service assessments and natural capital accounting. Model selection considerations in such exercises should capture the context of the area of interest, computational demands, data availability and structure, and research scope. Furthermore, for transparency and clarity, we encourage all researchers and practitioners to explain and justify their choice of model and variables in detail. The results presented are especially pertinent given the growing volume of available data from social media and the need for spatially explicit models for natural capital accounting and ecosystem service assessments.

CHAPTER 5 | Who is talking about bioeconomy? Stakeholder and sentiment analysis using social media

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Author contributions:

I conceived the research questions, designed the study, collected the data, conducted the analysis, produced the figures, wrote the draft of the manuscript, and led the revisions. Jane C. Stout and Cathal O'Donoghue provided guidance throughout and supervised the writing and revision process. All authors provided intellectual input and provided comments on the revised manuscript.

Status:

This manuscript has been published in *EFB Bioeconomy Journal* (2023), **3**, 100055, 10.1016/j.bioeco.2023.100055 (Neill et al., 2023a).

5.1 Abstract

The bioeconomy concept describes an economic system centred around biological resources, processes, and technologies. The concept lacks a singular definition but has been proposed as a bridging concept that connects stakeholders under a shared goal and has become embedded in governance and research systems. This trait leaves bioeconomy vulnerable to being misused and applied ambiguously without scrutiny. Broader societal use and representation of bioeconomy can be investigated using social media as a data source due to its wide user base and ability to forge connections across spatial scales and between otherwise disconnected groups. This study used Twitter to explore the broader societal representation and use of bioeconomy across a 12-month span beginning in June 2021. A total of 16,737 tweets using bioeconomy terms were retrieved from 5,480 user accounts. The geographic distribution of user accounts and the stakeholder groups those accounts represented were studied and network analysis was conducted. Sentiment analysis was used to investigate the language and ideas contained within bioeconomy tweets. Results showed a mix of stakeholders represented within the most active accounts led by the research sector, private individuals, and civil society. The geographic distribution of user accounts was dominated by European and North America-based accounts, and influential users included policy institutions, research projects, events, and private individuals. Sentiment analysis revealed a trend for positive language and view of bioeconomy, especially amongst the most active users. Associated themes included sustainability, circular economy, climate, carbon, innovation, newness, and specific industries (food, agriculture, energy, forestry). It was found that bioeconomy is present within broader societal discourse as represented on Twitter and demonstrates the ability to connect multiple stakeholder groups. However, those engaged disproportionately represented high-income, high-technology countries, and highly-educated individuals with limited evidence of engaging outsiders or those unfamiliar.

5.2 Introduction

Bioeconomy broadly refers to the replacement of non-renewable, unsustainable, fossil resources with biological resources, processes, and technologies in a way that reorganises how the economy is structured and respects environmental limits (EC, 2018; Patermann and Aguilar, 2021). The conceptual origin of bioeconomy was driven by aspirational goals from both political and academic spheres (Bell et al., 2018; Patermann and Aguilar, 2018, 2021). These goals included biotechnological discovery (Bueso and Tangney, 2017; Aguilar and Twardowski, 2022), carbon emissions and waste reduction (Richardson, 2012; Loiseau et al., 2016; von Braun, 2022), and development of the bio-based sector to support primary producing industries, sustain livelihoods, and generate economic growth (Ollikainen, 2014; Ronzon et al., 2017). Bioeconomy is associated with a familiar yet illusive promise of a “triple-win”; a transformative system that ends environmental degradation and respects ecological limits, provides societal benefit, and is economically compatible with the status quo (Morrison and Golden, 2015; Ingrao et al., 2018; Ramcilovic-Suominen et al., 2022). This wide remit has created challenges defining bioeconomy and there remains no singular definition amongst its users (Pülzl et al., 2014; Korhonen et al., 2020; Wohlgemuth et al., 2021).

Over the past decade, “bioeconomy” has increased in use within the literature and multiple different narratives have emerged emphasising specific elements of interest (such as the biotechnology, bioresources, and bioecology visions) (Bugge et al., 2016; Mougenot and Doussoulin, 2022). More recently, new perspectives such as “circular bioeconomy” and “biocircularity” have been proposed reflecting ongoing discussion and debate, and the evolution of bioeconomy terms (Carus and Dammer, 2018; Stegmann et al., 2020; Holden et al., 2022). Simultaneously, bioeconomy has been embraced within policy and governance systems with over 60 national strategies drafted across the globe in 2018 (Bracco et al., 2018; Aguilar and Twardowski, 2022), and spearheaded by the European Union (EU) Bioeconomy strategy first published in 2012 (EC, 2018; Patermann and Aguilar, 2021). Despite this, the use and understanding of bioeconomy beyond the realms of science and policy remain understudied (Sanz-Hernández et al., 2019).

The ability of bioeconomy to encapsulate a breadth of economic, social, and environmental ideas, while also being untethered from a precise definition, has led to critique. This characteristic allows the concept to be moulded around a user’s specific purpose, while leveraging desirable traits without scrutiny (D'Amato et al., 2017; Leipold and Petit-Boix, 2018; Korhonen et al., 2020). For example, the bio prefix has been argued as vulnerable to being used to evoke untested themes of inherent sustainability, greenness, and inexhaustible regeneration (Ramcilovic-

Suominen and Pülzl, 2018; Holden et al., 2022). Applying bioeconomy in such a limited manner may not engage with broader sustainability challenges including concerns of equity, geography, access to technology, biomass supply, temporal time lags, biodiversity threats, land use change, colonial legacies, marginalised communities, and access to justice (Lewandowski, 2015; Priefer et al., 2017; Székács, 2017; Sanz-Hernández et al., 2019; Holden et al., 2022; Ramcilovic-Suominen et al., 2022). As a result of this blurred meaning, bioeconomy has been labelled as a "master narrative" defined by ambiguity (Hausknost et al., 2017), a "chameleon of all notions" (Gawel et al., 2019), and an unchecked sustainability label at risk of greenwash (Ingrao et al., 2018; Gawel et al., 2019; Vivien et al., 2019).

Conversely, bioeconomy has been posited as a unifying force that can bring together disparate stakeholder groups across geographies, industries, and scales under one shared ambition, serving as a "bridging concept" that enables collaboration, and ultimately shaping multiple pathways convergent on a shared goal (Hausknost et al., 2017; Hodge et al., 2017; Korhonen et al., 2020; Wohlgemuth et al., 2021). Advocates argue that bioeconomy can facilitate linkages between science and politics, has successfully created mechanisms to spur investment and public-private partnerships (most notably the EU-backed Bio-based Industries Joint Undertaking (BBIJU)), and has inspired new sub-disciplines of education and research (Johnson et al., 2021; Wohlgemuth et al., 2021). One challenge articulated from this vantage point is the need for bioeconomy to increase social impact and reach stakeholders beyond the elite circles of its infancy (Patermann and Aguilar, 2021).

Studies investigating the use and representation of bioeconomy include bibliometric reviews of scientific literature (Bugge et al., 2016; Mougenot and Doussoulin, 2022) and policy documents (Meyer, 2017; Dietz et al., 2018; Neill et al., 2020; Sanz-Hernandez et al., 2020), small-scale, targeted stakeholder engagements (Scordato et al., 2017; Vivien et al., 2019; Zeug et al., 2019), and analyses of conventional media sources (Peltomaa, 2018; Kelleher et al., 2021). There is a lack of research regarding how bioeconomy is perceived and represented outside these specialised realms. This is important because societal acceptance of bioeconomy is necessary to realise its promise of transformational change (Wesseler and von Braun, 2017; Sanz-Hernández et al., 2019; Zeug et al., 2019). Understanding how bioeconomy is portrayed and the actors involved can provide insight into this broader societal acceptance and to what extent it has served as a "bridge" that facilitates connection and collaboration.

Social media provides a digital platform to investigate the representation of bioeconomy in broader societal spaces because it can break down isolation caused by geography, industry, or discipline (Ngai et al., 2015; Antonakaki et al., 2021). Such platforms can serve as vehicles for tacit knowledge sharing, information flows, storytelling, and discussion between users (Panahi et al., 2012), as well as facilitate science communication both internally (between subject experts) and externally (with the general public) (Jünger and Fähnrich, 2019). This process can expose new audiences to scientific dialogue and information, and may improve trust in scientific discovery and innovation (Su et al., 2017). Policy organisations and institutions are also present on social media and can use such platforms to reach stakeholders outside of traditional governance processes. The more informal space of social media allows these bodies to serve as brokers of information, lending legitimacy to specific ideas and potentially generating external support (Goritz et al., 2022).

Actors representing both the research and policy arenas—the two core drivers accredited with the emergence of bioeconomy (Patermann and Aguilar, 2018)—are active participants on social media platforms. These platforms provide a "digital public sphere of engagement and debate" (Davies and Hara, 2017) to investigate the wider societal discourse and representation of bioeconomy that is not available using only bibliometric sources. Furthermore, social media analyses allow for data collection at a scale that is rarely possible using alternative methods such as surveys, interviews, or questionnaires (Tenerelli et al., 2016; Pan and Vira, 2019). However, there are also some biases and shortcomings that must be acknowledged such as the self-selecting user base of social media platforms that skew towards certain groups, platform instability, and data access (Stewart and Quan-Haase, 2017; Zhang et al., 2022). These caveats mean that the results of social media studies should not be considered representative of all those engaged in bioeconomy-related discourse, but do provide a large sample across geographic, disciplinary, and temporal scales that would otherwise be challenging to access.

5.3 Methods

This study used data collected from the micro-blogging social media platform Twitter to investigate bioeconomy-related information and discourse over a 12-month period beginning in June 2021. A dual-approach was adopted to investigate both the message and the messenger of bioeconomy-related information by considering the content contained in bioeconomy-related tweets (user uploaded text) and the user traits of accounts that contribute such content (Williams et al., 2013). This approach provided insight into both the representation and mainstreaming of bioeconomy in wider societal discourse, and the main actors involved in shaping this flow of information. The research questions were as follows.

1. Who are the main users engaging with bioeconomy on Twitter with regards to geographic location and stakeholder group?
2. What ideas and sentiment are captured within bioeconomy-related content on Twitter?
3. How does the representation and use of bioeconomy on Twitter relate to potential mainstreaming and information flows relating to the bioeconomy concept?

Twitter was selected as the social media platform to collect bioeconomy-related content because of its ease of use, accessibility, and large user base (estimated at 330 million active users per month in 2018) (Stewart and Quan-Haase, 2017; Antonakaki et al., 2021). It represents an ecosystem of information flow through one-way interactions (follows, likes) that do not require mutual consent (Pilař et al., 2019). Key bioeconomy stakeholder groups represented on Twitter span core subject experts (for example political institutions and researchers) and those more distanced from bioeconomy initiatives (general public, civil society, and media organisations) (Dieken et al., 2021; De Lima, 2022). Furthermore, the Twitter platform has the potential to facilitate bridge building between stakeholders, enable research dissemination and scientific communication, and support bioeconomy mainstreaming via societal commentary and information flows (Jünger and Fähnrich, 2019; Klar et al., 2020; De Lima, 2022). Twitter has been used as a data source to explore scientific phenomena on social media in a range of fields including ecology (Pan and Vira, 2019), health sciences (Erskine and Hendricks, 2021), and sustainability (Pilař et al., 2019; De Lima, 2022).

Data were collected using the Twitter API, R v4.1.2 (R Core Team, 2021), and the academictwitteR package v0.3.1 (Barrie and Ho, 2021). This package retrieves information according to a set of user-specified parameters such as time range, key words, and content type. A search query was designed to search for original tweets (as opposed to reshared content (retweets)) containing a variation of the term bioeconomy ("bioeconomy", "bio-economy", "bio economy") posted over the 12-month period between June 2021 and June 2022. This procedure retrieved a total of 16,736 tweets from 5,480 accounts that was used as the sample for the following analysis. The temporal range was selected to capture an up-to-date, sufficiently large, and computationally manageable volume of data. All searches and data collection were conducted in September 2022. Only variables of interest were retained including tweet text, username, tweet ID, and user ID.

User ID codes were then used to retrieve corresponding account details (location, biography, follower count, tweet count). The location data reflected voluntary, user-supplied information and therefore were inconsistent and included instances of missing data. A cleaned location variable was created manually at the country level through inspection and supported by biographical information. As users may move around or engage in remote activity, and some accounts represent international projects or collaborations, there is some uncertainty in this process. For international organisations or projects, the headquarter location or project coordinator location was used. A continent-level variable was also created as a coarser measure. Accounts without a location or any discernible information were not included in this analysis. This process successfully constructed a location variable for 96% of accounts to give a sample size of 5,238 for analysis of user geographic distribution.

The total number of bioeconomy tweets per account was tabulated and ranged from one to 703, with a mean of three, and median of one, showing most accounts produced a low number of bioeconomy-related tweets and smaller number of highly active accounts. A subsample of the top 10% of accounts most active in sharing bioeconomy-related information were identified for further examination (accounts with > 5 bioeconomy-related tweets in 12 months) as the most involved in shaping bioeconomy-related discourse and information flow. This subsample consisted of

567 accounts labelled as the most active. These accounts were manually inspected and categorised into different stakeholder groups based on those cited in the literature as key stakeholders in the bioeconomy's development and success (private individuals, civil society groups and NGOs, policy bodies or organisations, research sector and academia, private companies, and media organisations) (Dieken et al., 2021). Categorisation was informed by information contained in account descriptions and linked official websites. Some accounts were not categorised due to a lack of information, uncertainty of ownership, or unclear legal structures. Overall, stakeholder group categorisation was successfully applied to 97% of active accounts to give 549 active accounts.

A network of potential information flow was created by retrieving a list of followers per each active account using the academictwitteR package. Media organisations and newsletters were removed from this analysis as they tended to reshare information rather than contribute original content as active participants. The retrieved follower list was filtered to only include those within the dataset of active users. This dataset was used to create a network of potential bioeconomy-related information sharing and interactions between those actively engaged in bioeconomy content and included a total of 509 active accounts. Network statistics calculated included connectedness (number of connections per account), betweenness centrality (number of times an account features in the shortest path between two other nodes in the network), and influence (page rank algorithm that scores each node in relation to its connections and its connections' connections). The top 10 accounts for these metrics were then summarised to identify key actors within the network. The mean number of connections for each continent and stakeholder group were compared using Welch's analysis of variance (to account for unequal variance between groups). A subsequent Games-Howell post-hoc test was then used to identify significant differences between specific groups. All statistical analysis was conducted using R v4.1.2.

An analysis of the text contained within English language tweets was conducted. Text was cleaned to remove emojis, links, hashtags, punctuation, and formatting, converted to lower case, and tokenised at the word level. A dictionary of English stop words provided by the tidytext package was used to remove stop words from the dataset (Silge and Robinson, 2016). The resulting word list was tabulated to identify the most common words and common pairwise word associations. The bing lexicon was used to assign positive or negative sentiment to the common words list (Hu and Liu, 2004).

A second analysis was conducted at the sentence level using a sentiment library accounting for valence shifters that modulate sentiment scores based on word combinations, for instance, amplifiers (for example "very"), negators (for example "don't"), and de-amplifiers (for example "somewhat"). The package Sentimentr v2.9.0 was used for this analysis, which applies the Jocker's dictionary contained in the Syuzhet package (Jockers, 2015). This procedure produced a mean sentiment score for each token with values greater than 0 indicating a more positive text, values of 0 indicating a neutral text, and values less than 0 a negative text. This procedure produced cleaned English language content suitable for sentiment score calculation for 15,126 tweets (90% of the total tweets) and 4,837 user accounts (88% of the total accounts).

5.4 Results

The analysis of user account geographic location produced a total of 106 countries. Accounts were concentrated in certain areas rather than equally distributed (Fig. 5.1a). The USA was the most common country (17%), followed by the UK (10%) and Germany (7%). The 10 most common countries contributed over 70% of all tweets collected and were all in North America or Western Europe, except for India. The subset of the most active accounts contributing > 5 bioeconomy-related tweets in the 12-month sample displayed a similar geographic distribution with some minor changes in ranking. The leading 10 countries in this sample contained 75% of active accounts and were all located in North America and Western Europe, led by the USA (13%), Belgium (9%), and the UK (8%) (Fig. 5.1b).

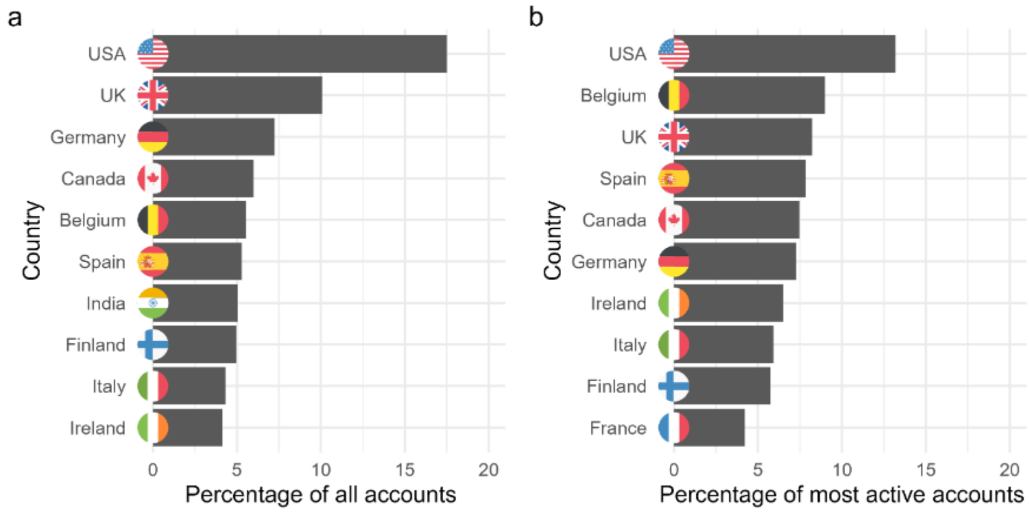

Figure 5.1: Estimates of geographic location for accounts engaging in the term bioeconomy. a) all accounts (n = 5,238), b) accounts using the term > 5 times in the 12-month sample (n = 523). A country-level geographic variable was determined for 96% of all accounts collected, and 92% of the most active accounts.

The stakeholder groups represented by the most active accounts showed a mix of users (Fig. 5.2). The largest stakeholder group was the research sector (27%), within which individual research project accounts made up the greatest sub-group, followed by universities, and other public research bodies. Accounts representing private individuals and accounts representing civil society groups showed similar representation with 23% and 21% respectively. Disaggregating within the civil society group showed that 4% of the overall accounts represented groups explicitly aligned with bioeconomy through their name or stated objectives. A further 3% were environmentally focused NGOs, and 6% represented industry associations, lobby groups, or sector-specific networks (examples included the paper and pulp sector, biofuels, life sciences, and biotechnology). The final stakeholder groups included private sector companies and finance entities (14%), information sharing accounts (7%), policy institutions (5%), and accounts created for specific events and conferences (3%). It was notable that many personal accounts representing private individuals included some detail in their biography related to a role within research, civil service, consultancy, or company affiliation suggesting that these individuals were highly educated or had a special interest or exposure to bioeconomy.

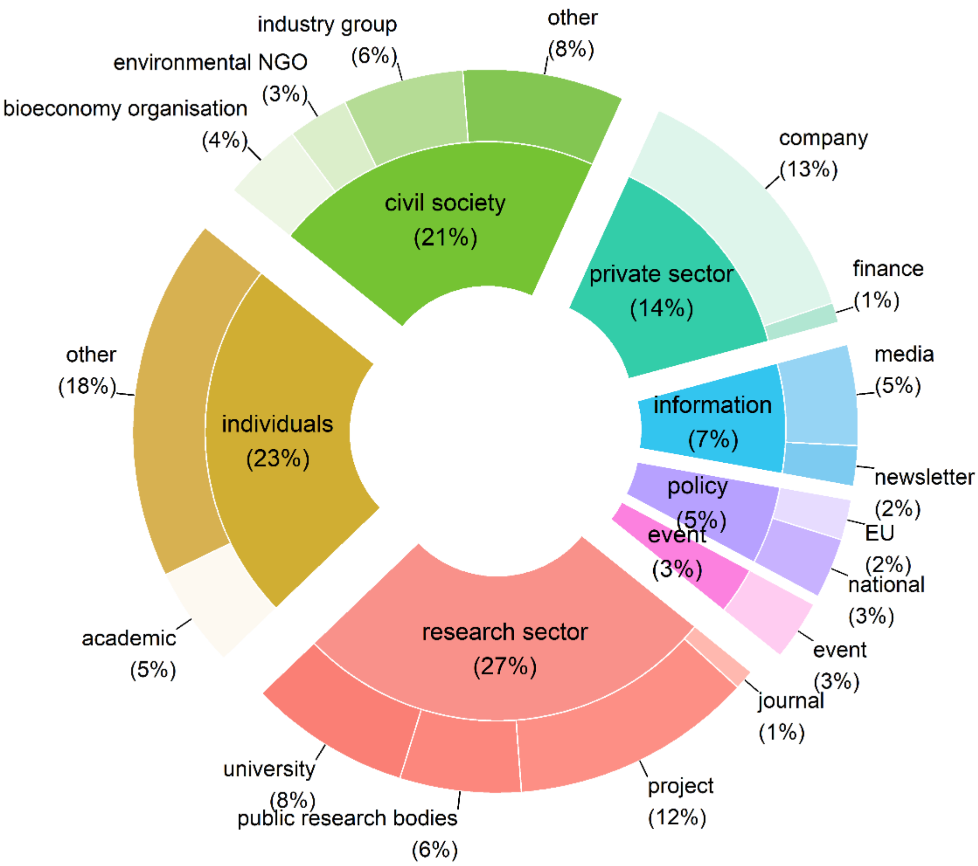

Figure 5.2: Stakeholder group distribution of most active accounts contributing to bioeconomy-related discourse on Twitter (n=549). Stakeholder group was determined for 97% of the most active accounts.

The network of follower connections between active accounts revealed a highly connected ecosystem of information sharing, with a mean degree connectedness value of 25. In other words, on average, each account follows or is followed by 25 other accounts in the network. Many of the accounts concentrated at the centre of the network with high connectedness values were based in Europe (Fig. 5.3a). This was supported by the Welch's analysis of variance analysis and Games-Howell post-hoc test that showed on average, Europe-based accounts had a significantly higher number of connections compared to accounts based in any other continent ($F = 12.9$, $p < 0.001$ at the 95% confidence level). This further supported evidence of a well-connected, established, and robust network of bioeconomy-related accounts concentrated in Europe. When considering the stakeholder user groups represented in the network, there was a blend of accounts located in the centre of the network including policy bodies, individual users, events, associations, and research (Fig. 5.3b). A significant difference between the mean number of connections based on stakeholder group was detected ($F = 5.4$, $p < 0.001$ at the 95% confidence level). The subsequent Games-Howell test revealed this difference was driven by policy-related accounts possessing a greater number of connections compared to accounts representing private sector groups or individuals.

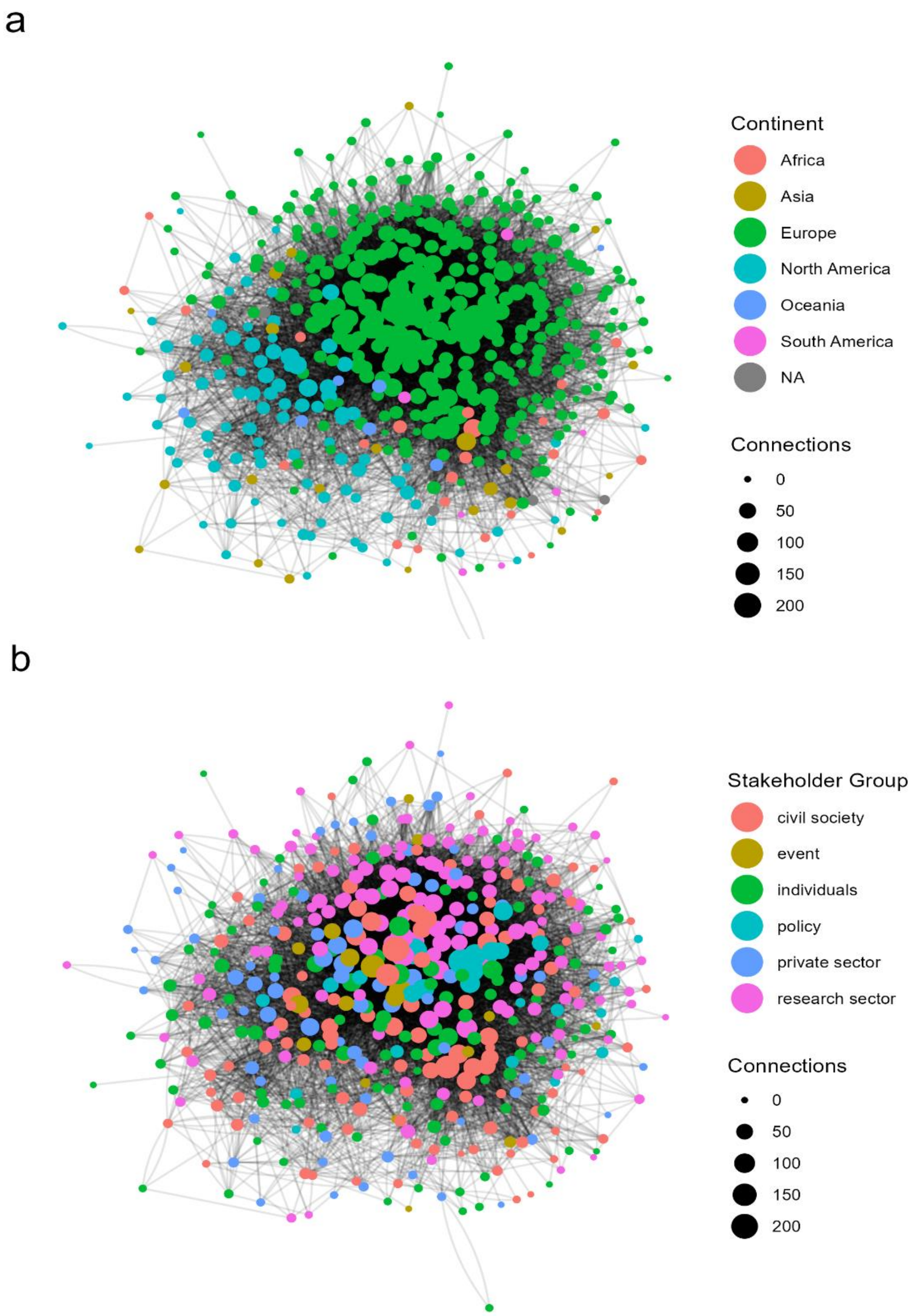

Figure 5.3: Network plots showing connected Twitter accounts based on followers. Size of nodes reflect total number of connections that node is involved in, and colour refers to **a**) geography, and **b**) stakeholder group.

All the leading accounts, based on measures of connectedness, centrality, and influence, were based in Europe (Table 5.1). The most well-connected accounts reflected official European Commission departments and funding schemes despite policy-related accounts making up a limited number of overall accounts within the network (5%). Policy-related accounts representing important nodes within the network included the Circular BBIJU (a public-private funding scheme part of Horizon Europe), EU Science and Innovation, EU Agriculture, and the EU Science and Knowledge Service. Other well-connected accounts included the World Economic Forum and two projects focused on EU rural development and innovation specifically related to the bioeconomy. The most central accounts (using the betweenness centrality metric) included a range of accounts representing research bodies, policy groups, and individuals that may serve as "bridges" for information sharing throughout the network. The influence metric (page rank) also revealed a blend of research projects, university centres, and individuals that may represent potential "broadcasters" throughout the network, although the normalised scores showed differences of only 0.001 suggesting that the difference was marginal, and many accounts show very similar measures of influence. While the most connected nodes were mostly high-profile policy-related accounts with a wide reach, centrality and influence metrics reflected a more diverse mix of account types suggesting a range of different actors were active within the network and possessed the potential to shape information sharing. The individuals identified in this analysis (anonymised for privacy and ethics considerations) appeared to be those with some vested knowledge, background, or exposure to bioeconomy-related concepts through their work and professional activities

Table 5.1: Summary of the top 10 accounts by connectedness (degree centrality), centrality (betweenness centrality), and influence (page rank). Usernames reflect display names at the time of data collection and anonymised in the case of personal accounts but consistent between metrics.

	Connectedness		**Centrality**		**Influence**	
Rank	Username and Description	Value	Username and Description	Value	Username and Description	Value
1	**CBE_JU** - Circular Bio-based Europe Joint Undertaking. EU funding program.	222	**CBE_JU** - Circular Bio-based Europe Joint Undertaking. EU funding program.	0.088	**Individual 1** - involved in circular bioeconomy research based in Europe.	0.013
2	**Biconsortium** - Bio-based Industries Consortium. Non-profit organisation representing bio-based industry.	206	**Bio_Markets** - Global bioeconomy event and connection platform.	0.051	**BETA_TechCenter** - University research centre. Rural development and circular bioeconomy transition.	0.012
3	**EUScienceInnov** - EU Director General of Research and Innovation.	200	**EU_MARE** - European Commission Maritime Affairs and Fisheries.	0.037	**CBE_JU** - Circular Bio-based Europe Joint Undertaking. EU funding program.	0.012
4	**Wef** - The World Economic Forum.	154	**LukeFinlandInt** - Natural Resources Institute of Finland, research and innovation in bioeconomy.	0.034	**Bio_Markets** - Global bioeconomy event and connection platform.	0.010
5	**Bio_Markets** - Global bioeconomy event and connection platform.	154	**BioeconomyForum** - World Bioeconomy Forum event and stakeholder platform.	0.032	**Susbind** - Research project developing, testing, and producing bio-based products.	0.010
6	**EUAgri** - EU Agriculture and Rural Development policy account.	149	**EuropaBio** - The European Association for Bioindustries	0.031	**Individual 2** - involved in European policy, research impact and feedback.	0.009
7	**EU_ScienceHub** - EU Commission's science & knowledge service - Joint Research Centre.	147	**Individual 1** - involved in circular bioeconomy research based in Europe.	0.030	**LukeFinlandInt** - Natural Resources Institute of Finland, research and innovation in bioeconomy.	0.009
8	**EuropaBio** - The European Association for Bioindustries	140	**Individual 2** - involved in European policy, research impact, and feedback.	0.028	**CBC_SW** - Circular Bioeconomy cluster for collaboration, technology, and innovation in South-West Ireland.	0.009
9	**SCALE_UP_HEU** - Project developing bioeconomy in European rural areas.	134	**Biconsortium** - Bio-based Industries Consortium. Non-profit organisation representing bio-based industry.	0.026	**Individual 4** - bioeconomy and agricultural expert at national level of an EU nation.	0.008
10	**Biovoices** – EU Project to promote all voices for a sustainable bioeconomy.	132	**Individual 3** – consultant involved in forestry and sustainability in Europe.	0.025	**Phenolexa** - Project converting agri-food side streams into bioactives.	0.008

The most commonly occurring words identified in 15,126 tweets in English were "circular" and "sustainable" showing that these terms were closely associated with bioeconomy (Fig. 5.4). Another descriptor or paradigm commonly used in relation to economic transformation, "green", was present, but at a lower frequency. Examples of environmental themes were limited to carbon and climate. The frequency of words such as innovation, new, research, future, opportunity, development, transition, and change were identified as words linked to a theme of creation, novelty, aspiration, and untapped potential. There was evidence of words related to traditional economic terms (resources, industrial, production, value, sector, products, materials, business), and particular sectors (energy, agriculture, forest) showing the aspiration of economic development core to the bioeconomy's origin was also present. Sentiment analysis of words suggested that words with a positive association occur much more frequently compared to negative words (Fig. 5.5). There was evidence of a coalescence around positive terms such as "sustainable" and to a lesser extent "innovation", whereas even the most common negative words were recorded at a much lower frequency of use.

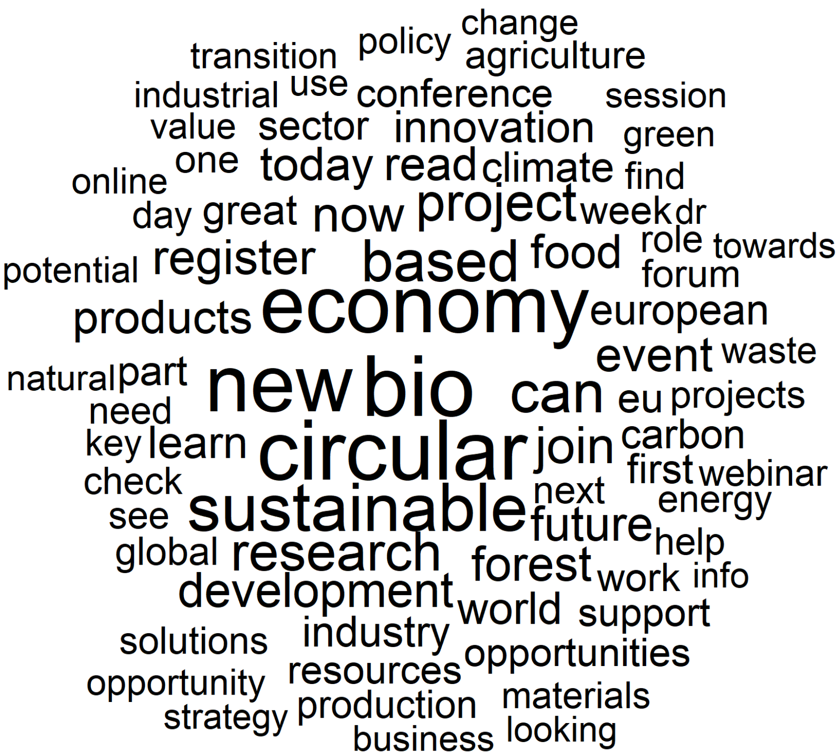

Figure 5.4: Most commonly occurring words (stop words removed) in tweets in English using bioeconomy terms. Size of text correlated to frequency.

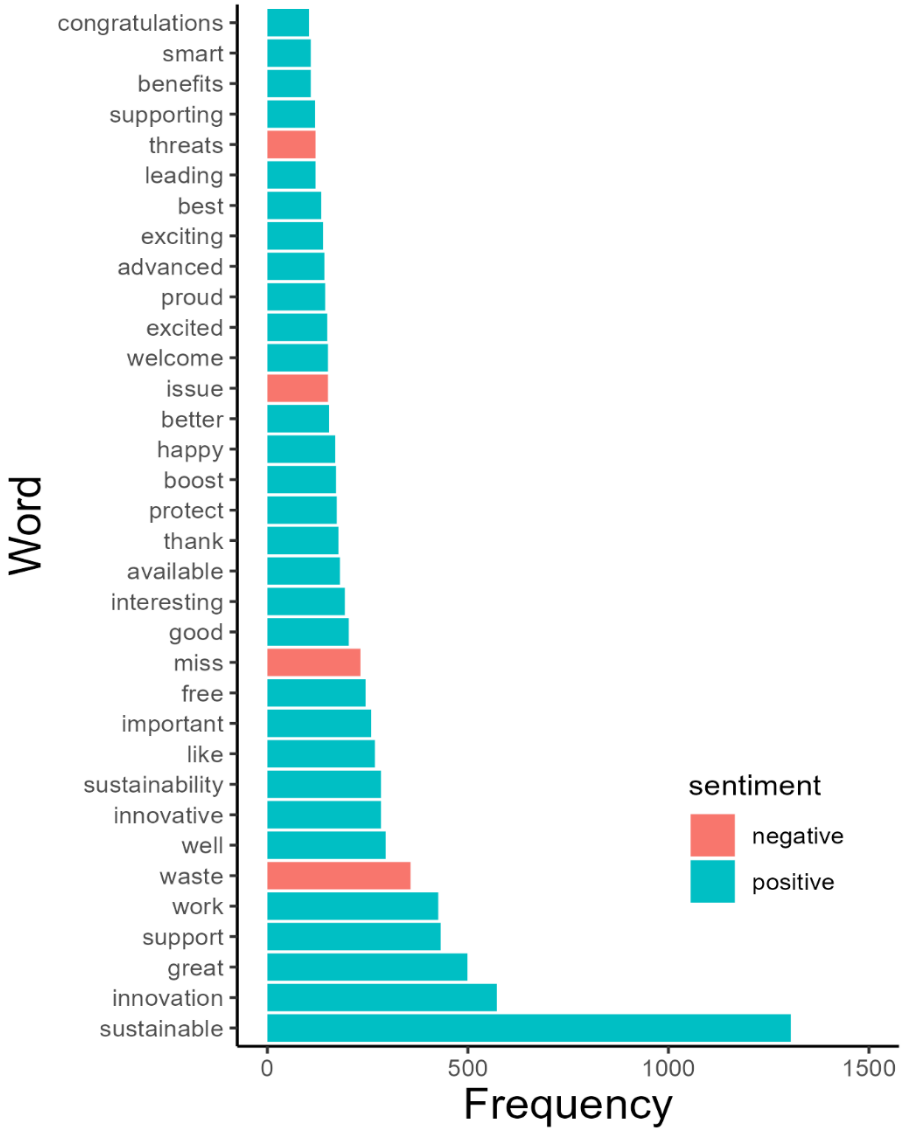

Figure 5.5: The most commonly occurring words assigned positive and negative sentiment using bing lexicon (positive words assign score of 1, negative words a score of -1).

Paired word analysis identified words that co-occur > 50 times (Fig. 5.6). These paired words fell into several themes including topics specific to certain geographies (Canada's bioeconomy, Ireland Bioeconomy Week, European Bioeconomy, Eastern Africa), specific industries (agriculture, synthetic biology, plant based and forest products, hemp growing, biofuels), and dedicated bioeconomy-related organisations (conferences, forums, journals). Other pair-wise associations mentioned included climate change and low carbon, and information sharing (stay tuned, info days, special issues).

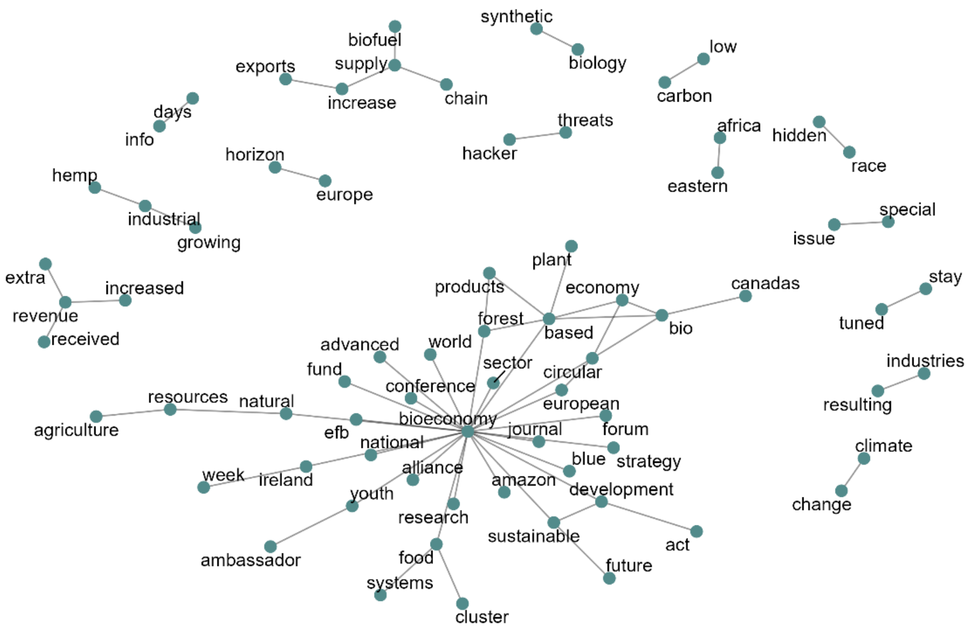

Figure 5.6: Network of paired words that co-occur > 50 times in the dataset of bioeconomy tweets in English.

The sentiment of language contained within bioeconomy-related tweets was positive on average. Tweet-level sentiment analysis resulted in a mean sentiment score of 0.25 (standard deviation = 0.22), ranging from -0.91 to 1.56 (Fig. 5.7a). Overall, only 7% of tweets had a negative sentiment, 12% neutral, and 81% positive. Aggregating the sentiment data by user account showed a similar distribution skewed towards net positive sentiment of each account engaging in bioeconomy content (mean = 0.21, standard deviation = 0.21) (Fig. 5.7b). The subset of the most active accounts was also positive in sentiment, with a narrower spread (mean = 0.22, standard deviation = 0.12) showing that those accounts most active in tweeting about the bioeconomy did so using consistently positive language and sentiment (Fig. 5.7b).

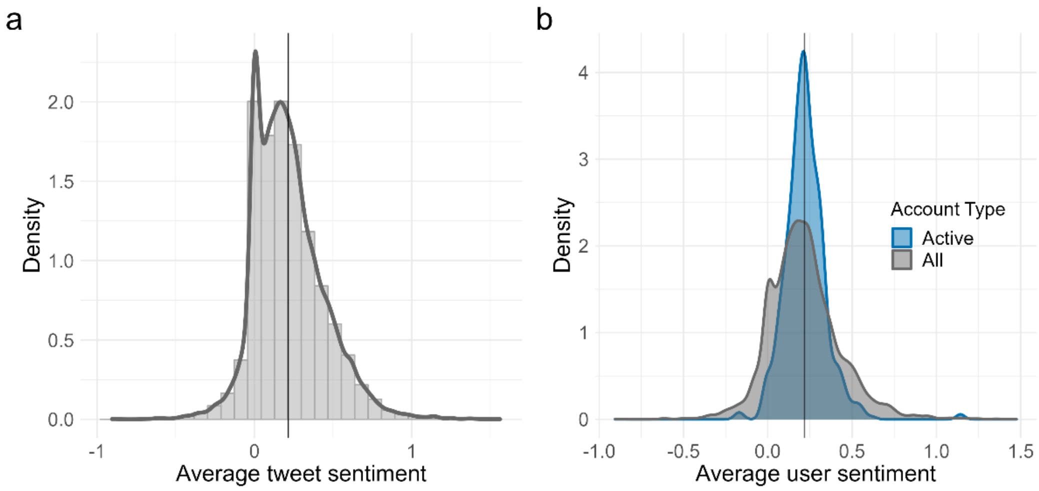

Figure 5.7: a) Distribution of average sentiment scores for cleaned tweet content in English (n = 15,126), **b)** distribution of average sentiment scores for cleaned tweet content in English per account showing all accounts (grey, n = 4,837) and the top 10% most active accounts (blue, n = 552). Vertical lines represent mean values (0.25 and 0.21 respectively).

5.5 Discussion

This study successfully used social media as a data source to explore the bioeconomy concept and analyse its use, representation, and main stakeholder groups in broader, informal societal spaces. The results contribute to the literature regarding bioeconomy by providing insight into how bioeconomy has served to connect stakeholders separated across disciplines and spatial scales, and identifying the main themes associated with its use outside the elite realms of governance and scientific literature. We found that bioeconomy was present on the social media platform Twitter with over 16 thousand individual tweets retrieved over a 12-month span, showing evidence of broader societal discourse beyond research and governance, although representing a niche topic amongst 500 million tweets contributed per day (Karami et al., 2020). Its main proponents were concentrated in Western Europe and North America and reflect a broad range of stakeholders, but typically those who are already familiar or aligned to the concept. Bioeconomy was represented alongside positive sentiments and aspirational ideas for biotechnological discovery, innovation, and economic prosperity, with more limited consideration for broader environmental, social, and sustainability challenges (with the exception of climate). There was evidence that bioeconomy can serve as a bridging concept that connects stakeholders across boundaries and disciplines, but primarily between those already engaged with the term in high-tech, well-educated contexts.

5.5.1 *Who is tweeting about bioeconomy?*

An active cohort of users engaged with bioeconomy was identified and found to be disproportionately representative of Western Europe and North America. These places may have a more established knowledge base and awareness of bioeconomy as its conceptual origins were spearheaded by high-tech, wealthy nations, particularly within the EU (Bugge et al., 2016; Patermann and Aguilar, 2018, 2021). Every country identified as a leading contributor to bioeconomy on social media in Fig. 5.1 has produced a national bioeconomy policy or strategy, while an underrepresentation of the Global South in bioeconomy-related governance has been previously noted (Dietz et al., 2018). On social media, this underrepresentation may be compounded by a lack of access or use of Twitter in those areas, however, over 100 countries were identified in the analysis of user geography and so there is evidence that some permeation beyond those core nations has occurred, including places where English is not the dominant language (discussed further below).

Some of the leading countries identified in this analysis have been highlighted as nations with strengths in their natural resource sectors and competitive advantages they seek to emphasise through the lens of bioeconomy (Ronzon et al., 2017; Ramcilovic-Suominen et al., 2022), such as Canada (Birch, 2016), Finland (Peltomaa, 2018; Korhonen et al., 2020), and Ireland (Devaney and Henchion, 2017). Belgium's representation is unsurprising given the concentration of EU institutions and associated organisations in Brussels, and the momentum provided through the EU's Bioeconomy Strategy (EC, 2018). This geographic concentration in high-tech, rich, but minority of countries, evokes familiar questions regarding the source of bioresource feedstocks that will serve as the engine of bioeconomy (Lewandowski, 2015; Holden et al., 2022) and how emergent technology (and its benefits) can or will be shared beyond those leaders (Dietz et al., 2018).

Stakeholder groups represented by Twitter accounts showed a range of different actors, not dominated by any one group. However, accounts typically represented users actively involved in promoting or supporting the concept or with objectives orientated to easily incorporate bioeconomy themes. This included i) research projects and labs working in the biosciences; ii) policy and funding institutions that have embedded the concept and lend political legitimacy; iii) individuals with a professional alignment and exposure to bioeconomy through their work (for example research students, civil servants, and consultants); iv) civil society organisations and industry associations premised on bioeconomy directly, or aligned with bioeconomy ideas; v) private companies involved in life and health sciences, biotechnology, and consultancy of bioeconomy-related industries; vi) events or gatherings created specifically as bioeconomy-related hubs. This suggests that the concept remains technical and insular in nature, adopted by those who see clear alignment or opportunity through its use and core adopters representing the "classical network of stakeholders" (Patermann and Aguilar, 2021). Reaching the wider community who do not have this foundational background remains uncertain as there is limited evidence of those further removed contributing to bioeconomy discourse on Twitter.

This range of stakeholder groups demonstrates the ability of bioeconomy to serve as a bridge between disconnected actors and has the potential to facilitate multidisciplinary collaboration—a proposed cornerstone for bioeconomy's success (El-Chichakli et al., 2016). While no stakeholder group was found to dominate network analysis, policy institutions were found to be key actors with wide reach and influence within the network and this is consistent with the comment that bioeconomy is highly sensitive to the regulatory frame it exists within (Aguilar and Twardowski, 2022). These institutions were typically those who have already demonstrated buy-in to the bioeconomy through public policy and strategic planning either at international level such as the EU (EC, 2018), or national level such as Finland (Bosman and Rotmans, 2016), and Germany (Meyer, 2017). As a core driver of bioeconomy development, policy organisations and institutions on Twitter may serve as information brokers and provide a form of self-legitimacy that further promotes bioeconomy under their framing (De Lima, 2022; Goritz et al., 2022). These governmental bodies have mobilised public finance towards bioeconomy-related projects and initiatives enabling a positive policy environment as a driver of bioeconomy's advance (Schütte, 2018; von Braun, 2022). This is further supported by the number of Twitter accounts representing research projects funded through the public-private partnership BBIJU that has served as an instrument to stimulate investment in bioeconomy and meet objectives within the European Green Deal (Johnson et al., 2021).

Civil society was well represented in the stakeholder analysis of Twitter accounts (21% of active accounts) and this group can potentially serve to provide a questioning voice or lend legitimacy to bioeconomy through raising awareness, advisory services, and whistleblowing (Meyer, 2017; Purkus et al., 2018). Many of those civil society groups were composed of industry associations representing particular interest groups (for example biofuels), or recently founded organisations with the bioeconomy concept core to their mission (for example the Irish Bioeconomy Foundation). Few environmental organisations were identified, and those that were present were linked to forestry-related activity or primary-production that can adopt bioeconomy into an already established message for stewardship of ecosystems that provide provisioning ecosystem services, for example The Food and Agriculture Organization (FAO), Organics Europe, Center for International Forestry Research. Sentiment analysis did not detect deviations of this group from the overall positive sentiment suggesting that questioning or dissenting perspectives from civil society organisations are not represented amongst the most active on Twitter, and instead they lean more towards lending legitimacy to the concept (Hausknost et al., 2017).

5.5.2 *How is bioeconomy represented on social media?*

The words used alongside bioeconomy were found to be dominated by positive sentiment, except for limited descriptions of negative problems that the bioeconomy might solve, such as waste. Specific industries (agriculture, forestry, energy) and ambitions (low carbon, economic growth, innovation, discovery) were identified showing the range of different applications envisioned by its users. The coalescence of ideas around bioeconomy in an almost universally positive sentiment supports its label as a "master narrative" that obscures alternative viewpoints and dissenting voices (Hausknost et al., 2017; Giampietro, 2023), and is similar to trends identified regarding circular economy on social media (De Lima, 2022).

The representation of primary producing industries is aligned with the bioresource or biomass visions of bioeconomy that place natural resources as central to bioeconomy's success (Bugge et al., 2016; Scordato et al., 2017; Vivien et al., 2019). This narrative of bioeconomy was found to be more prevalent in European research and policy (Bugge et al., 2016), and so this may be reflected on Twitter due to the high numbers of Europe-based accounts engaged in bioeconomy discourse. There was limited evidence of technical language tied to the biotechnology or bioscience visions such as particular technologies or processes (for example genetically modified organisms (GMOs), engineering, drugs, bacteria, fermentation). This may be a relic of Twitter as a medium that values brevity and prohibits more technical language due to the low character limits and the desire to communicate in an accessible way to a wide and general audience. The influence of policy organisations within the overall network of active bioeconomy-related contributors may also constrain the ideas presented to more general, overarching ambitions rather than high-tech specifics. Ideas captured by bioeconomy policy and strategies typically represent a more constrained perspective of bioeconomy and its priorities as a legacy of compromise and competing interests, which may have a spill over effect to the information shared on Twitter (Vainio et al., 2019; Patermann and Aguilar, 2021).

Environmental themes identified were restricted to low carbon, climate change, and the descriptor "green". This is not surprising given the ambition to reduce fossil fuel emissions was central to bioeconomy's emergence (Kircher, 2019; Vainio et al., 2019; Aguilar et al., 2021) and more recent bioeconomy projects shaped by objectives of the EU Green Deal (Johnson et al., 2021). Conceptual overlap between the paradigms of "green economy" and "bioeconomy" has been identified in previous work and may explain their co-occurrence within Twitter data (D'Amato et al., 2017). Adjacent environmental ideas present in bioeconomy literature, and to a lesser extent policy, were not detected such as ecosystem services, natural capital, environmental public goods, bioecology, biodiversity, conservation (Bugge et al., 2016; Székács, 2017; Neill et al., 2020; Holden et al., 2022). Conventional economic terms were common (production, business, work, industry) showing an orientation towards the "pro-growth" narrative of bioeconomy associated with the economic status quo, while social and environmental aspects were less prevalent (Vanholme et al., 2013; Ramcilovic-Suominen and Pülzl, 2018; Ramcilovic-Suominen et al., 2022). This phenomenon supports the view of bioeconomy as a reframing of the familiar rather than something inherently novel and transformative, and skews the "triple-win" ambition of bioeconomy towards the economic pillar (Pülzl et al., 2014).

The overall tone surrounding the representation of bioeconomy on Twitter was aspirational and positive, premised on innovation, research, and discovery. Bioeconomy has demonstrated success in the creation of collaborative networks, the dissemination of public funds, the proliferation of research projects, and the permeation of these ideas in wider societal spaces (such as Twitter). The hazy ambiguity of bioeconomy can enable the adoption of many positive ideas without in-depth scrutiny (Vivien et al., 2019), and thus represent “a useful buzzword” as suggested in other stakeholder analyses (Hodge et al., 2017). The coalescence around positive sentiment coupled with core bioeconomy users and practitioners serving as dominant information providers regarding bioeconomy on Twitter demonstrates how certain actors control information flow and representation of bioeconomy in a broader societal space (De Lima, 2022). This could be argued as a positive feedback loop perpetuating certain visions of bioeconomy as a form of self-legitimisation that fails to provide scope for reflexivity regarding the epistemological framing of bioeconomy and further embeds these frames as the norm (Ramcilovic-Suominen et al., 2022; Giampietro, 2023).

Analyses of other media engaging with bioeconomy also found either an overall positive, aspirational tone such as in Ireland (Kelleher et al., 2021), and in Finland (Peltomaa, 2018), or limited representation reflecting specific narratives for example in Spain (Sanz-Hernandez et al., 2020) and Germany (Dieken and Venghaus, 2020). More targeted, in-depth stakeholder studies have detected broader sustainability concerns such as land use and resource trade-offs, inequalities in access and benefits, and required behaviour change (Vainio et al., 2019; Vivien et al., 2019; Zeug et al., 2019), while vigorous interrogation of bioeconomy at the conceptual level is present in the academic literature (D'Amato et al., 2017; Gawel et al., 2019; Holden et al., 2022; Ramcilovic-Suominen et al., 2022; Giampietro, 2023). There is limited evidence that these more critical perspectives have disseminated as themes in broader societal discourse as captured on social media.

The most common words presented alongside bioeconomy in the text of tweets were “circular” and “sustainable”, and to a lesser extent, “green”. This shows an attachment of bioeconomy to other descriptive sustainability terms, blurring what each means in isolation and how they can be combined (D'Amato et al., 2017; Holden et al., 2022). It also represents an implicit acceptance that bioeconomy is not inherently sustainable or circular. The catch-all descriptive qualifier of “sustainable” consistently applied to bioeconomy masks the so-called “shades of green” (Kleinschmit et al., 2014) within the concept and avoids any attempt to untangle what this means in practice. This supports the point that bioeconomy is vulnerable to being conflated with an overall green image that is untested or scrutinised (Ramcilovic-Suominen and Pülzl, 2018). It also suggests an acknowledgement that the term “bioeconomy” in itself is insufficient to capture the desired sustainability vision users hope to communicate, and its confluence with "circular" reflects a step towards the proposed "circular bioeconomy" as a new paradigm that addresses shortcomings of the original bio- and circular economy concepts (Carus and Dammer, 2018; Kardung et al., 2021).

5.5.3 *Social media as an insight into broader societal discourse*

Social media was successful in capturing a large volume of data spanning a wide range of actors and geographies that would otherwise be costly and resource-intensive to assemble (Tenerelli et al., 2016; Ghermandi and Sinclair, 2019). However, there are some caveats to this analysis that must be acknowledged. Firstly, the retrieved dataset was limited to the English language. While there is evidence from this study that the term "bioeconomy" is being used internationally, including where the predominant language is not English, this analysis is unable to comment on any translated use. A cursory search showed the Spanish word "bioeconomía" was used at a similar frequency to the English term. This suggests there may be an active network of Twitter users based in South and Central America engaging in bioeconomy-related ideas not recorded in this study (Sasson and Malpica, 2018). This goes beyond the expertise and scope of this pilot social media analysis but represents a potential avenue to build on this research.

Another challenge is that the user base of social media is skewed towards a self-selecting population located in geographies with accessible and consistent connectivity and digital technologies (Zhang et al., 2022). This may underrepresent users from less wealthy places, places without an established online, digital culture of information sharing, or places that do not permit access to certain platforms such as China (Hargittai, 2020). Certain demographics may also be disproportionately represented on social media platforms such as younger, wealthier users, and there may be a gender bias (Ghermandi and Sinclair, 2019; Hargittai, 2020; Zhang et al., 2022). Twitter was used in this analysis as a platform with a large base, which is free to join and use, and with a low bar for sharing content and creating connections (Stewart and Quan-Haase, 2017; Antonakaki et al., 2021). This may make it easier for people to engage in societal discourse compared to other platforms, but these concerns remain relevant, and results should not be used to generalise all of society or bioeconomy-engaged groups.

The nature of Twitter as a micro-blogging site that limits the number of characters per shared content item can also have an impact on the type of information represented. Long-form content is less likely to be shared and this may stimy more critical, interrogatory perspectives that delve into more nuanced aspects of a given topic, with the exception of “threads” of short content pieces connected as a series by a single author (Antonakaki et al., 2021). It was notable that perspectives with a negative tone were uncommon and so even if those more critical perspectives are present in other venues, those engaging with bioeconomy on Twitter are not exposed to those ideas. There is also uncertainty regarding sentiment analysis applied to specialist fields such as bioeconomy (Pan and Vira, 2019). This study applied a commonly used dictionary scheme that was not created for this specific purpose, but successfully identified key themes and sentiment at a coarse level. This uncertainty was reduced by applying sentence-level sentiment analysis rather than relying on individual words, although there is still some degree of inaccuracy.

The data used in this study were collected prior to a major upheaval in the social media landscape due to changing ownership of the private company Twitter. Platforms such as Twitter serve as public forums for discourse and information sharing and these changes represent a risk to the long-term use of such sites, and the data contained within them (Kapoor et al., 2018). Users may choose to delete their accounts or stop using certain platforms if they are no longer deemed useful or relevant, and data access policies may change preventing the retrieval of records for research purposes. Similarly, privacy and ethical concerns regarding data collection remain an ongoing discussion within the literature and may change how such research is carried out in the future (Toivonen et al., 2019). It remains to be seen what this means for Twitter specifically, but the results of this study remain a pertinent window into bioeconomy discourse in 2021–2022.

Even with these considerations, the results from this analysis have implications for the mainstreaming and information flow of bioeconomy in broader societal spaces. There is evidence that the network of users actively engaged in bioeconomy has reached beyond the “elite” of highly technical experts in policy and research and includes individuals, researchers, civil society, and the private sector. The ambition to reach beyond core experts has been posited as a frontier of future bioeconomy development and this may indicate some first steps (Patermann and Aguilar, 2021). While the range of actors was found to be a mix of stakeholders, the most common themes captured in bioeconomy content reflected a conventional economic and technical vision of bioeconomy (such as innovation, growth, climate, industry), with the addition of the “sustainable” label. This is similar to prevailing narratives identified in literature engaging with bioeconomy and policy (Gould et al., 2023), and it may be that the few but well-connected and influential policy-based users within the network serve to set the tone for the flow of bioeconomy-related information on Twitter. This supports previous observations that bioeconomy is sensitive to the regulatory frame it exists within, and therefore, those who control this regulatory frame hold disproportionate influence over the narrative (Aguilar and Twardowski, 2022). Finally, the skewness of user backgrounds towards high-income, highly-educated contexts and professional backgrounds shows that while bioeconomy has permeated across geographies and user groups, it has not yet achieved the wider societal awareness and acceptance it requires to achieve its social sustainability aspirations (Sanz-Hernández et al., 2019).

5.6 Conclusion

Bioeconomy was detected within broader societal discourse as represented on the social media platform Twitter indicating a diffusion beyond the academic and governance realms. There is some evidence that the term has connected stakeholder groups otherwise separated by geography, discipline, or objective and thus supporting the claim that bioeconomy can serve as a bridging concept. However, engagement was concentrated amongst wealthy, high-tech, well-educated regions and users, especially within Western Europe and North America. Those users appear to have some prior interest and exposure to bioeconomy such as research projects centred on biological resources, political institutions that have a history of championing bioeconomy-related development, and industry actors involved in primary production or biotechnological investment. Most bioeconomy-related tweets were found to be positive in sentiment and herald the potential for future discovery and innovation that is sustainable, with limited evidence of dissenting voices or alternative perspectives. Overall, societal discourse of bioeconomy as reflected on social media is positive, hopeful, and concentrated on those already converted to the concept, rather than reaching those unfamiliar or opposed.

CHAPTER 6 | Discussion

6.1 Bioeconomy, natural capital, and ecosystems services

This thesis examined two concepts entrenched in contemporary environmental sustainability debates—bioeconomy and natural capital (and ecosystem services). Chapter 2 articulated a joint framework for how these concepts can be applied synergistically to achieve positive environmental outcomes through reframing the impacts and dependencies people have on nature. The subsequent chapters contributed to knowledge regarding the integration of natural capital and ecosystem services within governance systems (Kettunen et al., 2014; Chaudhary et al., 2015; Bouwma et al., 2018), furthered the development of cultural ecosystem service spatial assessment models (Wood et al., 2013; Zhang et al., 2022), and explored the use and representation of bioeconomy in the informal, public forum of social media. This work shows that these concepts can improve the awareness, recognition, and visibility of the contributions nature provides to people, especially given their increasing use within research, governance, and practice (Chaudhary et al., 2015; Bugge et al., 2016; Costanza et al., 2017; Hein et al., 2020). Evidence that these concepts can be operationalised was also discussed such as the institutionalisation of natural capital accounting and ecosystem assessments (Vardon et al., 2018; EEA, 2019a; Hein et al., 2020), and the use of bioeconomy as a catalyst for financial investment in environmental projects (EC, 2018; Johnson et al., 2021).

The role of politics in shaping bioeconomy is evident given the multitude of competing visions attached to the term (Bugge et al., 2016; Patermann and Aguilar, 2018; Vivien et al., 2019), and its blurred overlap with other sustainability paradigms (D'Amato et al., 2017; Carus and Dammer, 2018). The promise that bioeconomy can further economic growth and societal wellbeing, while ending environmental declines, provides an elegant and attractive umbrella for policymakers, especially in high-technology, bioresource-rich contexts (Dietz et al., 2018; Gawel et al., 2019). The role of political institutions, especially from Western Europe, in shaping the narrative of bioeconomy on social media is one example of this (Chapter 5). This can be a positive trait. The political legitimacy granted to bioeconomy as a flagship policy allows it to easily integrate alongside other political projects as exemplified by the EU Green Deal and the Bio-based Industries Joint Undertaking Initiative

(Johnson et al., 2021; Patermann and Aguilar, 2021). Therefore, it can be argued that bioeconomy serves as a vehicle for sustainability aspirations rather than possessing a well-developed musculature for practical sustainability action and assessment tools. This raises questions about the underlying assumptions required to realise the economic, social, and environmental triple-win scenario. Within the academic literature, the complexities of the environmental aspects of bioeconomy are increasingly scrutinised (Kleinschmit et al., 2017; Székács, 2017; Egenolf and Bringezu, 2019; Holden et al., 2022), but formal assessment criteria for bioeconomy projects remain unresolved. This thesis argues that while developing a sound bioeconomy evidence base for improving environmental outcomes is essential, this need not start from a blank canvas. Rather, it should build upon the foundation of other aligned environmental sustainability concepts that do possess established, practical tools such as life cycle assessments, environmental foot printing, ecosystem service assessments, and natural capital accounting (O'Brien et al., 2017; D'amato et al., 2020; Holden et al., 2022). Under this light, the hazy ambiguity of bioeconomy as a “master narrative” (Korhonen et al., 2020) could be viewed as a positive asset that enables borrowing from adjacent sustainability paradigms and accelerating their impact.

Natural capital and ecosystem service terminology is embedded in international environmental discourse (Chaudhary et al., 2015; IPBES, 2019). This has also occurred at the national policy level in Ireland, mirroring trends observed in other national contexts (Maczka et al., 2016; Claret et al., 2018; Dasgupta, 2021). The pressing challenge now is translating this into action that ultimately feeds back into decision-making systems (Guerry et al., 2015). Natural capital accounting and ecosystem service assessments are becoming more commonplace and enabled by systematic protocols and guidelines (Obst, 2015; van Oudenhoven et al., 2018; Vardon et al., 2018; Helm, 2019; Bateman and Mace, 2020; Hein et al., 2020; UN, 2021), including pilot cases in Ireland (Parker et al., 2016; Farrell et al., 2021). It appears the path forward for environmental assessments and reporting will be intertwined with these terms for the foreseeable future. Ecosystem services feature in Sustainable Development Goal 15, the most recent EU Biodiversity Strategy, and the draft reporting standards of the Corporate Sustainability Reporting Directive of the EU entering into force in 2024 (UN, 2015; EC, 2020; EFRAG, 2022). Meanwhile the System of Environmental-Economic Accounting: Ecosystem Accounting (SEEA

EA—a form of natural capital accounting) has been adopted by the UN Statistics Division and proposed as a future global standard (UN, 2021; Edens et al., 2022). A culture of open data and analysis tools has supported implementation exercises such as the Natural Capital Project's InVEST model software and database (Sharp et al., 2018; Natural Capital Project, 2020), the newly published Ecosystem Service Valuations Database (ESVD) (Brander et al., 2022; Brander et al., 2023), and online repositories such as GitHub (Braga et al., 2023). Such resources are assets for developing future assessments and should be supported in the long-term to efficiently build capacity for meeting those multilateral environmental policy goals.

Cultural services (or nature's non-material contributions to people) are especially challenging due to their context-specific characteristics, and diverse range of assessment techniques and corresponding metrics (Chan et al., 2012b; Cheng et al., 2019). While important concerns remain regarding the language, values, and valuation attached to these services (Baveye et al., 2013; Schröter et al., 2014; Chan and Satterfield, 2020; IPBES, 2022), providing some kind of information is preferable to their absence from decision-making systems entirely. Chapter 4 presents this kind of approach that acknowledges the assumptions and shortcomings of relying on one type of social media data but providing spatial assessment at a scale previously unavailable in an otherwise data-limited context. Complementing such broad, albeit shallower, studies with deeper dives into individuals' values, preferences, and lived experience—for example using mixed-methods and participatory approaches—is an important next step. This dual approach should be considered best practice to avoid losing the richness and diversity of cultural services.

6.2 Future directions for environmental sustainability research and practice

Chapters 2-5 outlined directions for future research that can build upon their contents. Two examples include continued monitoring of the science-policy trajectories of sustainability concepts and expanding this work to consider down-stream implementation (Kettunen et al., 2014; Claret et al., 2018), and complementing social media cultural ecosystem service studies with participatory approaches (Ghermandi and Sinclair, 2019; Zhang et al., 2022). The following section moves to make broader observations regarding environmental sustainability research and practice. Achieving systemic, transformative change for environmental sustainability is beyond simply scaling up small or local-level successes in one dimension (Chan et al., 2020). It is not appropriate to claim that any singular concept holds the key to halting environmental declines. However, there are lessons to be learned from the case-study examples presented in this thesis that can inform future work across scales. I outline three overarching themes gleaned from this thesis below: i) novel data sources and analysis, ii) acceleration and expansion of research, and iii) fragmentation.

6.2.1 *Novel data sources and analysis tools*

This range of potential data for environmental research is growing in terms of both volume and diversity of sources. This is showcased throughout this thesis that drew upon academic literature, policy documents and government reports, user-generated social media content and metadata, and spatial data of landscape features from local, national, and international sources. What might be considered traditional environmental data such as field surveys, biophysical monitoring, and experimental work are being augmented by so-called "big data" including remote sensing at high resolution (Pettorelli et al., 2018), and harvesting data from online content (Ghermandi and Sinclair, 2019; Toivonen et al., 2019). There is rich opportunity to apply this abundance of data to environmental research questions given the data-hungry characteristics of ecosystem assessment exercises (Schröter et al., 2015), but this is hampered by ill-equipped data infrastructure leading to inconsistent accessibility, formats, and resolution (temporally and spatially). One example is shown in Chapter 4 through the assembly of environmental predictor datasets using local, national, and international sources that had to be harmonised into a consistent extent and resolution. Similarly, technological innovation has unlocked advanced data processing through automation, machine learning, and open-access statistical tools (for example maximum entropy models (Phillips, 2017) or image recognition (Richards and Tunçer, 2018)). These tools, while computationally demanding in resources and expertise, can enable analysis workflows at a scale and speed previously unobtainable (Manley et al., 2022). Future environmental research will require harmonised datasets that address data gaps

(Hein et al., 2016; Farrell et al., 2021), and investment in preparation for an era of ever-increasing "big data" (Manley et al., 2022).

A concern regarding these emergent data sources and technologies is their privatisation. Corporate entities or individuals that accumulate ownership of such data and tools hold the power to alter data access, pricing, and long-term availability without warning or consultation. A recent example is the termination of the free academic licence for Twitter's API that removes access to the Twitter data archive (without paying for a premium service) that was previously accessible for non-profit use (Ledford, 2023). These data and analysis tools hold huge potential for unlocking research for the public good, including environmental sustainability (Ghermandi et al., 2023), but regulation has not kept pace with technological advancement, endangering this public good. There is a twisted parallel between the concentration of environmental data and analysis tools by a small number of wealthy corporations and individuals with the historical plundering of nature that has concentrated resources amongst the few at the expense of the many. In addition to access and ownership, there are also unresolved questions regarding privacy and the ethics of using such big data harvested without user knowledge or consent (Zhang et al., 2022; Ghermandi et al., 2023). These considerations represent potential barriers that will become increasingly pertinent for the research sector as technology and analysis techniques advance.

6.2.2 *Acceleration of research*

The use of bioeconomy, natural capital, and ecosystem service language within environmental research is increasing (Bugge et al., 2016; Costanza et al., 2017; Mougenot and Doussoulin, 2022). The proliferation of literature on the topic of bioeconomy was evident when writing this thesis as environmental debates discussed in Chapter 2 have already evolved in more recent academic literature (for example Holden et al. (2022) and Ramcilovic-Suominen et al. (2022)). Another example is the introduction of the term "nature's contributions to people", separate from ecosystem services, which has reinvigorated debate on the topic of people-nature relationships (Díaz et al., 2018a; Maes et al., 2018; Chaplin-Kramer et al., 2019; Kadykalo et al., 2019). Outside of academia, bioeconomy, natural capital, and ecosystem services are increasingly embedded in governance systems at multiple scales (Chapter 2, Chapter 3, Chaudhary et al. (2015); Dietz et al. (2018); IPBES

(2019)), and in practical applications such as natural capital accounting exercises (Helm, 2019; Hein et al., 2020).

The growing focus on environmental sustainability is promising but also represents challenges. The sheer volume of information, techniques, and concepts must be matched in an increase in the capacity of individuals and institutions—within governance, practice, and academia alike—to absorb and incorporate this knowledge. Additionally, while the integration of these concepts within policy dialogue and international commitments is one of the most influential levers over the mechanisms of environmental decision-making (Maes et al., 2013; Chaudhary et al., 2015; EC, 2018; IPBES, 2019), science-policy transitions are characterised by time-lags and uncertain trajectories (Posner et al., 2016; Saarikoski et al., 2018). There is uncertainty regarding how readily governance systems can respond to this rapid increase in emergent knowledge. This represents a potential friction between operationalising what is already present within policy and practice and adapting to ongoing scientific discovery. Two complementary pathways to reduce this friction and navigate the wealth of emergent environmental knowledge are streamlining the pipeline of science-policy transitions so decision-making systems can incorporate emergent science, and investment in expertise and capacity so as decision-making actors are primed and ready to receive and operationalise such science.

6.2.3 *Fragmentation*

An observation that re-occurred throughout this thesis was a pattern of fragmentation between ideas and stakeholders. Chapter 2 remarked on minimal overlap between bioeconomy and natural capital within the academic literature despite possible synergies and traits in common. One conclusion from Chapter 3 was that different policy departments showed varied integration of ecosystem service ideas creating a fragmented policy landscape. In Chapter 4, one of the reasons behind testing 4 different modelling approaches was that the literature lacked a clear guide for how to select the best approach and not all authors clearly reported their justification for selecting one statistical method compared to another. Chapter 5 showed a mix of stakeholders engaging with the bioeconomy term but from specific backgrounds and interest groups rather than the general population. Both concepts examined in this thesis showed some ability to serve as boundary objects—available to a range of users from different backgrounds and bringing together a diversity of knowledge (Abson et al., 2014; Baggio et al., 2015)—but this does not appear to be universal, creating gaps in their respective fields of sustainability discourse. This fragmentation limits the potential for sustained change because reframing people-nature interactions requires buy-in and support from all those who impact or depend on the environment, which is to say, everyone.

There are some characteristics that may be predisposed to facilitate this fragmentation. Firstly, the concepts examined in this thesis were more readily incorporated by individuals and institutions with a shorter conceptual distance to these emergent ideas due to a similar mission, self-interest, or exposure to similar epistemological framings. For example, policy areas whose core mission involved protecting, monitoring, and advocating for nature showed greater integration of ecosystem services (Bouwma et al., 2018). The same was true for bioeconomy that was popular amongst specific industry and research groups who may see the concept as an opportunity to access investment or regulatory benefits (Priefer et al., 2017; Vivien et al., 2019). Conversely, barriers may exist where emergent concepts are perceived as unrelated, irrelevant, or disruptive. Examples include ecosystem services' underrepresentation within economic reports, and bioeconomy's absence from regions without a history of high-technology industry (Dietz et al., 2018). One promising exception is the Dasgupta review of the economics of biodiversity commissioned by the UK treasury and led by independent economic experts (Dasgupta, 2021). These observations highlight that when using environmental sustainability concepts, there may be obvious champions that are primed and ready to respond to those efforts and have access to leverage points that can spur change in the wider system (Chan et al., 2020), while others may require more purposeful, targeted efforts to overcome an initial unwillingness or inertia.

This pattern raises questions about the space for reflexivity in environmental research. If those central to shaping the narrative for environmental sustainability concepts are those from a narrow epistemological background and are unable to bring other perspectives into the fold, it is unclear where dissenting or questioning voices can emerge from (Ramcilovic-Suominen et al., 2022). This leaves the field vulnerable to unintentionally embedding flawed assumptions or framings such as a dependence on monetary valuations, a neglect for alternative kinds of value, overlooking indigenous knowledge, a fixation on economic growth, or a reenforcement of colonial legacies (Baveye et al., 2013; Díaz et al., 2018b; Ramcilovic-Suominen et al., 2022; Giampietro, 2023).

Finally, the need for interdisciplinary research that brings together and integrates a range of knowledge in conjunction with a diversity of approaches is another challenge that can contribute to fragmentation. Even though bioeconomy and natural capital are premised on the confluence of economics and natural sciences, the two concepts showed limited overlap within the literature, and both have issued calls for greater integration with social science perspectives (Guerry et al., 2015; Sanz-Hernández et al., 2019). Chapter 4 of this thesis noted that the use of maximum entropy modelling for cultural services was led by authors suspected of having prior exposure to biodiversity habitat suitability modelling, and who have now introduced this tool to wider research topics such as aesthetics and tourism studies (Yoshimura and Hiura, 2017; Arslan and Örücü, 2021). Fostering a research ecosystem that is comfortable and supported traversing a range of fields to create those connections should be a priority given that the crisis of environmental sustainability is multidimensional and intersects with all fields of research. This should not be considered a chore, but a new frontier of scholarship that holds exciting potential for diverse teams and more robust science.

6.3 Concluding remarks

Human activity is driving the degradation of ecosystems and decline of biodiversity, jeopardising the environmental conditions that support all of society and economy (Steffen et al., 2015; Ceballos and Ehrlich, 2018; IPBES, 2019). In this thesis I have shown how people-nature interactions can be reimagined through the lenses of bioeconomy and natural capital. Beyond reframing the impacts and dependencies between socio-economic systems and the environment (Chapter 2), this work demonstrates how these concepts have become central to environmental policy at international and national scales (Chapter 3), can be used to provide practical spatial models to inform decision-making (Chapter 4), and can connect disparate stakeholders under a shared ambition (Chapter 5). Achieving transformative change that addresses environmental decline is immeasurably complex. Continued investigation of the use and application of these concepts from a multidimensional perspective is imperative to understand their progress towards achieving an end of environmental degradation. This is especially true given that these concepts have become central to environmental discourse, policy commitments and political dialogue, and interdisciplinary research; their relevance for future environmental decision-making is indisputable.

The work presented here identified potential enablers and barriers for environmental sustainability progress. Enablers include harnessing the opportunity of technological advancement, novel data sources, policy engagement, regulatory processes and standards, and individual demand for improved environmental outcomes. Potential barriers include embedded norms, unreliable data access, under resourced data infrastructure, a lack of interdisciplinary expertise and curiosity, a need for investment in capacity building, and addressing fragmentation. Ultimately, bioeconomy and natural capital can be used to spur positive environmental action that considers the variety of contributions nature makes to people's lives. This is not an inevitable conclusion, and it is uncertain if their capacity for generating positive change can match the enormous challenge of systemic environmental declines. Maximising this contribution requires continued monitoring and assessment of these concepts' evolution, integration within decision-making systems, and practical applications. This knowledge base will better equip humanity to end the erosion of nature and safeguard the wellbeing of people today, and future generations.

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APPENDIX A | Supplementary Material for Chapter 3

Table A1: List of 50 sampled policy and reporting documents showing year of publication, policy domain category, and the publisher at the time of publication. All documents were sourced online from respective organisation websites except for the 3 oldest "Ireland's Environment" reports that were accessed through request from the EPA.

Document Title	Year	Category	Published by
AgClimatise - National Climate & Air Roadmap for the Agriculture Sector	2020	Agri-food	Dept. of Agriculture, Food and the Marine (DAFM)
Agriculture Forest and Seafood Climate Change Sectoral Adaptation Plan	2019	Agri-food	Dept. of Agriculture, Food and the Marine (DAFM)
Naturally Ireland - A Guide to Agriculture, Fisheries and Food	2007	Agri-food	Dept. of Agriculture, Fisheries and Food
AgriFood 2010	2000	Agri-food	Dept. of Agriculture, Food, and Rural Development
AgriVision2015	2005	Agri-food	Agri Vision 2015 Committee
Foodharvest 2020	2010	Agri-food	Dept. of Agriculture, Food and the Marine (DAFM)
FoodWise2025	2015	Agri-food	Dept. of Agriculture, Food and the Marine (DAFM)
National Biodiversity Plan 2001	2001	Biodiversity	Dept. of Art, Heritage, Gealtacht and the Islands
National Biodiversity Action Plan 2017-2021	2017	Biodiversity	Dept. of Culture, Heritage and the Gaeltacht
Interim Review of the Implementation of the National Biodiversity Plan 2002-2006	2005	Biodiversity	Dept. of the Environment, Heritage and Local Government
Actions for Biodiversity 2011-2016 - Ireland's national biodiversity plan	2011	Biodiversity	Dept. of Art, Heritage and the Gaeltacht
Interim Review of the Implementation of the National Biodiversity Action Plan 2017-2021	2020	Biodiversity	Dept. of Culture, Heritage and the Gaeltacht

Interim Review of the Implementation of Actions for Biodiversity 2011-2016	2015	Biodiversity	Dept. of Art, Heritage and the Gaeltacht
Annual Review & Outlook for Agriculture and Food 2004/5	2005	DAFM	Dept. of Agriculture and Food
Annual Review & Outlook for Agriculture and Food 2005/6	2006	DAFM	Dept. of Agriculture and Food
Annual Review & Outlook for Agriculture and Food 2006/7	2007	DAFM	Dept. of Agriculture and Food
Annual Review & Outlook for Agriculture, Fisheries and Food 2007/2008	2008	DAFM	Dept. of Agriculture, Fisheries and Food
Annual Review & Outlook for Agriculture, Fisheries and Food 2008/2009	2009	DAFM	Dept. of Agriculture, Fisheries and Food
Annual Review & Outlook for Agriculture, Fisheries and Food 2009/2010	2010	DAFM	Dept. of Agriculture, Fisheries and Food
Annual Review & Outlook for Agriculture, Fisheries and Food 2010/2011	2011	DAFM	Dept. of Agriculture, Fisheries and Food
Annual Review & Outlook for Agriculture, Food and the Marine 2011/2012	2012	DAFM	Dept. of Agriculture, Food and the Marine
Annual Review & Outlook for Agriculture, Food and the Marine 2012/2013	2013	DAFM	Dept. of Agriculture, Food and the Marine
Annual Review & Outlook for Agriculture, Food and the Marine 2013/2014	2014	DAFM	Dept. of Agriculture, Food and the Marine
Annual Review & Outlook for Agriculture, Food and the Marine 2014/2015	2015	DAFM	Dept. of Agriculture, Food and the Marine
Annual Review & Outlook for Agriculture, Food and the Marine 2015/2016	2016	DAFM	Dept. of Agriculture, Food and the Marine
Annual Review and Outlook for Agriculture, Food and the Marine 2016/2017	2017	DAFM	Dept. of Agriculture, Food and the Marine

Annual Review and Outlook for Agriculture, Food and the Marine 2017/2018	2018	DAFM	Dept. of Agriculture, Food and the Marine
Annual Review and Outlook for Agriculture, Food and the Marine 2018/2019	2019	DAFM	Dept. of Agriculture, Food and the Marine
Annual Review and Outlook for Agriculture, Food and the Marine 2020	2020	DAFM	Dept. of Agriculture, Food and the Marine
State of the Environment Ireland 1996	1996	Environment	Environmental Protection Agency (EPA)
Ireland's Environment A millennium report	2000	Environment	Environmental Protection Agency (EPA)
Ireland's Environment Report 2004	2004	Environment	Environmental Protection Agency (EPA)
Ireland's Environment Report 2008	2008	Environment	Environmental Protection Agency (EPA)
Ireland's Environment: An assessment 2012	2012	Environment	Environmental Protection Agency (EPA)
Ireland's Environment: An assessment 2016	2016	Environment	Environmental Protection Agency (EPA)
Ireland's Environment: An integrated assessment 2020	2020	Environment	Environmental Protection Agency (EPA)
Forest Research Ireland FORI	2014	Forestry	Forest Service, Dept. of Agriculture, Food and the Marine (DAFM)
Forestry Programme 2014-2020: Ireland	2015	Forestry	Forest service, Dept. of Agriculture, Food and the Marine (DAFM)
Forests, products and people: Ireland's forest policy - a renewed vision	2014	Forestry	Forest Service, Dept. of Agriculture, Food and the Marine (DAFM)
Growing for the Future: A strategic plan for the Development of the Forestry Sector in Ireland	1996	Forestry	Dept. of Agriculture, Food and Forestry
Indicative Forestry Statement	2008	Forestry	Forest Service, Dept. of Agriculture, Fisheries and Food

Irish National Forest Standard	2000	Forestry	Forest Service, Dept. of Natural Resources
Management Guidelines for Ireland's Native Woodlands	2017	Forestry	National Parks and Wildlife Service and Dept. of Agriculture, Food and the Marine (DAFM)
Forest Recreation in Ireland	2006	Forestry	Forest Service, Dept. of Agriculture and Food
Harnessing our ocean wealth - review of progress 2018	2019	Marine	Inter-Departmental Marine Coordination Group
Harnessing Our Ocean Wealth	2012	Marine	Inter-Departmental Marine Coordination Group
Marine Planning and Policy Statement (Draft)	2019	Marine	Dept. of Housing, Planning and Local Government
National Strategic Plan Sus Aquaculture Development	2015	Marine	Dept. of Agriculture, Food and the Marine
Steering a new course - Strategy for a Restructured, Sustainable and Profitable Irish Seafood Industry 2007-2013	2006	Marine	Seafood Industry Strategy Review Group
The Irish Seafood National Programme	2010	Marine	Dept. of Agriculture, Fisheries and Food

Table A2: Categorisation matrix for coding ecosystem services based on CICES v5.1. Corresponding CICES classification codes are shown, and slight modifications outlined. Division codes (P = provisioning, R = regulating, C = cultural).

Division	Service	Description	CICES code	Notes
P	Biomass - food, feed	Production of biomass (of any origin) to be used to feed people directly or to feed livestock or animals.	1.1.x.1	CICES divides these classes by organism type (cultivated plant, animal agriculture, aquaculture, wild animal, etc). This differentiation is rarely present in sample texts. Coding scheme used aggregates accordingly.
P	Biomass - timber, materials	Production of biomass to be used in construction, building, furniture etc. (typically timber / wood).	1.1.x.2	CICES differentiates by organism type rather than function (see above). CICES also does not differentiate between the use of biomaterials produced. Here we split between biomaterials such as timber, and those for health benefits as this was a clear difference in the text of sampled documents.
P	Pharmaceuticals	Production of pharmaceuticals, medicinal compounds, extracts or isolates from plants or animals to be used in medicinal or healthcare setting.	1.1.x.2	CICES differentiates by organism type rather than function (see above). CICES also does not differentiate between the use of biomaterials produced. Here we split between biomaterials such as timber, and those for health benefits as this was a clear difference in the text of sampled documents.
P	Biomass - energy	Production of energy from either combustion of biomass or the fermentation and treatment of biomass to produce biogas or biofuels.	1.1.x.3	CICES differentiates provisioning services by organism type in the hierarchy. This scheme is focused on use (origin rarely useful as a differentiator in the text).

P	Genetic Resources	Genetic material that provides some benefit to people - includes wild relatives, use in selective breeding techniques, individual genes, or the use of novel or particularly targeted genes in specific technology.	1.2.x.x	Genetic resources form one clade in CICES hierarchy and replicated here at lower resolution. Use of genetic resources is not consistently clear in text e.g., seed production, individual genes, breeding, use wild relatives. Aggregated into one code for this study.
C	Amenity	Direct interaction with the environment that provide some benefit in a passive way.	3.1.1.2	Matches CICES definition but relabelled as amenity to match use in text.
C	Bequest	Characteristics of ecosystems that have an option or bequest value that have a benefit for future people / generations	3.2.2.2	Matches CICES. Often denoted only by mention of future generations in the text as rarely expanded on in other ways.
C	Biodiversity	Non-use, passive interaction of biodiversity that is deemed to have an existence or intrinsic value	3.2.2.1	CICES classify this as an "existence" value of biological systems. It is uncertain is all instances of biodiversity within sample are associated with "existence" values but all are grouped under this code unless sufficient justification otherwise e.g., biodiversity-mediated services.
C	Education	Characteristics of living systems that create opportunities for learning, education, and training.	3.1.2.1/2	CICES splits this in scientific learning (e.g., taxonomy) and other educational opportunities (outdoor classrooms). Grouped together here as difference rarely recognised.
C	Heritage and Culture	Characteristics of living systems that are resonant in terms of culture or heritage	3.1.2.3	Matches CICES.

C	Landscape	Characteristics of living systems that create pleasant landscape or seascapes.	3.1.1.2 & 3.1.2.4	Two CICES codes may overlap here as landscape / seascape is mentioned in text without explicitly outlining if the benefit is from passive experience or through aesthetic beauty.
C	Recreation	Direct interactions or activities with or within environment/ecosystems that provides some benefit or enjoyment by people local to the area.	3.1.1.1	This shares a definition with tourism, the difference being the description in text based on the origin of the people benefitting from the service. CICES does not make this differentiation but is very common within the text sample.
C	Spiritual	Spiritual or religious meaning from interactions with ecosystems or the environment	3.2.1.2	Matches CICES.
C	Symbolic and Reputation	Elements of living systems that have symbolic or reputational values. For example Ireland's "green" reputation.	3.2.1.1	Matches CICES and extended to also include reputation benefits that may not be physical emblems but a social construction attached to a specific nation or region e.g., "green image" of Ireland and Irish products.
C	Tourism	Direct interactions or activities with or within environment / ecosystems that provides some benefit or enjoyment for people who are not local to the area	3.1.1.1	This shares a definition with tourism, the difference being the description in text based on the origin of the people benefitting from the service. CICES does not make this differentiation but is very common within the text sample.
R	Acid Buffer	Regulation against extreme changes in pH chemical status of soil or water.	2.2.5.x & 2.2.6.x	Combines sub-divisions under CICES that refer to chemical status regulation. Creation of new code in this scheme due to instances of specific inclusion within sample.
R	Air quality	Regulation of atmospheric chemical composition and conditions	2.2.6.1	Sub-division of CICES category related to atmospheric conditions

R	Carbon sequestration (l)	Regulation of atmospheric chemical composition and conditions, specifically the sequestration of carbon by terrestrial ecosystems	2.2.6.1	Sub-division of CICES category related to atmospheric conditions
R	Carbon sequestration (m)	Regulation of atmospheric chemical composition and conditions, specifically the sequestration of carbon by marine ecosystems	2.2.6.1	Sub-division of CICES category related to atmospheric conditions
R	Climate resilience	Regulation or maintenance of conditions that enable adaptation under a changing climate regime.	2.3.X	Not present explicitly in CICES and falls under "other".
R	Coastal defence	Regulation of coastal conditions in terms of both erosion, wave damage, and flooding.	2.2.1.3	Sub-division of CICES category related only to coastal systems rather than all hydrological systems.
R	Disease resilience	Regulation of environment conditions through the control and mediation of disease	2.2.3.2	Matches CICES
R	Drought control	Mitigation or regulation of drought conditions / water shortages	2.2.6.2 & 2.2.1.3	Partially matches CICES. Includes both water shortages due to large-scale hydrological cycle and regulation of local conditions.
R	Erosion mitigation	Control of erosion rates.	2.2.1.1	Matches CICES
R	Extreme event control	Mediation of the impact of extreme events or natural disasters excluding floods. Examples include landslide, storms, wind.	2.2.1.2 & 2.2.1.4 & 2.2.1.5	Combines three CICES divisions (wind protection, fire control and mass movement) as very rarely included specifically in sample texts.

R	Flood control	Protection or mediation of flooding.	2.2.1.3	Sub-division of CICES category related only to terrestrial systems flood defence.
R	Habitats	Maintaining habitats in the environment to support species life history and basic needs.	2.2.2.3	Sub-division of CICES category related to habitats. Split due to specific mention of nursery and juvenile populations of target species compared to general habitat services.
R	Microclimate	Control of temperature and humidity conditions	2.2.6.2	Matches CICES
R	Noise regulation	Mediation of nuisances. Noise attenuation.	2.1.2.2	Matches CICES.
R	Nursery	Regulation of nursery habitats for young or juvenile populations of interest	2.2.2.3	Sub-division of CICES category related to habitats. Split due to specific mention of nursery and juvenile populations of target species compared to general habitat services in the sample.
R	Pest control	Regulation of environment conditions through the control and mediation of pest species	2.2.3.1	Matches CICES
R	Pollination	Pollination	2.2.1	Matches CICES
R	Pollution control	Mediation, treatment, or removal of anthropogenic waste or chemicals in the environment by ecosystems	2.1.1.x	Matches CICES by combining two classes (bioremediation and other forms of treatment).
R	Soil quality	Regulation of chemical and structural condition of soils.	2.2.4.1/2	Combines two CICES classes related to the regulation of soils.
R	Water quality	Regulation of the chemical condition of water systems.	2.2.5.1	Matches CICES

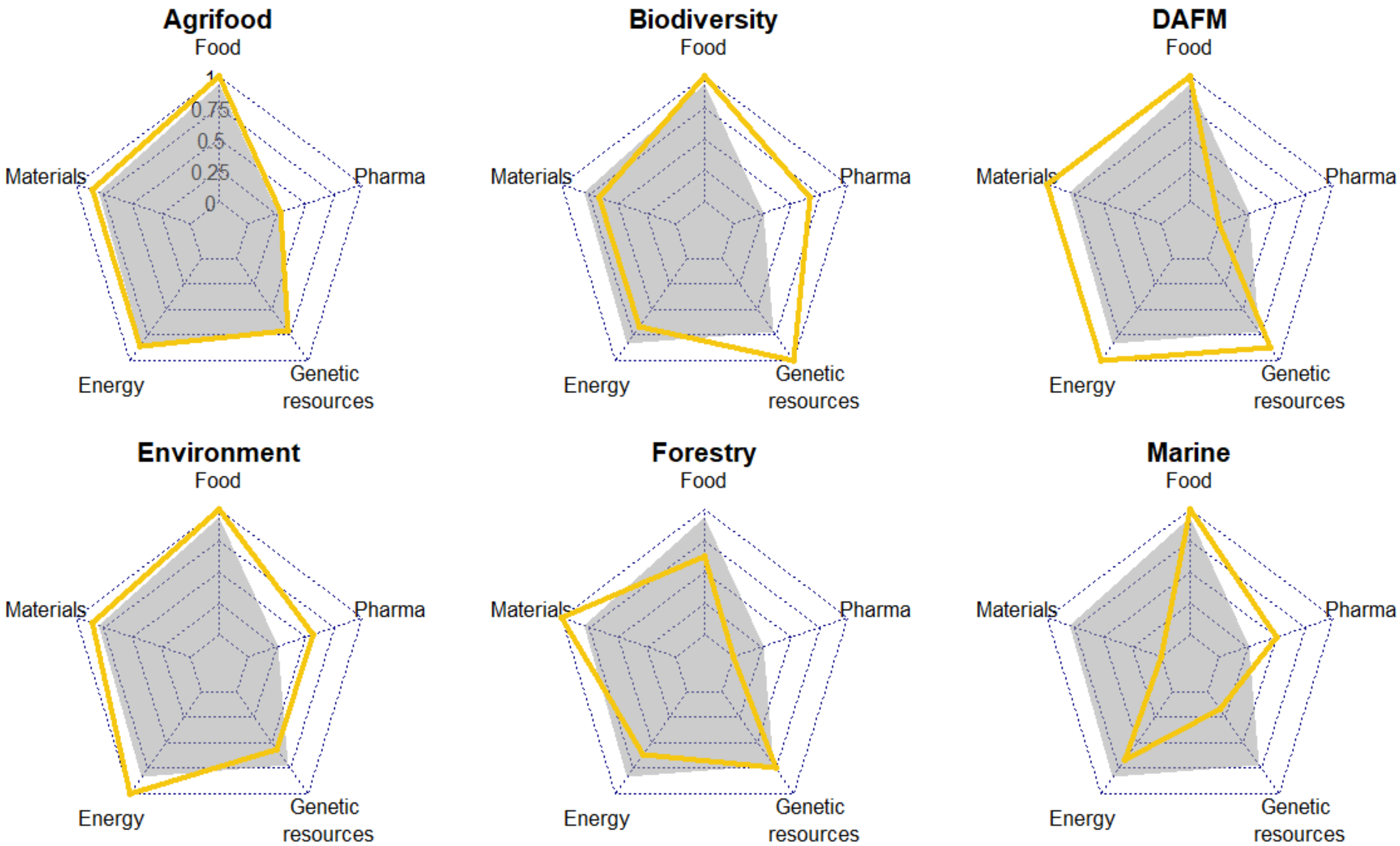

Figure A1: Radar plots showing the average inclusion of 5 provisioning ecosystem services within Irish policy documents (solid orange line) compared to the average of the entire sample (filled grey). Dashed lines represent 25% increments from 0 to 100% inclusion. DAFM refers to the Department of Agriculture, Food and the Marine annual reports.

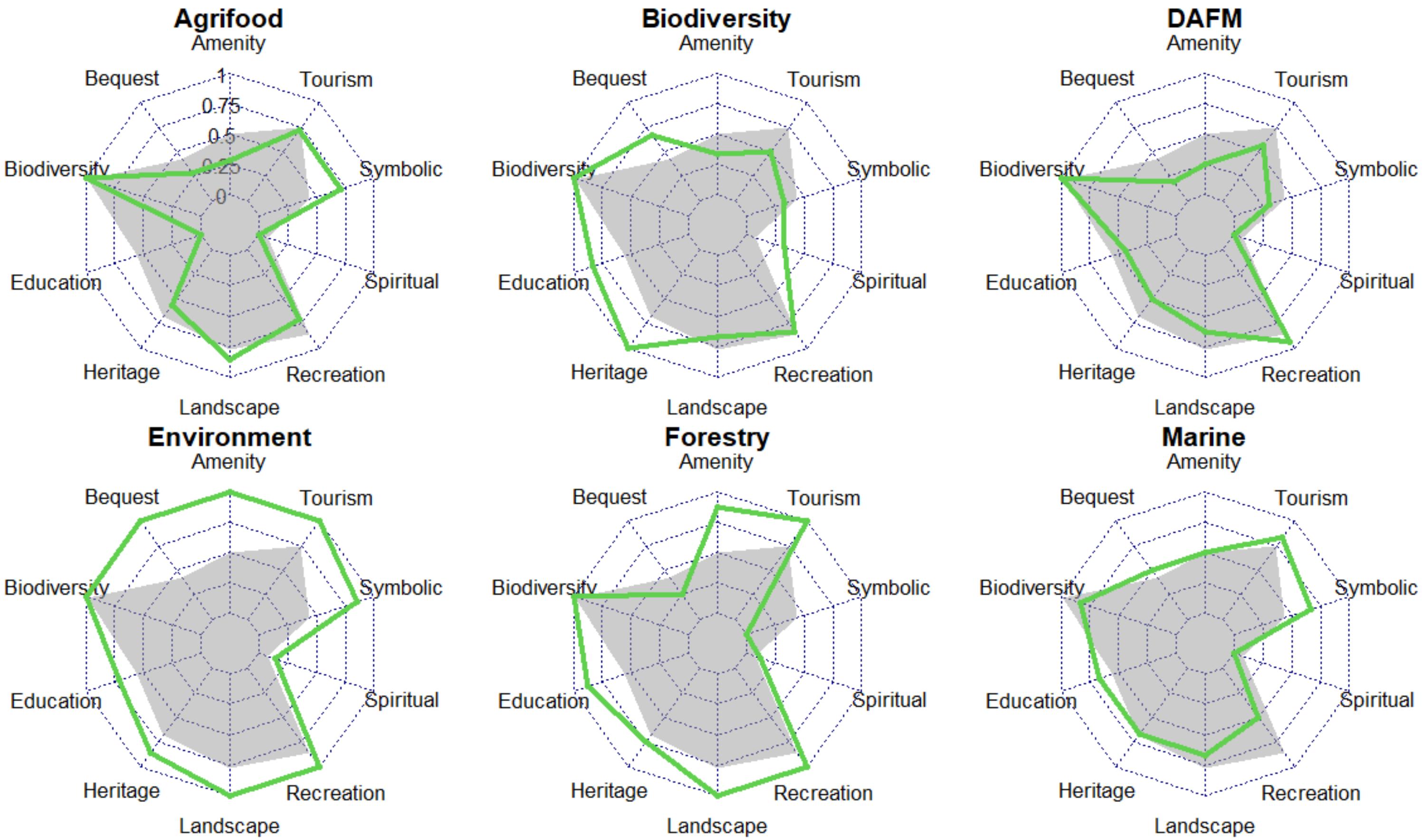

Figure A2: Radar plots showing the average inclusion of 10 cultural ecosystem services within Irish policy documents (solid green line) compared to the average of the entire sample (filled grey). Dashed lines represent 25% increments from 0 to 100% inclusion. DAFM refers to the Department of Agriculture, Food and the Marine annual reports.

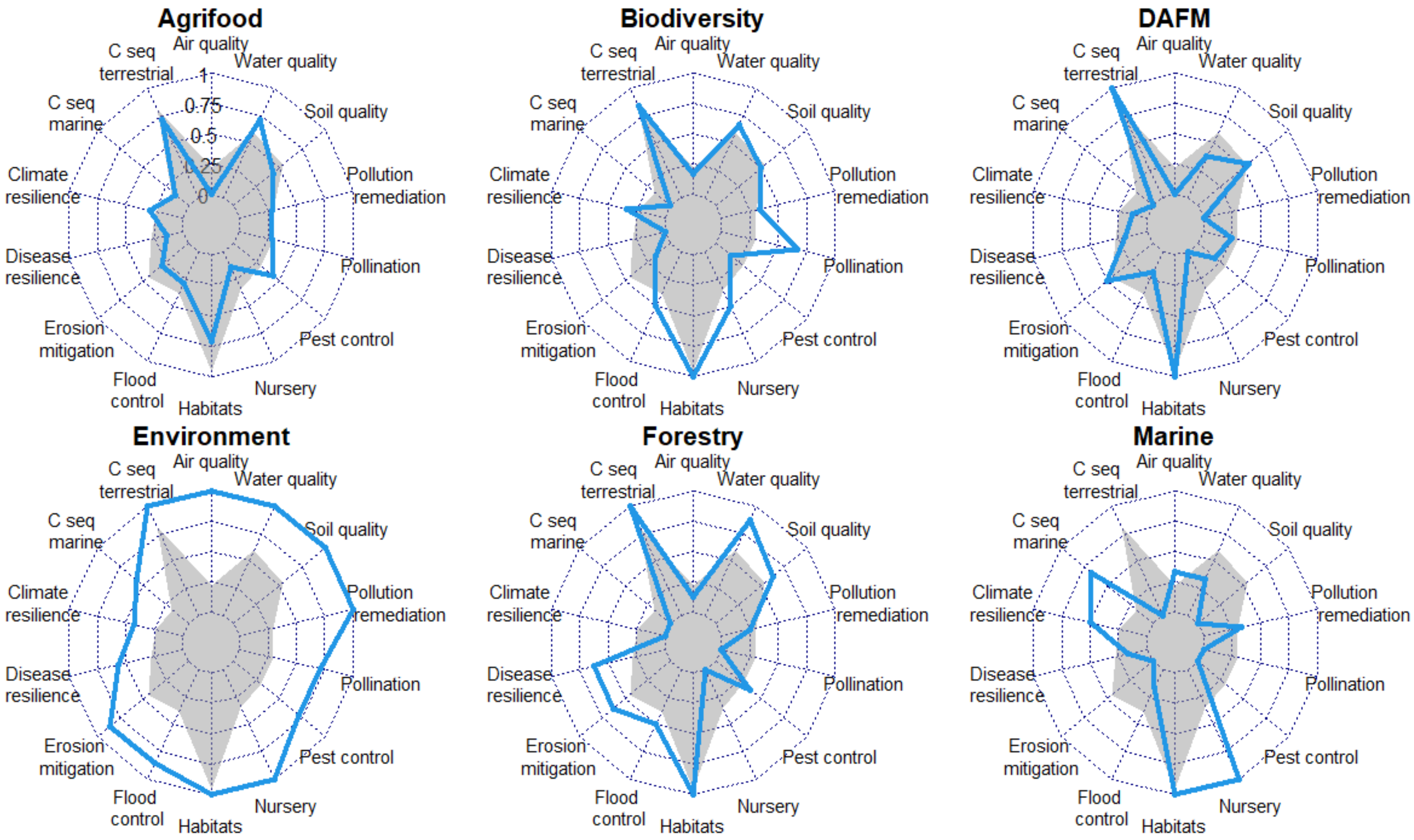

Figure A3: Radar plots showing the average inclusion of 14 regulating ecosystem services within Irish policy documents (blue) compared to the average of the entire sample (filled grey). The 14 most common services included of possible 20 for clarity. Dashed lines represent 25% increments from 0 to 100% inclusion. DAFM refers to the Department of Agriculture, Food and the Marine annual reports.

APPENDIX B | Supplementary material for Chapter 4

Table B1: List of 38 sites across Ireland and mean official visitor statistics used to validate the PUD social media indicator.

Site	County	Longitude	Latitude	Visitors
Aillwee Cave and Burren Birds of Prey	Clare	-9.1436674	53.0891282	116,890
Airfield	Dublin	-6.2369953	53.2881795	208,604
Belvedere House and Gardens	Westmeath	-7.369202	53.477197	134,215
Blarney Castle	Cork	-8.5707144	51.9291159	390,700
Bunratty Castle	Clare	-8.8119226	52.6995682	328,028
Castletown House	Kildare	-6.53029	53.349127	307,570
Clonmacnoise	Offaly	-7.9862945	53.3262773	143,547
Connemara National Park	Galway	-9.9455127	53.5506192	196,339
Doneraile Wildlife Park	Cork	-8.583008	52.2162916	472,030
Dublin Zoo	Dublin	-6.3052898	53.3561935	1,112,274
Duckett's Grove	Carlow	-6.8123156	52.8572812	63,546
Dun Aonghasa	Galway	-9.757413	53.129874	117,335
Farmleigh	Dublin	-6.3597857	53.3651921	376,838
Fota Wildlife	Cork	-8.3084214	51.8906645	419,230
Gallarus Castle	Kerry	-10.349411	52.172722	51,167
Glencar Waterfall	Leitrim	-8.37017	54.338177	76,895
Glenveagh Castle and Grounds	Donegal	-7.9685359	55.0360829	160,686
Grianan of Aileach	Donegal	-7.4278059	55.0238099	98,186
Hill of Tara	Meath	-6.611649	53.5788114	73,662
Irish national stud and gardens	Kildare	-6.9017749	53.1447762	119,451
JFK Arboretum	Wexford	-6.9337067	52.3209882	102,989
Johnstown Castle	Wexford	-6.5035972	52.2921747	63,645
Kilkenny Castle	Kilkenny	-7.2492979	52.6504624	301,802
Kilmacurragh gardens	Wicklow	-6.1478112	52.9292653	81,286
King Johns Castle	Galway	-8.6255223	52.669718	72,774
Kylemore Abbey	Galway	-9.8893127	53.5616392	487,531
Lough Key Forest Park	Roscommon	-8.2343938	53.9853501	90,254
Malaheide castle	Dublin	-6.164625	53.444904	152,916
Malin Head	Donegal	-7.3733878	55.3820014	140,111
Muckross House	Kerry	-9.5042922	52.0180827	238,984
National Botanic Gardens	Dublin	-6.27185819	53.37265435	572,034
Newgrange visitor centre	Meath	-6.4492874	53.6935317	107,246
Powerscourt House	Wicklow	-6.1866327	53.184251	323,360
Rock of Cashel	Tipperary	-7.8904522	52.5200763	305,837
Ross Castle	Kerry	-9.5314381	52.0412494	70,058
Russborough	Wicklow	-6.569867	53.14121	90,000
Sliabh Liag Cliffs	Donegal	-8.6847138	54.627438	160,773
Turlough Park	Mayo	-9.207509	53.883572	111,793

Table B2: InVEST parameters used for environmental indicator calculation within the model. For full details of InVEST model configuration, see (Sharp et al., 2018).

Variable ID	InVEST spatial statistic specified
Elevation	raster_mean
Slope	raster_mean
Population	raster_mean
Habitat diversity	raster_mean
Agriculture	line_intersect_length
Forest and Natural Area	polygon_area_coverage
Wetlands	polygon_area_coverage
River length	polygon_area_coverage
Water cover	polygon_area_coverage
Coast distance	raster_mean
Town distance	point_nearest_distance
Path Length	line_intersect_length
Geology distance	point_nearest_distance
Recreation distance	point_nearest_distance

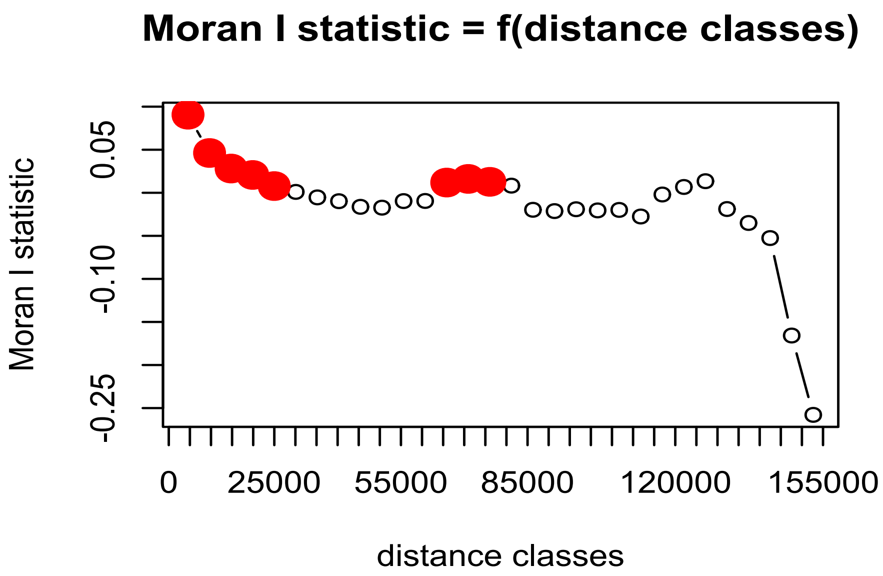

Figure B1: Moran's I correlogram of regional logistic model of PUD presence. Values shown in red show significance a $p < 0.05$ result and indicate spatial autocorrelation of the residuals. Computed using the pgirmess package in R studio.

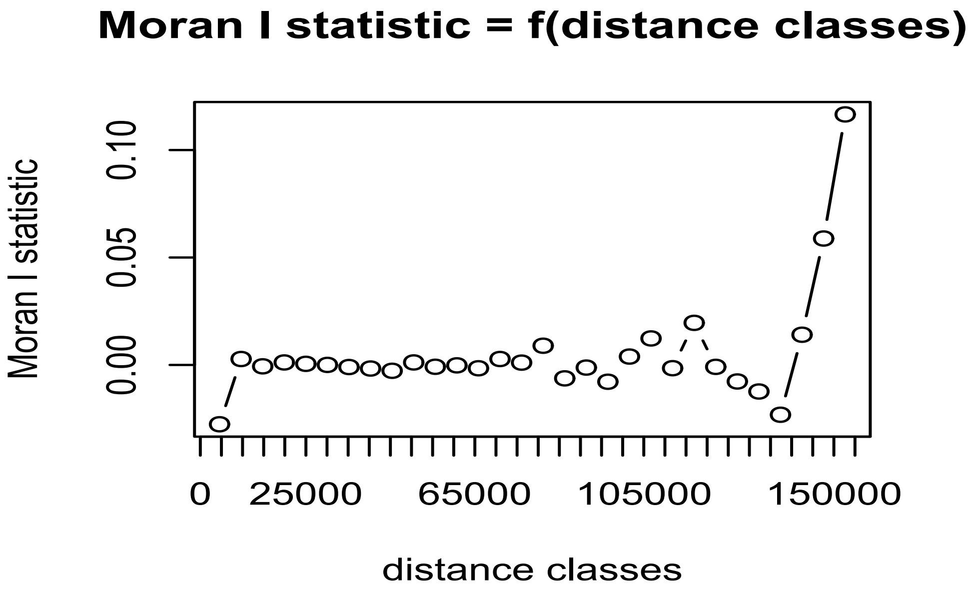

Figure B2: Moran's I correlogram of SAM model of PUD counts. No evidence of spatial autocorrelation was detected. Computed using the pgirmess package in R studio.

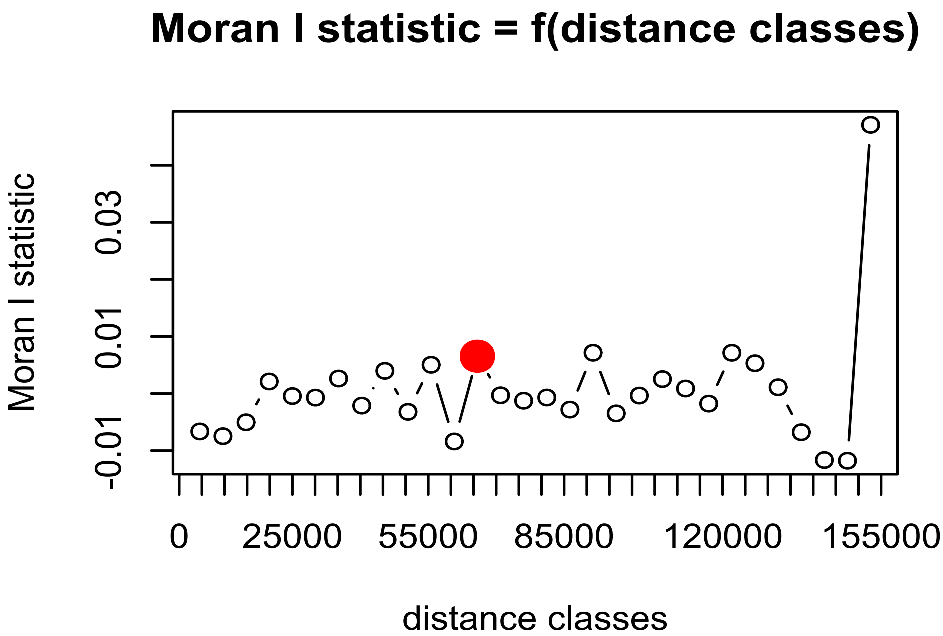

Figure B3: Moran's I correlogram of logistic GWR model of PUD presence. Result does not support spatial autocorrelation of the residuals. Computed using the pgirmess package in R studio.

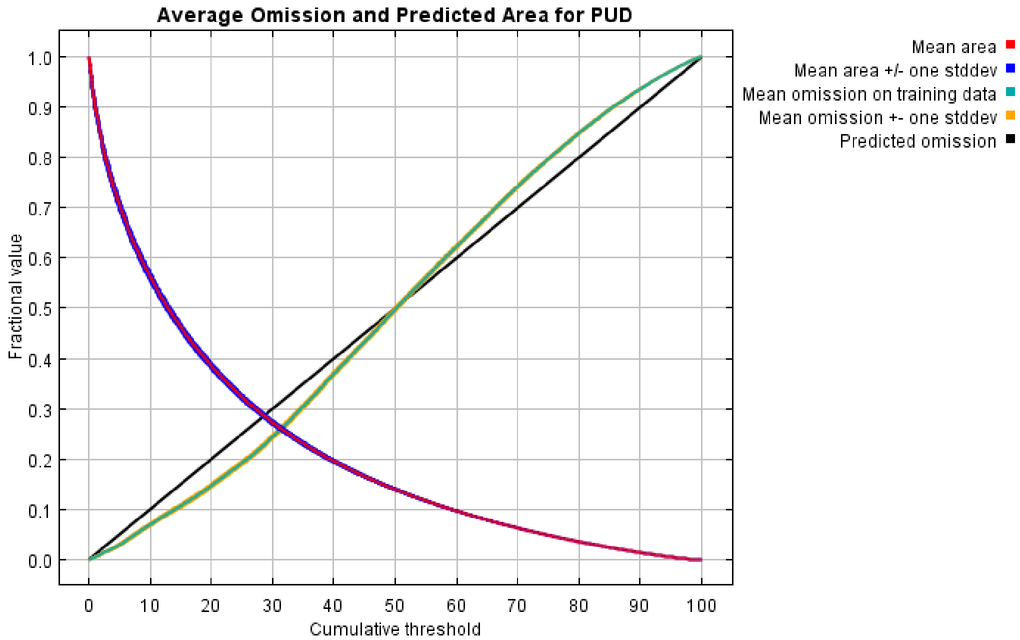

Figure B4: MaxEnt average omission and predicted area curve. MaxEnt model gain averaged across 100 bootstrap replicates of 75:25 training and test data partitioning.

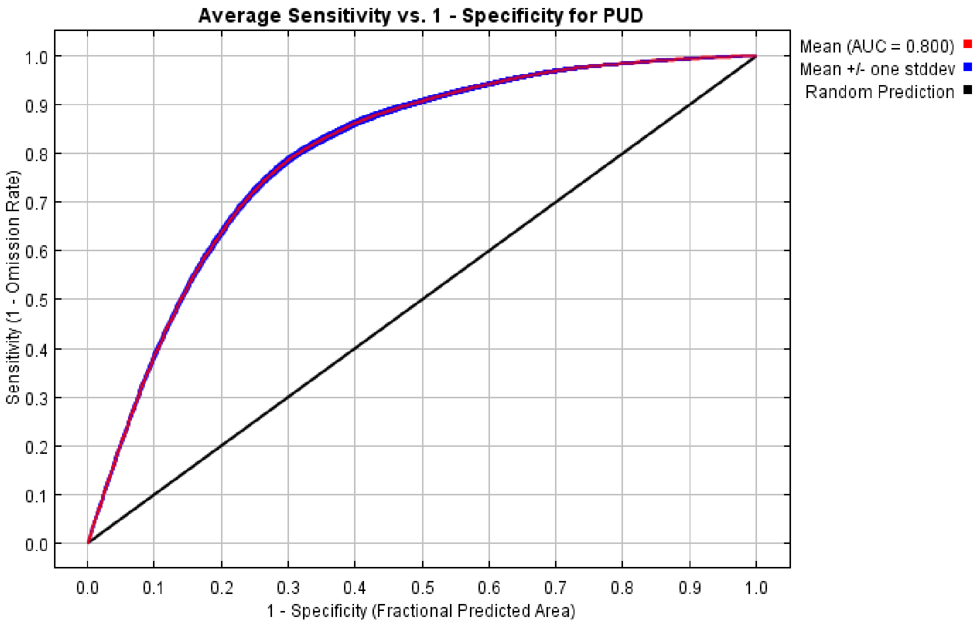

Figure B5: MaxEnt receiver operating curve plot averaged across 100 bootstrap replicates of 75:25 training and test data partitioning. AUC value of 0.8.

Figure B6: Response curve showing coastal distance variable.

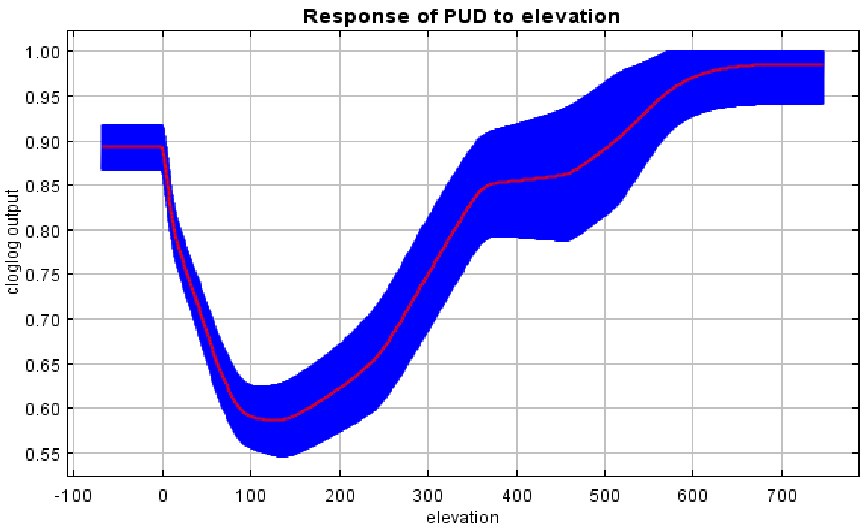

Figure B7: Response curve showing elevation variable.

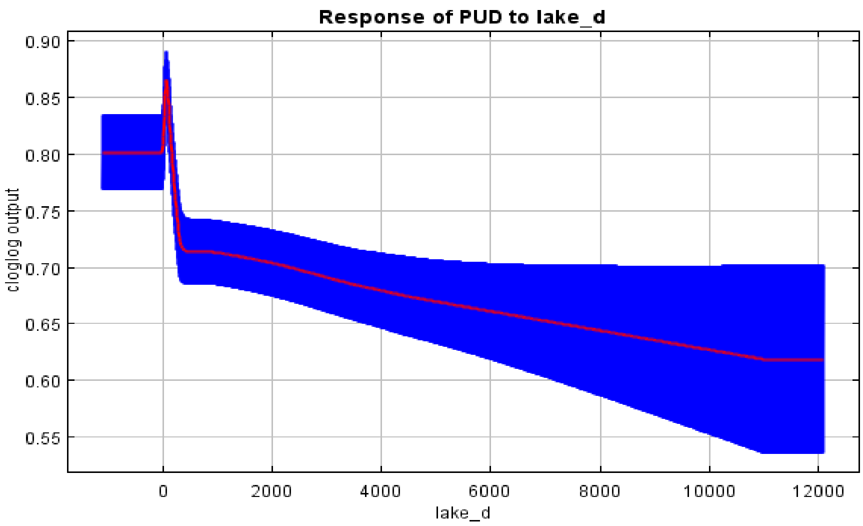

Figure B8: Response curve showing distance to lake variable.

Figure B9: Response curve showing distance to lake variable.

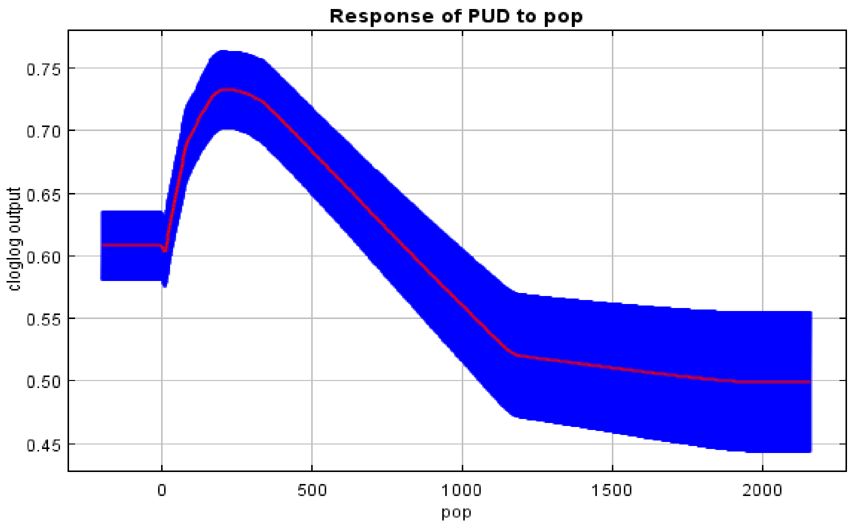

Figure B10: Response curve showing population variable

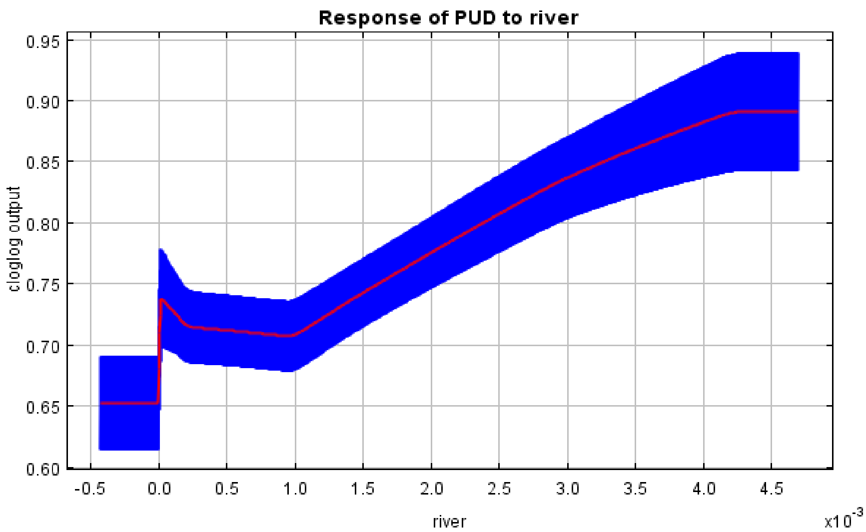

Figure B11: Response curve showing river length variable.

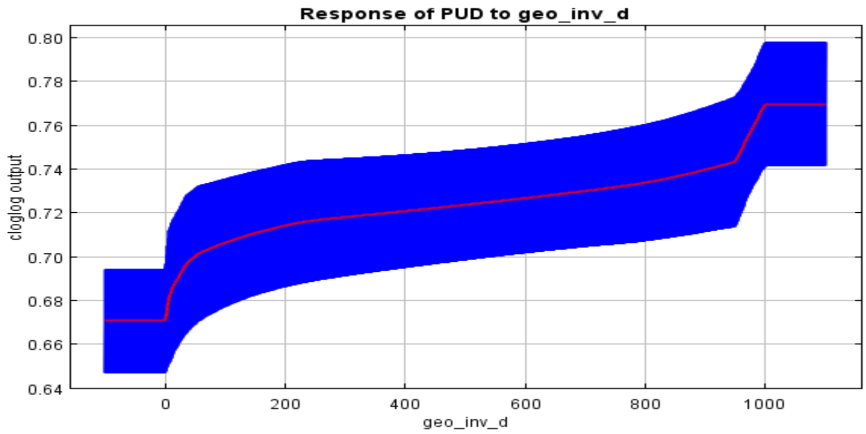

Figure B12: Response curve showing inverse distance to geological heritage (capped at 1000 m) variable.

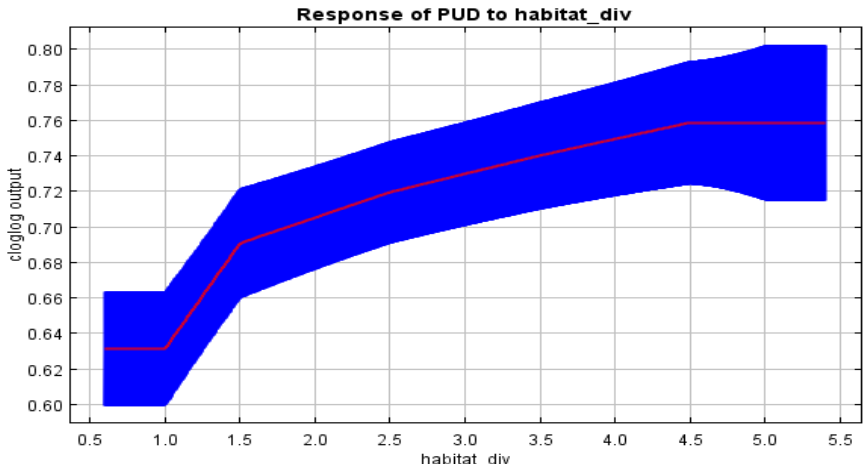

Figure B13: Response curve showing habitat diversity variable.

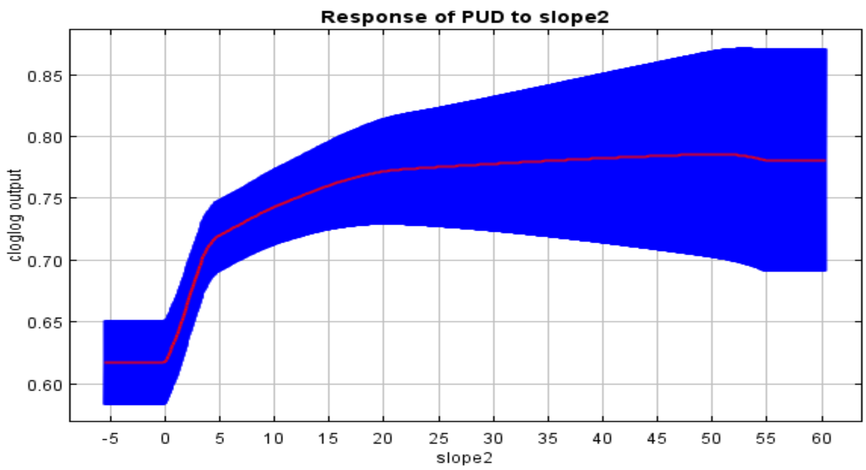

Figure B14: Response curve showing slope variable.

Figure B15: Response curve showing town distance variable.

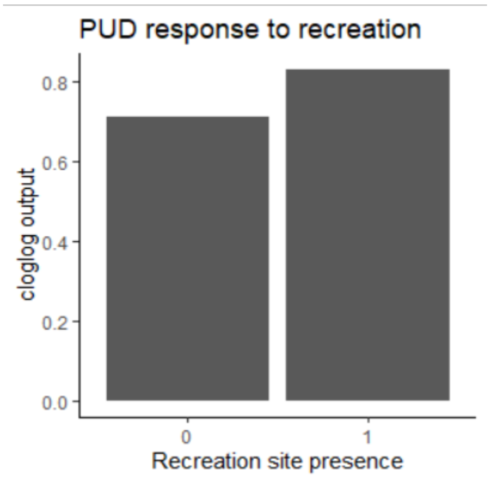

Figure B16: Response curve showing presence of recreational site variable.

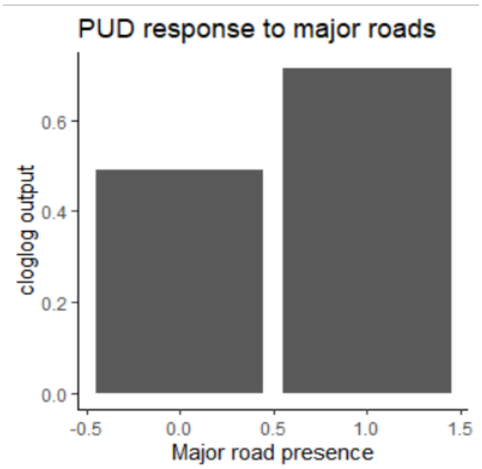

Figure B17: Response curve showing presence of major road variable.

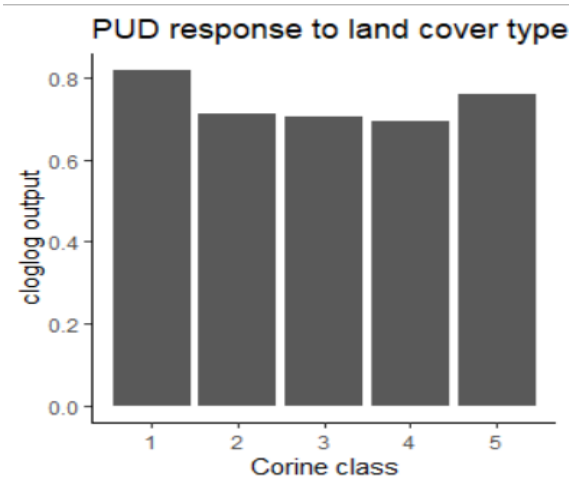

Figure B18: Response curve showing Corine land cover type variable. 1 = urban cover, 2 = agricultural, 3 = forest and natural areas, 4 = wetland, 5 = water cover.